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C-REACTOR I & E LOADING INSTABILITY LIMITS

AUTHOR

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C-REACTOR I & E LOADING INSTABILITY LIMITS

INTRODUCTION

The pilot charging of I & E fuel elements has been implemented at C-Reactor under Production Test IP-19-A.

It was necessary to provide adequate tube protection against flow interruption by establishing proper trip settings on the Panellit pressure gauges. The administration of these Panellit trip settings is done by trip-before-boiling tube outlet temperature limits, which are similar in principle to the current instability limits.

Trip-before-boiling limits for C-Reactor I & E fuel element loadings are presented in this document.

SUMMARY

The permissible tube outlet temperatures for I & E fuel element loadings were separated into several fundamental effects, and expressed in the form of basic temperature limits and correction factors. The limits presented herein are applicable to central zone venturi tubes only, although the calculation method may be employed for any orifice configuration. Administration of temperature limits to C-Reactor tubes on a production quantity basis is facilitated by the following curves:

Basic Outlet Temperature Limit	- Figure 1
Inlet Temperature Correction Factor	- Figure 2
Rear Header Pressure Correction Factor	- Figure 3
Tube Flow Resistance Correction Factor	- Figure 4
Relative Annulus Flow Correction Factor	- Figure 5

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The limits were established on the extremely conservative basis of providing Panellit trip protection before saturation conditions are exceeded in either channel. Current laboratory and analytical work is directed toward methods for securing adequate tube protection with more lenient tube temperature limits.

DISCUSSION

I. GENERAL BACKGROUND

The purpose of instability tube outlet temperature limits for solid slug loadings is to insure a reactor shut-down by the Panellit gauge before unstable flow conditions exist in the process tube. There is considerable data available at the present time, though not fully analyzed, to indicate that adequate protection is provided by a Panellit trip after instability. When a process tube operates at the limit determined by this philosophy the Panellit trip actually is caused by flow instability in the tube, and therefore instability must precede the trip. The real protection is provided to the tube by reducing the reactor, and tube, power as rapidly as possible to a value which permits adequate cooling through the plugged tube flow assembly. Under a trip-after-instability philosophy the power reduction would be delayed by instrument, safety circuit, and rod drop operating time requirements. Nevertheless, laboratory data indicates that safe reactor shut-downs would occur through Panellit trip after instability protection.

Current operating philosophy utilizes Panellit protection through trip-before-instability, thus eliminating concern over the uncertain effects of the various time delays. The Panellit trip of the reactor safety circuit occurs because of plugging in the flow assembly, and will always precede flow instability.

Internally and externally cooled slug loadings appear to be protected as well as, or better than, solid slug loadings. Two large channels, completely isolated from each other, are available for slug cooling. It is difficult to visualize both channels plugging simultaneously, even from a ruptured slug. If one channel becomes plugged, the other channel will furnish more than adequate cooling after the reactor is shut down. Thus, there is less question of adequate cooling of the remaining slugs in the case of an I & E slug rupture than in the case of a solid slug rupture. In the case of upstream (from the Panellit) flow plugging, boiling occurs at the Parker fitting first, and I & E loadings receive the same degree of protection from Panellit gauges that solid slug loadings receive.

To be consistent with the present philosophy that the Panellit trip be the result of the initial cause of flow reduction rather than the resulting flow instability, it was necessary to consider two unique cases of flow reduction. These two cases, which concern individual plugging of the hole or annulus channels, will be discussed in the next section. The limits presented in this report are intended to provide a Panellit trip-before-unstable flow can occur in either channel alone, or in the tube assembly as a whole. Because the special cases are more restrictive to tube operating power limits, the philosophy adopted for I & E limits is conservative. The limits will provide for a Panellit trip before unstable flow occurs in either channel. Illustrating the conservatism involved in the limits in this document, it now appears safe to provide protection on the basis of a Panellit

trip after (or because of) instability in one flow channel, but before instability in the other flow channel.

II. FLOW PLUGGING UNIQUE TO THE I & E GEOMETRY

The I & E slug loading geometry offers two flow channels, of fairly equal resistance, in the process tube. However, flow is not monitored individually in the two channels, but only the total flow is monitored by the Panellit gauges. Combined plugging of both channels downstream from the Panellit pressure tap, or plugging of the cone screen upstream from the Panellit pressure tap is similar to the two cases of plugging in solid slug loadings. Solid slug trip-before-instability limits may be employed in I & E loadings to cover these two cases, as will be discussed in more detail under "outlet temperature limits."

However, two special cases occur that are unique to I & E slug loadings. Plugging may occur downstream from the Panellit gauge, selectively in either the hole or the annulus flow channel. When this occurs, the tube inlet pressure increases and, since the flow decreases, the tube outlet pressure decreases. The active zone pressure drop therefore increases and flow will increase in the unplugged channel. The Panellit gauge can detect only the combined effect of the increased flow in one channel and decreased flow in the plugged channel. For this reason, the Panellit gauge is somewhat insensitive to plugging of one of the two flow channels in the I & E geometry.

The mechanism of hole plugging is illustrated in Figures A and B.

In Figure A the intersection of the normal supply and demand curves at A determines the normal flow and tube inlet pressure. At this flow the tube outlet pressure is B and the active zone pressure drop is A minus B. When plugging occurs in the active zone the new demand curve determines the flow and tube inlet pressure by its intersection with the supply curve at C. At this flow the tube outlet pressure is D, and the active zone pressure drop is C minus D.

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Figure B illustrates the effect when the active zone pressure drop increases from (A minus B) to (C minus D) in the case of simulated hole plugging. The annulus flow increases from 3 to 4, while hole flow decreases from 6 to 5. The case of annulus plugging is similar except that the larger initial flow restriction in the hole channel results in a smaller increase in hole flow as the annulus plugs.

III. MAJOR ASSUMPTIONS EMPLOYED FOR TUBE POWER LIMIT CALCULATIONS IN THE SPECIAL DOWNSTREAM PLUGGING CASES

Several major assumptions were made to simplify the calculation of these limits or their application to reactor loadings. It was necessary, also, to make conservative assumptions to minimize the amount of laboratory data, and analysis thereof, in order to expedite the limit calculations. The major assumptions will be discussed in detail after the following tabulation:

1. Flow instability will not occur in either channel, as the result of plugging in the flow stream of that channel, at coolant effluent temperatures below saturation at the downstream end of the slug column.
2. Under the normal single phase flow conditions, the relative heat, and temperature rise, in the two flow channels is primarily dependent upon the relative flow in the two channels, and may be predicted from the known or assumed hydraulic characteristics of the tube loading.
3. During and immediately after the plugging of a flow channel, the heat removed by that channel either remains constant or decreases.
4. The high top-of-annulus water temperatures observed at C Reactor do not significantly affect the flow stability or trip-before-boiling considerations.
5. The existing low trip instability limits, which are influenced mostly by boiling at the rear Parker fitting, may be applied, with a small safety factor, to I & E loadings.

1. Flow Instability

The assumption that flow instability does not occur at sub-saturation water temperatures is the basic requirement of a trip-before-boiling limit. It is then a simple matter to determine the effluent temperature increase associated with a flow reduction and to translate this information into a tube power or outlet temperature limit, based on the ability of the Panellit pressure gauge to detect the flow reduction. The use of bulk saturation temperature in one coolant channel, as a temperature limit, simplified the procedure for calculating the limits. It was unnecessary to obtain laboratory data over a large range of tube powers, organize and plot these data as "boiling curves," and normalize these curves into detailed predictions of the Panellit gauge pressure-flow characteristics.

The normalized pressure-flow characteristics are important only in considering the characteristics of a low pressure trip as will be discussed under item 5. The sensitivity of the high pressure trip to flow changes is determined by the front header pressure and the venturi characteristics. The two unique cases of flow reduction associated with I & E loadings, hole or annulus plugging, rely on high Panellit pressure trips for reactor protection. The minimum hole or annulus flow rates may be calculated for any set of tube hydraulic characteristics and front header and Panellit pressures.

If excessive water temperatures and local or bulk boiling occur in a particular channel because of partial plugging, the channel flow may decrease further because of the boiling pressure drop. This additional pressure drop will drive the Panellit pressure higher than the value it reached because of the initial plugging. The tube flow and slug cooling may be provided almost entirely by the unplugged channel. It is possible to maintain stable flow in the unplugged channel under these conditions, particularly if it is the annulus that is the unplugged channel. If the other channel becomes totally plugged, by steam if not physically, slug surface temperatures would be undesirably high and slug damage might occur. It is desirable to prevent the foregoing sequence of events by insuring that a Panellit high pressure trip occurs after or because of flow instability in one of the two flow channels.

After more is known about the flow stability of I & E loadings with various degrees of individual channel plugging, it will be possible to adopt a concept of Panellit monitoring using trip settings which are sensitive only to extreme plugging in either channel. The Panellit gauge would not detect (i.e., would not shut down the reactor) local or bulk boiling in either channel if that channel flow did not become unstable but remained near the initial boiling flow.

Under this concept it might be possible to operate unknowingly, for perhaps the entire in-pile exposure of a slug column, with local or bulk boiling in one channel. The possible consequences would be no greater than a slug rupture, however, because both the internal and external surfaces would be cooled adequately but one surface would be operating under conditions leading to increased corrosion rates. In all other respects, equivalent protection

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would be available with Panellit trip settings based on the trip after instability concept. This concept was not adopted for the limits herein, because it requires a more detailed knowledge of the instability characteristics of I and E loadings.

The basis employed for calculating these initial I & E loading tube powers and outlet temperature limits may be compared with the first solid slug tube power limits of the present type, which are based on Panellit gauge protection. These first limits were called "trip-before-boiling" limits, and were intended to insure that a Panellit gauge could detect a slow flow reduction before the tube outlet temperature increased to rear header saturation conditions. To determine the sensitivity of Panellit gauges to cone screen plugging, upstream from the Panellit pressure tap, the tube pressure drop-flow demand characteristics were employed. It was reasoned that these demand characteristics could be predicted for temperatures below saturation, but that such prediction became more difficult above the saturation temperatures. To insure that a Panellit trip would occur before cooling became inadequate, the concept of trip-before-boiling was adopted. This concept was modified to trip-before-instability when a more complete knowledge was obtained of the tube demand curve at high outlet temperatures.

Laboratory data obtained to date indicates that flow stability is maintained in individual internal or external flow channels at temperatures exceeding saturation at the end of the column. After boiling is initiated at the end of the active section, two-phase flow contributes significantly to the active section pressure drop. But apparently the pressure drop available across the active section, which is a function of the tube inlet assembly, outlet nozzle and dummy flow characteristics, remains greater than the pressure drop requirements in the plugged channel for temperatures well in excess of saturation. The laboratory data demonstrate flow stability over a wide range of plugging in either channel.

2. Relative Heat Removal

Assumption number two could be defined more properly as an observation rather than an assumption, based on the laboratory and in-pile data. The relative heat flow and temperature rise in the two channels is strongly dependent upon the relative flow rates in the two channels, and much less dependent on any other variables. Differences in slug geometry, which cause large changes in relative flow, have no greater effect on the relative heat distribution than the associated flow effects. Gross tube power, specific power, and tube flow rates have no significant effects on the relative heat distribution between channels. These statements will be supported more fully under the discussion of Figure 21, in the section devoted to laboratory data.

The relation between relative heat flow and temperature rise is necessarily qualified to apply only to single phase flow conditions in both channels. After boiling commences in one channel, the heat transfer conditions are changed. For a small range of channel flow rates local boiling occurs in the channel and the heat flow may tend to increase to that channel or just in that particular region of the tube. After general film boiling conditions prevail, the heat flow will move toward the non-boiling channel.

The relation between relative heat removal and relative coolant flow is used to establish initial, or normal, operating conditions in the I & E loading. It is possible to calculate theoretically, and to determine empirically in the flow laboratory, the relative coolant split between the internal and external channels. Figure 8 shows the coolant split expressed as the ratio of annulus flow to total tube flow. This ratio will hence forth be referred to as the relative annulus flow. The slug dimension parameters were fixed at 0.375 and 1.474 inches for the hole diameter and the slug outside diameter respectively, and the flow split is shown as a function of the tube inside diameter. The effect of the process tube ribs is neglected, and therefore the graph must be entered at an effective tube diameter which is slightly less than the actual vertical or horizontal tube diameter.

Figure 8 shows a range of possible slopes in the curves relating the flow split to the geometry. The curve with the higher slope is based on a relation derived by D. L. Condotta. The curve with the lower slope employs the same basic relationships used by Condotta, but an expression for the friction factor was determined empirically from actual Hanford reactor solid slug data. The use of either curve is based on the assumption that surface conditions, i.e., roughness, corrosion product, and weld beads, have proportionately equal effects in each channel. The effect of viscosity differences is also neglected, without much error for outlet temperature discrepancies of 10 C to 20 C between the two channels.

In an old process tube there may be considerably more surface roughness in the annulus channel because of repeated charging of the process tube. This effect is demonstrated by the lower slope of the more empirical curve in Figure 8. Offsetting this source of increased annulus resistance, the tube inside diameter will increase because of cumulative tube corrosion effects. To estimate the flow balance in a corroded process tube the curve based on R.J. Shield's empirical correlations should be employed because it will tend to compensate somewhat for higher surface roughness in the annulus. Also, it should be remembered that the curves in Figure 8 are based on constant geometrical cross-sections down the entire length of the charge, but tube corrosion results in an increasing tube cross-section as the rear of the tube is approached. At best, the curves may be used only as a guide for estimating the relative flow split between the internal and external channels. Then, with much greater accuracy, Figures 20 and 21 may be used to determine the relative heat removal rates, and temperature distribution between the two channels.

3. Heat Removal During Plugging

The third assumption was that the heat flow to a particular channel remained constant or decreased during plugging of that channel. This assumption was made in order to simplify the calculation of trip-before-boiling limits. By employing simple and straightforward hydraulic relationships the flow in either channel may be determined at the Panellit trip conditions. Knowing this flow and the permissible channel outlet temperature, i.e., saturation

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temperature, the permissible heat removal rate may be calculated for this channel. Then, from the relationship between the relative heat removal rates in the two channels, the total tube permissible heat removal rate may be calculated. This constitutes the trip-before-boiling tube power limit, which was converted to an outlet temperature limit for ease of administration.

Laboratory experiments, simulating selective annulus or hole channel plugging were used to obtain the data for Figures 20 and 21. These same experiments verify the conservatism of assuming a constant rate of heat removal from a channel during plugging. As the channel becomes plugged and its relative coolant flow rate decreases, the heat flow to that channel actually decreases.

Coolant Temperatures at the Top of the Annulus

High coolant and slug surface temperatures at the top of the annulus may impose severe restrictions on the use of I & E fuel elements. To compensate for the metal removed from the hole channel, and to balance the individual channel flow rates in order to provide approximately equal annulus and hole coolant outlet temperatures, the C-Reactor I & E fuel element is about 34 mils oversized. In a new process tube the oversized I & E fuel element will occupy a position eccentric toward the top of the tube. It is hypothesized that this eccentric position is responsible for the high coolant temperatures observed on top of the annulus in the current C-Reactor production test.

Shortened and full length loadings of I & E fuel elements have been charged into C-Reactor under PT-1P-19A. Thermocouple probes were installed in the downstream dummy section to monitor outlet coolant temperatures in the hole and annulus flow channels separately. Disproportionately high temperatures were observed at the top of the annulus, sometimes reaching approximately 150 per cent of the bulk annulus temperature. The thermocouples monitoring the hole, bottom or side of the annulus, and the total tube effluent temperatures, have been in good agreement with each other, but the top of annulus temperatures have been consistently high.

There is not sufficient data to provide a good correlation with eccentricity. In fact, it is not certain that eccentricity is the sole, or even the major, cause of these disproportionate temperatures. From the corrosion history of the C-Reactor process tubes it can be calculated that the I & E fuel elements should, if eccentric at all, be closer to the bottom of the tube. The extent of corrosion necessary to produce eccentricity toward the bottom of the tube may be verified in another manner. Data from the thermocouple probes and the bulk tube effluent thermocouple indicate a relative flow, annulus to total, of about 0.7 as determined from Figure 20. To obtain this flow split through corrosion of the process tube, Figure 8 indicates that an average or effective tube diameter increase in excess of 20 mils is required. The diametral increase would be particularly greater at the downstream end of the active section.

In this manner it was calculated that the downstream fuel elements in an I & E loading must be eccentric toward the bottom of the actual C-Reactor process tubes chosen for this production test.

In the face of these two demonstrations that the I & E fuel elements probably are not eccentric toward the top of the process tube, there is the more substantial and annoying fact that high temperatures exist at the top of the annulus. Temperatures of this magnitude might increase the rate of tube corrosion by a factor of ten to twenty, and tube life would be correspondingly shortened. The slug corrosion rate might be increased the same amount and a higher incidence of corrosion type slug ruptures might be expected. These features of the high top of annulus temperatures will be investigated further as a part of the C-Reactor production test of I & E fuel elements in production lot quantities.

On the optimistic side it might be believed that disproportionate temperatures are not much more a problem with the oversized I & E slugs than with the present 1.44 inch O.D. solid slug. It may be that a similar odd temperature distribution could be observed around the annulus of a solid fuel element loading, and that it contributes to the observed tube and fuel element corrosion rates. Available data from solid fuel element loadings is sparse and somewhat inconsistent with regard to annulus coolant temperature effects. Additional experimental work is contemplated, in the laboratory and possibly in-pile, to explore more fully the qualitative and quantitative effects of fuel element eccentricity with annular cooling.

For the purposes of a trip-before-boiling limit the high top-of-annulus temperatures must be considered in only one respect, and that is their effect on flow stability in the annulus or possibly in the tube as a whole. It is in this respect that the assumption is made to neglect the effect of high top-of-annulus temperatures, and it is believed that this assumption is conservative.

Local temperatures may exceed saturation conditions and contribute somewhat to an increased local pressure drop without causing flow instability in the entire annulus. When the boiling occurs in a small local area, most of the active section pressure drop occurs upstream from and/or in a different peripheral orientation from the local boiling. Therefore, even if the two phase pressure drop increases in the small region of local boiling, the larger single phase pressure drop in the remainder of the annulus active section continues to decrease as the flow decreases. As long as this pressure drop is decreasing with decreasing flow, instability cannot occur, because the available pressure drop increases with decreasing flow, and thus is better able to satisfy the annulus demand requirements at a lower flow rate.

Boiling in a local region may cause the minimum of the annulus demand curve to be reached at a higher flow, or lower bulk annulus channel outlet temperature, than it would with uniform annulus coolant temperatures. This will be compensated somewhat by the experimental evidence that flow stability exists at flow rates

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lower than the minimum. Also, because of measurement difficulties, it is not known whether disproportionate annulus temperatures existed in the laboratory mock-up, but if they did, to some extent the eccentricity will have been taken into account by virtue of a more exact simulation of actual in-pile conditions.

Another reason for neglecting the effect of high top-of-annulus temperatures is that annulus plugging is not as restrictive as hole plugging in determining trip-before-boiling limits. Of course, the high top-of-annulus temperature enters only into the case of annulus plugging or possibly of plugging upstream from the Panellit tap. The Panellit gauge detects annulus plugging more effectively than hole plugging, and therefore hole plugging is the restricting condition up to Panellit sensitivity factors exceeding 0.90. For the higher values of the ratio of annulus flow to total flow, which were used to obtain a conservative basic limit, the hole plugging case is extremely restrictive, and never becomes less restrictive than the case of annulus plugging.

During normal flow conditions at current tube powers, the top-of-annulus temperatures will not exceed saturation conditions anywhere in the active section. Even with a 10 C to 20 C water film temperature gradient the maximum water temperature at the slug surface probably will be below saturation. Thus, aside from the accelerated corrosion conditions associated with higher water temperatures, there should be no other hazards resulting from the high top-of-annulus temperatures. High top-of-annulus temperatures per se do not represent an extreme hazard, and may very well be indicative of conditions that have always existed in solid fuel element loadings.

5. Low Trip Protection

Trip-before-instability limits determined by low trip considerations must be employed for I & E fuel element loadings. The low trip limits are intended for protection against plugging upstream from the Panellit tap, the most common cause generally being cone screen plugging. Tubes with I & E fuel element loadings are just as susceptible to cone screen plugging as solid fuel element loadings, and at a given tube power will react in approximately the same manner.

As a slow or incremental cone screen plugging occurs, the tube flow and the Panellit pressure will decrease. As the tube flow decreases, at a constant tube power, the tube outlet temperature will increase. An outlet temperature is reached at which critical flow is initiated in the rear Parker fitting, and this critical flow persists at all lower tube flow rates and correspondingly higher outlet temperatures. The most important aspect of this critical flow, concerning its effect on the tube hydraulics, is the large increase in pressure drop across the rear Parker fitting. As the cone screen plugging progresses and tube flow decreases, the increased pressure drop across the rear Parker fitting more than compensates for the decreased active zone pressure drop which usually accompanies a flow reduction. Consequently, the Panellit pressure reaches a minimum value and then begins to increase. The present concept of trip-before-instability protection is based on insuring a Panellit low trip, by setting the low trip pressure at least 10 psi above the minimum Panellit pressure.

Critical flow at the Parker fitting plays the largest part in determining the minimum Panellit pressure. The Parker fitting critical pressure characteristics will be identical for the two types of fuel elements, i.e., I & E and solid elements. Since the minimum Panellit pressure, and therefore the tube outlet temperature limit, is determined largely by the Parker fitting characteristics, there should be no significant difference in the limits for the two types of loadings.

To a lesser extent than the Parker fitting characteristics, the active zone pressure drop contributes to the shape of the boiling curve and the value of the minimum Panellit pressure. As the incremental cone screen plugging progresses and the tube flow decreases, the active zone pressure drop deviates from a linear logarithmic relationship to flow. At lower flow rates the active zone pressure drop is higher than the theoretical flow relationship predicts, apparently because of boiling and two phase flow in the active section. Much of this effect occurs at bulk coolant temperatures which are below saturation temperatures in the active section, and therefore, must be the result of boiling in the water film adjacent to the fuel element surfaces. Boiling in the water film would be sensitive to film temperatures and would be influenced by specific power and fuel element geometry.

At a particular specific power and total tube flow rate, the water film temperatures surrounding I & E fuel elements might be expected to differ from temperatures around solid fuel elements. This would be the case particularly for extreme variations in the flow balance between the internal and external channels, or for conspicuous examples of the eccentricity effect on annulus film temperatures. In these extreme examples, film temperatures around I & E fuel elements might be expected to exceed solid fuel element film temperatures. The result would be more vapor formation in the active zone, leading to an increased active zone pressure drop, a higher minimum Panellit pressure, and ultimately to slightly lower tube outlet temperature low trip limits.

A laboratory simulation of cone screen plugging for a non-eccentric I & E loading produced a boiling curve which differed very little from boiling curves obtained for solid fuel element loadings. Thus, it was indicated that current low trip limits for solid loadings could be administered, to insure low trip protection for I & E loadings. Later laboratory experiments, simulating cone screen plugging in an eccentric I & E geometry indicated a noticeable increase in the minimum Panellit pressure. The effect is an odd bump in the boiling curve which may make the curves difficult to normalize.

To circumvent the difficulty in normalizing the boiling curves it seems advisable to apply the normalized solid fuel element curves by subtracting an arbitrary safety factor. For a flow balance within the range of annulus to total flow ratios of .63 to .75 and for eccentricities not exceeding that of a standard I & E fuel element in a new process tube, it is recommended that a 5 C correction factor be subtracted from the present low trip instability limits.

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IV. LABORATORY DATA

Most of the manipulations performed in order to express tube outlet temperature limits as a function of the Panellit sensitivity were a matter of theoretical, or well founded, hydraulics calculations. Simple hydraulic relationships were involved, in which good agreement usually is obtained between calculated and actual behavior. The relationships represent such calculations as active zone pressure drop, rear nozzle pressures, Panellit pressure, and tube outlet temperatures, as determined by tube flow. The more detailed or minute aspects of I & E fuel element heat transfer characteristics were not required for establishing the concept of providing Panellit trip protection before either channel becomes unstable. For example, during abnormally low flow conditions in one channel an increased percentage of the tube heat generation will be removed by the coolant in the other channel. This will be reflected partly through increased flow in the normal channel and partly by increased temperature rise. For the purposes of establishing the limits herein, no attempt was made for a quantitative measurement or thorough investigation of this heat shift phenomenon. It was sufficient to know that it existed, and thereby contributed to the conservatism of these limits.

Thus the laboratory data was basic and simple. Some of it contributed to the knowledge of fundamental hydraulic characteristics, and the rest served to verify the conservatism of certain simplifying assumptions.

Venturi Calibration Data

The basic hydraulic data are presented in Figures 9 and 10. Figure 9 presents the Panellit pressure and permanent pressure loss characteristics of the standard C-Reactor venturi. The tube outlet temperature limits are presented as a function of the Panellit sensitivity factor (C) and the Panellit pressure drop characteristics are involved in the calculation of this sensitivity factor. The only other appearance of the Panellit pressure characteristics is in the use of Panellit pressure as a variable for determining K_p , the tube flow resistance factor. Its use in this respect is directed toward second order correction factors to be applied to the basic tube outlet temperature limit for variations in the tube flow resistance, and the relative flow split between the internal and external channel.

There is known to be some variation between individual C-Reactor venturis in their Panellit calibration characteristics. The characteristic plotted in Figure 9 represents an average of observed values, so its use would not be conservative in some extreme cases. The errors that may be introduced in these second order corrections will be discussed in more detail in connection with the explanation of these second order corrections. The method of using these second order corrections will be a matter calling for considerable judgment. This judgment may be tempered by other knowledge not available to the perpetrator of these limits, such as the previous operating history of the tube(s) in question, the actual tube power and outlet temperature, or the degree of attention given by operating personnel to operating conditions in the tube(s). The venturi calibration problem properly belongs in this area of judgment. The exercise of judgment

in the venturi calibration problem, as well as all such items of a more direct process nature, has been left to those more closely connected with daily operational experience.

Actually, the errors associated with using an incorrect Panellit calibration characteristic are superficial, because they result from the method of setting up the second order correction curves. Also, there is no effect on the basic limit, so these errors may be eliminated by not using the second order corrections, or by using them conservatively. This is not true, however, of the permanent pressure loss across the venturi, from front header to tube inlet.

There should not be much variation in the permanent pressure loss characteristics between individual venturis, although there is little data available to substantiate this statement. Significant differences may be present between individual Panellit calibration characteristics as the result of minute variations in venturi throat diameter, or pressure tap location with respect to the throat, but these minute variations have a negligible effect on the overall friction loss in the venturi. Therefore, it is believed that the permanent pressure loss characteristics, graphically represented in Figure 9, may be employed for all tubes without much concern over the possibility of individual differences.

The permanent pressure loss is important because it is the connecting link between the Panellit sensitivity factor and the flow through a plugged internal or external cooling channel at the Panellit trip conditions. If the pressure loss is high, the tube inlet pressure will be low, and this pressure will increase more rapidly during a flow reduction than the tube inlet pressure associated with a low pressure loss characteristic. The higher tube inlet pressure makes a larger pressure drop available across the active zone, and this results in a higher flow rate through the unplugged coolant channel. However, the Panellit gauge senses only gross flow reductions. The flow reduction in a plugged channel would exceed that sensed by the Panellit gauge by an amount equivalent to the increased flow in the unplugged channel. Therefore, for a specified Panellit sensitivity factor, a high venturi pressure loss would result in lower flow rates in the plugged channel at the Panellit trip flow. The permanent pressure loss in C-Reactor venturis is rather high to begin with, so improvements in the venturi efficiency, which were affected in the K Reactor venturis, and the CG-558 old reactor venturis, should be expected to increase the plugged channel flow rate at trip conditions. Any increase in the plugged channel flow will be accompanied by a proportional increase in the permissible tube outlet temperature.

Conversely, the pressure loss characteristics of fringe tube orifice assemblies will result in more restrictive tube outlet temperature limits than those presented in this document. It was the intent, with these limits, to support a program of I and E fuel element irradiation in high power, central zone tubes.

Pressure at the End of the Active Zone

Pressures at the end of the active zone are presented graphically in Figure 10, taken from isothermal inlet temperature data by K. J. Bell. These pressure data influence the limit in two important respects. First, the saturation

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temperature at the end of the active zone was determined from the pressures in Figure 10. The limits were based on the pressure curve for a 5 psig rear header pressure. Therefore, the limits were based on conditions which are more representative of tubes at the top of the reactor, and will be conservative for tubes lower in the reactor. To permit the utilization of higher saturation temperatures at the bottom of the reactor, Figure 3 presents a tube outlet temperature correction factor for rear header pressure, as measured at the header elevation.

The second application of the pressure characteristic downstream from the active zone is in determining the pressure drop across the active zone. Subtracting this pressure from the tube inlet pressure, which is determined from Figure 9, the result is the active zone pressure drop. Since the two flow channels are paralleled this pressure drop is "seen" by both channels. Knowing the demand characteristics for an unplugged channel, the channel flow may be determined from the active zone pressure drop.

Since pressure drop is the primary interest in this application, the active zone and pressure, and corresponding rear header pressure, should be measured in the control room in order to be placed on the same elevation basis as Panellit and front header pressures.

Active Zone Pressure Drop

The active zone pressure drop characteristics were determined in a laboratory mockup, using standard I & E fuel elements and a new C-Reactor process tube. The pressure drop across the active zone was measured at different tube flow rates. Then the hole channels were plugged in each fuel element, and the characteristics of the annulus channel alone, were determined. By difference between total tube, and annulus characteristics, the flow characteristics of the hole channel were calculated.

The original measurements in a new C-Reactor process tube indicated a flow split of 0.638, expressed as the ratio of annulus flow to tube flow. In the reactor, as well as in this laboratory mockup, the relative annulus flow is determined by the relative resistance to flow in the two channels. Viscosity effects contribute to the unequal flow resistance when channel temperatures are unequal, but for small differences in temperature the viscosity effect may be ignored. The effect of viscosity will be to decrease the relative flow resistance in the higher temperature channel. Therefore, there will be a tendency for the flow to increase, and outlet temperatures to decrease correspondingly, in the higher temperature channel. For this reason, there may be a smaller disparity between actual channel outlet temperatures than that predicted on the basis of isothermal hydraulic data, using an assumed constant heat split between the two channels.

The new tube flow laboratory data represents the worst case with respect to plugging in the annulus channel and conversely, a best case with respect to hole plugging. The relative annulus flow of 0.638, in a new process tube, is the

minimum possible value in a normal C-Reactor process tube loading of 145 fuel elements. In cold, corroded C-Reactor process tubes the annulus channel is enlarged considerably, and flow resistance is reduced. According to theoretical relationships, the relative annulus flow rate will increase with tube inside diameter as depicted in Figure 8.

- The solid line in Figure 8 is based on a derivation by D. L. Coniotta, relating the flow split to the process tube and fuel element geometry. This simple relationship neglects possible differences in surface roughness, partial plugging through slug misalignment, and viscosity effects. The dashed line also neglects these differences, but takes actual friction factors into account. It is based on an empirical correlation by R. J. Shields, of solid fuel element pressure drop data in all Hanford reactors.

It should be noted that corrosion caused diameter increases become progressively smaller toward the front of the process tube and that Figure 8 is based on a uniform tube geometry through the entire length of the active zone. Figure 8 does not justify a strict interpretation for this reason, and also because possible surface differences between the two flow channels were neglected.

However, it should serve for an order of magnitude estimate of the flow split in old, corroded C-Reactor process tubes. A flow split of 0.700 was chosen as representative of the worst possible tube corrosion. It will be noted that a forty mil increase in tube diameter, or a removal of twenty mils from the tube inside wall, is required to produce this flow ratio. Since this is the average corrosion required on the active zone, the maximum corrosion must be somewhat greater. The higher relative annulus flow may occur in shorter tube charges, where the downstream highly corroded portion of the tube represents a higher percentage of the total active zone length. The run-to-rupture test charges in C-Reactor, consisted of 22 fuel elements in original C-Reactor process tubes, and should, therefore, represent a more unfavorable flow split. Although flow rates were not measured in the separate flow channels, hole and annulus coolant temperatures were measured by thermocouple probes immediately downstream from the charge. As discussed elsewhere, the observed relative coolant effluent temperatures may be used empirically to determine the flow split between the hole and annulus channels. The maximum annulus to total flow ratio, so determined, was about 0.70. Since in-pile data were consistent with the interpretation placed on Figure 8 it was believed that 0.70 was a reasonable choice of relative annulus flow for the basic limit.

It was mentioned previously that 0.038 was the minimum expected relative annulus flow rate. This is so because the annulus is much less prone to plugging than the hole channel, and because slug corrosion effects during the relatively short in-pile exposure, are negligible compared to the longer term tube corrosion effects. Slug misalignment, or cocking, causes a negligible effect on flow resistance in the annulus but the effect on the hole channel is noticeable. In the event of slug misalignment, there would be a slight increase in the relative

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annulus flow, with a corresponding decrease in the sensitivity of the Panellit gauge toward detecting further hole plugging to the saturation temperature limit.

The flow ratios 0.638 and 0.700 represent the limits of a range of relative annulus flow rates, which should cover all possible normal loading conditions at C Reactor. For the purpose of calculating the basic tube outlet temperature limits, and limit correction factors, relative flow values of 0.64, 0.67, and 0.70 were assumed. Curves for the hole, annulus, and total tube active zone flow characteristics are plotted in the form of the experimentally determined equation:

$$F = K_T (P_I - P_O)^{1/1.8}$$

Where

F = Total tube flow

P_I = Tube inlet pressure

P_O = Pressure downstream from the active section

K_T = The proportionality or flow resistance constant for the total active zone

The hole and annulus characteristic curves, of course, have smaller resistance constants (K), but the pressure drop term has the same exponent, so the curves are parallel on a logarithmic graph.

The experimentally determined resistance constant for 32 fuel elements in a new C-Reactor process tube was 2.27. For shorter tube charges, the active zone pressure drop will be reduced in direct proportion to the charge length, and the resistance constant may be adjusted accordingly. For example, at a given flow rate the pressure drop across a loading of 25 I & E fuel elements is 25/32 of the 32 element pressure drop and the resistance constant is 2.61. Thus, the effect of charge length on the tube temperature limits is covered by the correction factor for tube resistance.

These flow characteristics are presented in Figures 11, 12, 13, 14 and 15 for the benefit of those who may wish to follow the limit calculations more closely. It should be emphasized again that these do not represent laboratory data except in the form of the flow equation, but are merely assumed relative flow rates and resistance characteristics.

It has been mentioned that a conservative relative annulus flow of 0.70 was employed in calculating the basic tube outlet temperature limit. Since many tubes will not have relative flow conditions that are this unfavorable to the sensitivity of hole plugging detection, it was desirable to formulate a correction factor to be used upon indication of a more favorable division of flow. The less favorable flow split is the result of increased flow through a less resistant annulus. The hole flow characteristics remain unchanged, so the flow split may be expressed in terms of the total tube flow resistance constant. This is illustrated in Figure 16, where the relative flow rates of 0.64, 0.67, and 0.70 are

represented by total tube flow constants of 2.27, 2.50, and 2.76 respectively. Thus, in a tube without thermocouple probes or any other direct indication of hole or annulus channel flow rates, the relative flow rates may be surmised by measurement of the tube flow resistance characteristics.

This correction factor is based on the premise that annulus "unplugging" is responsible for the observed changes in tube flow resistance and the accompanying changes in relative channel flow rates. Partial hole plugging because of slug misalignment should be minimized by the Tru-line feature. Flow abnormalities caused by canning defects should be minimized by careful inspection before charging. Therefore, the most likely cause of variations in the relative flow split will be variations in actual tube size resulting from corrosion. However, if higher than normal flow resistance is observed this should be immediate cause for suspicion of partial or complete hole plugging. The limits in this document will not be applicable to the case of strongly suspected initial hole plugging, but the general method may be employed. The annulus resistance characteristics may be assumed conservatively or calculated from the knowledge of resistance characteristics with previous loadings. Then, the extent of hole plugging may be determined and the hole flow calculated. A tube outlet temperature limit may be calculated by the same procedures used in this document.

Tube flow is determined for a particular set of operating conditions by the solution of simultaneous equations representing the tube supply characteristics and the demand characteristics. This is done graphically in Figure 17 by plotting tube inlet pressure versus tube flow. Supply curves are presented for front header pressures of 390, 415, and 440 psig. Demand curves are presented for a rear header pressure of 25 psig and tube active zone resistance constants of 2.27, 2.50, and 2.76. The intersection of a particular pair of supply and demand curves represents the expected normal operating flow and the corresponding tube inlet pressure.

Because there is more interest in Panellit pressures than tube inlet pressures, the supply and demand curves are presented in Figures 18 and 19 as Panellit pressure versus flow. Both the supply and demand curves are shifted down, because the Panellit pressure is always lower than the tube inlet pressure when flow is monitored by a venturi meter. Figure 18 presents the demand curves with a rear header pressure of 0 psig, and Figure 19 is based on a 25 psig rear header pressure.

Most of the mental callisthenics involved in the I & E trip-before-boiling limits are concerned with hydraulic characteristics, and the ultimate relation between flow changes in one channel and Panellit pressure changes. For this reason, most of the illustrative graphs used for calculating the limits deal with the hydraulic properties of I & E loadings. The available heat transfer data were relegated to a position of less importance by the adoption of a trip-before-boiling concept of tube protection. The most important heat transfer data of a quantitative nature deal with the relative heat flow to the separate flow channels.

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Relative Heat Flow

The relative heat flow has been discussed to some extent in connection with the assumption that the heat flow to a channel decreases as the channel flow decreases. Experimental data that reflect on this observation are presented in Figures 20 and 21. The points plotted as open circles, and crosses, are laboratory data obtained from the electrical resistance heater tube, and the solid circles represent data from C-Reactor.

The open circle points were obtained from a test in which tube power, and annulus flow rate were maintained constant, and the hole flow rate was reduced by increasing the flow resistance in the hole flow channel. Thus, the points represent one geometry, and the correlation of relative temperature rise and heat removal with relative channel flow rates was natural because the hole flow rate was the only changing parameter.

The laboratory data represented by the crosses were obtained from tests at constant tube power also, but the tube total flow rate was varied over a large range in a simulation of cone screen plugging. The points remained in one position as plotted on the graphs, over a wide range of tube total flow rates. This indicated that the tube power and total flow rate may be varied independently, without significantly affecting the relative temperature rise and heat removal between the two channels. In other words, the relative channel flow rate is the most significant parameter affecting the relative heat removal and temperature rise in the two channels, and the correlation may be employed over a wide range of tube powers or flow rates.

The three points represented by solid circles were obtained from I & E fuel element tests at C-Reactor. The relative annulus flow rates were determined in the laboratory in a new C-Reactor process tube. If the in-pile test tubes were badly corroded, these relative flow rates may be somewhat low. However, as plotted, the data indicate that the reactor heat transfer data are in good agreement with data obtained from the electrical resistance heater tube assembly.

One additional observation might be deduced from the good agreement between in-pile and laboratory data. The in-pile flow ratio differed in these three points because the slug geometry differed. Three hole sizes, 3/8 inch, 7/16 inch and 1/2 inch inside diameters were employed with the standard 1.474 inch outside diameter C-Reactor I & E fuel element. Yet the data is in good agreement with laboratory tests in which the relative flow rates were adjusted by varying the flow resistance. This is one more indication that the relative flow rate is the most significant parameter affecting the heat split between channels. Apparently, there is no secondary effect of very large magnitude associated with variations in fuel element geometry.

This will be of immense value in I & E fuel element design. The implication is that if the hydraulic properties of a particular design may be calculated, then some of the heat transfer properties, also, may be calculated. Individual channel

heat removal, channel effluent coolant temperatures, fuel element surface temperatures, and maximum fuel element central metal temperatures may be estimated with a fair degree of precision.

V. TUBE OUTLET TEMPERATURE LIMITS

The tube outlet temperature limits were determined by the calculation method outlined in Appendix I. In order to simplify the problems of limit administration, the limits were expressed in terms of Panellit pressures, i.e. in terms of the Panellit sensitivity factor. For conservatism, extremely restrictive conditions were chosen for the basic outlet temperature limit. Correction factors are included to permit upward adjustment of the limits when the basic limit is too low. The basic limit curve and the correction factors will be discussed in detail.

Basic Outlet Temperature Limit

The basic tube outlet temperature limit is presented in Figure 1 as a function of G, the Panellit high trip sensitivity factor. The Panellit sensitivity factor should be calculated from the following equation:

$$G = \left(\frac{HP - HT}{HP - P_{an}} \right)^{1/2}$$

Where HP = Front header pressure
 HT = Panellit high trip pressure
 Pan = Normal Panellit pressure, or minimum Panellit pressure within a specified operating range.

The basic limit is determined by the more restrictive case of selective plugging in the hole flow channel. The case of annulus plugging is not restrictive at the relative annulus flow that was assumed in order to provide a conservative basic limit. Existing high trip outlet temperature limits for solid slugs will cover the case of combined plugging in both channels, and these solid slug limits will be higher than the limits determined from Figure 1.

The limits were based on conservatively restrictive values of the major parameters as listed in Table I.

Table I

<u>Item</u>	<u>Base Value</u>
Relative annulus Flow (F_A/F_T)	0.700
Tube Resistance Constant (K_T)	3.11
Tube Inlet Temperature	10° C
Rear Header Pressure	5 psig.

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It will be noted that the outlet temperature limit is extremely dependent on G , the Panellit high trip sensitivity factor. In essence, this sensitivity factor is merely the ratio of trip flow to normal operating flow. For example, a sensitivity factor of 0.9 indicates that a high trip will occur when plugging causes a 10 per cent flow reduction. The concept of I & E fuel element protection used herein, provides a large incentive for increasing the high trip sensitivity factor, possibly at the expense of the low trip sensitivity factor. Also, increased Panellit high trip sensitivity may be desirable from the monitoring, or trouble shooting standpoint. I & E fuel elements will be more susceptible to disturbances or variations in the normal downstream flow resistance characteristics. Increased sensitivity of Panellit gauges to these resistance effects may implement the detection of abnormal flow conditions. As an interim operating expedient it appears that the necessary high trip sensitivity may be obtained, partly, through the lower tube flow resistance and lower Panellit pressures associated with I & E loadings. Another valuable expedient may be that of reducing the Panellit operating range to enforce closer operation to the high trip pressure.

In addition to the high trip outlet temperature limits, a low trip limit is required. Existing C-Reactor solid slug trip-before-instability limits, reduced by 5° C, may be applied to I & E fuel element loadings. The 5° C limit reduction is required to allow for possible eccentricity effects on the active zone pressure drop. For the most part, the low trip instability limits are determined by critical flow characteristics of the rear Parker fitting. Therefore, by applying a correction factor to compensate for the small effect of the active zone flow characteristics, the existing low trip limits may be employed safely. It is then not necessary to normalize the I & E boiling curve data as was done to obtain solid loading low trip instability limits.

Inlet Temperature Correction Factor

As a matter of arbitrary choice, the basic outlet temperature limits were based on an inlet temperature of 10° C. The limit was based on a trip-before-boiling concept, which may be expressed in simple form as:

$$T_o = (T_s - T_i) G_* + T_i$$

Where: T_i = Inlet temperature

T_o = Outlet temperature limit in °C

T_s = Saturation temperature at the end of the active column in °C

G_* = Panellit pseudo - sensitivity factor, relating the hole flow reduction to the total flow reduction and, in turn, relating this to the Panellit gauge sensitivity.

The simple limit equation may be rearranged to the following form:

$$T_o = G_* T_s + T_i (1 - G_*).$$

By examining this form of the equation, it will be noted that the inlet temperature effect on the outlet temperature limit is proportional to $(1 - G_*)$. The correction factors in Figure 2 illustrate this point. The effect of the pseudo-sensitivity factor is covered by using the actual Panellit sensitivity factor as a parameter in Figure 2. Unfortunately, this correction factor is inter-related with the initial relative annulus flow, and the tube flow resistance. For conservativeness in the correction factor, extreme values of 0.700 and 2.27 respectively, were chosen from the possible range of both variables.

Rear Header Pressure Correction Factor

A 5 psig rear header pressure was employed for calculating the basic tube outlet temperature limits which was conservative on two accounts. First, higher rear header pressures will result in higher saturation temperatures downstream from the active zone. Therefore, higher tube outlet temperatures will be permitted at any particular value of Panellit high trip sensitivity factor.

The other effect of rear header pressures appears in the intricate hydraulics relationships associated with detecting a flow decrease in one of the I & E flow channels. At the trip flow, the active zone pressure drop may be calculated from the known flow characteristics of the outlet fittings, dummy section, and the tube inlet assembly. The active zone pressure drop is determined simply by subtracting the active zone outlet pressure from the tube inlet pressure.

A high rear header pressure will result in a higher active section outlet pressure and consequently, in a lower active zone pressure drop. The lower active zone pressure drop corresponds to a lower flow rate in the unplugged channel. The flow through the plugged channel will be higher at the high trip conditions because of lower flow in the unplugged channel. This may be summarized by saying that the higher downstream pressures inhibit the tendency for flow to increase in the unplugged channel. It is this tendency for the flow to increase in one channel which handicaps the ability of the Panellit gauge to detect flow reductions in the other channel.

Unfortunately, the rear header pressure correction is interrelated with the front header pressure and the tube flow resistance. Conservative values of 440 psig and 3.11 respectively, were chosen for these variables in computing the rear header pressure correction. It was necessary, also, to express this correction factor as a function of the Panellit high trip sensitivity factor, as is shown in Figure 3.

Tube Flow Resistance Correction Factor

The basic outlet temperature limit was based on a tube flow resistance factor of 3.11, which represents a tube loading of 25 I & E fuel elements in a tube with the effective diameter enlarged through corrosion to give a relative annulus flow rate of 0.700. The tube outlet temperature limit is increased considerably by more restrictive tube loadings, even when the unfavorable relative annulus flow of 0.700 exists. The reason for the tube outlet temperature limit increase is quite simple. At any particular relative annulus flow, then the

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flow restriction is increased equally in both channels, e.g., by charging additional fuel elements. At the trip flow conditions, the increased flow resistance in the unplugged channel inhibits the tendency for increased flow in that channel. Therefore, as was pointed out in the effect of increased rear header pressures, the Panellit gauge becomes more sensitive to a flow reduction in the plugged channel.

The tube flow resistance correction factor is presented in Figure 4. This correction factor is significant, increasing to about 150 C for the resistance expected in a new C-Reactor process tube loaded with 32 I & E fuel elements. The correction factor is predicated on the assumption that the increased flow resistance occurs equally in both flow channels, as by the simple increase of the charge length.

It may be difficult to differentiate between cases of partial plugging in one channel, and a simultaneous increase of flow resistance in both channels. Therefore, the application of this correction factor should be a matter of judgment, to be tempered by the extent of particular knowledge about the tube in question. Both the operating data for previous charges, and the comparative status of this particular tube with respect to similar I and E loadings should be considered, when using the tube flow resistance correction factor. For example if a tube with a high flow resistance is relatively new in the reactor there is good cause for believing that the indicated high flow resistance is legitimate and normal. However, if the corrosion history of this tube does not differ much from several other tubes of lower flow resistance, there is better reason for suspecting some type of flow abnormality, e.g., a misaligned fuel element.

Before the flow resistance correction factor may be applied, there must be a reliable method for determining the tube flow resistance. This may be done in terms of the principal pressure variables, front header pressure, Panellit pressure, and rear header pressure, as shown in Figure 6. Rear header pressure determines the point on the tilted Panellit pressure scale, from which the graph is entered horizontally to obtain the tube flow resistance (K_t). The curves are more precise for rear header pressures around 25 psig, but a fairly good approximation may be obtained even at lower rear header pressures.

Figure 6 is based directly on the normal flow rates and Panellit pressures obtained from the intersection of supply and demand curves in Figures 18 and 19. The flow resistance correction factor may be used to compensate for differences in charge length, film formation, viscosity effects, and tube corrosion, the four main causes for variations in the active zone flow resistance. The bland assumption is made, in using the tube resistance correction factor from Figure 4, that the relative flow split is unchanged. This assumption is true in the case of different charge lengths in a tube of uniform cross-section, approximately true for viscosity effects, and it may be approximated by film formation. However, tube corrosion definitely results in an increased relative flow in the annulus.

This is taken into account by the complete separation of two correction factors, one for relative flow split and one for active zone flow resistance. The flow resistance correction factor does not include any of the increased sensitivity to hole plugging which results from the lower annulus relative flow rates in less corroded process tubes. If a high tube flow resistance is known, or strongly believed, to be caused by restrictive annulus conditions (as in a new tube) then the flow resistance limit correction may be used without fear of misinterpreting a condition of plugging in the hole channel. In addition, in this case, the relative annulus flow correction may be used with almost the same degree of confidence.

Relative Annulus Flow Correction Factor

The basic outlet temperature limits are based on an assumed relative annulus flow of 0.700. This represents a considerable amount of conservatism for I & E loadings in most C-Reactor process tubes, since the relative annulus flow is only 0.538 in a new C-Reactor process tube. Total flow will be somewhat restricted in new tubes, so these tubes may be in need of the additional allowable temperature rise. A correction factor for more favorable relative annulus flow rates is presented in Figure 5.

It is a perfectly straight-forward operation to calculate tube outlet temperature limits based on any assumed initial or normal value of relative channel flow rates. Increased relative annulus flow rates will result from lower flow resistance in the annulus channel. All other things being equal, the trip flow conditions determine a particular tube inlet pressure and total flow rate. At a particular tube inlet pressure the lower annulus flow resistance will naturally result in a higher annulus flow. Because total flow is the same, the hole flow must be lower. Lower hole flow at the trip flow, as determined by a particular Panellit sensitivity factor, must reduce the allowable tube power, because the hole effluent temperature at trip flow is limited to the saturation temperature. Also, lower hole flow at the normal operating conditions results in a higher normal hole effluent temperature, so the flow decrease necessary to reach saturation temperature is lower.

The approach used in calculating the relative flow correction factor was simply to assume various relative flow rates and calculate the corresponding relationships between Panellit sensitivity factor and permissible hole flow reduction, or ultimately, the tube outlet temperature limit. The principal uncertainties enter into the administration of the relative flow correction factor in the process of attempting to measure the relative annulus flow. Of course, there is no flow or pressure measurement in the individual flow channels. Nor are there separate channel effluent temperature measurements in the majority of the I & E loadings, to permit a reasonable estimate of the normal operating relative annulus flow.

The problem becomes one of estimating the probable flow split between channels from the observed total flow resistance. The method is to assure that the hole flow characteristics are known. The variation in hole diameter between individual I & E fuel elements is insufficient to cause a noticeable error on the hole flow characteristics. The Tru-line feature should minimize misalignment and cocking of the fuel elements. However, slug cocking will be the principal source of error in the assumed hole flow characteristics.

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The effect of a cocked slug on annulus flow characteristics will be negligible but a measurable increase in flow resistance will occur in the hole flow channel. The effect on Panellit pressure of one cocked slug may be in the order of ten psi. Therefore, a high Panellit pressure may be an indication of slug cocking, or it may indicate greater restriction in the annulus. Since the annulus is not noticeably affected by slug cocking, the high resistance would be an indication of a smaller and more restrictive annulus. If the previous operating history of the tube, or of similar tubes made the smaller annulus explanation appear acceptable, then it would be justifiable to assume that slug cocking and partial hole plugging did not exist. On this basis the relative annulus flow correction factor could be added to those tubes with high flow resistance.

Another source of falsely indicated, favorable (to the hole plugging limit) low relative annulus flow rates, might be the high flow resistance resulting from the presence of solid slugs or dummies in the I & E loading. If these solid slugs were adjacent to the I & E loading, immediately upstream or downstream, they would shut off most of the hole flow and the effect would be obvious. If tubular dummies were employed in the downstream dummy pattern and a solid slug found its way among them, the increased resistance would be comparable to that with a similar occurrence in solid loadings, and again, the effect is large enough to be detected as a definite abnormality. Assorted solid dummies could find their way into the normal perforated dummy column and remained undetected. In this event, slight non-conservative errors would result from using the indicated tube resistance and relative flow correction factors. They would be compensated somewhat by the effect of higher pressures, and saturation temperatures, at the end of the active zone.

However, the effects of these solid dummies would be small and their likelihood appears small, so the problem does not appear to warrant much concern. The main point of the foregoing involved analysis should be to illustrate that careful consideration and judgment should be used before employing the relative flow correction factor. The probabilities are very much in favor of a correct usage, but the indicated flow resistance should be examined first as a possible indication of abnormal flow conditions in the tube.

On the basis of assuming normal hole flow characteristics, Figure 7 indicates the relation between total tube flow resistance and relative annulus flow expressed respectively in terms of K_T , the tube resistance factor, and F_A/F_T , the ratio of annulus flow to total tube flow. Separate curves are presented for loadings of 25 and 32 fuel elements, because these loadings comprise the bulk of the controlled C-Reactor loadings to date. Before using Figure 7, it is necessary to determine K_T from Figure 6. This will have been done in the process of determining the tube flow resistance correction factor, which should always be applied in preference to, or before, the relative flow correction factor. Finally, after the relative annulus flow has been determined, the appropriate correction factor may be obtained from Figure 5.

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APPENDIX I

The step-wise procedure for calculating the outlet temperature limit from one set of operating conditions is presented below. For illustrative purposes the case of high trip protection against hole plugging is selected, because it is most representative of the uniqueness of I & E outlet temperature limits.

Procedure for Limit Calculations

1. Assume, or select, values for the important parameters,
 - a. Front header pressure,
 - b. Rear header pressure,
 - c. Tube flow resistance characteristics,
 - d. Relative flow split between annulus and hole,
 - e. Tube inlet temperature.
2. These parameters will determine a normal tube flow rate.
3. Select a trip flow rate.
4. The ratio of trip flow to normal flow determines a value of G, the Panellit sensitivity factor.
5. At this trip flow rate, find the corresponding value of tube inlet pressure and active zone outlet pressure.
6. The difference, tube inlet pressure minus active zone outlet pressure, equals the active zone pressure drop.
7. Since this is the special case of selective hole plugging, the hole channel flow characteristics are unknown, but the annulus flow may be determined from the known active zone pressure drop.
8. Subtract this annulus flow from trip flow, (3) minus (7). This result equals hole flow rate at the high trip conditions.
9. Find the relative heat split between channels at the normal, or initial, flow conditions, from the empirical relationship between the heat split, and the flow split.
10. Assume the relative heat split remains constant during the selective plugging of the hole channel. (Actually the relative heat removed by the hole channel will decrease.)

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11. Find the saturation temperature which corresponds to the active zone outlet pressure at trip flow conditions.
12. Calculate the allowable hole power from the equation:

$$Q_H = 0.2635 (T_s - T_1) (F_H)$$

Q_H = Allowable hole power in KW

T_s = Active zone outlet saturation temperature in °C.

T_1 = Tube inlet temperature in °C.

F_H = The hole flow rate at trip conditions in GPM.

13. Divide the allowable hole power by the empirical relative heat split which was determined in step 9. The result is the allowable total tube power.
14. Determine the outlet temperature at the normal-tube flow rate.
15. The ultimate result of steps (1) through (14) has been the determination of a tube outlet temperature limit which is valid from one particular value of front header pressure, rear header pressure, tube flow resistance, initial relative flow split between annulus and hole, inlet temperature, and Panellit sensitivity factor.

Numerical Example

Step numbers in this numerical example will correspond to the indicated steps in the preceding procedure.

1. a. Front header pressure = 415 psi.
b. Rear header pressure = 25 psi.
c. $K_T = 2.27$ (defining the tube flow resistance).
d. Relative annulus flow = 0.670 (the ratio of annulus flow to total flow).
e. Tube inlet temperature = 10° C.
2. From Figure 17 tube flow rate is determined to be 48.1 gpm.
3. Assume trip flow = 45 gpm.
4. $G = 45/48.1 = .935$.
5. From Figure 9 the venturi permanent pressure loss at 45 gpm is 109 psi.
Tube inlet pressure = 415 - 109 = 306 psi.

From Figure 10 the active zone outlet pressure is 50 psi.

6. Active zone pressure drop = $306 - 50 = 256$.
7. From Figure 11 for $F_A/F_T = .670$ and $K_T = 2.27$ the annulus flow is 33.2 gpm, at a pressure drop of 256 psi.
8. Hole flow = $45 - 33.2 = 11.8$ gpm.
9. From Figure 21, at a relative annulus flow of 0.670,

$$\frac{\text{Annulus Power}}{\text{Total Power}} = 0.70$$

$$\frac{\text{Hole Power}}{\text{Total Power}} = 1 - 0.70 = 0.30$$

10. No calculation involved.
11. Saturation temperature at 50 psig = 147.5°C .
12. Allowable hole power:
 $Q_H = 0.2635 (11.8 \text{ gpm}) (147.5 - 10^\circ\text{C}) = 426 \text{ KW}$
13. Allowable total tube power:

$$Q_T = \frac{426}{0.30} = 1420 \text{ KW}$$

14. Outlet temperature limit

$$T = \frac{1420 \text{ KW}}{(0.2635) (48.1 \text{ gpm})} + 10^\circ\text{C} = 122^\circ\text{C}$$

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APPENDIX II

In the early days of the philosophy of individual tube protection by Panellit gauges the tube power was restricted to a trip before boiling limit. The outlet temperature limit was related to the Panellit gauge sensitivity factor by a simple equation, as follows:

$$T_o = (T_s - T_i) G + T_i$$

(See the definitions of symbols at the end of this Appendix.)

The trip-before-boiling limit presented in this document resolves itself into a similar equation. At the high trip conditions, after selective hole plugging, the hole power is calculated as follows:

$$Q_H = F_H * (T_s - T_i) (.2635)$$

The allowable total tube power is related to the hole power by:

$$Q_T = \frac{Q_H}{X} = \frac{F_H * (T_s - T_i) (.2635)}{X}$$

The allowable temperature rise under normal operating conditions is determined by dividing the allowable tube power by .2635 times the normal flow. By adding the tube inlet temperature during this calculation step the allowable outlet temperature is calculated.

$$\begin{aligned} T_o &= \frac{Q_T}{(.2635) (F_N)} + T_i \\ &= \frac{Q_H}{(X) (.2635) (F_N)} + T_i \\ &= \frac{F_H * (T_s - T_i)}{(X) (F_N)} + T_i \end{aligned}$$

This last equation looks very much like the original trip-before-boiling equation with the complication that the term $\frac{F_H}{(X) (F_N)}$ is substituted for the more

simple and direct term, G. In the I & E flow geometry there is a direct relationship between G and the term $\frac{F_H}{(X) (F_N)}$. The ratio of hole flow at trip conditions

to normal flow, F_H/F_N , is related to the more fundamental ratio of trip flow to normal flow by the hydraulic characteristics of the I & E loading. The relationship is shown in Figures 22 and 23.

In Figure 22 the effect of different relative annulus flow rates is shown. At lower values of the relative annulus flow rate the Panellit gauge is capable of detecting a larger reduction in hole flow.

In Figure 23 the effect of tube flow resistance is illustrated. At higher tube flow resistance (lower values of K_T) the Panellit gauge is capable of detecting a larger reduction in hole flow.

It is possible to use the relationships presented in Figures 22 and 23 for calculating special cases of Panellit high trip protection to I & E loadings. However, these may be handled more simply by using the limits and correction factors presented elsewhere in this document. Figures 22 and 23 were presented mainly because they represent more fundamental hydraulic characteristics of the I & E loadings, and hence, may aid in the better understanding of the limits.

It should be remembered in using Figures 22 and 23 in conjunction with the equation,

$$T_o = \frac{F_H^* (T_s - T_i)}{(X) (F_N)} + T_i$$

that the X term varies with the ratio F_A/F_t , and that the saturation temperature varies with the trip flow, and thus is a function of both G and the normal flow rate.

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SYMBOLS

- Q_H - Rate of heat removal by coolant flow through the hole channel, assumed to be constant for normal and trip conditions.
- Q_T - Total tube heat removal.
- X - The ratio, Q_H/Q_T , determined empirically.
- T_s - Saturation temperature. For solid loadings under the old concept of trip-before-boiling, this was the saturation temperature in the rear crossheaders. Under the concept presented in this document for I & E loadings this saturation temperature corresponds to the pressure immediately downstream from the active zone.
- T_i - Inlet temperature.
- T_o - Tube outlet temperature limit.
- F_N - Normal tube flow rate.
- F_H^* - Hole flow rate at trip conditions.
- G - Panellit sensitivity factor, or the ratio of trip flow to normal flow.

DISCLAIMER

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23.	F_{H_2}/F_N Versus Panellit Sensitivity

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BASIC OUTLET TEMPERATURE LIMIT

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FIGURE 1

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FIGURE 2

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FIGURE 3

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REAR HEADER PRESSURE CORRECTION FACTOR

Basis:

Front Header Pressure 44.0

Tube Resistance Factor, $K_T = 3.11$

CORRECTION FACTOR %

FIGURE 4

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FIGURE 5

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FIGURE 6

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FIGURE 7
 TUBE FLOW RESISTANCE VS.
 RELATIVE ANNULUS FLOW

FIGURE 8

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FIGURE 9

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VENTURI CHARACTERISTICS

- ① FRONT HEADER TO VENTURI THROAT $F = 3.10 \Delta P^{.52}$
- ② VENTURI THROAT TO TUBE INLET $F = 5.49 \Delta P^{.5}$
- ③ FRONT HEADER TO TUBE INLET

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FIGURE 10

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PRESSURE AT THE END OF
THE ACTIVE ZONE

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ACTIVE ZONE PRESSURE DROP

$$\text{FLOW} = 2.27 \Delta P^{1/1.8}$$

FIGURE 12

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ACTIVE ZONE PRESSURE DROP

$$\text{Flow} = 2.50 \Delta P^{1/1.8}$$

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FIGURE 13

ACTIVE ZONE PRESSURE DROP

$$\text{FLOW} = 2.61 \Delta P^{1/1.8}$$

FIGURE 14

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ACTIVE ZONE PRESSURE DROP

$$\text{FLOW} = 2.76 \Delta P^{1/1.8}$$

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FIGURE 15

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ACTIVE ZONE PRESSURE DROP

$$\text{FLOW} = 3.11 \Delta P^{1/1.8}$$

FIGURE 16

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ACTIVE ZONE PRESSURE DROP, CONSTANT HOLE FLOW RESISTANCE

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FIGURE 17
SUPPLY AND DEMAND CURVES
TUBE INLET PRESSURE VS FLOW

FIGURE 13
SUPPLY AND DEMAND CURVES
PANELLIT PRESSURE VS FLOW

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FIGURE 13
SUPPLY AND DEMAND CURVES
PANELLIT PRESSURE VS. FLOW

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Rear Header Pressure = 25 psig

FIGURE 20

RELATIVE ANNULUS FLOW vs.

RELATIVE ANNULUS TEMPERATURE RISE

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FIGURE 21

FIGURE 22

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FIGURE C 3

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F_H / F_N VS G, PANELLIT SENSITIVITY

BASED ON $F_A / F_T = .700$

F_H / F

.350

.300

.250

.200

.150

.100

.050

.75

.80

.85

.90

.95

1.00

(G)

2.27

2.61

2.76

3.11

END

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