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EFFECTS OF FUEL PLATE AND ASSEMBLY POSITION TOLERANCES ON STEADY-STATE THERMAL PERFORMANCE OF THE UNIVERSITY OF MISSOURI RESEARCH REACTOR (MURR) LEU CORE

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ABSTRACT

For the current design of the MURR LEU core, the effects of the ±8-mil (0.008-inch) manufacturing tolerance on coolant channel thicknesses between adjacent fuel plates, the assumed ±13-mil manufacturing tolerance on the end channel thicknesses, and the additional ±15-mil assembly clearance, which directly affects the end channel thicknesses and the relative positions of the fuel assemblies, are investigated. Both the neutronic effects on power distribution and the thermal-hydraulic effects due to changes in coolant channel thicknesses and flow areas are considered. The neutronic effects are found to be relatively small, about 2% or less in power, and are certainly within the assumed 1.10 uncertainty factor on power density, obviating the need to calculate specific power distributions for off-nominal geometric configurations. The thermal-hydraulic results support the conclusion that the hot channel factor components in the analytical model properly account for the effects of the ±8-mil channel thickness tolerance.

1. Introduction

The eight wedged-shaped fuel assemblies of the MURR low-enriched uranium (LEU) core are of identical design and are arranged in a circle, as shown in Figure 1. Each assembly has 24 curved fuel plates that are parallel to the inner and outer circular boundaries of the annular reactor vessel. In the proposed LEU design, the first and the last fuel plate of each assembly are 49-mils (1 mil = 0.001 inch) thick. All of the other 22 fuel plates are 38-mils thick. The 24 fuel plates are separated by 23 coolant channels that are 92±8 mils thick. Like the HEU element, the proposed LEU element rides on a series of rollers as shown in Figure 2. However, for the LEU design, the end coolant channels (D1 and D25 of Figure 2) are 95±28 mil thick. The 28-mil tolerance on end channel thickness has two components. First, a 13-mils manufacturing tolerance on the distance from an end plate surface to the outer envelope of the two nearest rollers as represented by dimension C in Figure 2. This tolerance is based on the existing tolerance for HEU fuel element. The remaining 15 mils represent the tolerance needed to enable the element to be inserted into the reactor vessel. It is assumed that a nominal 30-mil clearance (difference of dimensions A and B in Figure 2) is shared equally by the first and last coolant channels, thereby providing a ±15-mil tolerance for each.

It is important to study the effect that these tolerances on channel thickness have on the thermal performance of the MURR LEU core. Decreasing channel thickness decreases coolant flow rate in the channel. Shifting the position of the fuel and changing the sizes of the channel thicknesses has neutronic implications. A larger water gap near a fuel plate, in concept, causes higher power production in the plate. Moving a plate closer to the centerline of the core where the neutron fluxes are higher should increase the fuel plate power. Several perturbed core geometries were considered in order to quantify the effects of geometric tolerances/clearances on thermal performance. Power distributions were specifically generated with the MCNP5 code [1] for perturbed core geometries.

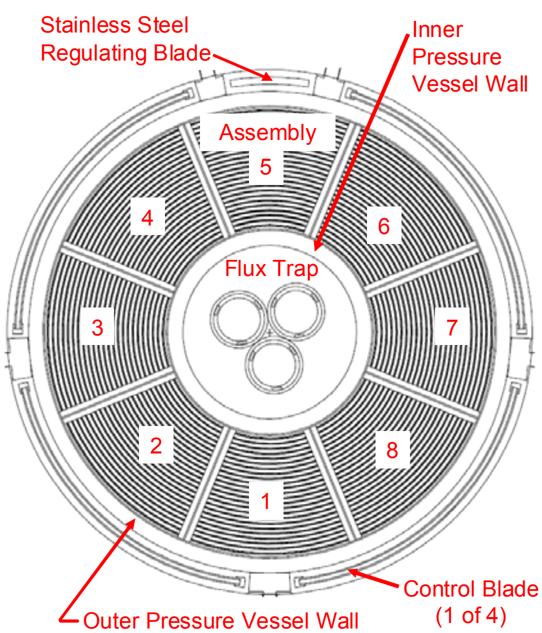


Figure 1 – Arrangement of the Eight MURR Assemblies

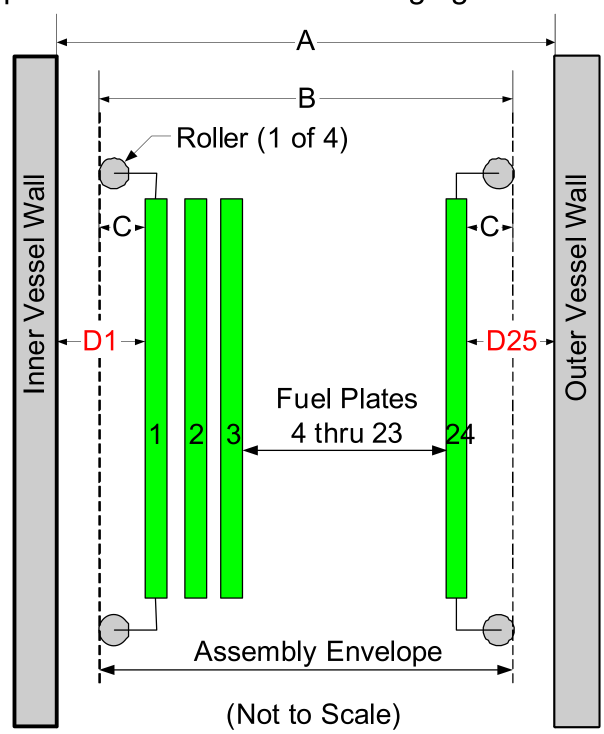


Figure 2 – Thicknesses of End Channels

2. Figure of Merit for Thermal Performance

The predicted margin to flow instability was the criterion used in qualifying the HEU core [2],[3]. Croft [4] and Waters [5] used tests in electrically heated channels to measure the onset of fuel burnout caused by flow instability in the Advanced Test Reactor (ATR). The ATR fuel elements are thermal-hydraulically similar to those in MURR. Since the Whittle and Forgan correlation [6] with a value of η of 32.5 accurately predicts flow instability in the Croft and the Waters experiments, this correlation will be used in the current analysis. Note that this correlation was not used in References [2] and [3].

The Whittle and Forgan criterion is:

$$\frac{T_{allowed} - T_{inlet}}{T_{sat} - T_{inlet}} = \frac{1}{1 + \eta \frac{D_h}{L_h}} \qquad (1)$$

where $T_{allowed}$ is the bulk coolant exit temperature at which flow instability is predicted to be initiated, T_{sat} is the coolant saturation temperature at the exit, T_{inlet} is the coolant inlet temperature, and D_h and L_h are the heated diameter and heated length of the channel, respectively.

3. Selection of Cases

Analysis of the nominal case for a fresh, clean LEU core showed that the limiting location based on flow instability is at channel 3 of assembly 5. Channels 1, 2, and 3 were found to be close to limiting. Channel 25 was found to be far from limiting. This behavior is to be expected given the relative heat fluxes of the fuel plates of assembly 5 shown in Figure 3.

As indicated in red on the figure, plates 3 through 23 have a fuel meat thickness of 18 mils. Plates 1, 2, and 24 have fuel meat thickness of 9, 12, and 17 mils, respectively. These three meats were made thinner than the rest in order to reduce their heat fluxes.

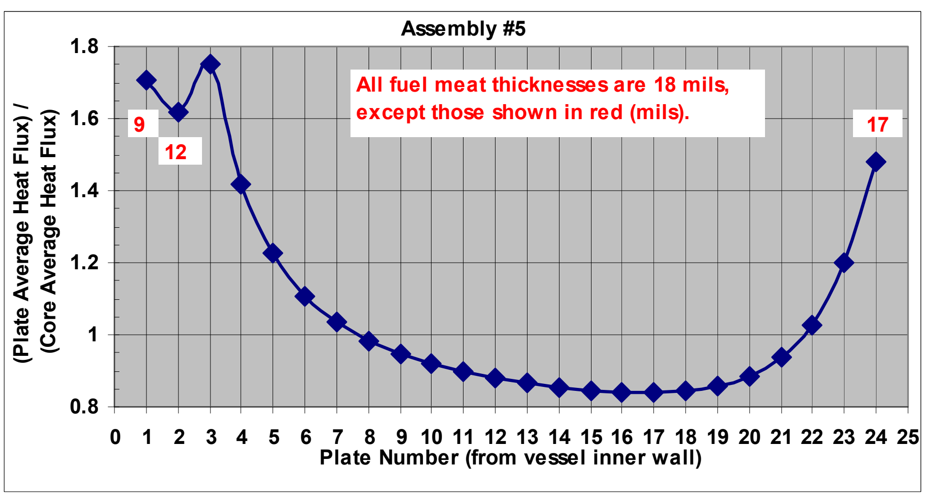
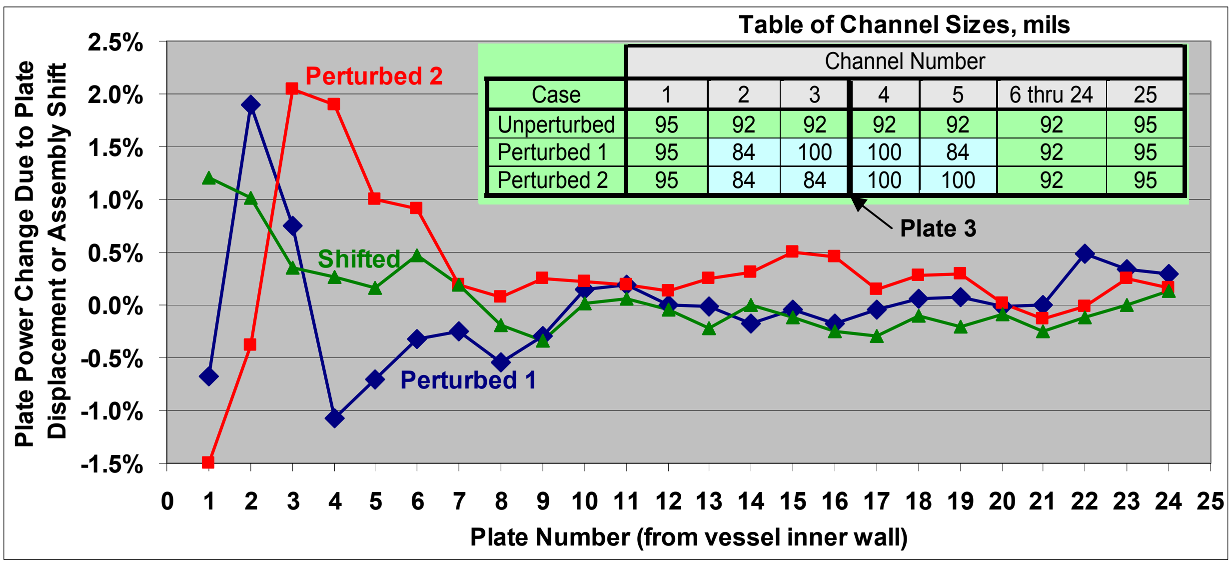


Figure 3 – Radial Heat Flux Distribution of Assembly 5 for Nominal Case

From a thermal-hydraulic standpoint, the aforementioned tolerances can result in a potentially limiting case if the power of plate 3 is increased and/or the thickness of channel 3, located between fuel plates 2 and 3, is minimized. Also, minimizing the thickness of channel 1 potentially could cause channel 1 to be limiting and could adversely influence channels 2 and 3. Channel 25 is sufficiently far from limiting in the nominal case that the extremes of channel thickness tolerances could not cause it to become limiting.

The table in the inset of Figure 4 shows the assembly 5 channel thickness configurations considered in this study. In all configurations shown in the table, all plates in all assemblies are at their nominal positions except in assembly 5. The changes in thickness of the internal channels were confined to channels 2 through 5 as indicated by the light blue shading in the table. The Perturbed 1 case was designed to increase the power by increasing moderation around the limiting plate, plate 3 (indicated in the table by a thick dark vertical line between channels 3 and 4). This was achieved by maximizing the channel thicknesses on either side of plate 3.



Case	Channel Number 1	2	3	4	5	6 thru 24	25
Unperturbed	95	92	92	92	92	92	95
Perturbed 1	95	84	100	100	84	92	95
Perturbed 2	95	84	84	100	100	92	95

Figure 4 – Change in Radial Power Distribution of Assembly 5

The blue curve of Figure 4 shows the plate-by-plate effect on power distribution for assembly 5 due to the Perturbed 1 plate distribution. The increase in water surrounding plate 3 caused its power to increase by only 0.75%. The greater increase in the power of plate 2, 1.90%, is due to moving plate 2 inward 8 mils into a region of higher neutron flux. These small power increases due to neutronic effects, however, are overshadowed by the greatly increased cooling caused the 8-mil increase in the thickness of the limiting channel, channel 3. Therefore, further study of Perturbed 1 plate distribution was abandoned in favor of the Perturbed 2 case, which minimizes the thicknesses of channels 2 and 3 and moves the limiting plate to a region of higher flux. The red curve of Figure 4 shows the plate-by-plate change in the power distribution relative to the Unperturbed case due to the Perturbed 2 plate distribution.

The 15-mil inward shift of assembly 5 was studied with all of its fuel plates shifted inward 15 mils, but otherwise at their nominal locations. The assemblies on either side of assembly 5, assemblies 4 and 6, were assumed to be shifted outward 15 mils, Figure 5. The purpose of this perturbation was to increase water-to-metal ratio near the inner plates and increase their powers while decreasing the thickness of the innermost channel. The green curve of Figure 4 shows the plate-by-plate relative differences in power in the limiting assembly, assembly 5, due the shifting assemblies 4, 5, and 6.

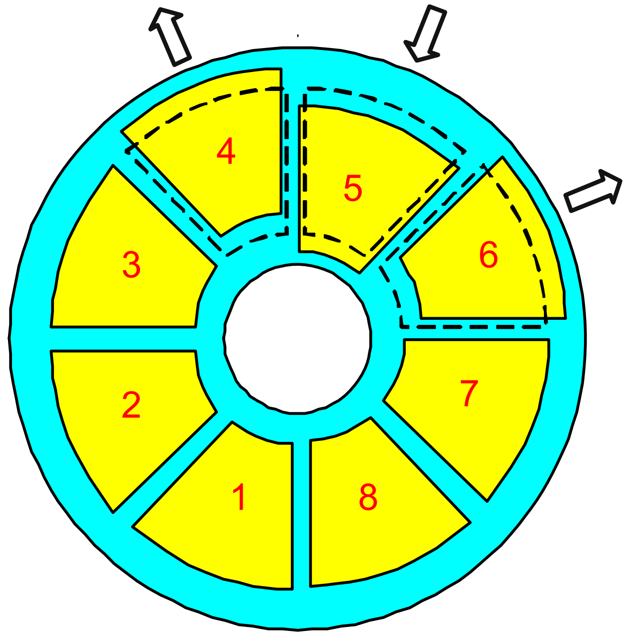


Figure 5 – Assembly Arrangement with Assembly 5 Shifted Inward 15 mils and Assemblies 4 & 6 Shifted Outward 15 mils (Shifted Case)

4. Thermal Analysis

The extremes of the Limiting Safety System Settings (LSSS) conditions used for the current HEU core were assumed for the current steady-state thermal-hydraulic analysis with the exception of power level. These LSSS conditions are a pressure of no less than 75 psia at the reactor pressurizer, a reactor inlet temperature of no greater than 155° F, a reactor flow rate of no less than 3200 gpm through the core, and a reactor power of no more than 125% of 12 MW, or 15 MW. Adjustments to these values to account for measurement uncertainties are not needed because the reactor safety system is configured so as to take measurement uncertainties into account. For example, if the uncertainty in flow rate measurement is 100 gpm, then the minimum flow trip would be set no less than 3300 gpm.

There is a series of hydraulic components leading from the pressurizer to the core inlet. References [2] and [3] provide values for the pressure drop through each of these components for one set of reactor operating conditions. Reference [2] also provides relationships that enable these pressure drops to be scaled to obtain the pressure drops for other reactor operating conditions. These scaling relationships can also be deduced from basic hydraulic principles. For the LSSS conditions described above, a core inlet pressure of 67.98 psia was derived in a separate set of calculations and used in the thermal-hydraulic analysis.

The PLTEMP/ANL code [7] was used in the thermal-hydraulic analysis of the MURR core. This code can explicitly represent every plate and every channel in every fuel assembly. In the code the axial length of the fuel plates are divided into a series of axial layer or nodes. Twenty-four equal-height layers were used in the current analysis to represent the length of the fuel meat, corresponding to the 24 axial nodes used in the

MCNP5 analyses. Within each assembly the PLTEMP/ANL code explicitly models conduction through the individual fuel plates. This enables coolant temperatures on one side of a fuel plate to influence those on the other side of it. The code also includes a hydraulics model that determines the distribution of flow among the parallel individual channels and assemblies. The PLTEMP/ANL code is capable of modeling parallel flat fuel plates and concentric tubes. For the MURR reactor core model, the concentric tube option was used.

The PLTEMP/ANL code also includes two sets of three hot channel factors – one set of global hot channel factors and another set of hot channel factors to include random uncertainties that occur independently of each other. The three global uncertainty factors account for uncertainty in reactor power, reactor flow rate, and surface heat transfer coefficient. The global uncertainty factors for reactor power and flow rate are each set to 1.00 since, as explained above, the reactor trip settings already take these uncertainties into account. The global uncertainty factor for surface heat transfer coefficient was set to 1.20 although, based on equation 1, flow instability power is not affected by film coefficient.

Table 1 lists all of the random uncertainties components, or “random errors”, that were considered in the analysis. The seven cells shown in yellow are independent variables. The 0.10 tolerance on power density, show in green, represents assumed inaccuracies in the power distribution obtained from the MCNP5 simulation of the MURR core. The 0.20 tolerance on flow distribution is due to the uncertainty in predicted flow due to modeling and variations in channel geometry. Both of these values are based on judgment. The values in the other five yellow cells should ultimately come from the

Table 1 – Hot Channel Factors Including 8-mil Channel Spacing Tolerance
(The results excluding 8-mil channel spacing tolerance are shown in parentheses.)

					hot channel factors		
uncertainty	**effect on bulk ΔT, fraction**	**value, inches**	**toler-ance, inches**	**toler-ance, fraction**	**heat flux, F_{flux}**	**channel temper-ature rise, F_{bulk}**	**film temper-ature rise, F_{film}**
random errors							
fuel meat thickness (local)				**0.02**	**1.02**		**1.02**
U235 homogeneity (local)				**0.00**	**1.00**		**1.00**
U235 loading per plate	**0.50**			**0.03**	**1.03**	**1.015**	**1.03**
power density	**0.50**			**0.10**	**1.10**	**1.05**	**1.10**
channel thickness	**1.00**	**0.092**	0.0080 (0.0000)	1.095 (1.000)		**1.169 (1.000)**	**1.034 (1.000)**
flow distribution	**1.00**			**0.20**		**1.20**	**1.157**
random errors multiplicatively combined					**1.16 (1.16)**	**1.49 (1.28)**	**1.38 (1.34)**

design and manufacturing specifications for the LEU fuel. The random errors listed in the table contribute components to the three hot channel factors, F_{flux}, F_{bulk}, and F_{film} that are evaluated at the bottom of the table. However, based on equation 1, only F_{bulk} affects flow instability power because the numerator on the left side of equation 1 is the bulk coolant temperature rise from channel inlet to channel outlet. In the PLTEMP/ANL code analysis, each bulk coolant temperature rise is multiplied by F_{bulk} before the power at which flow instability occurs is determined.

The 0.02 tolerance fraction for local fuel meat thickness contributes a 1.02 factor to the local heat flux, but does not affect the bulk coolant temperature since the effect is assume to be local to individual spots. A 0.03 tolerance fraction for the overall U^{235} loading of a fuel plate has a 3% effect on the heat flux, but only a 1.5% of the bulk coolant temperature rise because only one of two fuel plates that bound a coolant channel are assumed to be affected. The determination of the hot channel factor component due to the uncertainty in channel thickness requires thermal-hydraulic analysis that is provided by Reference [8].

In the original safety analysis of the HEU core a multiplicative approach was used in which the final value of the hot channel factor is the product of the individual hot channel factor components. This approach assumes that all uncertainties, random or otherwise, simultaneously adversely affect the limiting channel and plate in the reactor. Although it is unlikely that two or more random uncertainties will simultaneously adversely affect the limiting channel or plate, the current safety analysis is made more readily comparable to the original safety analysis by maintaining the multiplicative approach.

For the cases in which the limiting channel (channel 3) is explicitly modeled with the smallest thickness allowed by the tolerances (i.e., 84 mils), the hot channel factor component for channel thickness is set to 1.0, as indicated by the numbers in parentheses in Table 1.

5. Results

Table 2 summaries all of the cases analyzed with the PLTEMP/ANL code. Cases 0 through 3 are designed to investigate the neutronic and thermal-hydraulic effects of the 8-mil channel thickness tolerance. For these four cases only assembly 5 is explicitly represented in the PLTEMP/ANL model and it is positioned so that the first and last channels are each 95 mils thick. Case 0 is the reference case for the analysis studying the effect of internal channel thickness tolerance. In cases 1 through 3 the hot channel factors obtained from Table 1 assume that the hot channel factor component for channel thickness is 1.0 as explained above. This is the only difference between cases 0 and 1. The allowed flow instability power is about 17% greater in case 1 than in case 0 because the F_{bulk} factor component due to an 8-mil channel thickness tolerance is 1.169. Note that case 2 employs the nominal power distribution, while case 3 employs the one specially calculated with MCNP5 for the Perturbed 2 configuration.

Table 2 – Allowed Flow Instability Power

Case No.	Assembly Positions (See Note 1.)	Assembly 5 Internal Channel Sizes (See Figure table 1.)	Power Distribution	Flow Instability Power, MW	Comments
0	Nominal	Unperturbed	Nominal	20.16	Base Case
1	Nominal	Unperturbed	Nominal	23.55	See Note 2.
2		Perturbed 2	Nominal	20.97	
3		Perturbed 2	Perturbed 2	20.79	
4	Nominal	Unperturbed	Nominal	20.17	Base Case
5	As shown in Figure 5	Unperturbed	Nominal	20.18	
6			Shifted	20.04	
7	Assembly 5 inward 28 mils	Unperturbed	Nominal	20.15	

Notes:

1. **In the thermal-hydraulic analysis with the PLTEMP/ANL code only assembly #5 is explicitly modeled except in Cases 4 through 6 where all eight assemblies are explicitly modeled.**
2. **Hot channel factors exclude 8-mil tolerance on channel thickness.**

Cases 4 through 6 are design to assess the potential worst effects of shifting the assemblies in the radial direction. All eight assemblies are explicitly represented in the PLTEMP/ANL model. In all of these cases all of the coolant channels between parallel fuel plates are exactly 92 mils thick. In case 4 all eight assemblies are at their nominal radial position. This case represents the reference case for the analysis studying the impact of shifting the assemblies. Note that it essentially produces the same results as its single assembly counterpart, case 0. Case 5 uses the same nominal power distribution as used in case 4, but shifts assembly numbers 4 through 6 in the manner indicated by Figure 5. In case 6 the radial positions of the assemblies are shifted as in case 5 and the power distribution is the one that was specifically calculated with MCNP5 for this arrangement of assemblies.

Case 7 was designed to study the effect of making the thickness of channel 1 as small as possible, 67-mils. This was accomplished by modeling the assembly as if it were shifted inward by 28 mils, thereby making channel 25 as thick as possible, 123 mils.

6. Discussion

The only differences between cases 0 and 2 is that case 0 has a hot channel factor component to account for an 8-mil reduction in the thickness of the limiting channel due to the 8-mil channel thickness tolerance while in case 2 the limiting channel, channel 3, is explicitly modeled as being 8 mils thinner and the model assumes a 0-mil channel thickness tolerance. For case 2, PLTEMP/ANL predicts a flow instability power about 4.0% more for two reasons. First, making the channel thinner increases the power level at which flow instability will occur. Equation 1 above indicates that this is worth 1.9%. Second, a benefit that is not included in the hot channel factor determination is that the increase in bulk coolant temperature due to the thinning of channel 3 in case 2 causes more power to be redistributed to the two adjacent coolant channels via conduction through the fuel plates bounding the limiting channel. Channel 3 is bounded by plates 2 and 3. The PLTEMP/ANL outputs indicate that the fraction of power from plate 2 to channel 3 is essentially unchanged between cases 0 and 2, but that the fraction of power from plate 3 to channel 3 is decreased by an estimated 2.3% in case 2 relative to case 0. This is consistent with the narrowing of both channels 2 and 3 and the widening of channel 4.

The only difference between the inputs to cases 2 and 3 is in the power distribution. The differences in flow instability power should correspond to the changes in the plate 2 and 3 powers, as indicated in Figure 4. The Perturbed 2 case has 0.38% less power in plate 2 and 2.04% more power in plate 3 than does the unperturbed case. If one assumes that in case 3 the additional power deposited in channel 3 can be represented by the average change from both plates, (2.04% − 0.38%)/2 = 0.83%, then one would expect case 2 to have about 0.83% more flow instability power than case 3. This is consistent with the 0.87% larger flow instability power predicted by PLTEMP/ANL for case 2

Because the limiting location is far enough from the end channels, shifting the assembly without changing the power distribution should have a very minimal effect on the flow instability power. Therefore, as expected, cases 4 and 5 produce essentially the same result. The cause of the difference in flow instability power between case 5 and 6 is due to differences in power distribution. As shown in the Figure 4 green curve labeled "Shifted", plate 2 has 0.36% more power and plate 3 has 1.01% more power than in the nominal power distribution. The average of these two increases is 0.685%. This is consistent with the predicted 0.699% larger flow instability power in case 5 relative to case 6.

Since in case 7, where channel 1 is at its absolute minimum thickness of 67 mils, channel 3 remains the limiting location for flow instability, the effect of shifting the assembly inward 28 mils in the radial direction has essentially no effect on the flow instability power. Moreover, all of the cases that employ the nominal power distribution, the unperturbed internal channel thickness of 92 mils, and the hot channel factors with the 8-mil tolerance, cases 0, 4, 5, and 7, produce essentially the same results.

7. Conclusions

As Figure 4 attests, perturbing the channel thicknesses within their tolerances or shifting the assemblies in the radial direction within the ±15-mil assembly insertion clearance has a very minimal effect on power distribution, which is completely taken into account by the 1.10 uncertainty factor on power density shown in green in Table 1. Therefore, for future analyses, it would be sufficient to use the power distribution calculated for the nominal geometry and employ the hot channel factor approach in the thermal-hydraulic analyses to treat the off-nominal configurations.

The approximately 4% difference between case 0 and case 2 is due to second order effects which are identified and quantified. Hence, the comparison of case 0, where the limiting channel is at its nominal thickness and the 8-mil thickness tolerance is included via a hot channel factor component, and case 2, where the limiting channel is at its minimum thickness allowed by the 8-mil tolerance, supports the conclusion that the F_{bulk} hot channel factor component for the channel thickness tolerance, 1.169 in Table 2, is appropriately predicted.

Although shifting the limiting assembly inward in the radial direction has essentially no effect on the allowed power (case 7 versus case 0), it is essential to consider the minimum allowed thicknesses of the end channels in performing future thermal-hydraulic analyses in case one of these channels is limiting.

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