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CALCULATIONS FOR HFIR FUEL PLATE NON-BONDING
AND FUEL SEGREGATION UNCERTAINTY FACTORS

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ABSTRACT

The effect of non-bonds and of fuel segregation on the peaking factors of the heat flux in the High Flux Isotope Reactor (HFIR) are examined. The effects of the two defects are examined both separately and together. It is concluded that the peaking factors that are used in the present HFIR thermal analysis code are conservative and thus no changes in the peaking factors are necessary to continue to ensure that HFIR is safe.

A study was made of the effect of the non-bond spot diameter on the peaking factor. The conclusion is that the spot can have a diameter more than three times the maximum value allowed by the specifications before the peaking factor is greater than the maximum value specified in the present HFIR thermal analysis code.

1. EXECUTIVE SUMMARY

I have performed calculations using the HEATING6 code in which I studied the effect of a non-bond defect, a fuel segregation defect, and a combination of the two. My model for the defects is the same as that used by Hilvety and Chapman, at least as far as can be determined from the available documentation in ref. 1. Results are tabulated for both maximum and minimum fluxes on both the hot and cold sides. Fuel thicknesses range from 7 mils (0.007 in. = 0.000178 m) to 30 mils (0.030 in. = 0.000762 m).

I found no measurable difference between the peaking factors calculated for reactor powers of 100 MW and 85 MW (the peaking factors differed by less than 0.001). I conclude that the same uncertainty factors for these defects may be used for all reactor powers of 100 MW or less and may probably be used for powers as high as a few hundred MW.

For the hot side of a fuel plate, I conclude that the uncertainty factors used in the HFIR thermal analysis code are conservative. According to my calculations, the combined non-bond and fuel segregation is the worst case (i.e., gives the highest peaking flux) for the hot side. The model used in the HFIR thermal analysis code, which is based on results from Hilvety and Chapman, gives uncertainty factors that are 0.02-0.10 higher than my calculations for this worst case. Thus, I see no need to modify the uncertainty factors used for the hot side in the HFIR thermal analysis code. The hot side uncertainty factors could be lowered to match my results; however, it is difficult to determine that the advantages gained would be great enough to be worth the effort.

For the cold side of a fuel plate, I conclude that the uncertainty factors used in the current HFIR thermal analysis code are not conservative. For the cold side worst case (i.e., the case that gives the highest peak flux on the cold side), which is the combined non-bond and fuel segregation defect with the non-bond located between the fuel and the hot side cladding, I calculate that the uncertainty factor from the HFIR thermal analysis code is roughly correct at fuel thicknesses of 10 mils or less, about 0.09 low for a fuel thickness of 20 mils, and about 0.30 low at a 30-mil fuel thickness. Thus, my calculations suggest that the cold side uncertainty factors used in the present version of the HFIR thermal analysis code need to be substantially revised. However, the effect of the cold side uncertainty factors on reactor safety calculations is so small that it should be sufficient to make a very crude correction to the cold side factors used in the present HFIR thermal analysis code.

I did an analysis of the effect of varying the non-bond spot diameter in a non-bond-only defect. The object of the analysis was to determine what diameter of the non-bond spot gives a value of the peaking factor which is the same as that found for a combined non-bond and fuel segregation defect with the non-bond spot at the standard diameter. The non-bond spot diameter at which the factors are equal ranges from about 0.20 in. (0.00508 m) for the minimum fuel thickness to about 0.16 in. (0.00406 m) for the maximum thickness of fuel. The most important point for reactor safety calculations is the hot spot, which has a combined defect uncertainty factor that is about halfway between the maximum and minimum values of the factor. According to my calculations, the value of

the variable-diameter non-bond peaking factor equals the combined non-bond and fuel segregation peaking factor for the hot spot at a non-bond spot diameter of about 0.18 in. (0.00457 m) - a value nearly three times the diameter of the largest non-bond spot allowed by the specifications (0.0625 in. = 0.001588 m).

2. INTRODUCTION

As part of the analysis of the HFIR at its new operating conditions, it was requested that I study the problems of fuel segregation in the fuel plate and of non-bonding of the cladding to the fuel plate ("blisters"). These two types of fuel plate defects are separate and independent flaws. However, the worst-case scenario is that both would occur at the same location. In my calculations, I examined the effect of each of the defects independently and then the effect of having them occur simultaneously.

The reactive part of the fuel plate (see Fig. 1) is a cermet formed from a mixture of powders of U_3O_8 and aluminum. The thickness of the fuel, as shown in Fig. 2.8 of ref. 2, ranges from a minimum of about 8 mils (0.008 in. = 0.000203 m) to a maximum of about 26 mils (0.026 in. = 0.00660 m). An additional amount of aluminum powder (with a small amount of B4C for the inner annulus plates) is added on top of the fuel so that the total thickness of the material in a plate (this combination of layers of fuel and inert is often called the "meat") is 30 mils (0.030 in. = 0.000762 m). The U_3O_8 and aluminum powders that make up the fuel can never be perfectly mixed. As a result, there will be locations for which the percentage of uranium is higher than specified. This phenomenon, which is referred to as fuel segregation, leads to a local rise in the heat flux from the plate into the cooling water (hot spot). This is the first of the two fuel plate defects I studied.

The 30-mil thickness of fuel and filler which constitutes the meat is clad with a 10-mil-thick sheet of aluminum on each side of the meat. As was noted in the previous paragraph, the meat is itself composed of a layer of fuel and a layer of filler. Thus, a fuel plate is a four-layer sandwich, 50 mils thick, composed of a pair of 10-mil-thick aluminum cladding layers on either side of a 30-mil-thick layer of meat. In the fuel plate manufacturing process, the cladding sheets are rolled together with the meat so that the powders are sintered and the cladding sheets are bonded to the sintered fuel cermet and sintered filler. The rolling process leaves occasional defects in which the cladding is not bonded to the fuel cermet. These defects are called non-bonds or blisters. The thermal resistance of the pocket between the fuel and the cladding that occurs at one of these defects is much higher than that of a good bond. This area of localized high resistance forces much of the heat from the fuel to flow toward the cooling water on the opposite side of the plate from the non-bond creating a local rise in the heat flux on that surface. This is the second of the two fuel plate defects I studied.

In reactor safety analyses, it is necessary to study the worst plausible combination of defects. There is some evidence that the presence of a fuel segregation defect raises the probability of having a non-bonding defect. Further, as a consequence of the law of averages, it must be assumed that at least a few of the fuel plate defects will contain both segregation and non-bonding in the same location. Thus, the plausible worst case is a combination of the two defects in one location. This combination is a third defect that I needed to study to see how the two separate defects interacted.

The effects of the fuel segregation and non-bonding defects were studied by Hilvety and Chapman (ref. 1) and by Haack. Haack's results were

Fig. 1. Cross section of HFIR fuel plate (not to scale).

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Fig. 2. Heat flux peaking on hot side of fuel plate due to non-bonds.
Source: N. Hilvety and T. G. Chapman, *HFIR Fuel Element Steady-State Heat Transfer Analysis*, ORNL-TM-1903, Union Carbide Corp., Nuclear Div., Oak Ridge Natl. Lab., December 1967.¹

Fig. 3. Heat flux peaking on cold side of fuel plate due to non-bonds.
Source: N. Hilvety and T. G. Chapman, *HFIR Fuel Element Steady-State Heat Transfer Analysis*, ORNL-TM-1903, Union Carbide Corp., Nuclear Div., Oak Ridge Natl. Lab., December 1967.¹

published in ref. 3 (Figs. 12-14). My Figs. 2 and 3 show the results of Hilvety and Chapman and are duplicates of Figs. 3 and 4 of ref. 1. The results from the Hilvety and Chapman analysis were incorporated into the HFIR thermal analysis code. In Table II, p. 35, of ref. 1, factors U16 and U17 are given the value 1.30, are labeled "segregation flux peaking," and contain an additional note that "this value is governed by the fuel plate spot loading tolerance." On p. 69 of ref. 3, the uncertainty factors for fuel segregation, U18 and U19, are both 1.30 (note the change in the symbols for these uncertainty factors between ref. 1 and ref. 3). The uncertainty factors for the non-bond, U20 and U21, are given by Eqs. (12)-(15) of ref. 3. These equations apparently were derived by taking a fit to the Hilvety and Chapman curves of flux peaking factor for a single non-bond (ref. 1, Figs. 3-4) and then multiplying the result by other fits which represent the curves of fuel thickness vs distance along the fuel plate for the inner and outer annulus plates. These equations, which were derived by L. A. Haack, are still used in the current version of the HFIR thermal analysis code [ref. 4, p. 48, Eqs. (A-68c) through (A-68f)]. The products of U18 and U20 or of U19 and U21 comprise the total uncertainty factors for the combination of fuel segregation and non-bonding.

My charter for this task was to determine the uncertainty factors for the segregation and non-bond effects for the new 85-MW operating conditions. After studying the literature and some old design notebooks that had been pulled from the HFIR project's files, I concluded that the most reasonable approach was to recalculate the 100-MW uncertainty factors and then see how they changed when the power was lowered to 85 MW.

The uncertainty factor analysis by Hilvety and Chapman was done using calculated results from a very early version of the HEATING heat transfer code. The model that was used is documented in Fig. 5 of ref. 1 (the identical figure was published as Fig. 8 of ref. 3). This figure is duplicated in my Fig. 4. There are some details of this model which took me a while to understand. Because Hilvety and Chapman did not outline their thinking on all the details, I believe that it is worth mentioning some of the things I resolved.

In ref. 1, Appendix B, pp. 117-122, Hilvety and Chapman derived a desired inspection spot diameter of 0.084 in. (0.00213 m). The segregation spot radius used for the computer calculations, as shown in my Fig. 3, is 0.0082 in. (0.000208 m), which is a diameter of 0.0164 in. (0.000417 m). One of the questions I asked was why this diameter was roughly one-fifth of the inspection spot size specified. The answer took a while to discover. As one would expect, Hilvety and Chapman tried to create a segregation spot that would represent the worst case. Although the specification is that the total amount of extra uranium within the inspection spot is to be no greater than 30%, the worst case occurs if all of the excess uranium is packed as closely as possible in the very center and the rest of the inspection spot contains fuel with the nominal amount of uranium. The volumetric heat generation rate for segregated fuel shown in my Fig. 4 is 10.3 times the generation rate for normal fuel. I assume that this implies that Hilvety and Chapman estimated that the uranium fraction in the segregation spot is at least 10 times that of the normal fuel (due to self shielding, a region of higher than normal uranium concentration should have a somewhat lower neutron flux than the rest of the region; this, in turn, means that, for the ratio of volumetric heat

BASIC ASSUMPTIONS:

1. NO HEAT TRANSFER ACROSS NON-BOND
2. CIRCUMFERENTIAL SYMMETRY
3. PACKING FRACTION OF U_3O_8 PARTICLES IN SEGREGATION SPOT = 0.74

REGION	THERMAL CONDUCTIVITY		HEAT GENERATION RATE AT 100 MW (Btu/hr in. ³)
	(Btu/hr-in.-°F)	(Btu/hr-ft-°F)	
FUEL	8.08	97.0	$1.82 \times 10^7 / (50 - 1 - 10)$
U_3O_8 SEGREGATION	2.26	27.1	$1.87 \times 10^8 / (50 - 1 - 10)$
CLAD	8.08	97.0	1.51×10^9

Fig. 4. Model employed for calculation of non-bond and fuel segregation heat flux peaking factors. Source: N. Hilvety and T. G. Chapman, *HFIR Fuel Element Steady-State Heat Transfer Analysis*, ORNL-TM-1903, Union Carbide Corp., Nuclear Div., Oak Ridge Natl. Lab., December 1967.¹

generation rates to be 10, the ratio of uranium concentrations must be somewhat greater than 10). If one calculates the radius of a spot of material with 10 times the nominal uranium concentration that is necessary so that the average concentration is 1.30 times nominal for an inspection spot of diameter 0.084 in. (0.00213 m), the result is approximately 0.008 in. (0.000203 m). I consider this a reasonable method for determining the worst case.

The model shown in Fig. 4 has the non-bond placed at the boundary between the filler and the fuel. In effect, this is a boundary that is internal to the meat. According to inspections of actual fuel plates, the usual locations for a non-bond are boundaries between the meat and the cladding layers, either the boundary between the filler and the cladding or else the boundary between the fuel and the cladding. I presume that Hilvety and Chapman placed the non-bond between the filler and the fuel because that location gave the largest peaking factors. I ran six cases for which the non-bond was between the filler and the cladding. I also ran four cases for which the non-bond was between the fuel and the cladding. As will be seen in a later section, my results for those ten cases confirm that having the non-bond between the fuel and the filler is a worst case for peaking factors based on maximum flux on the hot side of the plate. For the cold side of the plate, the worst-case peaking factors for both maximum and minimum flux required placing the non-bond between the fuel and one or the other of the cladding layers.

There are some numbers used in the original (1967) computer analysis and shown in my Fig. 4 that I have not been able to explain. Note that in the previous paragraph, the concentration of uranium in the simulated most closely packed segregated fuel was more than 10 times that in the nominal fuel. On p. 19 of ref. 3, the packing fraction of U_3O_8 in the segregated fuel is 0.74 (this represents close packing of uniform spheres), the fraction for nominal inner fuel is 0.128, and that for nominal outer fuel is 0.193. Thus, the ratio of uranium concentrations between segregated fuel and normal fuel is 5.8:1 in the inner fuel and 3.8:1 in the outer fuel. If I were to make the assumption that somehow the packing fraction in the segregated fuel is 100%, the ratio between the segregated and normal fuels would be only 7.8:1. I cannot explain why the ratio used for the heat transfer calculations is greater than 10. Perhaps Hilvety and Chapman doubled the highest ratio in order to be more conservative. A last input that I cannot explain is that the volumetric heat generation rates for normal fuel and for the cladding shown in Fig. 4 give a surface heat flux that is 71% larger than the average value for heat flux in the reactor. As I will explain in the next section, the uncertainty factors are independent of the reactor power so that this does not matter.

After the study of the non-bond and fuel segregation defects was under way, George Flanagan asked me to consider the effect of changing the diameter of the non-bond spot. The object of this addition to the study was to find what diameter of non-bond spot was necessary so that the peaking factor for the non-bond defect alone was equal to the factor found by the combination of the standard non-bond spot (0.0625-in. = 0.001588-m diam) with fuel segregation. This additional study was easy to make. The model and results are discussed in Sects. 5 and 6.

3. DEFECT HEAT TRANSFER ANALYSIS FOR NON-BONDS AND FUEL SEGREGATION

My heat transfer analysis was done using HEATING6, which at the time I did the work was the most modern version of the HEATING heat transfer code. I ran the cases on the CRAY X/MP at K-25. My model was identical to that shown in my Fig. 3 except for two changes. The first change was that, instead of modeling the non-bond as a completely insulated surface, I modeled it as a pair of radiant heat transfer surfaces. The material surfaces on either side of the gap transferred heat to one another using one-dimensional radiant transfer, with the emissivity of each surface set to 0.05. This value corresponds to the emissivity of polished aluminum foil. I would expect that the true emissivities of the surfaces would be greater than this. However, underestimating the heat transfer across this gap is a conservative assumption. I ran one test calculation to examine the effect of assuming that the gap did not transfer any heat at all. The differences between the two assumptions were very small, which indicates that the gap (at least as I modeled it) transfers very little heat. The second change was that, for cases that assumed a reactor power of 85 MW, I multiplied the heat generation rates shown in Fig. 4 by 0.85. For all of these calculations, I used a cooling water temperature of 120°F which is the minimum value specified for this temperature in the HFIR design. Although the surface temperatures and temperatures inside the plate are dependent on the cooling water temperature, the surface fluxes and the uncertainty factors are not dependent on the cooling water temperature.

I initially ran cases for fuel thicknesses of 10, 20, and 30 mils and for reactor powers of 100 and 85 MW. Later, I completed the study by adding the 7-mil cases for the 85 MW power. For each thickness, I ran a case that had no defects and thus was a baseline, a second case with fuel segregation but without a non-bond gap, a third case with a non-bond gap but without fuel segregation, and a fourth case with both fuel segregation and a non-bond gap. The set of cases for 85-MW reactor power are summarized in Tables 1-4.

I have not included any results from the 100-MW cases. The peaking factors for the 100-MW cases were the same as those from the 85-MW cases (to three significant figures). This was a result that I should have expected. The heat conduction problem is mathematically linear. Thus, if the reactor power is scaled down, the surface fluxes should be reduced by the same fraction. Peaking factor is a ratio of local surface flux to a baseline value so that, because both the local flux and the baseline value are proportional to the reactor power, the ratios should be independent of the reactor power. Actually, the model calculations are not quite linear because the radiant heat transfer across the non-bond gaps is nonlinear. However, so little heat was transferred across these gaps that the effect of this small nonlinearity on the results from the cases was not detectable at the level of three significant figures.

I am defining peaking factor as the ratio of the maximum (or, in some cases, the minimum) local heat flux on a surface to the average value (i.e., half the sum of the top plus bottom fluxes) of heat flux that was found for the baseline case. I am further defining the uncertainty factor as the peaking factor for the worst case. This definition of peaking factor is consistent with the definition used in the HFIR thermal analysis code. It should be emphasized that this definition includes the effect of

the difference between hot and cold side fluxes for the cases where the fuel is thinner than 30 mils. In other words, the peaking factors for the baseline cases are not necessarily 1.0, but rather the hot sides (for fuel thickness smaller than 30 mils) have a peaking factor larger than 1.0, and the cold sides (again, for fuel thickness smaller than 30 mils) have a factor smaller than 1.0. This definition of the peaking factor is an important point that should be emphasized because the true definition of peaking factor was not obvious to me from my initial reading of refs. 1-4. At first, I thought that the peaking factor would be the perturbation caused by the presence of the defect, which would have neglected the bias between the hot and cold sides which occurs for fuel thickness smaller than 30 mils, even in the absence of any defects.

The baseline cases, cases 57 and 51-53, were done to determine the split between the fluxes that go to the hot and cold sides for each individual fuel thickness. As was noted in the previous paragraph, because the geometry is not symmetric on a top-to-bottom basis (except for the 30-mil cases), the heat flux on the side that is closest to the fuel (the bottom side of Fig. 4) will have a larger fraction of the heat flux than the opposite side and will thus be the hot side. The volumetric heat generation rates in Fig. 3 are scaled by the fuel thickness so that the amount of heat generated in the fuel is the same regardless of the fuel thickness. Because the cladding heat generation rate is not scaled, the total heat generation is not quite the same for each fuel thickness. However, the ratio of cladding heat generation rate per unit volume to the equivalent for normal fuel is about 1:1000, so that the difference in total heat generation rates is on the order of 0.1%. The reader should remember that the uncertainty factors calculated in this report are for the non-bond and fuel segregation only. Other uncertainty factors are used to account for differences such as the radial and axial location of the point.

The maximum temperatures and surface temperatures are included in Tables 1 and 2. However, these temperatures should not be interpreted as absolute values but rather as relative values. The first reason is that, as I noted in the previous section, the volumetric heat generation rates are about 71% higher than those needed to give the correct average heat flux. The second reason is that the calculations assume that the cooling water temperature is 120°F. The actual value of the water temperature will change as a function of location and other factors. However, because the problem is linear (at least to the precision to which I have tabulated the results), one can estimate the correct temperature at the surface or in the interior by subtracting 120°F from the values given in this report, scaling the difference by a ratio that gives the correct heat generation rate for the location and reactor power in question, and adding this last result to the local bulk cooling water temperature.

The ratios of maximum and minimum flux to the baseline values, which are used to get peaking factors and ultimately uncertainty factors, are given in the last two columns of Tables 3 and 4. Thanks to the hot side to cold side bias, the ratios given for cases 57, 51, and 52 in these columns are not 1.0.

The flux ratios based on maximum flux for the hot side (the fourth column of Table 3) increase with decreasing fuel thickness. This result was also found by Hilvety and Chapman. This, of course, results from the fact that the greater thickness of inert material between the fuel and the

Table 1. HEATING6 segregation and non-bonding cases:
descriptions and maximum temperatures^a

Case No.	Segregated	Non-bonded	Fuel thickness (mil)	Power (MW)	Maximum temperature ^b (°F)
57			7	85	218.3
51			10	85	217.5
52			20	85	214.8
53			30	85	212.3
67	Yes		7	85	321.4
61	Yes		10	85	319.8
62	Yes		20	85	297.5
63	Yes		30	85	278.3
77		Yes	7	85	235.7
71		Yes	10	85	234.0
72		Yes	20	85	228.5
73		Yes	30	85	223.7
87	Yes	Yes	7	85	424.3
81	Yes	Yes	10	85	396.2
82	Yes	Yes	20	85	330.3
83	Yes	Yes	30	85	297.2

For the next six cases, the non-bond was located at the boundary between the filler and the cladding. (Note that this location is abbreviated "fi-cl" in the following entries.)

77C	Yes	Yes(@fi-cl)	7	85	223.2
71C	Yes	Yes(@fi-cl)	10	85	222.9
72C	Yes	Yes(@fi-cl)	20	85	222.1
87C	Yes	Yes(@fi-cl)	7	85	327.5
81C	Yes	Yes(@fi-cl)	10	85	326.4
82C	Yes	Yes(@fi-cl)	20	85	306.4

Table 1. (continued)

Case No.	Segregated	non-bonded	Fuel thickness (mil)	Power (MW)	Maximum temperature ^b (°F)
For the next four cases, the non-bond was located at the boundary between the fuel and the cladding. (Note that this location is abbreviated "fu-cl" in the following entries.)					
77L		Yes(@fu-cl)	7	85	237.4
87L	Yes	Yes(@fu-cl)	7	85	418.7
81L	Yes	Yes(@fu-cl)	10	85	393.0
82L	Yes	Yes(@fu-cl)	20	85	329.7

^aNote: all of the cases shown in this table used a standard 0.0625-in. (0.001588 m) non-bond spot diameter and a 0.0164-in. (0.000417 m) fuel segregation spot diameter.

^bThese temperatures are relative, not absolute. Calculating the true maximum temperature at a particular location requires correction for both the local bulk cooling water temperature and the local heat generation in the fuel.

Table 2. HEATING6 segregation and non-bonding cases:
surface temperatures^a

Case No.	Maximum surface temperature ^b hot (°F)	Maximum surface temperature ^b cold (°F)	Minimum surface temperature ^b hot (°F)	Minimum surface temperature ^b cold (°F)
57	205.3	188.7	205.3	188.7
51	203.9	189.5	203.9	189.5
52	199.3	192.2	199.3	192.2
53	195.4	195.4	195.4	195.4
67	235.7	198.3	205.3	188.7
61	231.3	199.5	203.9	189.5
62	219.6	204.4	199.3	192.2
63	211.8	211.8	195.4	195.4
77	215.9	188.7	205.3	184.3
71	213.0	189.6	203.9	184.3
72	204.8	192.2	199.3	182.6
73	199.1	195.7	195.4	175.4
87	261.0	190.8	205.2	188.5
81	250.1	191.8	203.9	188.7
82	228.4	195.2	199.3	187.4
83	216.6	199.8	195.4	180.2

For the next six cases, the non-bond was located at the boundary between the filler and the cladding.

77C	208.7	188.7	205.3	170.5
71C	207.3	189.8	203.9	171.1
72C	202.8	192.5	199.3	173.0
87C	239.8	192.6	205.3	174.6
81C	235.4	193.5	203.9	175.3
82C	224.1	196.4	199.3	177.6

Table 2. (continued)

Case No.	Maximum surface temperature ^b hot (°F)	Maximum surface temperature ^b cold (°F)	Minimum surface temperature ^b hot (°F)	Minimum surface temperature ^b cold (°F)
77L	205.6	192.9	182.6	188.7
87L	210.0	205.3	187.9	188.7
81L	208.5	206.2	186.8	189.5
82L	203.8	210.1	183.3	192.2

For the next four cases, the non-bond was located at the boundary between the fuel and the cladding.

^aNote: all of the cases shown in this table used a standard 0.0625-in. (0.001588 m) non-bond spot diameter and a 0.0164-in. (0.000417 m) fuel segregation spot diameter.

^bThese temperatures are relative, not absolute. Calculating the true maximum temperature at a particular location requires correction for both the local bulk cooling water temperature and the local heat generation in the fuel.

Table 3. HEATING6 segregation and non-bonding cases:
maximum heat fluxes^a

Case No.	Maximum heat flux ^b hot (Btu/h-ft ²)	Maximum heat flux ^b cold (Btu/h-ft ²)	Ratio of maximum heat flux to average baseline hot	Ratio of maximum heat flux to average baseline cold
57	1.28E+06	1.03E+06	1.11	.89
51	1.26E+06	1.04E+06	1.09	.91
52	1.19E+06	1.08E+06	1.05	.95
53	1.13E+06	1.13E+06	1.0	1.0
67	1.74E+06	1.17E+06	1.50	1.02
61	1.67E+06	1.19E+06	1.45	1.04
62	1.49E+06	1.27E+06	1.31	1.11
63	1.38E+06	1.38E+06	1.22	1.22
77	1.44E+06	1.03E+06	1.25	.89
71	1.40E+06	1.04E+06	1.21	.91
72	1.27E+06	1.08E+06	1.12	.95
73	1.19E+06	1.14E+06	1.05	1.01
87	2.12E+06	1.06E+06	1.83	.92
81	1.95E+06	1.08E+06	1.70	.94
82	1.63E+06	1.13E+06	1.43	.99
83	1.45E+06	1.20E+06	1.28	1.06

For the next six cases, the non-bond was located at the boundary between the filler and the cladding.

77C	1.33E+06	1.03E+06	1.15	.89
71C	1.31E+06	1.05E+06	1.14	.91
72C	1.24E+06	1.09E+06	1.09	.96
87C	1.80E+06	1.09E+06	1.56	.94
81C	1.73E+06	1.10E+06	1.50	.96
82C	1.56E+06	1.15E+06	1.37	1.01

Table 3. (continued)

Case No.	Maximum heat flux ^b hot (Btu/h-ft ²)	Maximum heat flux ^b cold (Btu/h-ft ²)	Ratio of maximum heat flux to average baseline hot	Ratio of maximum heat flux to average baseline cold
For the next four cases, the non-bond was located at the boundary between the fuel and the cladding.				
77L	1.28E+06	1.09E+06	1.11	.95
87L	1.35E+06	1.28E+06	1.17	1.11
81L	1.33E+06	1.29E+06	1.16	1.12
82L	1.26E+06	1.35E+06	1.11	1.19

^aNote: all of the cases shown in this table used a standard 0.0625-in. (0.0015885 m) non-bond spot diameter and a 0.0164-in. (0.000417 m) fuel segregation spot diameter.

^bThese heat fluxes are relative, not absolute. Calculating the true heat flux at a particular location requires correction for the local heat generation in the fuel.

Table 4. HEATING6 segregation and non-bonding cases;
minimum heat fluxes^a

Case No.	Minimum heat flux ^b (Btu/h-ft ²)	Minimum heat flux ^b (Btu/h-ft ²)	Ratio of minimum heat flux to average baseline hot	Ratio of minimum heat flux to average baseline cold
57	1.28E+06	1.03E+06	1.11	0.89
51	1.26E+06	1.04E+06	1.09	0.91
52	1.19E+06	1.08E+06	1.05	0.95
53	1.13E+06	1.13E+06	1.0	1.0
67	1.28E+06	1.03E+06	1.11	0.89
61	1.26E+06	1.04E+06	1.09	0.91
62	1.19E+06	1.08E+06	1.05	0.95
63	1.13E+06	1.13E+06	1.0	1.0
77	1.28E+06	0.96E+06	1.11	0.84
71	1.26E+06	0.96E+06	1.09	0.84
72	1.19E+06	0.94E+06	1.05	0.83
73	1.13E+06	0.83E+06	1.0	0.73
87	1.28E+06	1.03E+06	1.11	0.89
81	1.26E+06	1.03E+06	1.09	0.90
82	1.19E+06	1.01E+06	1.05	0.89
83	1.13E+06	0.90E+06	1.0	0.80

For the next six cases, the non-bond was located at the boundary between the filler and the cladding.

77C	1.28E+06	0.76E+06	1.11	0.66
71C	1.26E+06	0.77E+06	1.09	0.67
72C	1.19E+06	0.80E+06	1.05	0.70
87C	1.28E+06	0.82E+06	1.11	0.71
81C	1.26E+06	0.83E+06	1.09	0.72
82C	1.19E+06	0.86E+06	1.05	0.76

Table 4. (continued)

Case No.	Minimum heat flux ^b hot (Btu/h-ft ²)	Minimum heat flux ^b cold (Btu/h-ft ²)	Ratio of minimum heat flux to average baseline hot	Ratio of minimum heat flux to average baseline cold
For the next four cases, the non-bond was located at the boundary between the fuel and the cladding.				
77L	0.94E+06	1.03E+06	0.81	0.89
87L	1.02E+06	1.03E+06	0.88	0.89
81L	1.00E+06	1.04E+06	0.87	0.91
82L	0.95E+06	1.08E+06	0.84	0.95

^aNote: all of the cases shown in this table used a standard 0.0625-in. (0.001588 m) non-bond spot diameter and a 0.0164-in. (0.000417 m) fuel segregation spot diameter.

^bThese heat fluxes are relative, not absolute. Calculating the true heat flux at a particular location requires correction for the local heat generation in the fuel.

cold side results in having more heat toward the hot side. The reader will probably notice that the largest hot side flux ratio for fuel segregation only, which was found for case 67, is greater than the 1.30 value assumed for the HFIR thermal analysis code as documented on p. 69 of ref. 3. This latter value was presumably chosen based on the fact that the specifications allow a maximum of 30% extra uranium in the inspection spot. However, as I discussed in an earlier paragraph, the model shown in Fig. 3 specifies a segregated fuel volumetric heat generation rate which is more than 10 times the rate for the normal fuel. If there were no cladding at all on the hot side, the flux ratio would be nearly equal to the ratio of volumetric heat generation rates for the segregated fuel to the normal fuel. The fact that the factor is only 1.51 for 7 mils of fuel is due to the ability of the 10 mils of aluminum cladding to spread out the extra heat before this heat reaches the surface. The reader may also notice that the flux ratio for the combination of the non-bond and the fuel segregation for any fuel thickness is larger than the product of the factors for the individual defects. Although the heat conduction problem is linear, the combined effect of the two different defects does not seem to be a linear combination of the individual effects, but instead the two defects combine in a synergistic fashion to produce an effect that is larger than the simple linear combination.

The flux ratios for the cold side show a more complex pattern than those for the hot side. On the hot side, all the maximum flux ratios are 1.0 or greater. The minimum flux ratios are the same for each value of fuel thickness, regardless of the presence or absence of any defects (with the exception of cases 87L, 81L, and 82L, for which the position of the non-bond defect has been reversed so that the definition of hot and cold sides is arbitrary). On the cold side, some of the ratios based on maximum flux (the last column of Table 3) are greater than 1.0 while others are less than 1.0. Some of the ratios based on the minimum flux (the last column of Table 4) are less than 1.0 while others are equal to 1.0. Hilvety and Chapman found that there was a minimum in the heat flux on the cold side for the non-bond which gave peaking factors for the non-bond that are less than 1.0. This fact is shown clearly in Fig. 3. I also found a minimum in heat flux for the non-bond defect, cases 77 and 71-73, which gave ratios less than 1.0. The ratios based on maximum flux for these same cases are the same as the ratios for the baseline cases based on the hot side maximum fluxes, a result which is simply an indication that the effect of the non-bond is no longer detectable at a large enough radius. The cases with segregation only, cases 67 and 61-63, show ratios based on maximum flux which are greater than 1.0. The ratios based on minimum flux for these cases are the same as the ratios for the baseline cases based on the hot side maximum fluxes, a result which is simply an indication that the effect of the fuel segregation is no longer detectable at a large enough radius. The ratios given by the cases for the combined non-bond and fuel segregation defects, cases 87 and 81-83, show values that are both less than and greater than 1.0. The cold side flux ratios for the combined defect are part way between the ratios for the two separate defects. This situation is true for ratios based on both maximum and minimum flux. The flux ratios for the combined defect on the cold side are most definitely not the products of the ratios from the individual defects.

The most accurate estimate for the change in cold side flux caused by the combined defect would require integrating the total heat loss over some appropriate area and comparing that to the baseline. The minimum flux occurs at the very center of the non-bond spot whereas the maximum occurs at a location that is somewhat greater than the outside radius of the non-bond. Because the area that sees the maximum flux is greater than the area which sees the minimum flux, the actual total heat flow from the cold surface into the water for the 1.0-in. (0.0254 m)-diam calculational area is greater for the combined non-bond and fuel segregation cases than it is for the baseline. Thus, for the combined defect, the averaged flux ratios are approximately equal to the ratios for maximum flux, the last column of Table 3. These ratios are less than those given by the cases with segregation only.

As I discussed in the introduction, the model shown in Fig. places the non-bond between the fuel and the filler, whereas the more probable locations are either between the filler and the cladding or else between the fuel and the cladding. I ran six cases, (77C, 71C, 72C, 87C, 81C, and 82C) for which the non-bond was located between the filler and the cold side cladding. Except for the change in non-bond location, these were repeats of cases 77, 71, 72, 87, 81, and 82. There was no need to run cases 73C or 83C because, with the fuel thickness at 30 mils, the filler thickness is zero; hence, the boundary between the fuel and the (nonexistent) filler corresponds to the boundary between the filler and the cladding. Thus, the cases would be the same as cases 73 and 83. The results for these cases are shown in Tables 1-4. For all of these "C" cases, the maximum temperatures are less than those given by the original cases (i.e., cases 77, 71, 72, 87, 81, and 82). The maximum surface temperatures on the hot side and the minimum surface temperatures on the cold side are lower than those from the original cases. The minimum surface temperatures on the hot side are the same as those for the original cases (to within 0.1°F, which is about the level of the tolerance for convergence). The maximum temperatures on the cold side are greater than or equal to those from the original cases.

For the "C" cases, the hot side flux ratios based on maximum flux are lower than those from the original cases. The differences range from 0.28 for the combined defect at a 7-mil fuel thickness to 0.07 for the combined defect at 20 mils, and 0.03 for the non-bond defect at 20 mils. As the fuel thickness approaches 30 mils, the difference should go to zero because, at a 30-mil fuel thickness, there is no filler so that the boundary between the fuel and the filler is the same as that between the filler and the cladding. The cold side flux ratios based on the maximum flux are slightly larger than those from the original cases for the combined defect and are equal to those from the original cases and also to one another for the non-bond defect. However, the maximum difference is only 0.02 for the combined defect at a 7-mil fuel thickness. The hot side flux ratios based on minimum flux are the same as those for the original cases. The cold side flux ratios based on minimum flux are smaller than those from the original cases. The differences range from 0.18 for the combined defect at a 7-mil fuel thickness and 0.17 for the non-bond at the same fuel thickness, to 0.13-0.14 for the either defect at 20 mils. Again, the differences should become zero when the fuel thickness reaches 30 mils.

Similarly, I ran four cases (77L, 87L, 81L, and 82L) in which the non-bond was located between the fuel and the hot side cladding. Except for the change in non-bond location, these cases were repeats of cases 77, 87, 81, and 82. There was no need to run a case 83L because such a case would be a mirror image of case 83. Also, the only information I wanted from the 77L case (and the hypothetical 71L and 72L cases) was the flux ratio based on minimum flux for the hot side. As will be seen later, by comparing this value with a value from case 73, I could tell that the value of this quantity for the non-bond for all fuel thicknesses between 7 and 30 mils would be the same. The results for the four "L" cases that I ran are shown in Tables 1-4. For the cases with the combined defect, the maximum temperatures are less than those given by the original cases (i.e., cases 87, 81, and 82). For case 77L, the maximum temperature is 1.7°F higher than for case 77. However, this value is so much lower than for cases with the combined defect at the same thickness that the difference doesn't matter. For the "L" cases, the non-bond is between the fuel and the hot side cladding. With the non-bond in this location, some of the heat that flows toward the hot spot in the original cases is instead sent to the cold side. This heat shift leads to rises in some cold side surface temperatures and heat fluxes compared to those from the original cases, and drops in some hot side values. In some cases, particular cold side surface temperatures and heat fluxes are greater than the corresponding hot side values. The comparisons between the surface temperatures that will be discussed in the remainder of this paragraph include a number of effects that are attributable to the reversal of the non-bond location. The hot side maximum surface temperatures for three of the "L" cases are lower than those from the original cases. However, the maximum surface temperature on the hot side for case 82L is actually less than the maximum surface temperature on the cold side. The cold side maximum surface temperatures for the "L" cases are higher than those from the original cases. The minimum surface temperatures on the hot side are lower than those from the original cases. The minimum temperatures on the cold side are greater than those from the original cases. Indeed, the cold side minimum surface temperatures are greater than minimum surface temperatures for the hot side.

For the "L" cases, the comparison between the flux ratios and those from the original cases is not straightforward. As I noted in the previous paragraph, because the location of the non-bond for the "L" cases is on the other side of the fuel compared to the original cases, there should be some tendency to have the cold side flux ratios larger than those from the hot side. Thus, a comparison of the hot side ratios from the "L" cases with the cold side ratios from the original cases, and vice versa, is often more significant than comparisons between flux ratios on the same side. As the fuel thickness approaches 30 mils, the differences between the "L" cases and the original cases should go to zero because at a 30-mil fuel thickness, there is no filler so that the hypothetical cases 73L and 83L would be merely mirror images of cases 73 and 83. The hot side flux ratios based on maximum flux for the "L" cases are much lower than those from the original cases. However, for the combined defect, these ratios are somewhat higher (by a maximum of 0.08) than the cold side flux ratios based on maximum flux. The cold side flux ratios based on the maximum flux are much larger than those from the original cases. However, these ratios

are much smaller than the hot side fluxes based on maximum flux from the original cases. The differences for the combined defect range from a high of 0.67 for a 7-mil fuel thickness to 0.33 for 20 mils. For the non-bond, the greatest difference is 0.14 for a 7-mil fuel thickness. The hot side flux ratios based on minimum flux for the combined defect are lower than those from the original cases. These ratios are also lower than the cold side ratios based on minimum flux from the original cases. The greatest difference is 0.06 at a 20-mil fuel thickness. For the non-bond, the hot side ratio based on minimum flux is 0.30 lower than the ratio from case 77. The value of this flux ratio for case 77L is almost equal to the value of the cold side flux ratio based on minimum flux for case 73. Because this value is the same as that which would be found for the hot side minimum flux ratio for the hypothetical case 73L, I can conclude that this ratio would be almost the same for the hypothetical cases 71L and 72L as it was for cases 71 and 72. The cold side flux ratios based on minimum flux are larger than those from the original cases. However, they are the same as the hot side flux ratios based on minimum flux from the baseline cases.

As I mentioned in the introduction, Hilvety and Chapman specified a ratio of heat generation rate in the segregated fuel to that in the normal fuel which is about twice as large as I can justify from the packing fractions specified for the fuel. I ran modifications of cases 63, 67, 83, and 87 with the heat generation rate in the segregated fuel cut about in half and the area of the segregation spot about doubled. These cases were a test to see how much conservatism was contained in the overly large heat generation ratio. For the hot side, the ratios based on maximum flux for all four of these extra cases were between 0.02 and 0.03 less than the results from the corresponding regular cases. These are not significant differences. For the cold side, the largest change in any of the flux ratios was less than 0.005 - a difference that is negligible.

4. DISCUSSION OF RESULTS FOR NON-BONDS AND FUEL SEGREGATION

Figure 5 is a plot of the peaking factors for the hot side vs fuel thickness. The plot is a version of Fig. 2 with an expanded vertical scale to include the factors from my calculations. The solid curve represents the non-bond factors from Hilvety and Chapman. The dashed curve represents the model for combined non-bond and segregation that is used in the HFIR thermal analysis code. This curve is simply the Hilvety and Chapman non-bond curve multiplied by 1.30. The square symbols represent my calculations of the non-bond factor, the results from cases 77 and 71-73. The calculations being documented in the present report were done in 1988 so that my results are labeled "1988 calculations" in Figs. 5 and 6. The diamonds represent my calculation of the factor for fuel segregation alone (cases 67 and 61-63) and the triangles represent my calculation for combined non-bond and fuel segregation (cases 87 and 81-83). No results from any of the "C" or "L" cases are included on this plot because the corresponding flux ratios were less than those from the original cases.

My non-bond peaking factors for the hot side are less than those calculated by Hilvety and Chapman except at the 30-mil fuel thickness. Further, my curve of non-bond factors has a smaller slope than that of Hilvety and Chapman. I cannot explain the differences between my non-bond peaking factors and those of Hilvety and Chapman. Many of the details of their calculations and model have been lost in the intervening quarter century so that I am not sure that I am correctly repeating their work. Fortunately, the fact that I show moderate differences between my calculations of the peaking factors for non-bonds and the results from Hilvety and Chapman is not very important for the reactor safety problem. The reason is that the worst case is not a non-bond, but rather a combination of a non-bond and a fuel segregation spot. My calculations of the peaking factors for this combined defect match those of Hilvety and Chapman reasonably well.

For the hot side peaking factors shown in Fig. 5, the comparison which is of the greatest interest to reactor safety is that between the dashed curve, which represents uncertainty factors used in the current version of the HFIR thermal analysis code, and the triangles, which represent my calculations of the effect of the combination of the two defects. In the range from a 30-mil to a 10-mil fuel thickness, my peaking factors are 0.02 to 0.10 less than those shown by the dashed curve. This difference means that I estimate that the uncertainty factors used in the HFIR thermal analysis code are 2 to 10% larger than they need be, which is in the conservative direction.

Figure 6 is a plot of the peaking factors for the cold side vs fuel thickness. The plot is a version of Fig. 3 with an expanded vertical scale to include the factors from my calculations. The solid curve represents the non-bond factors from Hilvety and Chapman. The dashed curve represents the model for combined non-bond and segregation that is used in the HFIR thermal analysis code. This is simply the Hilvety and Chapman non-bond curve multiplied by 1.30. The open squares represent my calculations of the non-bond factor, the results from cases 77 and 71-73. The open diamonds represent my calculation of the factor for fuel segregation alone, the results from cases 67 and 61-63, and the open triangles represent my calculation for combined non-bond and fuel

LEGEND

- 1988 calculations for non-bond
- ◇ 1988 calculations for fuel segregation
- △ 1988 calculations for combined non-bond and fuel segregation
- Hilvety and Chapman curve for non-bond
- Hilvety and Chapman model for combined non-bond and fuel segregation

Fig. 5. Heat flux peaking for hot side of fuel plate.

Fig. 6. Heat flux peaking for cold side of fuel plate.

segregation, the results from cases 87 and 81-83. The three sets of points just mentioned all use flux ratios based on the maximum flux. The solid squares represent my calculations of the non-bond factor based on the minimum flux, and the solid triangles represent my calculation of the factor for combined non-bond and fuel segregation, both again based on the minimum flux. The five sets of symbols described so far in this paragraph are from calculations that have the non-bond between the fuel and the filler, as shown in Fig. 4. The "x" marks represent my calculations for the combined defect with the non-bond between the fuel and the hot side cladding, the results from my cases 87L, 81L, 82L, and the hypothetical case 83L. These ratios are based on the maximum flux. The "+" marks are factors for the same combined defect with the reversed defect location, and contain results from the same four "L" cases, but are based on the minimum flux. The solid diamonds represent my calculations for the non-bond defect with the non-bond between the filler and the cold side cladding, the results from my cases 87C, 81C, 82C, and the hypothetical case 83C. These ratios are based on the minimum flux.

The non-bond factors for the cold side from my calculations that are the equivalent of those of Hilvety and Chapman are based on the minimum flux and are shown by the solid squares on Fig. 6. These factors are smaller than those calculated by Hilvety and Chapman. Further, this curve has a smaller slope than that of Hilvety and Chapman. As was also the case with the hot side factors, I cannot explain the differences between my cold side non-bond peaking factors and those of Hilvety and Chapman. Fortunately, as was again the case with the hot side, the fact that I show large differences between my calculations of the peaking factors for non-bonds and the results from Hilvety and Chapman is not very important for the reactor safety problem. As will be discussed in a succeeding paragraph, the worst case for the cold side comes from the combined non-bond and fuel segregation defect with the non-bond located between the fuel and the hot side cladding using the flux ratio based on the maximum flux. Unfortunately, my calculations of the cold side worst-case factors don't match those from the Hilvety and Chapman worst case nearly as well as was true for the hot side.

It is not clear which flux ratios should be used for the appropriate cold side peaking factors: the ratios based on the maximum flux or those based on the minimum. If the object of the cold side calculation is to find the least amount of heat delivered to the cooling water, then the ratios given by the minimum flux for the non-bond defect with the non-bond located between the filler and the cold side cladding (the solid diamonds in Fig. 6) are the appropriate peaking factors. Those values are less than 1.0. If, on the other hand, the object of the cold side calculation is to find the greatest amount of heat delivered to the cooling water, then the ratios given by the maximum flux for the combined non-bond and fuel segregation defect with the non-bond located between the fuel and the hot side cladding (the "x" marks in Fig. 6) are the appropriate peaking factors. The values are greater than 1.0. The current version of the HFIR thermal analysis code uses a peaking factor which is a product of two terms. The first is the Chapman and Hilvety peaking factor for the non-bond which is based on the minimum flux and which is less than 1.0. The second is a constant 1.30, which is an estimate of the peaking factor for the fuel segregation defect. This approximation appears to be intended to

give the largest amount of heat from the combined defect. Thus, I must presume that the uncertainty factor for the cold side is that which gives the largest amount of heat into the channel (the "x" marks in Fig. 6).

For the cold side peaking factors illustrated in Fig. 6, the comparison which is of the greatest interest to reactor safety is that shown between the dashed curve, which is a representation of the uncertainty factors used in the current version of the HFIR thermal analysis code, and the "x" marks which represent my calculations of the effect of the combined non-bond and fuel segregation defect located between the fuel and the hot side cladding. At a 7-mil fuel thickness, my peaking factor is about 0.01 smaller than that shown by the dashed curve, a difference which is not significant. My calculations of the peaking factors for the cold side worst case and the Hilvety and Chapman model for the combined defect diverge with increasing fuel thickness so that, at a 30-mil fuel thickness, my factor is about 0.30 greater than that from the HFIR thermal analysis code. Unfortunately, this means that I estimate that the HFIR thermal analysis code is not conservative on the cold side.

5. DEFECT HEAT TRANSFER ANALYSIS FOR VARIABLE NON-BOND DIAMETER

I ran a series for which the diameter of the non-bond spot was increased. The reader may wonder about the origin of the spot diameters. These were points at which I increased the width of the radial mesh in the original calculations (i.e., cases with a constant non-bond spot diameter and/or with no non-bond). I ran the cases with a variable non-bond spot diameter using the same radial mesh as the cases with a constant non-bond spot diameter and/or with no non-bond. In order to check on the sensitivity of the large spot diameter cases to radial mesh size, I ran a repeat of the 71F case (non-bond spot diam, 0.2535 in. - 0.006439 m) for which I cut the radial width of all the mesh points for a diameter greater than 0.1876 in. (0.004675 m) in half. None of the fluxes in this test case changed by as much as 0.005 compared with the 71F case, which leads me to believe that the results of my calculations will not be sensitive to radial mesh spacing.

I ran variable non-bond spot diameter cases for both the 10-mil and 30-mil fuel thicknesses in an effort to see if the variation of flux peaking factor with non-bond spot diameter was greatly different depending on the fuel thickness. I ran one additional calculation, case 81B (which included the fuel segregation), to get an estimate of the effect of increasing the non-bond spot diameter for a case with fuel segregation, as well.

6. DISCUSSION OF RESULTS FOR VARIABLE NON-BOND DIAMETER

The results from the variable diameter non-bond spot series (cases 71J, 71, 71B, 71D-H, 73J, 73, 73B, and 73D-H) are shown in Tables 5-8. A plot of the results from these cases is shown in Fig. 7. The peaking factors for 30 mils of fuel are smaller than those for 10 mils. The curves coincide for large values of spot diam (about 0.7 in. = 0.0178 m, or greater).

As I noted in an earlier section, the object of the variable non-bond spot diameter study was to determine what value of spot radius was needed to give an uncertainty factor that was the same as that found for a combined standard non-bond spot (0.0625-in.-diam = 0.001588-m-diam) and fuel segregation spot. I took the fits for the uncertainty factors as used in the HFIR thermal analysis code [ref. 3, p. 18, Eqs.(12-15), and ref. 3, p. 69] and determined the maximum and minimum possible values of the combined defect factor for the outer and inner annuli (this combined factor is the product of U18 times U20). The maximum for the outer annulus is 1.70 at the outer edge of the plate [Eq.(14) from p. 18 of ref. 3 evaluated at plate width = 2.92 in. (0.0742 m) and then multiplied by 1.30] and the maximum for the inner annulus is 1.71 at the inner edge of the plate [Eq.(12) from p. 18 of ref. 3 evaluated at plate width = 0.09 in. (0.00229 m) and then multiplied by 1.30]. These peaks occur at the plate edges farthest from the gap between the two fuel annuli. The minimum values were 1.35 for the outer annulus and 1.39 for the inner annulus. These minima occurred near the middles of the respective plates.

In ref. 5, p. 7, W. E. (Bill) Thomas shows an estimated value of 1.64 for the combined non-bond and fuel segregation uncertainty factor at the hot spot. This hot spot occurred at the inner radius of the outer fuel annulus. The value 1.64 needs a little interpretation. It is the value of the factor U_x in ref. 7, Eq.(3), p. 6. It does not represent the product of U18 and U20, but rather is this product corrected for the local film coefficient [see ref. 3, p. 17, Eq.(11)]. According to Thomas, the actual value of U18 times U20 at the hot spot was about 1.53 (ref. 6). In the previous paragraph it was shown that this is not the largest value that the product of the non-bond and fuel segregation uncertainty factors can attain. Instead, the combination of all the other uncertainty factors and the assorted geometric factors was such that the hot spot did not occur at the point of maximum combined non-bond and segregation uncertainty factor. The maximum values occur at the plate edges farthest from the gap between the two fuel annuli. Because the hot spot occurs next to the gap, the fact that combined non-bond and fuel segregation uncertainty factors larger than 1.53 can be found for other locations does not really matter to the hot spot calculation.

There is not a single value of combined non-bond and fuel segregation factor that can be used to compare with the variable spot diameter non-bond results. Instead, the values range from about 1.35 near the center of the outer plate, through about 1.53 for the hot spot, to about 1.70 for both the inner edge of the inner fuel and the outer edge of the outer fuel. These last two locations are on the opposite edges of their respective plates from the hot spot. For the hot spot, the fuel thickness is about 15 mils (ref. 1, Fig. 2.8, p. 2-14). The value of the peaking factor for a 15-mil fuel thickness should be about halfway between the values for 10

Table 5. HEATING6 variable-diameter non-bonding spot cases: descriptions and maximum temperatures^a

Case No.	Fuel thickness (mils)	Non-bond spot diameter (in.)	Maximum temperature ^b (°F)
71J	10	0.0164	219.8
71	10	0.0625	234.0
71B	10	0.1086	250.1
71D	10	0.1547	264.7
71E	10	0.1876	273.1
71F	10	0.2535	284.7
71G	10	0.3852	294.8
71H	10	0.6486	298.2
73J	7	0.0164	212.6
73	7	0.0625	223.7
73B	7	0.1086	239.3
73D	7	0.1547	254.9
73E	7	0.1876	265.1
73F	7	0.2535	281.9
73G	7	0.3852	302.3
73H	7	0.6486	315.1
81B	10	0.1086	416.4

This single case combined both non-bond with a larger than standard spot diameter (0.1086 in. - 0.002758 m) and fuel segregation.

^aNote: all of the cases shown in this table are non-bonded, but have no fuel segregation. All have an 85-MW reactor power.

^bThese temperatures are relative, not absolute. Calculating the true maximum temperature at a particular location requires correction for both the local bulk cooling water temperature and the local heat generation in the fuel.

Table 6. HEATING6 variable-diameter non-bonding spot cases:
surface temperatures^a

Case No.	Maximum surface temperature ^b hot (°F)	Maximum surface temperature ^b cold (°F)	Minimum surface temperature ^b hot (°F)	Minimum surface temperature ^b cold (°F)
71J	204.2	189.5	203.8	189.4
71	213.0	189.6	203.9	184.3
71B	213.0	189.6	203.9	173.1
71D	239.8	189.5	203.9	161.9
71E	247.3	189.6	203.9	154.5
71F	257.6	189.5	203.9	143.0
71G	266.5	189.5	203.9	130.6
71H	269.5	189.4	203.8	123.7
73J	195.5	195.4	195.4	194.2
73	199.1	195.7	195.4	175.4
73B	208.8	196.5	195.4	154.4
73D	220.4	197.5	195.4	139.6
73E	228.3	198.3	195.4	132.9
73F	241.5	199.3	195.4	125.8
73G	257.7	200.3	195.4	121.8
73H	267.7	201.7	195.9	121.2
This single case combined both non-bond with a larger-than-standard spot diameter (0.1086 in. = 0.002758 m) and fuel segregation.				
81B	267.5	189.9	203.9	175.3

^aNote: all of the cases shown in this table are non-bonded, but have no fuel segregation. All have an 85-MW reactor power.

^bThese temperatures are relative, not absolute. Calculating the true maximum temperature at a particular location requires correction for both the local bulk cooling water temperature and the local heat generation in the fuel.

Table 7. HEATING6 variable-diameter non-bonding spot cases;
maximum heat fluxes^a

Case No.	Maximum heat flux ^b hot (Btu/h-ft ²)	Maximum heat flux ^b cold (Btu/h-ft ²)	Ratio of maximum heat flux to average baseline hot	Ratio of maximum heat flux to average baseline cold
71J	1.26E+06	1.04E+06	1.10	.91
71	1.40E+06	1.04E+06	1.21	.91
71B	1.60E+06	1.04E+06	1.39	.91
71D	1.80E+06	1.04E+06	1.56	.91
71E	1.91E+06	1.04E+06	1.66	.91
71F	2.06E+06	1.04E+06	1.79	.91
71G	2.20E+06	1.04E+06	1.91	.91
71H	2.24E+06	1.04E+06	1.95	.91
73J	1.13E+06	1.13E+06	1.0	1.0
73	1.19E+06	1.14E+06	1.05	1.01
73B	1.33E+06	1.15E+06	1.18	1.01
73D	1.51E+06	1.16E+06	1.33	1.03
73E	1.62E+06	1.17E+06	1.43	1.04
73F	1.82E+06	1.19E+06	1.61	1.05
73G	2.07E+06	1.20E+06	1.83	1.06
73H	2.22E+06	1.23E+06	1.96	1.08
81B	2.21E+06	1.05E+06	1.92	.91

This single case combined both non-bond with a larger than standard spot diameter (0.1086 in. = 0.002758 m) and fuel segregation.

^aNote: all of the cases shown in this table are non-bonded, but have no fuel segregation. All have an 85-MW reactor power.

^bThese heat fluxes are relative, not absolute. Calculating the true heat flux at a particular location requires correction for the local heat generation in the fuel.

Table 8. HEATING6 variable-diameter non-bonding spot cases:
minimum heat fluxes^a

Case No.	Minimum heat flux ^b hot (Btu/h-ft ²)	Minimum heat flux ^b cold (Btu/h-ft ²)	Ratio of minimum heat flux to average baseline hot	Ratio of minimum heat flux to average baseline cold
71J	1.26E+06	1.04E+06	1.09	0.90
71	1.26E+06	0.96E+06	1.09	0.84
71B	1.26E+06	0.80E+06	1.09	0.70
71D	1.26E+06	0.63E+06	1.09	0.55
71E	1.26E+06	0.52E+06	1.09	0.45
71F	1.26E+06	0.34E+06	1.09	0.30
71G	1.26E+06	0.16E+06	1.09	0.14
71H	1.26E+06	0.07E+06	1.09	0.06
73J	1.13E+06	1.11E+06	1.0	0.98
73	1.13E+06	0.83E+06	1.0	0.73
73B	1.13E+06	0.52E+06	1.0	0.46
73D	1.13E+06	0.29E+06	1.0	0.26
73E	1.13E+06	0.19E+06	1.0	0.17
73F	1.13E+06	0.09E+06	1.0	0.08
73G	1.13E+06	0.03E+06	1.0	0.02
73H	1.14E+06	0.02E+06	1.0	0.016
This single case combined both non-bond with a larger-than-standard spot diameter (0.1086 in. = 0.002758 m) and fuel segregation.				
81B	1.26E+06	0.83E+06	1.09	0.70

^aNote: all of the cases shown in this table are non-bonded, but have no fuel segregation. All have an 85-MW reactor power.

^bThese heat fluxes are relative, not absolute. Calculating the true heat flux at a particular location requires correction for the local heat generation in the fuel.

Fig. 7. Hot side non-bond flux peaking factor vs non-bond spot diameter.

and 30 mils. From Fig. 7, the peaking factor for 15 mils of fuel is 1.53 at a spot diam of about 0.18 in. (0.00457 m). At the edges where the combined defect peaking factor is 1.70, the fuel thicknesses are about 10 mils. As shown in Fig. 7, this corresponds to a non-bond spot diameter of 0.20 in. (0.00508 m). The maximum fuel thickness is about 26 mils. For this thickness, the variable diameter non-bond spot peaking factor is 1.35 at a diameter of about 0.16 in. (0.00406 m).

7. CONCLUSIONS

I have done calculations using the HEATING6 code to study the effect of a non-bond defect, a fuel segregation defect, and a combination of the two. Results were tabulated for both maximum and minimum fluxes on both the hot and cold sides. Fuel thicknesses ranged between 7 mils (0.007 in. = 0.000178 m) and 30 mils (0.030 in. = 0.000762 m). My model for the defects is almost the same as that used by Hilvety and Chapman, at least as far as can be determined from the available documentation in ref. 2.

I ran some cases with the reactor power at 100 MW, as well as those at 85 MW, and found no measurable difference between the peaking factors calculated for the two different powers (the peaking factors differed by less than 0.001). I conclude that the same uncertainty factors for these defects may be used for all reactor powers of 100 MW or less and may probably be used for powers as high as a few hundred MW.

For the hot side of a fuel plate, I conclude that the uncertainty factors used in the HFIR thermal analysis code are conservative. According to my calculations, the combined non-bond and fuel segregation is the worst case (i.e., gives the highest peaking flux) for the hot side. The model of Hilvety and Chapman gives uncertainty factors that are 0.02-0.10 higher than my calculations for this worst case. Thus, I see no need to modify the uncertainty factors used for the hot side in the HFIR thermal analysis code. The hot side uncertainty factors could be lowered to match my results. This would yield slightly larger values for the maximum power. However, I believe that the increases that would be gained are likely to be small and thus may not be great enough to be worth the trouble of changing the uncertainty factor fits.

For the cold side of the plate, I must conclude that the uncertainty factors used in the current HFIR thermal analysis code, which come from the model of Hilvety and Chapman, are not conservative. For the cold side worst case (i.e., the case that gives the highest heat flux on the cold side), which is a combined non-bond and fuel segregation defect with the non-bond located between the fuel and the hot side cladding, I calculate that the uncertainty factor from the HFIR thermal analysis code is roughly correct at fuel thicknesses of 10 mils or less, about 0.09 low for a fuel thickness of 20 mils, and about 0.30 low at 30 mils fuel thickness. Thus, my calculations suggest that the cold side uncertainty factors used in the present version of the HFIR thermal analysis code need to be substantially increased. It is probable that raising the factor U19 from the value of 1.30 used in the present HFIR thermal analysis code to a value of about 1.70 (i.e., 1.30 times 1.28/0.98) should be sufficient to compensate for the difference. Although this would lead to a 71% overestimation of the uncertainty factor for the minimum fuel thickness, the effect of the cold side uncertainty factors on reactor safety calculations is quite small so that the overestimate should not matter.

I did two series of cases (87C, 81C, 82C, 87L, 81L, and 82L) which were designed to see what was the effect of moving the non-bond from the junction between the filler and the fuel to its more probable locations at either the junction between the filler and the cladding, or else the junction between the fuel and the cladding. In order to examine the effect of these alternative non-bond locations on reactor safety calculations, I need to compare the largest flux ratios for the hot and cold sides with the

highest ratios from the original cases. On the hot side, the flux ratios are less than those from the original cases, (87, 81, and 82) so that having the non-bond between the fuel and the filler is a worst case for the hot side. For the cold side, I want to compare the flux ratios based on maximum flux with those from the cases with segregation only. On the cold side, the flux ratios for the cases with the non-bond between the fuel and the cladding are larger than those from the original cases. The greatest difference is 0.09 at a 7-mil fuel thickness.

For the fuel segregation defect and for the combined non-bond and fuel segregation, Hilvety and Chapman specified a ratio between the uranium concentration in the segregation spot and that in the normal fuel which I estimate is about twice as large as it would be in a real segregation defect. I did a short series of cases to determine the effect of this conservative value for the ratio of heat generation rates. For the hot side, use of a more realistic set of heat generation rates lowers the uncertainty factors by 0.02-0.03 compared with those that I calculated using Hilvety's and Chapman's rates. These differences in uncertainty factors are not significant, and the result is increased conservatism as was expected. For the cold side, the difference between the uncertainty factors is less than 0.005, which is negligible. Thus, using realistic values of the segregated fuel heat generation rates does not reduce the need to increase the cold side uncertainty factors used in the HFIR thermal analysis code.

I did an analysis of the effect of varying the non-bond spot diameter in a non-bond only defect. I estimated that values of the uncertainty factor for the combined non-bond and fuel segregation defect range between about 1.35 and 1.70. The value at the hot spot is about 1.53 (ref. 6). According to my calculations, this value corresponds to a non-bond spot diameter of about 0.18 in. (0.00457 m), which is about three times the diameter of the largest non-bond spot allowed by the specifications (0.0625 in. = 0.001588 m). The variable non-bond spot diameter peaking factor reaches 1.70 at a spot diameter of about 0.20 in. (0.00508 m) and falls to 1.35 at a diameter of about 0.16 in. (0.00406 m). The object of the variable spot diameter study was to determine the spot diameter for which the peaking factor was equal to the combined non-bond and fuel segregation peaking factors. The most important point in the reactor safety calculation is the hot spot. Thus, the most significant value for the variable non-bond spot diameter is 0.18 in. (0.00457 m), the diameter which gives the peaking factor for the hot spot.

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