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Abstract

The hot spot analysis procedure has been revised to include new correlations for heat transfer coefficient and burnout heat flux. Based on these new correlations and current HFIR design data, the calculated maximum hot spot conditions (not including blister effects) are as follows:

Bulk water temperature	236°F
Water film drop	108°F
Oxide - water surface temp.	344°F
Maximum heat flux	1.52×10^6 Btu/hr-ft ²
Burnout heat flux	3.49×10^6 Btu/hr-ft ²
Maximum possible oxide - metal surface temp.	576°F

Calculations have shown that at 100 Mw operation with a 900 psi nominal ($\pm 10\%$) inlet pressure the presence of 0.05 inch diameter blisters (i.e., areas where there is no bond between the fuel and clad) in the 10 mil thick meat portion of the plate will be sufficient to raise the hot spot heat flux to one-half the calculated burnout value. A 0.094 inch diameter blister in the 30 mil thick meat region will produce the same reduction in burnout margin.

An investigation of the effect of local fuel segregation area size and degree of segregation indicates that a 5% increase in local heat flux will result from an increase in fuel concentration of 20% over a 58 mil diameter area, or from a 10% concentration increase over a 111 mil diameter area.

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I. Introduction

The need for a revised hot spot analysis arises due to several factors. First of all, the design and fabrication of the HFIR fuel element has progressed to a point where many dimensions and tolerances affecting the hot spot calculations have been established. Second, experimental investigations of forced convection heat transfer and burnout have indicated correlations which are more reliable than those used in earlier analyses. Third, several factors not included in the preliminary investigations, such as low pressure burnout heat flux and the effects of off-center meat, blisters, and small areas of fuel segregation in the fuel plates need to be considered. Finally, oxide film buildup on the fuel plates requires re-evaluation in the light of recent HFIR dynamic aluminum corrosion test data.

The general method of analysis employed is that outlined in the preliminary hot spot report. Revised correlations for heat transfer coefficient and low pressure burnout heat flux have been included. By utilizing the total hot spot heat generation rate and heat transfer coefficients obtained in the hot spot calculation, the additional effects of off-center meat, blisters, and areas of segregated fuel are evaluated via a matrix solution. Experimental data on the rate of formation of aluminum oxide film on HFIR fuel plate materials has been used in conjunction with the calculated hot spot water surface temperatures in order to establish expected rates of oxide film formation in the HFIR fuel element.

II. Hot Spot Analysis

1. Revisions to Analysis Procedure

The principal revisions to the hot spot analysis procedure are the inclusion of new correlation equations for local heat transfer coefficient and low pressure burnout heat flux. The HOT SPOT code now contains two heat transfer coefficient correlations: the Levy equation used in the previous analysis, and the Hausen equation reduced by 10% as recommended by Gambill and Bundy¹ for use in calculating HFIR fuel element heat transfer. The Hausen equation for calculation of local heat transfer coefficients, reduced to the form and nomenclature of the HOT SPOT code, is as follows:

$$h_{hs} = (U8)(C_1 - C_2 T_{B\hs} + C_3 T_{B\hs}^2) \frac{1}{\epsilon} \left[\left(\frac{0.6 \rho_{B\hs} v_{B\hs} \epsilon}{\mu_{B\hs}} \right) - 125 \right] \left[1 + \frac{1}{3} \left(\frac{1.667 \times 10^{-4} \epsilon}{a} \right)^{C_4} \right] \left[\frac{T_{S\hs}}{T_{B\hs}} \right]^{C_5}$$

where C_1 , C_2 , C_3 , C_4 , and C_5 are input constants. Nominal values for the constants are indicated in Table 1. The code automatically selects the Levy or Hausen equation on the basis of whether the value of C_4 or C_5 is 0.164.

Table 1

HFIR Hot Spot Analysis Input Data

Input No.	Symbol	Definition and Dimensions	Value
		<u>Core Dimensions</u>	
1	a	Distance from top of fuel element to hot spot, ft.	1.833
2	w	Fuel plate thickness, mils.	50
3	e	Coolant channel average thickness, mils.	47
4	2H	Coolant channel total length, ft.	2.0
		<u>Operating Conditions</u>	
5	ΔP_{core}	Core pressure drop, psi.	73.5
6	T_i	Coolant inlet temperature, °F.	120
7	Q/W	Nominal hot channel heat input per unit width, Btu/sec-in.	71.74
8	q	Radial average heat flux in hot channel at hot spot elevation, Btu/hr-ft ²	1.1723×10^6
9	f	Fraction of heat liberated above hot spot.	1.00
10	P	Operating pressure at core inlet, psi.	900
11	r	Radial max/avg power density ratio in hot channel.	1.00

(Table 1 cont'd)

Input No.	Symbol	Definition and Dimensions		Value
<u>Uncertainty Factors</u>				
12	U1	Fuel element flow distribution		0.95
13	U2	Local flow disturbances		0.9225
14	U3	Channel roughness		1.15
15	U4	Channel mixing		0.00
16	U5	Power level measurement accuracy		1.02
17	U6	Inlet temperature measurement accuracy		1.01
18	U7	Accuracy of measurement and maintenance of operating pressure		0.90
19	U8	Heat transfer coefficient uncertainty		1.00
20	U9	Burnout heat flux uncertainty		0.7702
21	U10	Local flux peaking and fuel segregation		1.05
22	U11	Variation between calculated and experimental power density		1.10
23	U12	Time-wise power density variation		1.00
24	U13	Meat distribution tolerance		1.10
25	U14	Deviation in plate fuel content		1.02
<u>Heat Transfer Correlation Constants</u>				
			Levy Correlation	Hausen Correlation
26	C ₁	Constants employed in correlations for calculating heat transfer coefficients.	1,402.	478.205
27	C ₂		12.758	0.91233
28	C ₃		0.014838	7.854 x 10 ⁻⁴
29	C ₄		0.164	0.667
30	C ₅		0.654	0.164

Three burnout heat flux correlations are included in the HOT SPOT code; two high pressure burnout correlations and one low pressure burnout correlation. Current high pressure burnout calculations for the HFIR have been based on the Zenkevich-Subbotin correlation with the 1.3 uncertainty factor recommended by Gambill and Bundy.¹ The use of the Zenkevich-Subbotin forced flow burnout correlation is limited to hot spot pressures in excess of about 300 psia. In order to investigate the loss of pressure accident in the HFIR it was necessary to employ a correlation which is valid at lower pressure levels. The equation chosen for this study was developed at Savannah River and is valid in the pressure range of 25 to 85 psia². The equation for calculating low pressure burnout heat flux, q_{bo} , reduced to HOT SPOT nomenclature is as follows:

$$q_{bo} = 4.79 \times 10^5 (1 + 0.0365 v_{hs\ bo}) [1 + 0.00507 (T_{sat} - T_{B\ hs})] \\ (1 + 0.0131 P_{hs\ bo}) (U9).$$

2. HOT SPOT Input Data

Table 1 indicates the values employed in evaluating the hot spot conditions in the HFIR. The physical dimensions employed are indicated in input numbers 1 through 4. As in the previous analysis, the hot spot is assumed to occur in the inner fuel annulus at the bottom of the active fuel region. The coolant channel thickness has been fixed at 47 mils, which is the minimum average channel thickness under present design tolerances.

Operating conditions are indicated by input numbers 5 through 11. The ratio of radial average power density at the hot spot location to core average power density was assumed to be 1.45, and the ratio of average power density in the inner annulus to core average power density was set at 1.15, as in the previous analysis. Radial power distribution in the hot channel was assumed to be flat, except for variations induced by the uncertainty factors.

The uncertainty factors employed are as follows:

U1 - The fuel element entrance and side plate flow effects factor has been set at 0.95, as was done in the previous analysis.

U2 - In evaluating the local flow disturbance factor, it was assumed that the local fluid velocity is proportional to the 0.5 power of the channel thickness. With a minimum channel thickness of 40 mils and an average channel thickness of 47 mils, the value of U2 is then 0.9225.

U3 - The channel roughness factor was set at 1.15 as recommended by Gambill and Bundy.³

U4 - Channel mixing was assumed to be zero, since this is the most pessimistic value.

U5 - Power level measurement in the HFIR will be based on water flow and temperature increase measurements. Accuracy of this method has been estimated at $\pm 2\%$ as was the case in the previous analysis.

U6 - Inlet temperature measurement and control accuracy has been assumed to be $\pm 1\%$, as before.

U7 - Since there will probably be no attempt to control the nominal HFIR operating pressure within close limits, the pressure measurement and control accuracy has been set at 0.9.

U8 - The heat transfer coefficient correlation employed in this analysis is the one recommended for use in the HFIR design;¹ consequently, the uncertainty factor on this term has been assigned the value of 1.0.

U9 - The burnout heat flux correlation utilized is also the recommended equation, with the exception of the multiplying constant. A value of U9 of 0.7702 is used to convert to the desired correlation.

U10 - It appears that most of the local heat flux peaking occurring within the HFIR core will be due to segregation within the fuel plate meat. Experience to date indicates that a 5% segregation allowance on local fuel concentration should be adequate in the HFIR core.⁴ A value of 1.05 is thus established for U10. This factor is applied in such a manner as to neglect heat flow parallel to the fuel plate surface. Consequently, the total surface area of the region where such segregation occurs is not critical so long as there is no appreciable change in bulk water temperature. If fabrication techniques are such that high degrees of segregation occur over very limited surface areas, the area of the segregation spot will be important. This problem is especially critical in the area of thin meat sections since particle sizes in the compact meat plates may be as high as 5 mils,⁵ and a relatively small amount of segregation could result in a considerable increase in local heat generation. Evaluation of small areas containing high degrees of fuel segregation has been based on methods similar to those employed in the blister evaluation and is included in the latter part of this report. It should be noted that any hot spot due to local segregation in the thin meat sections where the flux level is high will tend to burn out. Such spots occurring early in the run would not be nearly as detrimental as they would be later when an appreciable plate oxide film has built up. It is assumed in the hot spot analysis that the segregation hot spot is not burned out during the fuel lifetime, and that it still exists at the end of the fuel cycle.

U11 - The deviation allowance between calculated and actual hot spot power densities has been set at 10% as in the previous study. Based on experience with the critical experiment, HFCE-2, it appears that this value is probably conservative.⁶

U12 - The time-wise power density variation has been set at zero. This is a conservative assumption since nuclear calculations have shown the maximum power density to occur at the start of the fuel cycle.⁷

U13 - The fuel distribution factor has been set at 1.10 since a + 10% factor is the maximum permissible within bounds of the present specifications.⁸

U14 - Deviation in U-235 content per plate has been set at 2% for the same reasons.⁸

3. Calculated Hot Spot Conditions

The calculated HFIR hot spot operating conditions are indicated in Table 2. Some of the heat transfer variables influence operating conditions over the entire fuel plate, while others can influence only a narrow strip down the coolant channel length or a local spot on the plate. Since the strength of the plate is quite sensitive to the size and shape of the area which is operating at the hot spot conditions, some of the design variables may thus have greater importance than others in determining fuel plate strength. Consequently, the results are divided into 3 sections:

- (1) Nominal maximum hot spot operating conditions.
- (2) Hot spot conditions neglecting all factors which can influence only local spot conditions (hot streak conditions).
- (3) Hot spot conditions resulting from only those factors influencing operating conditions over the entire plate (hot plate conditions).

The data utilized in evaluating the oxide film buildup is shown in Figure 1.⁹ These data were obtained from the HFIR dynamic corrosion tests conducted under the direction of J. C. Griess. The particular method of correlation employed is felt to be the most desirable, since the oxide film drop evaluation involves neither a measured oxide film thickness nor a conductivity value for the oxide film. The major question involved in the oxide film evaluation appears to be in the shape of the correlation curve. Since the range of interest is at the higher temperatures, an error in the shape of the curve could cause an appreciable error in oxide film evaluation.

Table 2

Calculated HFIR Hot Spot Operating Conditions

	Hot Spot Conditions	Hot Streak Conditions	Hot Plate Conditions
Hot spot bulk water temperature, °F	236	236	220
Hot spot heat transfer coefficient, Btu/hr-ft ² -°F	1.40×10^4	1.48×10^4	1.48×10^4
Hot spot heat flux, Btu/hr-ft ²	1.52×10^6	1.45×10^6	1.32×10^6
Hot spot oxide - water surface temperature, °F	344	334	307
Burnout heat flux, Btu/hr-ft ²	3.49×10^6	3.51×10^6	3.65×10^6
Rate of plate temperature increase due to oxide film buildup, °F/day	15.5	14.1	10.2
Metal surface temperature after 15 days operation, °F	576	546	460

Figure 1.

Since the HFIR normal operating pressure has not been firmly fixed, and since there exists the possibility of a loss-of-pressure accident, the effect of pressure on burnout heat flux is of particular interest. Results of the operating-pressure-effect calculations for the reactor design specified in Table 1 are indicated in Figure 2. The Zenkevich-Subbotin correlation has been employed in calculating high pressure burnout, and the Savannah River correlation has given low-pressure burnout information. Burnout power levels in the pressure range of 85 to 300 psi (where neither burnout correlation is applicable) have been approximated by a smooth curve joining the two sets of results. It can be seen from this plot that a nominal (10% tolerance) operating pressure of 425 psi is required to maintain a burnout margin of 2.0 with the present HFIR core design. Below operating pressures of about 300 psi there is a sharp decrease in burnout power level with decreasing pressure.

Since it will undoubtedly be desirable to occasionally operate the HFIR at reduced flow rates, the effects of reduced flow on permissible power levels and hot spot temperature are of particular interest. The effects of core pressure drop on coolant velocity, hot spot temperature, and calculated burnout power level are indicated in Figures 3 and 4.

A very precise radial fuel distribution is required in the HFIR core in order to achieve a nearly flat radial power distribution. Consequently, the meat thickness must be closely controlled, and local fuel segregation must be reduced to a minimum. The required meat profiles and design loadings and tolerances are indicated on the HFIR fuel element drawings.⁸ The effects of profile thickness variations on hot spot temperature and calculated burnout power level are indicated in Figure 5. In applying this increased local loading factor it is assumed that the high concentration area extends vertically from the top to the bottom of the fuel plate. This assumption results in the maximum predicted effects on plate temperature and burnout power level. The present design calls for a maximum local loading tolerance of + 10%.⁸ The importance of maintaining or, if possible, reducing this tolerance is evident from Figure 5, where a change in local loading of 5% results in a 10 Mw change in calculated burnout power level and about a 10°F change in plate temperature. ORNL fabrication experience on HFIR mockup and critical experiment cores obtained to date indicate that it may be necessary to increase the tolerance on local fuel loading to + 15%⁴ due to fabrication capabilities.

The effects of increases in local fuel concentration due to segregation within the meat are indicated in Figure 6. This factor is handled differently from the fuel profile factor in that the segregation is assumed to occur only at a spot rather than in a strip extending the length of the fuel plate. The effects of heat conduction parallel to the plane of the fuel plate have not been included in these results. Figure 6 then represents comparatively large size segregation areas, the size being limited only to that which will result in no appreciable increase in local bulk water

Figure 3.

Figure 4.

Figure 6.

temperature. The effects of segregation area size are discussed in part IV of this report.

III. Blistered Fuel Plates and Off-Center Meat

The problem of fuel plate blistering is particularly critical in the HFIR since this reactor will be operating only about a factor of 2 below the calculated burnout value. A study of blister size effects has been undertaken in order to evaluate the size of blisters which must be detected by the fuel plate inspection techniques. The model chosen for this study consists of a cylindrical matrix, the matrix axis being perpendicular to the plane of the fuel plate and passing through the center of the blister. The blister is assumed to be circular, with no heat transfer across the blister. Since there will be no heat transfer in the matrix circumferential direction, the problem can be reduced to a two dimensional system, which is readily solved by the GHT code.¹⁰

The fuel distribution profile has considerable influence on the blister effects, due to the nonsymmetrical nature of the fuel plates. The HFIR fuel plates consist of a shaped meat section varying in thickness between 10 and 25 mils, clad on one side with 10 mils of aluminum and on the other side by sufficient aluminum to give a 50 mil total plate thickness. In the thinnest meat sections a 10 mil thick meat is clad by 10 mils of aluminum on one side, and by 30 mils of aluminum on the other. Since the cross sectional area for flow of heat in the plane of the fuel plate is least in the case of a blister located between the 10 mil meat and 30 mil clad, a blister in this location will result in the maximum increase in plate temperatures.

A thermal conductivity value of 97 Btu/hr-ft²-°F/ft has been employed for both the 6061 aluminum clad¹¹ and the fuel plate meat¹² materials. Although there will probably be some reduction in thermal conductivity due to radiation damage, this effect has not been included due to a lack of experimental data. The magnitude of this effect is expected to be low¹³ (probably under 10%). Also, the matrix solution will be appreciably affected only if the change results in a significant difference between the meat and clad conductivities.

The results of these studies are indicated in Figure 7. Three meat thicknesses have been considered (10 mil, 20 mil, and 30 mil), with blister diameters ranging up to 0.2 inch. The intercept of these curves at zero blister diameter indicates the effect of the off-center meat on local heat flux. Thus, since the 30 mil thick meat plate is symmetrical, there is no nonsymmetry effect exhibited by this plate. Figure 7 indicates that maintaining a burnout margin of 2.0 for the present HFIR design, with fuel plate blisters, will require detection of blisters above a 50 mil diameter. Present plans call for 100% inspection of plates for blisters as small as 0.125 inch diameter. Inspection to this blister diameter would give an overall calculated burnout margin of 1.6. Since one of the factors generally accounted for by the burnout margin is that of undetected fuel plate blisters, a burnout margin of 1.6 with blisters

Figure 7.

may be quite satisfactory, particularly when the conservative assumptions of no heat transfer across the blister and no allowance for hot spot area size in the burnout power level calculation are considered. On the other hand, the oxide buildup rates at the hot spot locations appears to be prohibitively high if 125 mil blisters are present at the hot spot.

IV. Segregation Area Size Effects

The model and method of calculation employed in the segregation area investigation are identical to those of the blister evaluation. Only the case of a 10 mil thick meat section has been considered, since this is felt to be the most critical portion of the plate from a segregation standpoint. It appears that a segregation allowance of 5% over a comparatively large area should represent a reasonable design basis;⁴ consequently, the heat transfer analysis has been based on a 5% increase in local heat flux due to segregation. The effects of an increase in local fuel concentration over a limited fuel plate area are indicated in Figure 8. In order to meet the assumed value of 5% heat flux increase due to fuel segregation, it will thus be necessary for the HFIR fuel plates to fall below the 5% curve of Figure 8.

V. Conclusions

The hot spot conditions listed in Table 2 have been adjusted to account for nonsymmetrical fuel plates and for the presence of 50 and 125 mil diameter blisters. These maximum hot spot conditions are indicated in Table 3. In order to insure a burnout margin of 2.0, it is essential that the HFIR fuel element maintain the present design tolerances, along with detection of blisters down to 0.050 inches diameter. Blister sizes up to about 0.07 inches diameter could be permitted with a symmetrical fuel-clad profile, with a burnout margin of 2.0, and 1/8 inch blisters may be permitted with the present fuel element design if the blister included calculated burnout margin is allowed to fall to 1.6.

In the 10 mil thick meat portion of the HFIR fuel plates an increase of 5% in local heat flux will result from a 10% increase in fuel loading due to segregation in a 111 mil diameter area, or from a 20% loading increase in a 58 mil diameter area.

Table 3

Maximum HFIR Hot Spot Operating Conditions with Blistered Plates

	<u>Maximum blister diameter in 10 mil thick meat section:</u>	
	<u>50 mils</u>	<u>125 mils</u>
Hot spot bulk water temperature, °F	236	236
Hot spot heat flux, Btu/hr-ft ²	1.80×10^6	2.25×10^6
Calculated burnout heat flux, Btu/hr-ft ²	3.49×10^6	3.49×10^6
Hot spot oxide - water surface temperature, °F	364	395
Rate of plate temperature increase due to oxide film buildup, °F/day	18.4	22.8
Metal surface temperature after 15 days operation, °F	640	737

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