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IRRADIATION PROCESSING DEPARTMENT

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SUB-COOLED BURNOUT RELATIVE TO HANFORD REACTORS

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MASTER

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1. INTRODUCTION

In the Hanford production reactors failure of the fuel element cladding must precede release of fission products into the cooling water. Such cladding failure could result from the establishment of heat generation rates in the fuel which exceed the heat removal capacity of the coolant system. If the heat generation rate were increased under constant conditions of coolant flow and pressure, nucleate boiling at points on the fuel surface would be initiated, and with a further increase in the heat generation rate the fuel element heat transfer surface would become covered with a vapor blanket. Since the heat transfer capability of the vapor blanket is very much less than that of liquid water, the fuel element surface temperatures would rise rapidly, leading to failure of the cladding. This phenomena is known as "sub-cooled burnout" since the bulk temperature of the coolant is below the saturation temperature at the time of failure or "burnout" of the fuel cladding. Thus, for a given fuel and process tube geometry with fixed coolant pressures and flow rates, the heat generation rate at which sub-cooled burnout would occur establishes a limit to allowable reactor power levels. This document compares present and potential power level limits at the Hanford production reactors with power level limits established by sub-cooled burnout.

2. SUMMARY AND CONCLUSIONS

The sub-cooled burnout limits were determined by the use of limited experimental data obtained at Hanford on laboratory process tube mockups. These data were extended by conservative application of published empirical correlations of pertinent experimental data obtained by others.

Although the predicted burnout heat fluxes are conservatively low, the present and planned operational heat fluxes are well below these limits. However, a continuing experimental and theoretical program at Hanford will refine the determination of burnout limits well in advance of any operational approach to these limits. It is anticipated that the major program of refinement of limits will be completed during the next year.

A review of the potential for sub-cooled burnout at equilibrium power levels in existing Hanford reactors indicates that at current administrative power level limits the actual operating fuel element heat-flux densities are less than one-half the heat-flux densities at which film boiling leading to burnout could occur. The analysis further indicates that the reactors would operate safely within burnout limits at power levels determined by limitations imposed by the Speed of Control Criteria at the B, D, F, and C Reactors, and at 4900 MW at the K Reactors, which are not speed-of-control limited. At C-Reactor, which would be most nearly limited at the speed-of-control power level limits, a 25% power level surge combined with a 30% flow decrease would yield fuel element heat-flux densities which are about 6% below conservative burnout limits. It should be noted that these are very severe conditions and the probability that these events will occur simultaneously is very low. The status of the Hanford production reactor with respect to sub-cooled burnout power level limits at present

administrative power level limits and at power level limits determined by the Speed of Control Criteria are summarized in the table below.

POWER LEVEL LIMITS

Reactor	Administrative Limit (MW)	% of Sub-Cooled Burnout Limit	Speed of Control Limit (MW)	% of Sub-Cooled Burnout Limit
B,D,DR, F,H	1900	34	2500	53
C	2100	42	3200	64
KE,KW	4000	48	4900*	54

*The K-Reactors are not speed-of-control limited.

Due to the chopped cosine power distribution which occurs along the normal Hanford process tube, sub-cooled burnout would be initiated at a point along the fuel charge. Thus, slightly exceeding the heat flux required for film boiling would result in rupturing one or two fuel element in the column--perhaps with jacket melting--but would not lead to general fuel column meltdown.

3. DISCUSSION

3.1 Data and Correlations

The heat generated in a Hanford process tube is normally transferred to the coolant without boiling along the fuel charge. The heat transfer conditions are shown in Figure 1 which is a plot of pertinent temperatures as a function of length along the fuel charge. The cosine heat generation normally obtained is also shown. Heat transfer coefficients are high enough so that surface temperatures are well below the saturation temperature, and heat transfer occurs without boiling in the active section with maximum heat fluxes as high as 900,000 BTU/hr-ft². With an increase in heat flux or decrease in the heat removal rate, boiling may occur in the active section of the process tube.

Boiling can occur in two ways without net generation of steam: nucleate boiling and film boiling. Nucleate boiling occurs when the surface temperature exceeds the saturation temperature by a given amount. Heat transfer coefficients in the nucleate boiling region are about twice those in the non-boiling region and thus, the maximum heat flux which can be accommodated with nucleate boiling is higher than that which can be accommodated without boiling.

As the heat flux increases above the maximum that can be transferred by nuclear boiling, film boiling begins, blanketing the surface with a vapor film that greatly impedes the heat transfer. The temperature of the fuel element surface rises rapidly, and may exceed the melting temperature of the fuel cladding material. Consequently, this limiting heat flux must be considered both as a limitation on normal power and as a factor that becomes important under accidental reactor transient conditions.

This maximum, or burnout heat flux, has not been precisely defined for Hanford geometries and operating conditions. However, a large number of studies have been conducted at several university and AEC sites using electrically heated test sections cooled by water in turbulent flow. These studies have resulted in a number of theories and correlating equations describing the burnout phenomena. Although this work has progressed rapidly, no generally applicable theory of burnout has been developed, and an empirical approach is used for the present. Existing empirical correlations relate the burnout heat flux to the conditions and properties of the coolant. Pertinent variables have been shown to be the local conditions of pressure, velocity, sub-cooling, and hydraulic diameter. Only a limited number of studies have been performed with a range of these variables typical of Hanford operations. The bulk of these studies have been performed at the Savannah River Site.

Reference 1 describes the results of 65 experiments conducted at the Savannah River Laboratory at low pressure. These results were correlated with a maximum deviation of 16% by the following equation:

$$(Q/A)_{B.O.} = 478,800 (1+.0365 V)(1+.00914 T_s)(1+.0131 P) \quad (1)$$

Where:

$(Q/A)_{B.O.}$ = Heat flux at burnout, BTU/hr-ft²

V = Coolant velocity, ft/sec.

T_s = Sub-cooling; the difference between the saturation temperature and coolant temperature, °C.

P = Pressure, psia.

The range of variables covered in the experimental work and by the correlation is as follows:

- (1) Velocity - 5-45 ft/sec.
- (2) Sub-cooling - 5-75°C.
- (3) Pressure - 25-85 psia.
- (4) Equivalent diameter of the coolant passage - 0.21-.46 inches.
- (5) Geometry of heated surface - flat strips and tubes.
- (6) Flow of water - downward.
- (7) Heat flux - 900,000 to 3,240,000 BTU/hr-ft²

Reference 2 describes a survey of all known available experimental burnout determinations conducted using liquid water as the coolant and fits all the data, some 184 cases including those described in Reference 1, with the following empirical equation.

$$(Q/A)_{B.O.} = \alpha \frac{(1 + \beta_0 T + \beta_1 V/D)(1 + \gamma_0 V + \gamma_1 V/D)}{1 + \delta_1/D} \quad (2)$$

Where:

$(Q/A)_{B.O.}$ = Burnout heat flux, MW/ft²

T = Sub-cooling, °C.

V = Coolant velocity, ft/sec.

D = Equivalent diameter, ft.

$\alpha, \beta_0, \beta_1, \gamma_0, \gamma_1$ and δ_1 = empirical coefficients.

The empirical coefficients were presented in the reference as pressure dependent functions. The range of variables covered by the data is as follows:

Q = 340,000 - 4,100,000 BTU/hr-ft².

P = 14.7 to 2200 psia.

V = 0 - 54 ft/sec.

T = 0 - 146°C.

D = .012 - 1.77 ft.

The author of Reference 2 suggests that a safety factor of 1.43 be applied to Equation 2 to obtain a safe operating value. This factor was chosen so that the heat flux so calculated is less than 95% of the experimental values of burnout heat flux at given conditions.

An experimental program is being conducted by the Hanford Laboratories to determine the burnout heat flux in Hanford geometries and the effects of certain non-uniform conditions on the burnout phenomena. Preliminary data on a K-Reactor geometry are shown below: (3)

Flow (gpm)	Coolant Bulk Temperature, (°C)	Pressure (psig)	Saturation Temperature, (°C)	Burnout Heat Flux (BTU/hr-ft ²)
50	93.3	25	130.5	1.25x10 ⁶
20	93.3	25	130.5	0.83x10 ⁶

These limited data are correlated by either Equation 1 or 2 by applying a 1.66 safety factor as shown below:

$\frac{(Q/A)_{B.O.}}{\text{Experimental}}$	$\frac{(Q/A)_{B.O.}}{\text{Equation 1}}$	$\frac{(Q/A)_{B.O.}}{\text{Equation 2}}$
1.25×10^6	1.21×10^6	1.26×10^6
0.83×10^6	0.83×10^6	0.82×10^6

Equation 2 was fitted so that half the experimental values are higher than the calculated $(Q/A)_{B.O.}$ and half are lower. In the region of interest in this study, use of a safety factor of 1.43 gives a 95% chance that the calculated $(Q/A)_{B.O.}$ will be less than the experimental value of $(Q/A)_{B.O.}$. Thus, the two Hanford data points fall on the low side of the band of the observations used in the derivation of Equation 2.

It should be noted that in the Hanford experiments the burnout heat flux was considered to be that value at which a sharp rise in rod temperature occurred. In the 20 gpm experiment further power increases were imposed after the cutoff point at 830,000 BTU/hr-ft², and stable operation was established at 1,000,000 BTU/hr-ft² with a maximum measured rod temperature of 590°C. In the 50 gpm run, 1.5×10^6 BTU/hr-ft² was achieved without melting of the test section. This occurred because the water temperatures were about 10°F higher at the top of the test section (about the 11 o'clock position), and the temperature increases were observed to occur at the top of the heater-rods only. Thus, film boiling covered only the upper part of the heater-rods where the water temperatures were higher. Film boiling did not occur on the lower part of the heater-rods, and thus, most of the heat was removed through the bottom of the test sections. Since cooling was achieved through the lower part of the heaters, the surface temperatures under the film at the top of the specimens did not reach aluminum jacket melting temperatures. Higher top-of-annulus water temperatures may have resulted from non-uniform heat generation or from eccentric placement of the heater rods in the process tubes.

Differences between the actual reactor operating conditions and the experimental tests which indicate the experimental values of burnout heat flux are conservative and from the fact that the reactor fuel elements are much more massive than the heater tubes used in the tests. Reference 2 estimates the burnout heat flux may be up to 30% higher in the reactor for this reason. Also, the Hanford reactors use tubular fuel elements cooled in both an outer annulus and an inner hole. The heat flux in the hole is about 40% higher than the heat flux in the annulus while conditions of pressure and temperature are nearly the same. This complicates the analysis of the burnout point, but, assuming burnout conditions are reached first on the surface with the highest heat flux, it is expected that the heat load would shift to the other cooling surface and that melting temperatures would not be reached with the initiation of film boiling on the surface of the fuel element. However, there

are other variables which are not taken into account in the experimental tests which may lower the burnout heat flux. Chief among these are 1) the fact that the tests are run with a uniform heat generation, while the reactor process tube sees a chopped cosine heat generation, and 2) possible effects of eccentric placement of the fuel element in the process tube. Therefore, it is prudent to apply a safety factor over and above that which statistically gives a 95% probability that the calculated burnout heat flux falls below the range of experimental data. The estimates of burnout heat flux presented in this document are 60% of the values calculated by Equation 2 in the belief that this approach is conservative. Equation 2 was chosen over Equation 1 because the experimental data from which it is derived more adequately covers the range of variables encountered in the Hanford reactors. The application of this relationship to the Hanford reactors is described in the following sections.

3.2 Application at Hanford

3.2.1 Analysis

The experimental tests are run with a uniform heat flux and, thus, burnout occurs near the end of the heater sections where the coolant temperature is highest and coolant pressure lowest. The heat distribution along a Hanford process tube is described by a chopped cosine curve as shown in Figure 1. With this distribution of heat flux the critical point for burnout occurs downstream from the point of maximum heat flux but upstream from the point of highest coolant temperature and lowest pressure. The relationship is shown in Figure 2 which is a plot of heat flux as a function of position from the front of the active charge. A burnout condition in the process tube is indicated when the line describing the heat flux required for burnout coincides with the heat flux from the fuel element. It can also be seen that this occurs when the line describing the burnout heat flux is tangent to the heat generation curve. Thus, when a limiting heat flux is reached in the process tube, film boiling is initiated at a single point in the process tube and probably affects but a single fuel element. The critical point occurs about eight feet from the exit end of the active section of the process tube. This suggests that sub-cooled burnout is not a nuclear safety problem, but rather an economic problem in that it would result in one or possibly two fuel element failures and not charge melting. This is discussed further in later sections of this report. The relationship between the calculated burnout heat flux and the fuel element heat flux under various conditions of reactor operation are shown in Figure 3, 4, and 5 for the B, D, F, C, and K type reactors, respectively. In these figures the heat flux is plotted as a function of sub-cooling (the difference between local coolant saturation temperature and the local bulk coolant temperature). The top straight lines show the burnout heat flux. The lower curves show the heat flux in the hole of the I&E fuel element (annular heat fluxes are about 40% lower). Let us first examine operation under current administrative power level limits.

As shown in the figures, the burnout heat flux at the critical point in the process tube ranges from 2.9 times the operating heat flux at the BDF-type reactors to a factor of 2.1 at the K Reactors at these power levels. The difference occurs primarily because of geometrical differences in the reactors. The C and K reactors have less restrictive outlet fittings and therefore active zone pressures are lower, which results in less sub-cooling at a given section of the process tube. It should be noted that in addition to applying a safety factor to the calculation of burnout heat flux, conservatism results from the assumption of single phase coolant flow in outlet fittings. Actually, critical flow occurs in the rear crossheader fittings of most reactor tubes which raises the end of charge pressure above that calculated assuming single phase coolant flow throughout. This is especially true in the old reactors which have more restrictive outlet fittings.

3.2.2 Effect of a Power Level Increase

Expansion studies at Hanford have indicated that from an engineering standpoint reactor power levels are limited by the speed with which the control system operates during total emergency conditions. Based on the present control systems and twice the present average exposure this level is 2500 MW at the B, D, and F Reactors and 3200 MW at C-Reactor.⁽⁴⁾ The K-Reactors are not speed-of-control limited. The 4900 MW limit shown in Figure 4 is based on future water flow rates and a 95°C bulk outlet water temperature. Higher levels are feasible at lower exposures or if the control rod insertion time is improved. However, attaining these levels is generally contingent upon also increasing flow.

As shown in the figures, increasing power levels to the values given would reduce the operating margin to a factor of 1.5 to 2.0 below burnout conditions. Since raising reactor power to these levels also means increased flow rates, the limiting heat flux is higher at the K Reactors due to increased coolant velocities, assuming use of the present fuel element designs. At C-Reactor, the flow increase is hinged to a reduction in active zone pressure drop and so flow areas will increase with the result that the coolant velocity and burnout flux are unchanged. At the B, D, and F Reactors, obtaining the required flow rates involves the use of less restrictive fittings (similar to those at C and K Reactors) and the use of fuel elements with less hydraulic resistance. Thus, although the burnout heat flux is reduced, the operating heat flux at a given power level is also reduced. Present estimates indicate the fuel element surface area will increase 30%. The net effect is a reduction in the ratio of burnout to operating heat flux from about 2.5 to about 1.9. Thus, these power levels, based on present control limitations at B, D, F, and C Reactors and water plant expansion at the K Reactors, can be achieved without exceeding the heat flux at which sub-cooled burnout may take place in the process tube at normal operating conditions. The closest approach to film boiling at normal

operating conditions would occur at the C-Reactor where the burnout heat flux would be at least 50% higher than the normal operating heat flux. However, non-uniform conditions of flux or a flow decrease will change this relationship. These are considered in the following section.

3.2.3 Effect of Coolant Flow Loss and Power Peaking.

The Panellit gages are set to shut the reactors down upon a flow decrease of about 30% which is about the flow reduction which initiates flow instability in the process tube. With rapid flow reductions beyond this point an immediate scram is assured and laboratory experiments have shown that adequate flow is available to prevent burnout at the decreased post-scram heat output.⁽⁵⁾ Sub-cooled burnout, then, may be limiting if it occurs at flow reductions which are less than those which automatically scram the reactors. This condition may be aggravated by flux peaking so that the operating heat flux is raised above the normal cosine value at a given location in the tube. Under present operating conditions the flux may peak as high as 25% above the cosine.⁽⁶⁾ Control of this situation will be obtained with improved front to rear flux monitors and improved control systems and methods which are scheduled for installation at all reactors. However, a worst (although improbable) case for sub-cooled burnout may be considered to be under conditions which give a flow reduction of 30% (with no scram) coinciding with a flux peak at the critical point which is 25% above the expected chopped-cosine power distribution.

This condition is shown on the figures by plotting the burnout heat flux at 30% flow reduction and assuming no sub-cooling at the fuel element furthest downstream in the process tube. A 25% power increase above the maximum power levels considered in the report is shown by assuming it occurs at every position in the tube rather than in a limited area. At no position in the process tube does the operating heat flux under these very severe and improbable conditions exceed the calculated limiting heat flux. The worst case occurs at the C-Reactor where the ratio between burnout heat flux and operating heat flux is 1.06. This analysis is conservative from the standpoint that it is based on a flow reduction just sufficient to prevent a reactor shutdown coinciding with a front to rear flux peak which occurs at the critical point in the process tube.

3.2.4 Effect on Reactor Safety

As shown in the figures, when sub-cooled burnout conditions occur in the process tube, this condition exists only over a short length of the fuel charge because of the effect of the cosine heat generation in the process tube. Since film boiling in a sub-cooled region occurs without bulk coolant boiling in the process tube the consequences of this phenomenon are limited to one or two fuel elements in the process tube. It is concluded from the analyses described above that the maximum attainable heat flux before burnout occurs will not be exceeded at the maximum power levels considered feasible from current speed-of-control considerations, either under equilibrium or transient conditions.

If a sub-cooled burnout limit is reached at lower levels because of non-uniform conditions not taken into account in this analysis or because of variables unaccounted for in the empirical correlation, power levels will need to be reduced only because it is not economic to operate with a high fuel rupture rate. Reactor safety is not significantly affected.

3.3 Experimental Program

A program is being conducted by the Hanford Laboratories to determine the heat flux at which film boiling occurs in the various Hanford geometries at typical Hanford operating conditions. Included in this program is an investigation of the variables of fuel and tube eccentricity and non-uniform heat flux. This program is expected to be completed within the next year.

3.4 Allied Phenomena

3.4.1 Boiling Burnout During Accidental Transients

As shown above, a large safety factor exists under normal conditions of operation against fuel jacket melting and its ensuing problems. Heat transfer coefficients are high enough so that high heat fluxes are dissipated to the cooling water while maintaining non-boiling conditions in the active zone of the process tube. Under conditions of accidental flow reduction or power surge, however, the heat removal rate may not be sufficient to prevent bulk boiling in downstream sections of the process tube. These conditions raise outlet temperatures which cause increased amounts of boiling in the process tube outlet fittings. If the flow reduction or power surge is large enough the available supply pressure may be insufficient to overcome the increased resistance to flow caused by this boiling. When this occurs, the flow undergoes a rapid self-aggravated reduction to rates at which bulk boiling takes place in the active zone of the process tube. This phenomenon is termed flow instability, and when it occurs the reactor must be rapidly shut down to prevent possible fuel jacket melting.

Flow instability represents the prime individual tube protection problem at the Hanford reactors. Thus, the bulk of the Hanford experimental heat transfer studies have been applied to obtain an understanding of this process. A large amount of data have been obtained to study the effects of single tube plugging incidents, loss of front or rear process tube connectors, and total reactor flow loss and power surges on the transient conditions existing in the process tube. In general, these experiments have shown that a single tube flow reduction just short of total loss may be endured without burnout if the reactor is shut down within seconds after the accident occurs at process tube power levels up to 1500 KW. These experiments are being extended to higher power levels.

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The results of these experiments are used as a basis for setting reactor trip points to assure the adequacy of coolant flow under all conditions of individual tube flow reductions short of total loss. (7) Individual tube protection is provided by a Panellit gage which measures the pressure in a venturi or orifice at the inlet to each process tube. High and low pressure trips are set on these gages to automatically shut down the reactor when conditions of inadequate flow occur.

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FIGURE 1
HEAT TRANSFER CONDITIONS IN TYPICAL BDF PROCESS TUBE
(PRESENT OPERATION)

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FIGURE 2
COMPARISON OF BURN-OUT HEAT FLUX WITH FUEL ELEMENT
HEAT FLUX — BDF CURRENT CONDITIONS

FIGURE 3
SURFACE HEAT FLUX VS SUB-COOLING - BDF REACTORS

FIGURE 4
SURFACE HEAT FLUX VS SUB-COOLING - C REACTOR

FIGURE 5
SURFACE HEAT FLUX VS SUB-COOLING - K-REACTORS

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