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December 11, 1960

TITLE

LABORATORY DATA FOR REVIEW OF OUTLET WATER
TEMPERATURE LIMITS FOR BDF TYPE REACTORS

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AUTHOR

E. D. Waters
D. E. Fitzsimmons

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December 11, 1960

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LABORATORY DATA FOR REVIEW OF OUTLET WATER
TEMPERATURE LIMITS FOR BDF TYPE REACTORS

ABSTRACT

A knowledge of the thermal and hydraulic conditions within a reactor fuel channel during an inadvertent flow reduction is needed to establish reactor operating limits. Such limits, which are based on outlet water temperature, are called "trip-after-instability" limits by the reactor operating personnel. Laboratory experiments were performed to update the knowledge of such conditions in a BDF reactor type fuel channel while using internally and externally cooled fuel elements (I&E's) at tube powers up to 1530 KW. In addition to a general extension of previous data, the new data were used to review certain specific details involved in "trip-after-instability" limit calculations.

It was found that in calculating the limits, the isothermal pressure drop across the fuel elements must be related to flow rate by the exponent 1.8, ($\Delta P \propto F^{1.8}$), rather than the more convenient value of 2.0. It was found that this method of limit determination is applicable to the high rear header pressures presently attained on the reactors and also applicable to tubes with very low Panellit pressures. And finally, the validity of certain analytical transformations of experimental data, called generalization of hydraulic demand curves, was reaffirmed for the above conditions.

INTRODUCTION

One of the operating limits for the Hanford reactors is a limit on the normal outlet water temperature from any single fuel coolant channel. This temperature limit, coupled with the response of the Panellit gage (flow monitor) system, is designed to protect the reactors against excessive fuel temperatures following inadvertent flow reductions. This limit is called a "trip-after-instability" limit by reactor personnel.

The determination of actual limit values is based largely on laboratory experiments using electrically heated test sections. Previously available experimental data for BDF type reactors (1,2,3)* were obtained some time ago and with test sections simulating solid fuel elements. However, the reactors presently have I&E (internally and externally cooled) fuel elements, have higher rear header pressures in some cases, and are operating at higher

* Numbers in parentheses refer to entries in the Bibliography, page 16.

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flow rates. Therefore it was deemed advisable to update the experimental thermal-hydraulic data for BDF type reactors, and in particular, study certain Panellit pressure effects during flow reductions caused by plugging. An additional reason for obtaining new data was that significant improvements in experimental equipment and operating techniques have been made and thus it was possible to carry these experiments to much lower flow rates and to higher tube powers than was done in previous experiments.

The data obtained in the present series of experiments included hydraulic pressure drop curves for constant heat generation rates under steady state conditions and transient demand characteristics following sudden flow reductions by upstream plugging incidents. The objectives of the experiments might be stated as follows for the steady state hydraulic demand data:

- (1) Compare experimental hydraulic demand curves with calculated demand curves (as described in HW-42469-D) (4).
- (2) Determine if Panellit high trip back-up is available for severe plugging.
- (3) Determine Panellit response to slow plugging - i.e., is there either high trip or low trip.
- (4) Establish the approximate upper flow rate limit of the film boiling region.

Similar objectives might be stated as follows for the transient flow experiments where flow reductions were caused by sudden plugging of the flow channel upstream of the Panellit tap:

- (1) Determine the deviation between experimental minimum Panellit pressure and theoretical minimum Panellit pressure during a plugging transient.
- (2) Check the validity of generalizing data from tube inlet pressure to any desired initial Panellit pressure.
- (3) Determine the rate of change of Panellit pressure during a plugging occurrence.
- (4) Illustrate that no damage will result for scrams initiated at the time film boiling is reached.

This report will be limited to the essential data and discussion to support conclusions regarding the above objectives. As such, it is assumed that the reader is familiar with the terms and techniques involved in obtaining and interpreting hydraulic demand data of this type. For background discussions, the reader is directed to the document references given in the Bibliography.

SUMMARY AND CONCLUSIONS

Steady state and transient heat transfer experiments were conducted in the 189-D Heat Transfer Apparatus with a standard EDF reactor process channel assembly. Electrical d.c. resistance heating of a "heater tube" was used to simulate a normal 32 piece charge of O-II I&E fuel elements. Tube powers of 475 to 1530 KW were investigated at rear header pressures of 25 to 125 psig and outlet temperatures of 70 C to 130 C.

In light of the experimental data, it is concluded that present analytical methods of establishing "trip-after-instability" limits will not result in conservative operating limits, especially at higher tube powers. However, by refining the empirical relations used in establishing these limits to more nearly reflect the frictional pressure drop across the fuel charge, then accurate limits will be predicted. Using the refined relations, the test results show that high rear header pressures, low Panellit pressures, particular flow meter geometries, or the use of I&E fuel elements would not affect the method of determining TAI limits but will affect the actual limits.

The data for the steady state experiments with 75 psig rear header pressure are presented on Figures 1, 2, and 3 and from them the following specific conclusions were drawn:

- (1) The continued use of the straight line approximation for the "non-boiling demand" curve will result in the prediction of non-conservative Panellit low trip limits, especially at high tube powers.
- (2) The empirically calculated "boiling demand" curve accurately predicts tube inlet pressures (or Panellit pressures) in the region of the unstable flow point with present front header pressures. See Figure 3.
- (3) Steady state data indicate that a Panellit high trip would give back-up protection to a low trip caused by sudden upstream plugging if the tube power is greater than about 530 KW with front header pressure = 550 psig and initial Panellit pressure = 250 psig. (However, the transient data show that for very severe plugging occurrences, the high trip would not be attained in time to prevent excessive fuel temperatures.)
- (4) Slow plugging occurrences with tube powers of 475 KW or more will result in the Panellit pressure passing through at least one trip point (high or low) before reaching the film boiling region with trip settings of 10-90 on the Panellit dial.
- (5) The approximate beginning of the film boiling region is identified by symbols on Figures 1 and 2 for steady state tube powers of 475 to 1190 KW.

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- (6) There would be no unstable flow point with slow upstream plugging occurrences at tube powers less than about 740 KW with 550 front header pressure.

Using the same equipment, transient data were recorded for sudden upstream plugging occurrences with initial tube powers of 650 to 1340 KW. Various conditions of flow meter geometry, initial outlet temperature, rear header pressure, and severity of plugging occurrence were used. Electrical power reductions were programmed to simulate a 1100 ih scram. Some of the results of these experiments are shown on Figures 4 to 9 and the following conclusions have been made:

- (1) For nominal tube powers of 700, 1100, and 1400 KW, "sudden plugging" simulation was carried out with sudden plug flow rates as low as 2 to 3 gpm from initial outlet temperatures of 130 C. In no case did heater rod damage occur due to excessive temperatures even though power reduction was delayed until after severe film boiling had been detected. In no case was power reduction initiated less than 4 seconds after plugging and obtaining minimum Panellit pressure.
- (2) There is very little deviation between the experimental minimum Panellit pressure during a plugging transient (as seen by an electromechanical pressure transducer) and the predicted minimum Panellit pressure based on the non-boiling isothermal demand curve as calculated by the equation

$$P_{an} = K_2 F_R^{1.8} - K_1 F_R^{2.0} + RH$$

- (3) The actual value of rear header pressure has no apparent effect on deviation between measured and theoretical minimum Panellit pressure and no apparent effect on the validity of the generalizing technique. It was indicated that an increase in rear header pressure will allow a small increase in the time lapse between flow plugging and power reduction.
- (4) The time sequences of Panellit pressure change following a sudden flow reduction are illustrated on Figures 4 through 9.
- (5) The technique of "generalizing" tube inlet pressure data to any desired initial Panellit pressure, as outlined in HW-42469-C,(8) was verified for two different venturi sizes and for a double orifice combination.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experiments were conducted with the 189-D Heat Transfer Apparatus which is a prototypical mock-up of a single process channel with nuclear heat

being simulated by d.c. electrical resistance heating in a metal "rod". A description of the apparatus and laboratory in general is given in HW-65722.

(5) Various metal alloys were utilized in constructing the "heater rod" such that the stepped cosine power distribution resulted in a peak power to average power ratio of 1.39. The "heater rod" had outside and inside diameters equivalent to those of O-II-N I&E fuel elements; it was internally and externally cooled when placed in a standard ribbed BDF process tube and small holes connected the internal and external channels at ~ 9 inch intervals along its length to simulate the interjunction flow characteristics of reactor fuel charges. The outlet fittings of the process assembly utilized standard BDF type fittings (du Pont helical pigtail).

The steady state hydraulic demand data were obtained by throttling the pump discharge and recording data for each flow rate after allowing equilibrium or steady state temperatures and pressures to be attained. The actual data points, as shown on Figure 1, indicate a spread of up to ± 2 per cent which is the same as the estimated limits of combined accuracy using Heise gauges to measure pressures and turbine flow meter indicators to measure flow.

For the transient experiments, pressures, flow rates, electrical power input, and some temperatures were recorded on a high speed oscillograph type recorder (Visicorder). Electromechanical pressure transducers (Statham-strain gage type) were used as the pressure sensing elements. Turbine flow meters were retained as the flow sensing elements. Data obtained in this manner are generally less accurate than the steady state data for at least three reasons:

- (1) the scale is greatly compressed generally being 50, 100, or 200 psi per inch of chart width,
- (2) the high speed recording equipment picks up many pressure fluctuations and oscillations which may or may not be important, and
- (3) the electronic signal amplifiers may experience zero shift or span change over a period of several individual test runs.

However, by frequent careful calibrations, it is felt that the accuracy of the transient pressure and flow data is in the range ± 2 to 4 per cent.

During steady state runs, it was determined that the power input to the heater rod, taken as the product of the voltage drop across the rod and the amperage, was about 5 per cent greater than the measured heat output to the coolant as measured by flow rate and temperature rise. In order to eliminate any non-conservatism, the tube power values reported herein are based on actual heat output values rather than voltage times amperage.

Conditions of film boiling were detected during the transient experiments by a rapid rise in the temperature of the heater tube near its surface at any of several locations along its length. When the surface temperature reached about 400 C, the power input was reduced by a recorder-controller to simulate an 1100 ih scram. The values of heat input versus time were taken from

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HW-33870 (6), Figure 1, using both delayed fission heat and fission product decay heat. The abscissa of this figure was assumed to be the time since full power operation.

DISCUSSION

Method of Determining 'TAI' Limits

Evolution of the geometry and process conditions associated with old reactor coolant channels has brought about a need to review the reactor "trip-after-instability" (TAI) operating limits. The desirability of reviewing the philosophy and the data bases of the TAI limits was emphasized by Hess when these limits were first set down as "Specification A-020" in 1957 (7). In addition to process changes which have evolved including fuel element change, tube power change, and header pressure change, significant improvements have been made in the experimental equipment of the 189-D Heat Transfer Apparatus. For these reasons, a complete new set of steady state and transient hydraulic demand data have been obtained from the laboratory while incorporating these changes.

A simple statement of the TAI limits might be made as follows:

Panellit Low Trip

Having specified Panellit low trip pressure and Panellit gage span, what is the maximum permissible normal coolant outlet temperature which would still result in a Panellit low trip for a sudden upstream plug just sufficient in magnitude to cause flow instability?

Panellit High Trip

Having specified a normal Panellit pressure value and set the maximum allowable normal outlet temperature equal 130 C, what is the high trip setting necessary to secure a high trip when a flow reduction of 30 per cent has resulted from slow downstream plugging?

The Panellit high trip limits are based on the assumption that flow instability will not occur at outlet temperatures less than about 180 C with current front header pressures (i.e., $\frac{130^\circ - 20^\circ}{0.70} + 20^\circ = 177^\circ\text{C}$) and thus the Panellit high trip will be attained during a slow downstream plug at about the time or just immediately after instability. Similarly, the Panellit low trip would occur after a sudden upstream plug just sufficient to cause process tube flow instability. These limits would result in a scram after the flow instability had begun--hence the phrase "trip-after-instability" limits.

It can be stated that the basic philosophy used in establishing the TAI limits appears sound when considered in the light of all available experimental results and verifications. Thus the TAI limit philosophy was a significant

step forward in establishing higher realistic reactor operating limits. However, the present studies indicate that certain specific details in the mechanics of calculating actual limits for the old reactors need to be revised to reflect process changes if the limits are to continue to be conservative for higher reactor tube powers. These details will be discussed under the separate headings which follow.

Comparison of Empirical Demand with Experimental Demand

a. 'Boiling' Demand

Experimental data on Figure 1 show steady state flow rate versus the pressure drop across a simulated BDF process assembly with various constant heat input rates. Each data point was achieved by steady state operation at that condition. These data were then transformed or generalized, as discussed in HW-42469-C, (8) to a Panellit pressure basis as shown on Figure 2 by use of the equation*

$$P_{an} = TI - K_1 (F/F^*)^{2.0} = TI - K_1 (F_R)^{2.0} \quad (A)$$

where P_{an} = Panellit pressure - psig

TI = Tube inlet pressure - psig
(equals Rear Header pressure plus ordinate of Figure 1.)

K_1 = a constant - psig

F = flow rate of data point - gpm

F^* = flow rate sufficient to give a tube outlet temperature equal to basis of generalization - gpm

$F_R = F/F^*$ - dimensionless

Since the Panellit pressure at $F_R = 1$ was selected to be 250 psig on Figure 2, then K_1 values were determined from experimental TI pressure data at $F = F^*$ so that equation (A) becomes

$$K_1 = TI^* - P_{an}^* = TI^* - 250 \quad (B)$$

where superscript * indicates a condition with $F_R = 1.0$.

Of course, the value of K_1 will vary with F^* and hence with tube power. The curves on Figure 2 then represent generalized 'boiling' demand curves with the bases of generalization being 250 psig Panellit at a flow rate sufficient to result in an outlet temperature of 125 C.

* A table of nomenclature is presented on page 15.

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Experimental boiling demand curves can be approximated by 'empirically calculated' boiling demand curves according to the following relations (4):

$$TI = K_2(F_R)^{1.8} + RH \text{ or } P_{sat} (\uparrow) \quad (C)$$

where K_2 = a constant - psig

RH = Rear Header pressure - psig

P_{sat} = saturation pressure corresponding to tube outlet temperature - psig

($\uparrow$) denotes that one use either RH or P_{sat} , whichever is larger

Since RH is generally larger than P_{sat} at F^* , then K_2 can be determined by

$$K_2 = TI^* - RH \quad (D)$$

A value of 1.8 is used as the exponent in the term $K_2(F_R)^{1.8}$ of equation (C) because the majority of the pressure loss is assumed due to fluid 'friction' and can be considered approximately proportional to the 1.8 power of the inlet flow rate as dictated by the usual friction factor-Reynold number relations.

The empirical boiling demand curves can be placed on a Panellit pressure basis by combining equations (A) and (C) to give

$$Pan = K_2(F_R)^{1.8} - K_1(F_R)^2 + RH \text{ or } P_{sat} (\uparrow) \quad (E)$$

Both K_1 and K_2 should be determined from the best available pressure drop data at $F_R = 1.0$.

Two empirically calculated boiling demand curves are shown as curves A and B on Figure 3 and compared with experimental data points which were generalized as in Figure 2. Notice first that the agreement between the empirical curve and the experimental data points is very good in the crucial region--that is, the region of incipient flow instability. Next, one must notice that the empirical boiling curves vary with tube power. This is inherent in equation (E) which is used to calculate the empirical curve because the K_1 and K_2 values, while constants for a given tube power and F^* , will vary quite markedly from one tube power to another with a fixed geometry. It is true that the empirical boiling curve for BDF reactors at 1000 KW may be quite close to that for K reactors at say 1600 KW. But this is because of geometry differences. To be most accurate in calculating empirical boiling curves, the effect of tube power must be considered.

b. Isothermal Demand

The 'non-boiling' demand pressure-flow rate relationship, which would be obtained if the tube power were decreased with flow rate to give a constant tube outlet temperature, can also be expressed empirically by equation (E).

In this case, the outlet temperature selected at $F_R = 1.0$ is nearly always low enough so that P_{sat} is less than RH and the equation reduces to

$$P_{an} = K_2(F_R)^{1.8} - K_1(F_R)^{2.0} + RH \quad (F)$$

The K_1 and K_2 values would be the same as those used for the empirical 'boiling' curve and, once again, they would be variable with tube power. This is illustrated by curves C and D of Figure 3. One will immediately notice the appreciable differences between these empirical 'non-boiling' demand curves and the familiar 'approximation' to the non-boiling demand curves. The 'approximation' is merely constructed by drawing a straight line between the normal Panellit at $F_R = 1.0$ and a Panellit pressure equal to rear header pressure at $F_R = 0$. This approximation could be expressed as

$$P_{an} = K_3(F_R)^2 + RH \quad (G)$$

The difference between values predicted by equations (F) and (G) will depend again on the tube power for a given geometry.

Actual data are shown on Figure 4 to make a comparison with the true empirical non-boiling demand curve and with the non-boiling demand curve 'approximation' (straight line). The data points, ϕ , are actual Panellit pressure readings as the flow rate and tube power were changed in steps to maintain an outlet temperature of 70 C. At $F_R = 1.0$, the tube power was 680 KW. The comparison between the data points and the empirically calculated curve is fairly good. At least, the steady state data Panellit pressures are definitely above the straight line approximation and in order to be conservative in predicting Panellit low trip limits, the empirical non-boiling demand curve, as defined by equation (F), must be used. The validity of equation (F) was further checked by simply measuring the slope of flow versus pressure drop data plots from Hydraulics Laboratory studies for various fuel charge and flow meter geometries. It was found that the flow rate exponent, as given in equation (F), generally varies from 1.80 to 1.85 for fuel charges (K_2) and from 1.96 to 2.04 for various flow meter assemblies (K_1). Using an exponent of 1.85 in place of 1.8 in equation (F), it was found that the empirical non-boiling demand curve agreed identically with the data points on Figure 4. But retaining an exponent of 1.8 would result in slightly conservative TAI limit selection.

The necessity of using equation (F) to predict the non-boiling demand curve is further born out by the data from the transient experiments. One objective of these experiments was to determine whether the Panellit pressure signal follows the non-boiling demand curve during a sudden plug flow transient; specifically, does the Panellit pressure signal reach the minimum value as predicted by the non-boiling demand curve just after a sudden upstream plug. Of course, if the Panellit pressure did not go as low as predicted by this curve, then trip limits based on this curve would be non-conservative. Conversely, if the Panellit pressure went appreciably below the values predicted by this curve, the trip limits might be ultra-conservative.

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During the flow plugging transient experiments, Panellit pressure was monitored on a high speed recorder as a function of time. Within 0.1 second after inserting the flow channel plug, the Panellit pressure had dropped to the minimum values as indicated by the symbols Δ on Figures 4 through 9.* Comparing these minimum values with the applicable isothermal or non-boiling demand curves, one finds very good agreement. It is therefore concluded that equation (F) will accurately describe the non-boiling demand curve and that this curve will accurately describe the minimum Panellit pressure which will result following a sudden upstream plugging occurrence.

Minimum Tube Power Which Causes Unstable Flow

As illustrated in Figure 3, page 21, when a supply curve can be drawn such that it is tangent to a 'boiling' demand curve then flow instability can occur. If the supply curve dropped slightly from the tangency position, either due to further plugging or due to a slight drop in front header pressure, a further self-induced flow rate reduction would occur. The flow rate would decrease until operation in the film boiling region occurred and the fuel elements would be destroyed if full power reactor operation continued.

But for lower tube powers, a supply curve cannot be drawn tangent to the boiling demand curve from a 550 psig front header pressure, and flow instability would not occur for this tube power-front header pressure combination. For the present data as generalized in Figure 2, flow instability could not result with a tube power which is less than about 740 KW with a front header pressure of 550 psig. For a 450 psig front header pressure, flow instability could not occur for tube powers below about 620 KW. Reducing the initial Panellit pressure (the Panellit pressure at $F_R = 1.0$) would reduce slightly the respective tube power values stated above.

Panellit Response to Slow Plugging

If slow plugging should occur by material build-up on the screens or cross-wires upstream of the Panellit tap, the Panellit pressure will then begin to follow along the appropriate tube-power curve of Figure 2. In fact, these curves are actually obtained by incremental closing of a valve between the supply pump and the Panellit pressure tap. For low tube powers with no unstable flow point, the Panellit pressure would trace the entire 'boiling' demand curve to the film boiling region. For initial conditions as shown on Figure 2, the difference between minimum and maximum Panellit pressures on the 475 KW curve is greater than 110 psi. Since this difference is greater than the maximum possible Panellit trip span, then one could be assured that the Panellit pressure would pass at least one trip point if slow upstream plugging occurred on a 475 KW tube. However, if the tube power was about 400 KW or below, then it is possible that neither the high trip or the low trip of the Panellit gage would be passed during the slow plugging incident. For high tube powers, slow plugging would cause the Panellit pressure to

* See Appendix A, page 17, for a discussion of the pressure oscillations during the early part of the flow transient.

progress along the appropriate tube power curve, as on Figure 2, until a point of incipient instability is reached. Further plugging would cause flow instability with a self induced flow reduction and a rapid rise in Panellit pressure. Hence, if the low trip is not reached then a high trip will be reached at or before a film boiling condition is attained.

High Trip Back-Up

Although the Panellit high trip is not 'officially' recognized as offering scram protection during incidents of sudden plugging upstream of the Panellit pressure tap, it will offer a secondary back-up to the low trip under certain conditions. The attainment of a back-up high trip depends on the following: Panellit gage span, tube power, severeness of the plugging incident, and initial Panellit pressure.

The Panellit gage span is taken as high trip minus low trip, which on the old reactors is generally 80 psi. Sketching this gage span onto Figure 2, the steady state data indicate that high trip back-up should be available after very severe plugging occurrences for tube powers which are greater than about 530 KW (initial Panellit pressure equal 250 psig and rear header pressure equal 75 psig). If the initial Panellit pressure were lower or the gage span were smaller, then high trip back-up would be available at a tube power slightly below 530 KW. The effect of initial Panellit pressure could be investigated by generalizing the data from Figure 1 to the new desired basis.

The severity of the plugging occurrence will greatly influence the attainment of high trip back-up. Generally one assumes that the attainment of high trip back-up is crucial only for plugging incidents which lead to flow instability or which would otherwise result in operation in the film boiling region. However, for the very severe plugging occurrences, high trip back-up might not be useful in completely preventing fuel damage even though the steady state data indicate that high trip back-up would be attained. This is because there is a definite time interval required to achieve pressurization in the tube after the plugging occurrence. During this interval and before the heat generation rate is actually reduced, excessive fuel temperatures may be reached. This is illustrated by transient experimental data as shown on Figures 5, 8, and 9.

On these figures, the Panellit pressure data are plotted versus flow ratio squared, $(F_R)^2$, for various times after suddenly inserting a plug or flow restriction upstream of the Panellit pressure tap. When the plug is inserted, the flow and Panellit pressure instantly drop along the non-boiling demand curve until the new 'plugged' supply curve is reached. The flow and pressure then progress along the 'plugged' supply curve, indicated by a solid line, as boiling occurs in the process tube and outlet fittings. (By connecting data points for equal time after plugging, the time parameter lines are obtained--the dashed lines on Figures 4 through 9.)

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For a small resistance flow plug, the transient run was complete when the steady state boiling curve was reached. For the severe plugs, tube power input was reduced after film boiling conditions were detected by sharp temperature rises (to about 400 C) near the surface of the heater rod. The various conditions at the beginning of the power decay are indicated by the symbol D on the figures. Since there is approximately 3 seconds delay between the time of a reactor Panellit trip and the time the VSR poison is completely effective, then a Panellit trip should have occurred 2 to 3 seconds before beginning of power decay. Note that for the very severe plugs, the time of trip and even the beginning of power decay occurred before the Panellit pressure was high enough to give high trip back-up. This does not necessarily mean that high trip would not be attained eventually since the Panellit pressure did continue to rise until the beginning of the power decay. It does indicate, however, that if the reactor trip were delayed until high trip back-up was attained, then the reactor fuel temperatures would reach values higher than those reached in the experimental apparatus. Since maximum experimental heater rod temperatures reach 400 to 500 C, during these transient runs, the possibility of fuel damage is apparent.

It is also worthy of note on Figures 5, 8 and 9 that for some severe plug cases, power reduction did not occur until after conditions were well within the region defined as the steady state film boiling region as shown on Figures 1 and 2. In fact, for the very severe plugging occurrences, the plug flow condition was within the film boiling region at all times. This situation is not as important from the standpoint of reactor operation with the Panellit gage trip system as it would be with a true flow monitor trip system for individual tube plugging detection. With a true flow monitor system, the boundary of the film boiling region might represent a reasonable trip limit.

Effect of Rear Header Pressure on TAI Limits

The simultaneous occurrence of high rear header pressure and low Panellit pressure was one cause to initiate this experimental study. However, the experimental data of Figures 5 and 7 show that such a condition had no apparent effect on the deviation between measured and theoretical minimum Panellit pressure during transient runs. Data from these runs also showed no apparent effect on the validity of the generalizing technique or calculation of the boiling demand curve when using the true empirical equations. Thus, it is concluded that the method of TAI limit calculation will not be affected by variations in rear header pressure, but the actual limits will be affected.

Comparison of the data on Figures 8 and 9 does indicate that a high rear header pressure may postpone boiling a few seconds. This is reasonable that it would take a slightly longer time to raise the water temperature to the higher saturation temperature at which boiling occurs. This then indicates that an increase in rear header pressure would allow a small increase in the time lapse between flow plugging and power reduction.

Peculiar 'Plugged Supply Curve' Shapes

- The solid 'vertical' lines of Figures 4 through 9 represent the supply curves during plugging incidents. These curves are indicative of the flow-pressure drop relation across the throttle valve which was used as the 'plug' during the experiments. One might be inclined to discount the accuracy of the data points because of the peculiar shapes or slopes of these various plugged supply curves. However, previous experimental studies (9,10) have shown that actual and simulated upstream (inlet screen) plugging can result in these odd shaped supply curves. This is generally attributed to a combination of critical flow conditions across the plug, and a deformation or variation in plug flow area as the pressure drop across the plug is changed.

Validity of Generalization from Panellit Pressure to Tube Inlet Pressure

Transformation or generalization of demand pressure data is accomplished by equation (A) as discussed previously.

$$P_{an} = T_I - K_1(F_R)^{2.0} \quad (A)$$

There seems to be no reason to doubt the validity of this transformation, especially with steady state flow conditions. However, to be reassured of the transformation accuracy and validity, both steady state and transient data were used to make a comparison between calculated and experimental values. This comparison was made for two different venturi sizes, for a double orifice assembly, and for various conditions of rear header pressure, initial outlet temperature, and initial Panellit pressure. In all cases, the agreement between measured Panellit pressure and Panellit pressure generalized from tube inlet pressure data was very good. Even the transient data show good agreement, although the decreased accuracy of the high speed recording equipment and data read-out did show up by increased data scatter.

E. D. Waters, Engineer

D. E. Fitzsimmons, Engineer

Thermal Hydraulics Operation
HANFORD LABORATORIES OPERATION

ED Waters:DE Fitzsimmons:leb

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NOMENCLATURE

F = flow rate - gpm

F^* = flow rate sufficient to give a tube outlet temperature equal to basis of generalization - gpm

F_R = flow ratio = (F/F^*) - dimensionless

K_1, K_2, K_3 = constants - psig as determined from equations (B), (D) or (G)

P_{an} = Panellit pressure - psig

P_{sat} = saturation pressure corresponding to tube outlet temperature - psig

RH = rear header pressure - psig

TAI limits = Trip-after-instability limits

TI = tube inlet pressure - psig

T_{inlet} = tube inlet water temperature - °C

T_o = tube outlet water temperature - °C

T_o^* = tube outlet water temperature at basis of generalization - °C

(↑) denotes that one use either RH or P_{sat} , whichever is larger.

Superscript * indicates the value of the variable at bases of generalization (i.e. $F = F^*$).

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APPENDIX A

Pressure Oscillation During Early Flow Transients

During the flow plugging transient experiments, the Panellit pressure versus time trace appeared about as follows:

where A represents the initial Panellit pressure at the normal flow conditions. When the plug was inserted, the Panellit pressure dropped very rapidly and was 'down' within 0.1 second. There was then a damped oscillation lasting from 0.25 to 0.50 second. These are thought to be real pressure fluctuations caused by water hammer shock waves set up in the flow system and/or in the approximately 30 feet of 3/16" O.D. copper sensing line between the pressure transducer and the Panellit tap. The Visicorder light beam galvanometers are fluid damped and have a frequency response within about 3% at 600 cycles per second. The pressure transducers have a very small volume displacement and have a natural resonant frequency of several kilocycles per second. Hence, the recording system should be able to accurately follow the relatively slow oscillations illustrated above. Similar oscillations of about the same magnitude showed up in the front header pressure and tube inlet pressure traces. Although detailed frequency and amplitude comparison of these three traces was not undertaken, it is thought that this situation is a peculiarity of the single tube experimental apparatus which would not affect the validity of the data in this report.

The value, B, on the above sketch represents the 'eyeballed' arithmetic average of the peak to peak oscillations. For less severe plugs this value corresponded well with the Panellit pressure at about 1 second after plugging. But for very severe plugs, the pressure had begun to rise above the B value at 1 second after plugging. In either case the minimum Panellit pressures reported on Figures 4 through 9 correspond to the value B as illustrated above.

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Figure 1. Steady State Hydraulic Demand Data

Basis: BDF Standard Outlet Fittings

Simulated 32 - O-II I&E's

Inlet Water Temp. = 14 to 17 C

Rear Header Pressure = 75 psig

Shaded symbols indicate film boiling conditions.

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Figure 2. Generalized Steady State Hydraulic Demand

Basis: BDF with Standard rear fittings
 Simulated 32 - 0-II I&E's
 $F_R = 1.0$ at 125 C outlet temperature
 Inlet water temperature = 14 to 17 C
 Rear Header pressure = 75 psig
 Shaded symbols indicate film boiling conditions.

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D[⊙] 12.0 D[⊙] 19.5

D[⊙] 9.2

D[⊙] 7.2

Figure 9. Transient Data - High Rear Header Pressure

Basis of Generalization:

$T^* = 44.8$ gpm

$P_{an}^* = 360$ psig

$T_I^* = 555$ psig

$RH = 125$ psig: $F_{M1} = 630$ psig

$T_o^* = 130$ C

Tube Power = 1340 KW

D 19.5 means power decay was initiated 19.5 seconds after plugging occurred.

Δ = minimum Panellit pressure during transient

+ = steady state was achieved at this condition without power reduction

Dashed Curves = time (seconds) since plugging

BDF 0.310 inch venturi

Panellit Pressure - psig

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