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PROPOSED TUBE POWER LIMITS FOR THE PRTR
58-INCH MK I FUEL ELEMENT

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December, 1965

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PURPOSE

This report presents the results of calculations to determine tentative maximum tube powers for the 58-in. Mk I fuel element to be used in the High Power Density core in the Plutonium Recycle Test Reactor (PRTR) based on boiling burnout. The calculations make use of a modified method of determining boiling burnout limits for pressure tube reactors.

INTRODUCTION

The changes in the PRTR to use a higher power density core require the establishing of new tube power limits based on boiling burnout. This provides an opportune time to modify and improve the calculational procedure to determine boiling burnout tube power limits. The modified procedure is reported in BNWL-176.* The modified procedure differs in its application from the one currently used for the PRTR in that it does not yield one maximum tube power and heat flux for the reactor, but rather gives maximum permissible tube powers as a function of fuel element and operating conditions.

This procedure was used to calculate boiling burnout tube power limits for the HPD core for the PRTR. The calculations were done to 1) provide tentative values to the several factors used in the procedure, 2) provide tentative tube power limits for the HPD core, and 3) provide an illustration of the use of the proposed procedure.

It is expected that values for the various factors will change as the conditions for the high power density become firm. However, the tube powers presented herein are not expected to change significantly.

SUMMARY AND CONCLUSIONS

Numerical values of those factors affecting the possibility of the occurrence of boiling burnout were determined for the PRTR 58-in. Mk I fuel element and are listed in Table I. These factors were used in the calculational procedure outlined in BNWL-176 to determine the boiling burnout tube power limit for several flow rates and inlet coolant temperatures. The tube power limits are summarized in Figure 5, which gives the permissible tube power, based on boiling burnout, as a function of inlet coolant temperature and coolant flow rate.

Examples of permissible tube powers at an inlet temperature of 450°F are 1760 kw and 2028 kw at flow rates of 135 and 165 gpm, respectively.

*G. M. Hesson. Determination of Maximum Nuclear Tube Powers Based on Boiling Burnout, BNWL-176. December, 1965.

NOMENCLATURE

A_s	Heat transfer area per unit length (sq ft/ft).
L	Length of fuel element (ft).
P	Tube power (kw).
PE	Maximum error in power measurement.
PR	Maximum range of power drift before corrective action is mandatory.
W	Coolant flow rate (lb/hr).
WE	Maximum error in flow measurement (dead band).
WC	Maximum error in flow calibration.
WR	Maximum drift in coolant flow rate before corrective action is mandatory.
ΔH_x	Nominal enthalpy increase of coolant to any point, x , along fuel element (Btu/lb).
ΔH_{ox}	Maximum enthalpy increase of coolant to any point, x , along the fuel element (Btu/lb).
φ_x	Radial average heat flux at any axial point, x , along the fuel element (Btu/hr-sq ft).
φ_{ox}	Maximum heat flux at any axial point, x , along the fuel element (Btu/hr-sq ft).
φ_A	Maximum azimuthal fuel element flux peaking.
φ_R	Maximum radial fuel element flux peaking.
$f(x)$	Relationship giving the ratio of the specific power at any point along fuel element to average specific power.
$g(x)$	Relationship giving the fraction of total coolant enthalpy increase at any point along fuel element.

TABLE I.

FACTORS AFFECTING BOILING BURNOUT

<u>Factor</u>	<u>Value</u>	<u>Remarks</u>
Flow Dead-Band Error	1.02	Best estimate of flowmeter dead-band error.
Flow Calibration	1.03	Best estimate of maximum flowmeter calibration error.
Flow Range	1.10	The maximum the flow can vary before corrective action is mandatory.
Inlet Enthalpy Error	4 Btu/lb	Best estimate of the inlet temperature error.
Power Error	1.05	Best estimate of the maximum power error.
Power Range	1.07	The maximum the power level can vary before corrective action is mandatory.
Fuel Element Azimuthal Flux Peaking	1.05	Best estimate obtained from calculations of neutron flux gradient across the reactor.
Fuel Element Radial Flux Peaking	1.30	See explanation in text which follows.
Axial Flux Distribution	Given in Figure 1.	See explanation in text which follows.
Axial Flux Skewing Factor	1.00	See explanation in text which follows.
Fuel Element Manufacturing Variables	1.00	See explanation in text which follows.
Boiling Burnout Relation	Given in Figures 2 & 3.	See explanation in text which follows.
Burnout Consequence Factor	1.33	See explanation in text which follows.

EVALUATION OF FACTORS AFFECTING BOILING BURNOUT

The first step in determining a boiling burnout limit is to evaluate those factors affecting the possibility of its occurrence. A summary of these factors and the numerical value assigned to each is given in Table I. The factors which are significantly different from those used in previous boiling burnout analyses are discussed below.

Fuel Element Radial Flux Peaking Factor

There is a significant depression of the neutron flux, and hence of the heat generation, from the surface to the center of a fuel element due to self-shielding. The extent of the self-shielding varies, inter alia, with the nuclear enrichment and will be greater for the more highly enriched fuel elements of the HPD batch-loaded core than was the case for the graded core. Calculations were made* which show that the heat flux from the outside quadrant of each of the outer 12 rods of the fuel element enriched to 2.0 wt% Pu will be 1.36 times the average heat flux. Conservatively, 1.36 could be used for the fuel element radial flux peaking factor. However, there is experimental evidence which shows that the coolant between the fuel element and pressure tube wall is considerably cooler than the bulk average coolant temperature. The boiling burnout data to be used in this analysis were obtained with electrically heated test sections which had a uniform heat flux from all of the rods. Boiling burnout always occurred on the inner surfaces, and this determined the reported boiling burnout heat flux. The boiling burnout heat flux on the outer surfaces would have been higher due to the cooler coolant they see. For this reason, the fuel element radial flux peaking factor is reduced to 1.30.

Axial Flux Distribution Factor

The axial flux distribution proposed for this analysis is that calculated for the HPD core with 106 in. moderator level and 81 ppm boron in the moderator†, and is shown in Figure 1. Also shown in Figure 1 is a curve giving the result of the integration of the axial flux distribution. This curve gives the total heat to the coolant at each axial position.

Axial Flux Skewing Factor

This analysis assumes no axial skewing. That is, the axial heat flux distribution will not depart from that of Figure 1. This would be the case if no mechanical shim rods were used, or probably, if mechanical shim rods were used in either a full out or a full in position.

*Letter, "PRTR Flux Peaking Factors," R. E. Peterson to G. M. Hesson, November 12, 1964.

†R. I. Smith and J. L. Maryott. Calculated Reactor Parameters for the High Power Density Core in the PRTR, HW-84544. December 3, 1964.

Fuel Element Manufacturing Variables Factor

A value of 1.00 is assigned to this because the dimensional tolerances of the test section used to obtain the boiling burnout data used for the analysis are such that their effect on boiling burnout is believed to approximate the effect the fuel element manufacturing variables might have on boiling burnout. Previously, a value of 1.05 had been assigned to this factor. More recent electrically heated model tests have been performed with test sections that more closely approximate the actual fuel design.

Boiling Burnout Relation Factor

Insufficient boiling burnout data exist at conditions of interest for the HPD core with test sections having the cross-sectional geometry of PRTR 19-rod bundle fuel elements. There are, however, data available covering the desired range of flows and enthalpies obtained with test sections with a narrower space between rods. The test sections had a spacing of 0.050 in. between rods, a constant radial heat flux distribution, and were either 19-1/2 or 76 in. long. These may be compared with the HPD core fuel element which has a 0.074 in. spacing between rods, has a significant nonuniform radial flux distribution and is 58 in. long. Those data obtained with experimental test sections with a cross-sectional geometry identical to the HPD core fuel element at flow rates of interest had heat fluxes 40 to 50% greater than those obtained with the 0.050-in. spaced test section. It is proposed, therefore, to use the data from the 0.050-in. spaced test section (versus an actual 0.074) as a conservative basis for the boiling burnout relation for the HPD core until data from a more prototypical test section can be obtained. The 0.050-in. spaced data and the proposed boiling burnout curve are shown in Figures 2 and 3 for mass flow rates of 2,000,000 and 3,000,000 lb/hr-sq ft, respectively. Also shown in Figures 2 and 3 for comparison are the data obtained with 0.074-in. spaced test sections. Mass flow rates of 2,000,000 and 3,000,000 lb/hr-sq ft correspond to flow rates of about 110 and 165 gpm, respectively, at inlet temperatures of interest. It is further proposed that a linear interpolation between these boiling burnout relations be used for coolant flow rates between 110 and 165 gpm.

The data were obtained at a pressure of 1200 psig. Decreasing pressures from 1200 to 1000 psig cause an increase in the boiling burnout heat flux. The data are, therefore, applicable at pressures between 1000 and 1200 psig.

Boiling Burnout Consequence Factor

A further factor in the boiling burnout analysis is proposed; namely, the boiling burnout consequence factor. This is a term provided to give additional assurance that boiling burnout will not occur. That is, the burnout analysis is presumed to have taken into account all those factors affecting the possibility of boiling burnout and to have accounted for them exactly, or, if not exactly, conservatively. Operation at the tube powers predicted by the analyses should, then, give heat fluxes just at the boiling burnout heat flux. The burnout consequence factor is introduced to cause operation

at heat fluxes below that just at the boiling burnout heat flux. The magnitude of this consequence factor is a measure of the need for assurance that boiling burnout will not occur. It may be emphasized that the burnout consequence factor differs from the usual boiling burnout safety factor in that it is not intended to correct for any uncertainties in the analysis. These have already been accounted for in the appropriate steps in the calculations.

A boiling burnout consequence factor of 1.33 is proposed for the PRTR High Power Density core. Since the magnitude of the burnout consequence factor is largely a matter of judgment, a quantitative justification is not possible. However, a discussion of some of the considerations influencing this choice is appropriate.

First, similar factors of other analyses were examined. It is realized that what has been done in the past should not necessarily dictate what is to be done, but it does provide some guide lines.

A BOSF of 1.4 is used in one instance,* where the BOSF takes into account uncertainty in the data used to define the boiling burnout heat flux. The BOSF corresponds to the consequence factor of this report except for the fact that it does account for one of the uncertainties. A consequence factor of something less than 1.4 would be consistent with this analysis.

Second, the boiling burnout tube power limit currently used for the PRTR uses a safety factor of 1.85† where the 1.85 accounts for 1) experimental error in boiling burnout experiments, 2) lack of conformity of the test section to the fuel element, 3) indeterminate reactor conditions including axial flux skewing, 4) variations within manufacturing tolerances, and 5) the consequences of the occurrence of boiling burnout.

A factor of 1.10 would be appropriate for each of the first three of these and 1.05 for the fourth. Their product is 1.4 which, when divided into 1.85, implies a consequence factor of about 1.32. The consequence factor of 1.33 proposed for this analysis, then, is about the same as that included in the 1.85 burnout safety factor currently used for the PRTR.

Third, since the term under consideration is a measure of the desire to avoid the consequences of boiling burnout, the expected consequences should be examined. There is accumulating evidence that a reasonable heat transfer coefficient exists when boiling burnout has occurred, at least in the quality region. Heat transfer coefficients of 600 to 1600 Btu/hr-sq ft-°F

*D. S. St. John, et al. Preliminary Hazards Evaluation of the Heavy Water Components Test Reactor (HWCTR), DP-383. May, 1959.

†G. M. Hesson and J. M. Batch. Thermal Hydraulics Analysis of PRTR Fuel Elements at 1800 kw Tube Power, HW-75728. December, 1962.

are reported.* In the low quality region and at flow rates and pressures of interest, a heat transfer coefficient of 1500 to 2000 Btu/hr-sq ft-°F seems reasonable. If this is so, the 600,000 to 700,000 Btu/hr-sq ft boiling burnout heat fluxes typical of a high power tube in the HPD core would probably have a temperature excursion of the order of 500°F upon the onset of boiling burnout.

A temperature excursion of the magnitude expected may well result in a fuel element failure, but probably would not result in any catastrophic fuel element failure. Such a result might have economic implications, but should not constitute a hazard to the reactor.

These considerations suggest that a consequence factor of 1.33 is reasonably large. The foregoing argument does, in some cases, require an extrapolation of the boiling burnout heat transfer coefficient data into the subcooled region. The heat transfer coefficient data do not exist for subcooled coolant, it is believed, primarily due to the fact that boiling burnout heat fluxes under such conditions are large, on the order of 1.5×10^6 Btu/hr-sq ft. The temperature excursions associated with these large heat fluxes are so large, even with reasonable heat transfer coefficients, that the tests must be terminated or the test sections will be destroyed. In other words, the data needed cannot be obtained because the boiling burnout heat fluxes (and the subsequent temperature increases) are much larger than the heat fluxes (and temperature increases) contemplated for reactor operation. This is a measure of the conservatism of this analysis.

CALCULATIONS

The axial power distribution is shown in Figure 1 which gives the ratio of the local to average specific power generation as a function of fractional fuel element length. The average radial heat flux at any axial location is the local specific power divided by the heat transfer area per unit length. The local specific power is the total tube power divided by the total length times the appropriate factor given by Figure 1.

That is,

$$\phi_x = \frac{P}{L} \cdot \frac{3413}{A_s} f(x) , \quad (1)$$

where the terms are defined in the Nomenclature on Page 2. The term $f(x)$ is read from the axial flux distribution given in Figure 1.

*E. E. Polomik, S. Levy, and S. G. Sawachka. Heat Transfer Coefficients with Annular Flow During "Once Through" Boiling of Water to 100 Per Cent Quality at 800, 100, and 1400 psi, GEAP-3703. May, 1961.

J. E. Hench. Transition and Film Boiling Data at 600, 1000, and 1400 psia in Forced Convection Heat Transfer to Water, GEAP-4492. February, 1964.

The maximum heat flux at any point along the length of the fuel element may be greater than the average calculated by Equation (1) by the amount the knowledge of the power may be in error and by the amount of the fuel element radial and azimuthal flux peaking.

That is,

$$\varphi_{ox} = \frac{P}{L} \cdot \frac{3413}{A_s} \cdot PE \cdot PR \cdot \varphi A \cdot \varphi R \cdot f(x) . \quad (2)$$

The fuel element length is 4.833 ft and the heat transfer area (per foot) is 2.805 sq ft/ft. Evaluation of Equation (2) with these values and the appropriate values from Table I gives:

$$\varphi_{ox} = 384.8 P \cdot f(x) . \quad (3)$$

Columns 1 and 2 of Table II are then constructed from Equation (3). Column 1 is the fractional length along the fuel element. Column 2 is the result of the multiplication $384.8 P \cdot f(x)$ for the respective fractional lengths.

The enthalpy increase of the coolant to any point along the fuel element is obtained by dividing the power generated up to that point by the flow rate. The power generated up to any point is the integrated power relation given in Figure 1. The nominal enthalpy increase is then:

$$\Delta H_x = \frac{P \cdot g(x)}{W} , \quad (4)$$

where $g(x)$ is read from the integrated power distribution of Figure 1.

Both the flow and power may differ from their nominal values, thus:

$$\Delta H_{ox} = \frac{P \cdot PE \cdot PR \cdot 3413}{W \cdot WE \cdot WR \cdot WC} g(x) . \quad (5)$$

Putting the appropriate values from Table I into Equation (5) gives

$$\Delta H_{ox} = 4392 \frac{P}{W} g(x) . \quad (6)$$

Column 3 is the result of the multiplication of the integrated power times the factor 4392 from Equation (6).

Table II is used to develop a heat flux vs. enthalpy relationship for a given tube power, flow rate, and inlet enthalpy. The maximum heat flux at any point along the length of the fuel element is the product of the tube power and Column 2. The enthalpy increase to this point is the product of the tube power times Column 3, divided by the flow rate. The enthalpy at any point is the inlet enthalpy plus the calculated enthalpy increase plus

the inlet enthalpy error. These calculations were done for a flow rate of 165 gpm and tube power of 1800 kw, and are summarized in Table II. Column 1 is the fractional length along the fuel element. Column 4 is the maximum heat flux at each length. Column 5 is the enthalpy increase of the coolant. Columns 6, 7, and 8 are the enthalpies at each fractional length for inlet enthalpies of 440, 456, and 470 Btu/lb.

TABLE II.

TABULATED CALCULATIONS FOR BURNOUT ANALYSIS

1	2	3	4	5	6	7	8
x/L*	ϕ_{OX}/P	$\Delta H \cdot W/P$	ϕ_{OX} Btu/hr-sq ft	ΔH_{OX} Btu/lb	H_{OX} , Btu/lb		
					$H_{in} =$ 440	$H_{in} =$ 456	$H_{in} =$ 470
0.00	325	0	0.585	0.0	440.0	456.0	470.0
.05	284	132	.511	3.2	443.2	459.2	473.2
.10	300	299	.540	7.3	447.3	463.3	477.3
.15	332	492	.598	12.0	452.0	468.0	482.0
.20	368	707	.663	17.2	457.0	473.2	487.2
.25	400	932	.720	22.7	462.7	478.7	492.7
.30	425	1171	.765	28.6	468.6	484.6	498.6
.35	445	1430	.801	34.8	474.8	490.8	504.8
.40	460	1679	.829	40.8	480.8	496.8	510.8
.45	471	1940	.849	47.3	487.3	503.3	517.3
.50	475	2205	.855	53.7	493.7	509.7	523.7
.55	470	2475	.846	60.1	500.1	516.1	530.1
.60	459	2750	.826	67.0	507.0	523.0	537.0
.65	441	3060	.795	74.5	514.5	530.5	544.5
.70	421	3260	.759	79.5	519.5	535.5	549.5
.75	394	3480	.710	84.7	524.7	540.7	554.7
.80	364	3700	.655	90.1	530.0	546.1	560.1
.85	325	3900	.585	95.0	535.0	551.0	565.0
.90	290	4080	.522	99.3	539.3	555.3	569.3
.95	272	4250	.490	103.6	543.6	559.6	573.6
1.00	306	4392	0.551	107.0	547.0	563.0	577.0

*x/L = Fraction of Fuel Element Length

The values of maximum heat flux and local enthalpy at each fractional length from Table II are plotted on Figure 4 for each of the inlet enthalpies. The next step is to determine which of these has heat fluxes greater than the boiling burnout heat flux. To do this, the boiling burnout relation for a mass flow rate of 3,000,000 lb/hr-sq ft given in Figure 3 is used. It will be remembered that an axial flux skewing factor of 1.0 and a boiling burnout consequence factor of 1.33 were proposed. The heat flux we wish to stay below is then the boiling burnout heat flux divided by the product of these two factors, or by 1.33. The curve obtained by this division is also plotted on Figure 4. It can be seen that a portion of the operating heat flux-enthalpy relation for an inlet enthalpy of 470 Btu/lb lies above our boiling burnout curve, and this is not permitted.

The operating curve for an inlet enthalpy of 440 Btu/lb lies well below the boiling burnout curve, which shows that a higher tube power could be permitted at this inlet temperature. The relation for an inlet enthalpy of 456 Btu/lb is just tangent to the boiling burnout curve and represents a maximum permitted operating condition. In other words, for a flow rate of 165 gpm and a tube power of 1800 kw, the maximum permissible inlet temperature is that whose enthalpy is 456 Btu/lb or 484°F.

Calculations of the type illustrated above were repeated for a variety of conditions. The results are plotted in Figure 5 which gives the maximum permitted inlet temperature as a function of tube power with parameters of flow rate. It may be noted that for several of the combinations of inlet temperature and tube power at the lower tube powers, the outlet temperature would be greater than 540°F, the maximum permitted for a tube in the reactor. In these cases, the tube power would be limited by a bulk outlet temperature limit rather than by a boiling burnout limit.

Figure 6 was constructed to give an illustration of the boiling burnout situation arising from the tube power limits given by this analysis. The nominal operating curve for a tube with 163 gpm flow, 484°F inlet temperature, and 1800 kw is shown on Figure 6. The operating curves obtained by assuming that all those variables affecting boiling burnout are operating in both their most adverse and most favorable directions are also shown in Figure 6. At any given time, the actual operating curve will lie some place between the most adverse and the most favorable curves. The most probable position of the actual operating curve would be near the nominal curve; the probability that it is near one of the extremes is very small.

Also shown in Figure 6 are the boiling burnout relation used in this analysis and the best guess as to the actual boiling burnout relation for the HPD core. Figure 6 shows that the boiling burnout ratio (ratio of boiling burnout heat flux to operating heat flux) is most probably about 2.25.

RESTRICTIONS

It may be pertinent to summarize the restrictions to the use of Figure 5, which are scattered through the report - both implied and expressed:

1. The Mk I 19-rod bundle fuel element, 58 in. long.
2. Pu enrichment no more than 2 wt%. It will be conservative for lower enrichments.
3. Moderator level - 106 in. It will be slightly nonconservative for lower moderator levels.
4. Boron in moderator is 81 ppm. It will be conservative for lower boron concentrations.
5. No mechanical shims or mechanical shims which do not distort the axial heat flux.
6. Flow rates between 110 and 165 gpm. It will be nonconservative for flow rates outside this range.
7. System pressure between 1000 and 1200 psig.

Figure 1. Specific Power and Power Generated Distribution along HPD Fuel Element with 106-inch Moderator Level and 81 ppm Natural Boron

Figure 2. Boiling Burnout Relation for Mass Flow Rate of 2,000,000 lb/hr-sq ft

Figure 3. Boiling Burnout Relation for Mass Flow Rate of 3,000,000 lb/hr-sq ft

Figure 4. Illustration of Determination of Boiling Burnout Tube Power

Figure 5. Maximum Permissible Tube Power, for the HPD Core of the PRTR, Based on Boiling Burnout

Figure 6. Illustration of Proximity to Boiling Burnout

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