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POTENTIAL FOR PROCESS TUBE BURNOUT
DURING TRANSIENT CONDITIONS

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April 22, 1960

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POTENTIAL FOR PROCESS TUBE BURNOUT DURING
TRANSIENT CONDITIONS

by

P. A. Carlson

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S. S. Jones

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1. INTRODUCTION

The potential for inadequate heat removal within a process tube which might result from accidental flow decrease or power level increase is of the utmost importance in evaluating reactor hazards. The events which might cause a flow decrease or power surge in a process tube are varied, and may generally be classed as 1) those that affect only a single process tube, and 2) those which affect all or a large portion of the tubes in the reactor. A great deal of time and effort have been devoted to the study of the flow, pressure, and temperatures within a process tube during events affecting single tubes. (1-5)

This report is an interpretation of these data as applied to the most severe (rapid) K-Reactor transients which are credible. These transients would result from such abnormal and improbable events as: 1) sudden power level surge, 2) primary power failure, and 3) sudden loss of flow from one or more pumps such as might occur in a pipeline rupture or pump shaft failure. Present reactor power levels and existing pumps are considered. The cases covered in this document assume the availability of secondary power in the case of BPA failure, and no loss of power for the pump loss and power surge cases. The extremely improbable case of loss of both primary and secondary power is the subject of another report. (10)

The transient conditions existing during these accidental events are more severe at the K-Reactors than those existing under similar transients in the other Hanford reactors. At the B, D, DR, F, H, and C Reactors no fuel channel burnout will occur during primary power failure or sudden loss of flow from one or two process pumps. Also, the potential for burnout in the case of a power surge is less than at the K-Reactors because of lower equilibrium power levels and because of greater assurance of early reactor scram due to a more rapid Panellit response to the increased pressures accompanying a power level increase. Therefore, this document reviews the K-Reactor transient burnout since it represents the most severe case.

2. SUMMARY AND CONCLUSIONS

The power level and coolant flow rate of the reactor are so coordinated that a factor of safety of greater than two exists between the actual heat flux and the heat flux at which film boiling at the surface of the fuel element could occur. However, during a transient condition the potential for burnout will change. The effects of these changes are considered in this report.

Analyses indicates that no fuel channel burnout will result from a BPA power loss to the process pumps. For the case of the sudden loss of a single K process low-lift or high-lift pump no burnout problem exists during six or five pump operation. For the extremely improbable case of the simultaneous loss of two process pumps some fuel channel burnout could occur. The fact that very severe flow reduction tests have been run in the laboratory without fuel rod burnout is very encouraging. However, a quantitative transfer cannot be made in all cases between the single tube laboratory results and the multiple tube reactor.

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In the case of a local accidental power level surge the Panellit system provides the primary protection against fuel jacket melting. An analysis by G. R. Parkos (unpublished) indicates that a 70 - 90% local power level surge is possible at the K-Reactors in the case of inadvertent withdrawal of a top control rod or accidental discharge of a top poison column. Although film boiling conditions are expected to occur in K process tubes at power level increases well below these values (28% for the 5-pump case, and 35% for the 6-pump operation), a Panellit gage high-trip is expected to shut the reactor down before jacket melting occurs. This is assured if there is no significant multiple tube effect. The occurrence of such a power surge incident would require a gross operating error or failure of a piping component which is not unduly stressed. Further control over the magnitude of power surges will be obtained from improved nuclear instrumentation scheduled for installation.

The future program in this area consists of continued periodic review of transient burnout conditions at the Hanford reactors in advance of increasing the severity of operating conditions. In addition, continued and expanded experimental studies are being made to evaluate total reactor as well as single tube events.

3. DISCUSSION

3.1 History of Burnout Protection

During normal reactor operation the cooling provided to a process tube is sufficient to remove large quantities of heat without experiencing high fuel element temperatures. With a reduction in flow or power increase these conditions are changed so that coolant boiling may occur in the process tube and rear fittings, which increases the pressure drop across the tube. At some value of flow reduction or power increase the coolant supply is inadequate to overcome the increased resistance to flow and the flow rate drops to a very low rate soon after the instant of change. If the reactor is not shut down when this unstable flow condition occurs, film boiling takes place on downstream fuel elements and jacket melting may occur because of the increased resistance to heat transfer. The Hanford problem in preventing boiling burnout, then, has been to operate the reactors to assure the stability of the coolant flow, and to shut down rapidly when conditions of inadequate flow occur.

Since the initial startup of the Hanford reactors, several methods have been used to specify process tube outlet temperature limits that assure

the stability of the coolant flow. Initially, the reactors were operated under excess header pressure limits. This required that sufficient front header pressure be available to yield a supply pressure 23% above the peak of the theoretical boiling curve. With this high pressure available the Panellit tube inlet pressure monitoring system was kept on automatic alarm and manual scram after 20 seconds. Thus, in the event of serious but temporary flow stoppages, the available process water pressures would be sufficient to sweep out any steam formed by boiling in the tube. The fallacy of this concept was that the flow interruptions may not necessarily be temporary in nature, and that unstable boiling, and possible fuel element melting could occur without automatic scram of the reactor.

With the installation of improved Panellit gages and the recognition of this situation, a new concept was developed that relied upon automatic reactor scram when Panellit trip limits were exceeded and at the same time eliminated the excess header pressure requirement. This led to the "trip-before-boiling limit" which was adopted after it had been shown that by rather simple changes in Panellit gage trip settings, tube power limits could be increased with greater safety than had been provided by excess header pressure limits with no automatic reactor scram. Reliance was placed on the Panellit gages to detect any type of flow reduction. These Panellit trip points were set so that a reactor scram was automatically initiated when the tube flow was reduced to a value slightly greater than that required to cause tube outlet temperatures to reach rear crossheader saturation temperature. Thus, it was thought that the flow rate which caused boiling at this point in the flow system was the instability flow rate. The next step, operation under "trip-before-instability" limits, was instituted when it was shown that the instability flow rate, or the flow rate corresponding to the minimum point of the boiling curve, was not the same as the boiling flow rate. Since the basic concern in the concept is instability, the boiling terminology was dropped, and limits were developed on the basis of instability. It should be emphasized that, conceptually, there is no difference between trip-before-boiling and trip-before-instability because they both rely on the Panellit gage to initiate a reactor scram at the time of an individual tube flow reduction. The only difference in the two is that some of the conservatism in the former limit was removed when further knowledge revealed that the reactor power levels were unnecessarily restricted by its use.

Further improvements in the pressure monitoring system and a considerable back-log of experimental data showed that this limit, too was extremely conservative. Currently the reactors are operated by the "trip-after-instability" limit. This limit is also conceptually the same as the earlier "trip-before-boiling" limit, and relies on the Panellit gage to detect flow reductions of sufficient magnitude to bring on unstable flow rates. The terminology is based on the fact that the laboratory data

which revealed the large amount of conservatism in the trip-before-instability limit also showed that even in the event of a partial flow reduction sufficient to cause boiling and flow instability the reactor could be safely scrammed. This occurs because pressurization from boiling in the tube outlet fittings will initiate a high pressure trip in time to prevent slug jacket melting. The terminology is, in fact, erroneous because low trip protection from rapid upstream plugging events is conservatively applied to trip before instability and the trip after instability remains as backup.

3.2 Present Status

3.2.1 Experimental Studies

A large number of experiments have been made in the Thermal Hydraulics Laboratory to determine the flow and pressure relationship which exists in a process tube during both steady-state and accidental transient operations at the K-Reactors.⁽¹⁻⁵⁾ These tests were made on a full scale model of a K-Reactor process tube, i.e., a ribbed tube, and an electrically heated simulated fuel column. Flow reductions were accomplished with the use of quick acting valves in the supply piping. From the steady-state experiments an estimate may be made of the instantaneous flow and pressure at the point where film boiling begins in the process tube and at the point of the initiation of flow instability. Most recent data are shown in Table I.

TABLE I
BURNOUT CONDITIONS IN A K REACTOR PROCESS TUBE*

Tube Power kw	Initial Flow gpm	Tube Temperature Rise, °C	% Flow Reduction to Initiate		
			Instability- Rapid Loss	Instability- Gradual Loss	Film Boiling
1000	36.1	105	24%	52%	67%
1250	47.4	100	19%	37%	67%
1500	54.2	105	16%	24%	63%

*Source: HW-54369 and HW-64029

NOTES: Supply pressure is constant at 325 psig.
Inlet temperature is approximately 20°C.
Graphite moderator sensible heat neglected.

These data, then, indicate the flow reduction at which unstable flow conditions are initiated in the tube as a result of either a gradual or rapid flow loss at a constant supply pressure. At a lower supply pressure these flow rates would be higher and instability would occur at lower percentage flow reductions. They also show the relationship between burnout conditions and the conditions at which flow instability is initiated in the process tube. Thus, a certain amount of time is available for shutdown, after flow instability starts in the process tube before burnout conditions are reached. The time sequence has been investigated in transient experiments in which the following types of individual tube events were covered:

- a) Plugging upstream of the flow measuring orifice or venturi.
- b) Plugging downstream of the active charge.
- c) Loss of front or rear pigtail.
- d) Loss of front header pressure such as the effect of a process pump failure or a process line rupture.
- e) Loss of pumping power.
- f) Tube power level surge above normal operating conditions.

These experiments generally have shown that with some flow and front crossheader pressure available following the reactor scram adequate heat transfer conditions will exist. The demonstration of adequacy stems from observations that surface temperatures of the heater rod do not exceed the melting point of aluminum. Single tube events as severe as an instantaneous 80% reduction in flow at 1250 KW power level have been investigated and the data show that film boiling will not occur in a K-Reactor fuel channel as long as the Panellit gage scrams the reactor within 3 to 5 seconds after the flow loss.

These are very severe conditions and their cautious application to the total reactor would indicate that the reactor could handle a sudden decrease in flow of up to 15% without fuel burnout or serious reactor damage. Caution is indicated primarily because in a total reactor flow reduction a large number of high power tubes are involved in the transient, and the effect of parallel channel flow on burnout conditions has not been determined.

3.2.2 Analytical Methods

For constant water-film coefficient and fuel physical properties, strictly theoretical solutions have been developed for the fuel temperatures as a function of time after a reactor scram. These generally yield a summation of Fourier and Bessel Function series solutions. However, for the case of variable water film coefficient and two-phase flow no strictly theoretical solution is known by the authors. It is possible, by means of an

iterative method and machine calculations to obtain a reasonable approach to actual conditions in most cases.

In general, there are two cases of concern:

- a) Sub-cooled burnout of a fuel element at high heat flux, and
- b) Unstable boiling followed by a rapid flow decrease leading to film boiling and fuel channel burnout.

In the case of sub-cooled burnout, the heat flux (heat leaving the fuel surface per unit area, q/A), is a function of:

- 1) The local coolant pressure,
- 2) The amount of sub-cooling, i.e., coolant boiling temperature minus the coolant local temperature,
- 3) The coolant velocity, and
- 4) The coolant channel equivalent diameter.

A recent report⁽⁶⁾ presents an empirical equation, based upon many different burnout studies on uniformly heated geometries, in the form:

$$(q/A)_{B.O.} = \alpha \frac{(1 + \beta_0 T + \beta_1 T/D)(1 + \gamma_0 V + \gamma_1 V/D)}{1 + \delta/D} \quad (1)$$

Where: $(q/A)_{B.O.}$ = probable burnout heat flux, MW/ft²

T = Amount of sub-cooling ($t_{\text{saturated}} - t_{\text{bulk}}$) at given channel position - °C.

D = Equivalent channel diameter - ft.

V = Coolant velocity - ft/sec.

and $\alpha, \beta_0, \beta_1, \gamma_0, \gamma_1$, and δ , are corre-

lating functions given in the report as a function of local coolant pressure.

Based upon a study of the data spread in this correlation it is concluded that 60% of the value calculated in Equation (1) represents a conservative limiting reactor heat flux. This correlation was applied to experimental runs on the K geometry made in the Hanford Thermal Hydraulics Laboratory with the following results.⁽⁷⁾

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Flow gpm	Bulk Temperature °C	Pressure psig	(q/A) Exp. BTU/hr ft ²	(q/A) Calc. BTU/hr ft ²
50	93.2	25	1.25 x 10 ⁶	1.26 x 10 ⁶
20	93.2	25	0.83 x 10 ⁶	0.82 x 10 ⁶

Where $q/A \text{ calc.} = .60 (q/A)_{BO}$ from Equation (1).

The reference describing the Hanford burnout tests (7) pointed out that although these burnout heat fluxes were evidenced by a rise in heater rod temperature, the temperatures were not extreme and stable operation continued without melting of the heater rods. In the 20 gpm case, for example, operation was stable at 1,000,000 BTU/hr ft² and maximum measured rod temperatures were 593°C which is below the melting temperature of aluminum. Thus, these limited data indicate that 60% of the value obtained from Equation (1) gives conservative estimates of sub-cooled burnout conditions in Hanford reactor geometries.

In the case of flow instability the situation is even more empirical than for sub-cooled burnout. In this range, however, there is a great deal of laboratory data which has been used to establish burnout conditions. From these data an empirical technique has been developed which conservatively predicts the point where unstable flow conditions are initiated in a process tube. This technique employs "boiling curves" which are plots of inlet pressure versus flow or outlet temperature for any particular hydraulic system but at constant power, inlet temperature, and discharge pressure. It represents a hydraulic system demand curve in that it gives the pressure required to maintain a given flow rate regardless of supply characteristics. The relationship between the supply characteristics and the boiling curve determine the flow conditions which exist in the tube. This is described more fully in the Appendix. A method for calculating boiling curves which give conservative values of the flow rate where unstable flow begins has been described by McEwen and Batch.(8) The method is based on the principle that in the Hanford hydraulic system, the maximum possible increase in pressure drop due to boiling is that corresponding to a hypothetical increase of the discharge duct pressure just sufficient to quench boiling. Thus, tube inlet pressures are calculated by adding together the single phase pressure drop across the active and dummy sections of the tube and the discharge pressure necessary to prevent boiling at the tube exit. Calculated on this basis, the curves provide pressures which equal or exceed the actual pressures associated with any flow rate in the K geometry. This is confirmed by comparisons with experimentally determined boiling curves. The method calculates tube inlet pressure by the following expression:

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$$P_F = KF^{1.8} + (\uparrow) P_R \text{ or } P_{STO}$$

Where P_F = Tube inlet pressure, psig.

P_R = Discharge duct pressure, psig.

K = Proportionality constant depending on the geometry of the system.

F = Flow rate at tube inlet, gpm.

P_{STO} = Saturation pressure corresponding to the tube outlet water temperature.

($\uparrow$) = Indicates "whichever is greater".

Using this technique a boiling curve may be constructed such as shown in Figure 1, in which the tube inlet pressure required to maintain a given flow at constant power, tube inlet temperature, and discharge pressure is plotted as a function of the square of the flow rate. Plotted in this way the supply curves may be shown on the same plot as straight lines. The relationship between the supply and demand curves determine the instantaneous flow-pressure conditions which are present in the tube. With reference to Figure 1,* the intersection of the normal supply curve FA with the demand curve at (A) gives the normal equilibrium operating point. The supply pressure at zero flow is the front header pressure (F).

When the operating point (A) falls on the straight section of the boiling curve the flow is all in the liquid phase. As the flow is reduced the pressure required decreases as a function of the liquid-phase pressure drop. The boiling curve deviates from this straight line when boiling begins in the rear fittings. As the flow is further reduced increased amounts of steam are formed until a minimum point is reached on the boiling curve where the increase in pressure drop due to steam formation just balances the decrease in pressure drop due to liquid-phase pressure drop. With further decreases in flow, boiling progresses farther upstream towards and into the active section and the pressure rises sharply.

The effect of a sudden flow loss is evaluated by using line AR which approximately represents the flow-pressure relationship at constant outlet water temperature. With a rapid flow decrease, the outlet water temperature remains constant for the few seconds required for boiling to occur in the rear fittings to cause a rise in pressure and further decrease in flow shown at the intersection of the new supply curve with the boiling curve. If after a flow reduction the pressure available exceeds the pressure required to

* See Page 14.

maintain that flow constant the flow is stable. Any flow greater than that at point B in Figure 1 is a stable operating point. Point B is the point of incipient flow instability, or the flow at which instability is initiated at the supply pressure shown for a rapid flow loss. At a higher supply pressure this point occurs at a lower flow. At flow rates below this value the supply pressure is not sufficient to overcome the increased resistance to flow due to boiling and the flow suffers a further self-induced rapid reduction to very low values where fuel burnout can occur if the reactor is not shut down shortly after the instant of change. Thus, the reactors must be operated so that conditions of inadequate flow are immediately detected initiating a reactor shutdown.

3.2.3 Transient Events with Potential for Burnout

Under steady-state equilibrium operation, the limitation of no bulk boiling supplies ample protection against fuel burnout. For the usual reactor scrams the power level is reduced before the reactor flow and the burnout potential is continuously reduced during such transients.

The significant reactor events which under improbable conditions could lead to fuel burnout are the following:

- 1) Electrical power failure to the process pump motors.
- 2) Loss of a pump shaft or rupture of a process lines.
- 3) Reactor power level surge such as could be caused by the inadvertant complete withdrawal of two control rods at maximum speed.

Laboratory data have shown that no fuel burnout will occur at flow rates greater than the flow at which unstable flow occurs in the process tube. Even after flow instability, a finite time exists before film boiling occurs, depending on the severity of the flow reduction and initial power level. The potential for burnout while the water is sub-cooled is very low because the cosine heat distribution along the charge means that the heat flux is less than 200,000 BTU/hr ft² at the location of near saturated conditions. A comparison between the operating heat flux and the sub-cooled burnout heat flux under various conditions is shown in Table II. At an equilibrium level of 1500 kw/tube a safety factor of 2.4 is calculated. Under emergency transient conditions, and assuming the conditions existing at the worst time during the transient are in the steady-state to make the calculations, Table II shows that sub-cooled burnout conditions will not be exceeded. It is concluded that sub-cooled burnout will not occur at the K-Reactors under emergency transients. These data further indicate that sub-cooled burnout will not be a problem in Hanford reactors until power levels are considerably above present levels. The problem of boiling burnout associated with flow instability represents the prime hazard.

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Flow Instability

Based upon laboratory data a series of charts have been prepared showing the relationship between cooling demand and the coolant supply pressures following various accidental K-Reactor incidents. Figure 1 shows the potential for flow instability in K-Reactor process tubes following a BPA power failure for either 5 or 6-pump operation. A maximum power level of about 1250 kw will be obtained with 5 pumps when the inlet temperature is 20°C. The present peak power with 6-pump flow is 1500 kw based on fuel element rupture behavior. The supply curves in Figure 1 give the pressure available as the flow decays following the loss of pumping power. The demand curve gives the equilibrium pressure required at various reactor flow reductions to maintain flow at the new value. The isothermal line (AR) shows the approximate decrease in flow due to a sudden loss. An additional decrease in flow due to boiling pressurization in the rear fittings after a step flow decrease is shown by the intersection of the new supply curve with the steady-state demand curve.

TABLE II
APPROACH TO SUB-COOLED BURNOUT CONDITIONS DURING
TRANSIENT OPERATION AT K-REACTORS

<u>Operating Condition</u>	<u>Tube Flow (gpm)</u>	<u>Tube Power (kw)</u>	$(q/A)_{\text{Max.}}^{(1)}$ <u>(MW/ft²)</u>	$(q/A)_{\text{B.O.}}$ <u>(MW/ft²)</u>	$\frac{q_{\text{Max.}}^{(2)}}{q_{\text{B.O.}}}$
Equilibrium Operation	58	1500	.17	.42	.41
BPA Failure ⁽³⁾	49	1500	.17	.35	.49
Loss of One Pump ⁽³⁾	47	1500	.17	.30	.57
Loss of Two Pumps ⁽³⁾	35	1500	.17	.20	.85
50% Power Surge ⁽³⁾	58	2250	.25	.34	.74

- (1) Maximum operating heat flux at point of closest approach to sub-cooled burnout conditions in tube.
- (2) Ratios greater than 1.0 indicate sub-cooled burnout conditions have been reached.
- (3) Calculations made at point in transient where burnout heat fluxes are at their lowest values. A 3 second interval between initiation of transient condition and reactor scram was assumed.

The figures are for the initial period where the reactor flow is decreasing at a constant reactor power level, before an effective scram has been achieved. The criterion for conditions of stable

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flow are that the supply curves do not fall below the minimum point on the steady-state demand curve before the instant of effective reactor scram. The sharp drop in heat generation following the scram will assure that the supply exceeds the demand thereafter. As shown in Figure 1, if the reactor is effectively scrammed within 4 seconds after BPA failure in the case of either 5 or 6 pump operation, flow instability will be avoided. In the actual case, a scram is effective following a BPA failure after about 2 seconds.

It should be pointed out that flow instability does not necessarily mean channel burnout. A finite time exists between the onset of instability and the onset of film boiling in the process tube.

Figure 2 shows the effect of a line rupture or pump shaft failure on flow instability. Under these conditions the total flow change occurs within one second while the reactor would not be effectively scrammed for two seconds. The scram would be initiated in less than one second after the instant of change through a low Panellit gage trip. Consequently, the new supply curve must be higher than the minimum point on the demand curve to avoid flow instability. This corresponds to a maximum flow decrease of 18% for 5-pump operation and 21% for 6-pump operation. As shown in Figure 2, loss of flow from one pump can be sustained without experiencing unstable flow conditions in any process tubes, while loss of two of five or two of six leads to flow instability in many reactor channels. It should be stressed that this does not mean that boiling burnout would occur under these conditions.

Recent laboratory tests have been run wherein the inlet flow line to a simulated K fuel channel was suddenly opened.⁽³⁾ This reduced the inlet pressure to zero psig and fuel cooling was obtained by back flow with a pressure driving force of 16 to 38 psi. Under these test conditions no fuel burnout was obtained at rear header pressures in excess of 30 psig.

The loss of reactor pump-sets reduce the header-to-header pressure drop down to the values shown below:

- a) One of six pumps: 300 psi.
- b) One of five pumps: 177 psi.
- c) Two of six pumps: 187 psi.
- d) Two of five pumps: 120 psi.

The driving force in all of these cases is well above that required experimentally to prevent fuel burnout. These experimental tests must be qualified to the following extent:

- a) K-Reactor central tube powers are up to 1500 kw (with 6 pumps) and these tests only went up to 1000 kw.

FIGURE 1
—K REACTOR BPA LOSS—
EFFECT ON FLOW INSTABILITY AT CONSTANT POWER

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FIGURE 2

--K REACTOR PUMP LOSS--

EFFECT ON FLOW INSTABILITY AT CURRENT POWER

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- b) The heat supplied to the coolant amounted to only about 55 to 70 percent of that expected in the reactor.
- c) The onset of hydrodynamic instability between parallel fuel channels in the reactor might cause burnout in one or more channels when average conditions are safe. (Parallel channel flow is being studied to evaluate this potential.)

Therefore, it appears prudent to operate in a manner that will prevent our reaching the condition of unstable flow in any fuel channels.

The third type of event, the effect of a power level surge on instability is shown in Figure 3. Here, there is only one supply curve and the demand curves increase with power level. The criterion for stable flow conditions is that the reactor be shut-down before the supply curves fall below the minimum point on a steady-state demand curve. Figure 3 shows that unstable flow conditions are initiated after more than a 28% power increase for the 5-pump case, and more than 35% increase for 6-pump operation. It is expected that boiling pressurization plus the effect of reduced flow rate caused by the increased boiling will initiate a high Panellit trip before unstable flow conditions are reached. However, the time sequence of this transient is not known, and the power level will continue to increase after detected by a Panellit gage for the 2 to 3 seconds required for effective shut-down. If the surge is large enough and sufficiently rapid, flow instability could occur in a few tubes during the 2 to 3 second interval required to effectively scram the reactor after reaching high trip conditions. An analysis by G. R. Parkos indicates that a local power level surge as high as 90% may occur if two top control rods were inadvertently withdrawn and the reactor not shutdown. This may occur because the Beckman flux monitor chambers which are normally expected to detect this situation are situated in the bottom of the reactor and are shielded by other control rods and poison columns from seeing all but a small portion of the power increase.⁽⁸⁾ Even under these extreme conditions it is expected that the Panellit system will initiate a reactor shutdown in time to prevent fuel jacket melting. Again, uncertainty arises as to possible multi-channel effects. The occurrence of a power surge requires a gross operating error or the highly improbable event of loss of a rear cap on a poison column tube which will permit the poison column to discharge. Also, the installation of improved nuclear instrumentation is scheduled which will reduce the magnitude of possible power level surges below those which initiate unstable flow conditions in individual process tubes.

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—K REACTOR POWER SURGE—

EFFECT ON FLOW INSTABILITY AT CONSTANT POWER

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3.2.4 Research and Development Programs

The laboratory work on this general problem is continuing. A major laboratory modification project has been completed that permits power level increases from the present limit of 1250 kw up to a maximum of 2500 kw. Studies to be conducted in the coming fiscal year include the following:

- a) Investigation of the effect of the loss of a front connector, i.e., low tube power, reverse flow studies of the K-Reactor geometry.
- b) Steady-state and transient boiling curves for the K geometry at the higher tube powers.
- c) Effects of loss of flow through plugging upstream of the Panellit gage.
- d) Definition of conditions leading to sub-cooled heat transfer burnout for all reactor geometries including the effects of eccentric slug loadings and non-uniform heat flux.

This program is mainly directed towards single tube incidents. Although the probability of a single tube incident appears considerably greater than a total reactor event, the potential hazards of the latter are very much greater. Therefore, laboratory studies will include investigation of the following events:

- a) A rapid reduction in front header pressure by means of the programmed opening of a by-pass valve.
- b) A programmed rapid increase in power level at constant front header pressure.
- c) Investigation of the possible aggravation of channel flow instability caused by parallel channel dynamic effects.

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APPENDIX

Discussion of Typical Boiling Curves

In the past several years the laboratory forces in the Thermal Hydraulics Unit have obtained some very valuable data on the flow transients that accompany sudden imposed flow reductions with the fuel channel maintained at constant power level. Before translating these to the reactor, it is in order to summarize the flow instability problem and how it is handled at Hanford.

Let us examine the relationship between the flow supply or pressure available to a process tube and the pressure required to maintain a given flow rate constant at a given tube power. Consider the curves shown below in Figure A-1.

The boiling curve represents the pressure required for the indicated flow rate at constant power, inlet water temperature, and discharge pressure. When the operating point (A) falls on the straight section of the boiling curve the flow is all in the liquid phase. As the flow is reduced the pressure required goes down as the liquid-phase pressure drop is reduced at lower flow rates. The demand curve deviates from this straight line when boiling begins in the rear fittings. As the flow is further reduced increasing amounts of steam are formed as boiling progresses farther upstream from the rear fittings. At point (B) the decrease in liquid phase pressure drop is balanced by the increase in two-phase pressure drop due to boiling in downstream sections of the system. With further decreases in flow, boiling progresses toward and into the active section and the pressure rises sharply

until a peak pressure is reached. At this point the higher pressures reduce the rate of coolant volume increase associated with boiling and further reductions in flow result in a decreased pressure requirement.

The line (FA) represents the normal supply characteristics or pressure available to the process tube as a function of flow. The intersection of the supply line with the demand curve defines the process-tube normal operating pressure and flow. To be stable the intersection must be such that if the flow rate were to be decreased slightly, more pressure would be available than required, and the rate would return to its previous value. Continued stable operation with different degrees of boiling in the tube is possible only if such a stable operating point exists. If the pressure available is less than pressure required as shown by supply line (FC), no stable operating point exists except at very low flow rates (point D) and the flow rate suffers a further self-induced reduction to point (D). Although (D) represents a stable operating point, high steam qualities are present in the tube and unless the reactor is shutdown heat transfer burnout occurs. This self-induced flow reduction is known as flow instability, which will lead to fuel element melting if the reactor is not rapidly shutdown when it occurs in a single tube in the reactor.

Application to Process Tube Protection

As shown above, it is possible to identify conditions of adequate and inadequate flow on the basis of general regions of the boiling curve. It is possible further to detect the transition from one region to another by high or low inlet pressure trips to scram the reactor when conditions of inadequate flow occur. The rapid reduction in power generation following the scram restores adequate single phase cooling and fuel element melting is prevented. This is accomplished at Hanford by measuring the pressure at the throat of a venturi or orifice located between the front crossheader and the tube inlet nozzle with a Panellit gage. Disturbances in flow or power are indicated by either a high or low pressure reading. Instrumentation is set to trip the reactor whenever the pressure indication exceeds the set points by a certain amount.

It is, of course, extremely important that the Panellit gages and associated circuitry be reliable, "fail-safe", and responsive to changes in pressure. Laboratory tests have shown that the gages adequately perform this function. Gage response is not too critical in the case of plugging events downstream of the Panellit tap because the increased pressure losses associated with two-phase flow supplement the added pressure loss from plugging and causes the Panellit pressure to increase. The case of sudden plugging upstream of the Panellit trip is of more concern. In this case the pressure is first reduced depending on the degree of flow reduction, and then, in the case of flow reductions beyond the point of instability, increases rapidly as the amount of boiling increases at the tube outlet. If this increase in pressure is rapid enough or the gage sluggish a low trip may not occur. However, laboratory data have shown that the rapid pressurization results in a high trip in sufficient time to prevent burnout even if the low trip does not occur for the upstream event.

Panellit trip settings are applied so that a high pressure trip will occur at or before conditions of flow instability are initiated in the process tube in the

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event of a flow restriction downstream of the point of pressure measurement. The most probable event for which these trip settings are needed is the swelling of a fuel element failure. Low trip settings are established to initiate a reactor shutdown at or slightly beyond the point of flow instability initiated by a rapid flow reduction caused by a disturbance upstream of the point of pressure monitoring. In both cases, the trip will occur in sufficient time that if some flow and front crossheader pressure is available after the shutdown, adequate cooling will be supplied to the process tubes to prevent fuel element jacket melting.

A large safety factor exists in these instability limits through the assumption that plugging occurs just to the point of instability because more severe plugging would result in a greater drop in Panellit pressure, and from the fact that laboratory experiments have shown that the reactor scram can safely be delayed until after instability occurs in the process tube and the reactor shut down by a high pressure trip. Thus, the high trip provides backup to the low trip for most cases of upstream plugging.

To verify that reactor scram settings do indeed protect against fuel jacket melting requires a knowledge of the pressure-flow relationship as a function of time or transient experimentations. Transient experiments simulating sudden plugging upstream of the point of pressure monitoring have been run at tube powers up to 1250 kw and 125°C outlet temperatures for flow reductions to 3 gpm. A typical flow chart is shown in Figure A-2. The time curves were plotted from pressures obtained as a function of time following given flow reductions holding the front header pressure constant. For example, for an initial flow reduction to point (0), instability occurs in the process tube. There follows a self-aggravated flow reduction to the film boiling condition which is a stable operating point. Immediately following the applied flow reduction the pressure is shown by the intersection of the plugged supply line (FO) and the intersection of the zero second line. Similarly, the pressure-flow relationship is shown for various other times after the flow reduction. A film boiling condition is shown to occur about seven seconds after the flow loss. A flow reduction in which a loss of front header pressure also occurs is shown by the supply line F'O. This roughly represents the case of loss of two pumps at 5-pump operation. The effect of also reducing the front header pressure is evident in the decreased time to reach film boiling. Also, these data indicate that a low trip must occur to prevent damage for there may not be sufficient pressurization to also cause a high trip. However, in an incident such as this which effects a great many tubes, it is inconceivable that all Panellit gage low trips will be inoperative. Although a trip is assured, film boiling will probably take place in some tubes and, thus, the chart indicates that some fuel damage may occur in severe incidents of this type if there is a significant multi-channel effect. Further data of this type will be obtained to investigate flow reductions in which a decrease in front header pressure occurs.

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