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**Effects of Fill Gas Composition
and Pellet Eccentricity:
Comparison Between
Instrumented Fuel Assemblies
IFA-431 and IFA-432**

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April 1979

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Fuel Behavior Research Branch
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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Pacific Northwest Laboratory (PNL), under sponsorship of the Nuclear Regulatory Commission (NRC), has designed two 6-rod, instrumented test assemblies to provide well-characterized data for verifying fuel modeling computer codes and developing a better understanding of fuel behavior. These assemblies, designated IFA-431 and IFA-432, are designed to study the effects of fabricated fuel - cladding gap size, fuel density and stability, fill gas composition, linear heat rate, and burnup.

Rod 4 of each assembly was designed to study the effects of fuel - cladding geometry and minimum gas thermal conductivity upon heat transfer across the gap between the fuel and cladding. To accomplish this, mechanical restraint was used to form a concentric fuel - cladding geometry in the upper end of the rod, and an eccentric geometry in the lower end of the rod; the rod was then backfilled with xenon gas. The eccentric fuel region of the xenon rod was observed to have lower fuel temperatures, for equal power, than the concentric fuel region. It is concluded that fuel - cladding eccentricity enhances the azimuthal average gap conductance, thus reducing the fuel center-line temperature.

The xenon-filled rods were compared to rods backfilled with helium. As expected, the xenon rods had higher fuel temperatures than the helium-filled rods in the assemblies, although not as high as was initially predicted. It is concluded that the reduced temperatures (relative to the predicted temperatures) were the result of a greater decrease in fuel - cladding gap size than is predicted to occur from thermal expansion alone. The ratio of the gap conductances for a xenon rod and a helium rod with equal operating thermal radial gaps, is equal to the ratio of the gas thermal conductivities for the two rods. This is in agreement with the ideal model of gap conductance.

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1.0 INTRODUCTION

Previous studies have specified a number of factors which affect the gap conductance of a fuel rod. Two of these are fill gas thermal conductivity and the degree of asymmetry present in the fuel - cladding geometry. Cohen et al.⁽¹⁾ Horn,⁽²⁾ and Lawrence et al.,⁽³⁾ have studied fill gas thermal conductivity in particular. They report that large portions of xenon must be mixed with the original helium fill gas before there are significant changes in the gap conductance. However, there is a lack of concurrence about the effects of fill gas thermal conductivity and fuel - cladding geometry.

Because of this lack of concurrence, PNL considered fill gas thermal conductivity and fuel - cladding geometry in its design of the NRC-RSR/PNL Halden fuel assemblies IFA-431 and IFA-432. These two well characterized,⁽⁴⁾ virtually identical, boiling water reactor (BWR), six-rod assemblies have been undergoing irradiation in the Halden Boiling Water Reactor (HBWR) in Norway. They are part of a program established by the NRC to verify the GAPCON⁽⁵⁾ and FRAPCON⁽⁶⁾ series of computer codes which are used to check vendor codes during licensing procedures.

One rod from each of these assemblies was designed specifically to study the effects of fill gas thermal conductivity and fuel - cladding eccentricity upon fuel performance. Each of these rods, designated rod 4, was built with two instrumented, geometrically different fuel regions; one concentric and the other eccentric. Then, during assembly, the rods were backfilled with xenon gas at one atmosphere pressure.

The startup history of rod 4, IFA-431 has already been examined⁽⁷⁾ and two major conclusions were reached:

- For equal operating gap sizes, the ratio of gap conductances in two rods with different gas mixtures is approximately equal to the ratio of thermal conductivities of those two gas mixtures.
- For equal local power, the eccentric region of rod 4 exhibited a higher gap conductance (indicated by lower fuel centerline temperature) than the concentric region.

This report examines the startup of rod 4, IFA-432 and compares it with the startup of rod 4, IFA-431 to check the conclusions reached in the first report. In addition, ex-reactor gap conductance data is examined and compared to the in-reactor data; and a qualitative analysis is made of the thermal and mechanical behavior of the constrained fuel regions.

2.0 EXPERIMENT DESIGN

The test parameters for IFA-431 and IFA-432 that are of particular interest include the effects of fuel-cladding diametral gap, fill gas composition, fuel density and stability, linear heat rating, and burnup. To monitor these effects, each rod in each assembly is instrumented with two fuel centerline thermocouples and a cladding elongation sensor. In addition, three of the rods in each assembly are equipped with fill gas pressure transducers. Self-powered neutron detectors are utilized for local linear power determination. A computer-controlled acquisition system records data every fifteen minutes. This data is then sent to Pacific Northwest Laboratory (PNL) where it is analyzed, and appropriate corrections (e.g., axial flux shape and radial flux tilt) are made.

The individual rods in each assembly are of the following designs and purposes:⁽⁴⁾

- Rod 1 simulates a typical BWR-6 fuel rod (initial diametral gap of 0.0229 cm) and serves as a reference standard.
- Rod 2 simulates instantaneous densification with an initial 0.0381 cm^(a) diametral gap.
- Rod 3 has a small fabricated diametral gap (0.051-0.076 cm) and its high gap conductance provides an internal, independent check on rod linear heat ratings through both steady-state and transient analysis.⁽⁸⁾
- Rod 4 was backfilled with 100% xenon to study the effect of minimum gas thermal conductivity. Also, this rod contains two mechanically constrained fuel regions to compare the thermal behavior of concentric and eccentric fuel-cladding geometries.
- Rods 5 and 6 provide further fuel density and stability data.

The initial fill gas used in rods 1, 2, 3, 5, and 6 is helium at one atmosphere. The fuel in all six rods consists of flat-ended, 1.27 cm (0.5 in.) long, sintered

(a) Engineering Unit equivalents may be found in Table 2.1.

**TABLE 2.1. Design Parameters and Instrumentation
for IFA-431 and IFA-432**

IFA-431 [Peak Power - 10 kW/ft (328 W/cm)]

Rod No.	Diameter Pellet		Cold Diametral Gap ^(a)		Fill Gas	Fuel Density % TD	Fuel Type ^(b)	Burnup MWd/MTM	Instrumentation			Cladding Length
	in.	mm	in.	mm					Temperature Upper	Temperature Lower	Pressure	
1	0.4205	10.681	0.009	0.229	He	95	Stable	4,000	TC ^(c)	TC	PT ^(d)	ES ^(e)
2	0.4145	10.528	0.015	0.381	He	95	Stable	4,000	TC	TC	--	ES
3	0.4275	10.858	0.002	0.051	He	95	Stable	4,000	TC	TC	--	ES
4	0.4205	10.681	0.009	0.229	Xe	95	Stable	4,000	TC	TC	--	ES
5	0.4205	10.681	0.009	0.229	He	92	Stable	4,000	TC	TC	PT	ES
6	0.4205	10.681	0.009	0.229	He	92	Unstable	4,000	TC	TC	PT	ES

IFA-432 [Peak Power - 15 kW/ft (492 W/cm)]

1	0.4205	10.681	0.009	0.229	He	95	Stable	20,000	TC	TC	PT	ES
2	0.4145	10.528	0.015	0.381	He	95	Stable	4,000 ^(f)	UT ^(g)	TC	--	ES
3	0.4265	10.833	0.003	0.076	He	95	Stable	4,000 ^(f)	TC	TC	--	ES
4	0.4205	10.681	0.009	0.229	Xe	95	Stable	4,000 ^(f)	TC	TC	--	ES
5	0.4205	10.681	0.009	0.229	He	92	Stable	20,000	TC	TC	PT	ES
6	0.4205	10.681	0.009	0.229	He	92	Unstable	20,000	TC	TC	PT	ES
7	0.4145	10.528	0.015	0.381	He	95	Stable	16,000	--	--	--	--
8	0.4205	10.681	0.009	0.229	He	95	Stable	16,000	--	--	--	--
9	0.4225	10.732	0.007	0.179	He	95	Stable	16,000	--	--	--	--

(a) Cladding for all rods has an OD of 0.5035 in. (12.789 mm) and an ID of 0.4295 in. (10.909 mm). Diametral gap is cladding ID minus pellet diameter.

(b) With respect to in-reactor densification.

(c) TC = Thermocouple

(d) PT = Pressure Transducer

(e) ES = Elongation Sensor

(f) Removable rods replaced by Rods 7, 8, and 9.

(g) UT = Ultrasonic Thermometer

UO₂ pellets that have been enriched to 10 wt% ²³⁵U. Table 2.1 summarizes the design parameters and instrumentation for each assembly.

Figure 2.1 is a schematic of rod 4, the subject of this report. Rod 4 is backfilled with xenon at one atmosphere and is designed to provide data on the thermal variations induced by low conductivity fill gas and eccentric fuel - cladding gap conditions. Thermocouples and molybdenum rods inserted through the centerline of the pellets hold 10% of the fuel column near the top

FIGURE 2.1. Schematic of Rod 4 Fuel Column

concentrically and 10% near the bottom eccentrically, with respect to the cladding. The "oversize" pellets are the same size as in rod 3 of each respective assembly; they have flats ground on the periphery to allow axial fill gas communication.

HBWR, in which these assemblies were irradiated, uses natural circulation of heavy water for cooling and has the following operating parameters:

Power level	12 MW
Reactor Coolant Pressure	3.45 MPa (500 psi)
Heavy Water Saturation Temperature	240°C (464°F)
Coolant Inlet Temperature	237°C (459°F)
Thermal Neutron Flux	$\sim 3 \times 10^{13}$ n/cm ² -sec
Fast Neutron Flux (>1, MeV)	$\sim 5 \times 10^{11}$ n/cm ² -sec
Average Power Density	14.8 W/g

The configuration of the fuel assembly is shown in Figure 2.2.

FIGURE 2.2 Schematic of Instrumented Fuel Assembly--IFA-431

IFA-431 was irradiated from June 1975 to February 1976, with rod 4 obtaining an average burnup of 4280 MWd/MTM. All instrumentation for rod 4, IFA-431 was still operating at the time irradiation was completed. IFA-432 was charged into the HBWR in December 1975 and is currently (November 1978) still being irradiated. However, rod 4 was removed from the assembly after three months (average burnup of 2450 MWd/MTM) and replaced with another rod. Although both thermocouples in rod 4 failed after the first two weeks, the cladding elongation sensor provided data for the entire three months.

3.0 ANALYSIS

3.1 STARTUP HISTORY

This report examines the experimental data obtained for rod 4 of assemblies IFA-431 and IFA-432. As it is concerned only with the startup period of the assemblies, the report examines only the history of the first two ramps to power for each assembly. The report describes a possible fuel - cladding interaction mechanism based on the centerline temperatures and cladding extension changes.

IFA-431 first rose to power on June 8, 1975. Its second power ramp was twelve days later on June 20, 1975. IFA-432 experienced its first rise to power December 8, 1975 and its second ramp on December 14, 1975. Figure 3.1

FIGURE 3.1. Startup History,
Rod 4 Concentric (Upper)
Fuel Centerline Temperature

presents the upper (concentric region) centerline temperature of rod 4 as a function of linear power for the first and second ramps of assemblies IFA-431 and IFA-432.

The most interesting portion of the temperature history involves the first ramp of rod 4, IFA-431. The centerline temperature underwent an increase of 110°C while the linear heat rate increased from 163 to 165 W/cm. The second ramp of the same rod was not discontinuous, but the centerline temperatures were higher for equivalent linear heat rate. The temperature response of rod 4, IFA-432 was similar during ramps 1 and 2; however, the temperatures in both ramps were higher than those of IFA-431.

A fifth curve labeled GT3 is observed in Figure 3.1 This curve was produced by modeling the upper fuel region of rod 4, IFA-431 (including the two oversize fuel pellets), with the thermal/mechanical fuel performance code GAPCON-THERMAL-3.⁽⁵⁾ Notice that these predicted temperatures are higher than the observed temperatures for IFA-431, but are close to the temperatures for IFA-432.

Figure 3.2 shows that the eccentric (lower) regions behaved in a manner similar to the concentric (upper) regions for both number 4 rods; the primary difference is that the eccentric regions experienced lower temperatures than the concentric regions for equivalent local linear powers. The first ramp of IFA-431 shows the same temperature increase at constant power that was observed for the concentric region; it occurred at the same time. Also, the second ramp again produced higher temperatures for IFA-431. Both ramps of rod 4, IFA-431 exhibited approximately the same temperature response.

As was discussed in Section 2, the concentric and eccentric fuel regions of rod 4 are constrained in position through the use of oversize pellets. The first fuel - cladding interaction for these rods would therefore be expected at the position of the oversize pellets, and this interaction would probably occur at a relatively low power. Rod 4 of IFA-431 would also be expected to display a greater amount of interaction than IFA-432 because of the smaller fabricated diametral gap between the oversize pellets and cladding. Figure 3.3 illustrates the cladding axial extensions that occurred for rod 4 of both assemblies. Two points are of interest:

FIGURE 3.2. Startup History, Rod 4 Eccentric (Lower) Fuel Centerline Temperature

- Significant amounts of cladding extension occurred at low powers, thus indicating the expected early fuel - cladding interaction.
- As expected, rod 4, IFA-431 experienced greater cladding elongation than rod 4, IFA-432.

The following analysis compares rod 4 with two rod types which were initially backfilled with 100% He. Rod 1 of each assembly was used as the standard rod. It had the same fabricated diametral gap as the concentric region of rod 4. Although the fabricated diametral gap of rod 3 was small, the previous report⁽⁷⁾ concluded its operating gap was the same as rod 4 at 200 W/cm. Figure 3.4 provides centerline temperatures for the upper region of rod 1, and Figure 3.5 provides centerline temperatures for the upper region of rod 3. Two features are worth noting: as expected because of the smaller

FIGURE 3.3. Startup History, Rod 4 Cladding Elongation

gap, rod 3 experienced the lowest temperatures; and the temperature-power response between the first and second ramps for each rod is consistent.

3.2 CONCENTRIC FUEL REGION

From observing the startup response of the concentric (upper) region of rod 4, as detailed in Figure 3.1, it was found that the experimental centerline temperatures were lower than had been predicted analytically. Consistencies between the temperature and cladding elongation data indicate that a pellet - cladding interaction (PCI) mechanism caused a reduction in the radial gap from its expected value. This reduced radial gap then resulted in less of a temperature drop across the gap and lower fuel centerline temperatures.

To illustrate the importance of the gap size upon the thermal behavior of rod 4, Figure 3.6 shows fuel centerline temperature as a function of radial gap. Notice that relatively small changes in the gap size of a xenon-filled rod produce major changes in centerline temperature. This figure shows that

FIGURE 3.4. Startup History, Rod 1 (Upper) Fuel Centerline Temperature

FIGURE 3.5. Startup History, Rod 3 (Upper) Fuel Centerline Temperature

the approximate step increase of 110°C observed in Figure 3.1 for the first ramp of rod 4, IFA-431 could have been produced by an increase of only 2 to $3\text{ }\mu\text{m}$ in the radial gap. Therefore an attempt will be made to quantify the operating gap conditions, based on the calculated gap temperature drop, for rod 4, and those estimates will be compared to similar calculations for rods 1 and 3. The methodology for this is outlined in the appendix; the nomenclature used in the following analysis is in the appendix.

Thermal Analysis

Figures 3.7 to 3.9 illustrate the physical radial gap and total gap conductance that were inferred from the experimental thermal data. The fuel centerline temperatures used to calculate the curves in Figures 3.7 and 3.8 are average values for each rod type based on the first two ramps to power for each assembly. The linear power and averaged centerline temperatures are listed below.

FIGURE 3.6. Fuel Centerline Temperature as a Function of Physical Gap at 200 W/cm

Linear Power W/cm	Upper Centerline Temperature, °C		
	Rod 1	Rod 3	Rod 4
50	409	370	814
100	542	470	1065
150	681	558	1259
200	815	663	1483
250	958	750	1640
300	1092	853	1817

The uncertainty bands that are included in Figure 3.7 define the 3σ (99.7%) confidence limits; they were determined as described in Reference 9. The uncertainty bands in Figure 3.8 were determined by applying the method of linear propagation of uncertainties⁽¹⁰⁾ to the following simplified solution for the gap size:

$$G_p = \frac{K_g}{h_g - h_r} - T_j$$

There are two notable features in Figure 3.7:

- Most importantly, the gap conductance for each rod type is definitely separable at any power level (no overlap of uncertainty bands).

FIGURE 3.7. Inferred Gap Conductance versus Linear Power

FIGURE 3.8. Inferred Physical Radial Gap versus Linear Power

- The designed small diametral gap of rod 3 has resulted in the expected high values of gap conductance.

Figure 3.8 provides estimates of the average physical radial gap for each rod type as a function of power. As might be expected from the fabricated dimensions, rod 3 had approximately one-third the hot radial gap of rod 1. However, as the figure shows, calculations indicate rod 4 operated with a smaller radial gap (in the region of the upper thermocouple) than did rod 1, even though both rods were fabricated with the same initial dimensions. In addition, rods 3 and 4 have approximately equal physical radial gaps, especially for local linear powers above 200 W/cm.

Figure 3.9 provides greater detail into the behavior of the radial gap for rod 4 of assemblies IFA-431 and IFA-432. Because of the difference in behavior of rod 4 between the first and second ramps of IFA-431, both ramps are presented. Note the radial gap increase which occurred during the first ramp at approximately 165 W/cm (at the upper thermocouple position). For IFA-432, behavior of the first and second ramps was very similar; therefore, their centerline temperature response as a function of linear power was averaged to provide a single set of input conditions. Figure 3.9 illustrates two points of interest:

- Extrapolation of the first ramp of IFA-431 will place it in close agreement with the second ramp for powers greater than 200 W/cm. The difference below 200 W/cm due to mechanical interaction (see Section on mechanical analysis).
- The radial gap of rod 4, IFA-432 is consistently inferred as larger than that of IFA-431. As will be discussed later, the reason for this is believed to be smaller (1.0833 cm diameter) oversize fuel pellets in IFA-432 (1.0833 cm diameter) than in IFA-431 (1.0858 cm diameter).

As mentioned in the introduction, it had been concluded from earlier work⁽¹⁻³⁾ that xenon in the gap might not be as detrimental to heat transfer as originally expected. The data from the current program might even support that conclusion if one examined only centerline temperature versus power (as in Figure 3.1) and assumed design dimensions. However, this work has concluded that the improved heat transfer is due to greatly decreased gap sizes

Figure 3.9. Detailed Description of Inferred Physical Radial Gap for Rod 4, Concentric Region

for the xenon rods. In fact, it has been inferred, for powers greater than 200 W/cm, that the operating gap for the xenon rods is approximately equal to that of the small-gap helium rods (Figure 3.9).

From the ideal model for an open gap, the gas conductance portion of the total gap conductance is seen to be equal to the ratio of the gas conductivity to the thermal gap (nomenclature in the appendix):

$$h_c = h_g - h_r = \frac{K_g}{G_p + T_J} = \frac{K_g}{G_T}$$

If one then takes the ratio of gas conductance (h_c) for two different gas mixtures, at equal thermal gap sizes (G_T), then that ratio is equal to the ratio of the gas conductivities:

$$\frac{h_c (\text{He})}{h_c (\text{Xe})} = \frac{K_g (\text{He})}{K_g (\text{Xe})} \quad (1)$$

Since the data analysis procedure provides estimates of the fuel surface and cladding inner surface temperatures, estimates may be obtained for the total gap conductance and radiative component, which are not dependent upon the gas conductivity:

$$h_g = \frac{q}{\pi d_g (T_{fs} - T_{ci})}$$

$$h_r = f (T_{fs}, T_{ci})$$

Thus, if the ideal model holds for the particular conditions of interest, Equation 1 should be verified by the experimental data.

Unfortunately, Equation 1 cannot be fully verified from in-reactor fuel rod measurements. This is because while the gas conductivity and gap conductance may be separable, the inference of the thermal gap is dependent upon the assumed gas thermal conductivity. However, Equation 1 and fuel rod data can be used to check the self consistency of the established thermal models. Figure 3.10 shows that the ratios of gas conductivity and gap conductance are equal for identical thermal gaps and, therefore, the modeling is consistent.

Full verification of Equation 1 requires independent measurements of gap size and the associated gap conductance. Current ex-reactor work at PNL is supplying this type of information.⁽¹¹⁾ Measurements of gas conductance for both helium and argon in the gap have been made for differing gap temperatures and known physical gaps. Table 3.1 lists some of the data which has been obtained for both helium and argon in the gap; Figure 3.11 presents this information in the same form as Figure 3.10. Again, for two gaps of equal thermal gap size but different gas thermal conductivities, the ratio of gas conductances for the two gaps is approximately equal to the ratio of the gas thermal conductivities.

FIGURE 3.10. BOL Relationship Between Inferred Thermal Gap, Gas Conductivity, and Gas Conductance for Concentric (Upper) Fuel Region

FIGURE 3.11. Ex-Reactor Relationship Between Thermal Gap, Gas Conductivity, and Gas Conductance

TABLE 3.1. Ex-Reactor Gas Conductance Between UO_2 and Zry-4 for a Physical Gap of $29.8 \mu m$

Helium in Gap		Argon in Gap	
Gap Temperature °K	Gas Conductance $W/cm^2-^{\circ}C$	Gap Temperature °K	Gas Conductance $W/cm^2-^{\circ}C$
479	0.486	474	0.0781
480	0.492	484	0.0800
480	0.498	490	0.0768
676	0.524	675	0.0971
870	0.599	668	0.0958
		848	0.112
		860	0.135

Mechanical Analysis

The temperature response for rod 4 of IFA-431 during its first ramp, Figures 3.1 and 3.2, indicates an extensive amount of fuel - cladding interaction. A scenario for the fuel - cladding behavior follows:

Because of the small initial diametral gap between the oversize pellets and cladding ($51.0\text{ }\mu\text{m}$), contact was made and fuel - cladding lockup occurred at low linear power. As the power increases, a combination of fuel relocation and elastic diametral reduction of the cladding results in a reduced fuel - cladding gap in the thermocouple region, as illustrated in Figure 3.12. This in turn produces lower temperatures than would be predicted without this mechanical interaction. At approximately 165 W/cm for the upper fuel region, the axial forces overcome the radial forces and slip occurs between the fuel and cladding. This results in an increase of the fuel - cladding gap and the step increase in centerline temperature observed in Figures 3.1 and 3.2. After the slipping, fuel - cladding lockup reoccurs and gap reduction continues to the peak power of the ramp. Figure 3.13 identifies the areas of gap reduction and slip on the temperature response curve for the upper fuel region of rod 4, IFA-431 during its first ramp.

FIGURE 3.12. Schematic of Rod 4 Pellet-Cladding Interaction

The second ramp of IFA-431 produced higher temperatures and provided no evidence of slipping. An axial gamma scan of rod 4 (Figure 3.14) has shown the presence of axial gaps in the vicinity of the oversize pellets. This leads to the conclusion that at the completion of the first ramp, and

FIGURE 3.13. Identification of Gap Reduction and Slippage for the First Ramp of Rod 4, IFA-431

FIGURE 3.14. Rod 4, IFA-431, Axial Gamma Scan

subsequent ramps, the oversize pellets remained locked in their final position. However, the standard size pellets upon cool-down experienced a reduction in their thermal expansion and opened up the observed axial gap. Thus, during the second ramp, this axial gap had to be closed before radial gap reduction could again occur. Therefore, higher temperatures were recorded for the second ramp until gap reduction began again at powers greater than 200 W/cm.

As discussed in the appendix, the thermal analysis for estimates of gap conductance and gap size is scarcely affected by assuming either a reduction in cladding diameter or an increase in fuel radius. However, from the standpoint of overall fuel rod behavior, it is important to differentiate the mechanism of gap closure. Therefore, it is necessary to demonstrate that the qualitative behavior of rod 4, IFA-431 can be approximated analytically; that is, that the phenomena of pellet - cladding slipping and cladding elastic diametral reduction can be modeled.

A code called SLIPR (Figure 3.15) was written to perform this task.^(a) This code was set up to model one half of the concentric test section, as shown in Figure 3.16. Use of the axial heat flux and axial forces as couplings between the oversize and test pellets allows this model to analytically reach the thermal and mechanical equilibria. The code first solves for the thermal and mechanical equilibrium conditions at the oversize pellet; it finds the friction force between the fuel and cladding. Then it finds thermal and mechanical equilibrium conditions for the test (instrumented) section. If the axial forces in this region are greater than the friction forces above, slippage occurs.

After the power-temperature history for the test section is read in, the solution for the oversize section proceeds as follows: An axial heat flux is assumed and a volume average temperature is calculated using the integral conductivity method and the "effective power" for the oversize pellet (input power minus axial heat flux). Then an inner loop converges with the gap temperature drop such that the gap conductance calculated from mechanical

(a) GAPCON-THERMAL-3, which was used in Figure 3.1, does not allow axial slippage between the fuel and cladding.

FIGURE 3.15. Flowchart for SLIPR

FIGURE 3.16. Model for SLIPR

considerations (contact and gas conduction) agrees with that calculated from purely thermal considerations (effective power divided by gap temperature drop). Plane stress formulas for thick-wall cylinders are used in these calculations. Upon convergence, a new volume average temperature for the oversize pellet is found using the assumed axial heat flux and the volume average temperature of the test pellets. The axial heat flux converges when the two volume-average temperatures for the oversize pellet are equal. Upon convergence, the interfacial friction force that occurs between pellet and cladding (PCF) is calculated using a specified friction factor.

The code next solves for mechanical and thermal equilibrium in the test section. First, a reference value for the strain energy of the fuel and cladding in the test region is calculated assuming that axial slipping between fuel and cladding is zero. A reference axial force for the test section is found this way. If this reference axial force is less than the friction force above, then a solution is found and the results are printed. If it is greater, the code must solve for the amount of slippage and relocation.

To solve for the slippage and relocation, the axial force is set equal to the friction force, and a small amount of slippage is assumed. Then an inner loop converges on the amount of relocation for the specified slippage when the gap sizes calculated from thermal and mechanical considerations are equal. Then the change in strain energy of the fuel and cladding is calculated. The outer (slippage) loop converges when the work done by slippage (friction) equals the change in the strain energy. When convergence is reached, results are printed and the code goes to the next power step. In this manner, a solution is found for each power step in approximately 0.3 seconds execution

time. It should be kept in mind that the stress and strain calculations are relatively simple; more elaborate methods will require longer solution times.

The power-temperature history for rod 4 of IFA-431 was approximated with six points and input to SLIPR. Two cases that were run are shown in Tables 3.2 and 3.3. The resulting cladding axial strains are shown in Figure 3.17.

From thermal considerations using the data, a thermal radial gap increase of $3.9\text{ }\mu\text{m}$ is necessary to produce the observed temperature discontinuity at approximately 165 W/cm . The elastic changes in fuel and cladding radii from step 4 to step 5 are 1.54 and $1.95\text{ }\mu\text{m}$, respectively. These numbers represent the calculated amount of available elastic gap behavior between equilibrium states at the beginning and end of the temperature discontinuity; this is about half the required gap increase. However, total release of the oversize pellet produces calculated gap increases of 8.28 and $15.4\text{ }\mu\text{m}$, which are two to four times as much as required. So the actual amount of slippage was somewhere between the two cases.

However, total release between fuel and cladding did not occur because the cladding elongation monitor showed a monotonically increasing readout. This is reasonable because the step increase in fuel temperature resulted in fuel thermal expansion that increased the PCF monotonically. Most likely, the uppermost oversize pellet (concentric region) slipped more than its lower companion, and the rest of the fuel - cladding elongation was maintained. The lower oversized pellet (for the concentric test section) also must have slipped, though not as much as the uppermost oversize pellet, since the eccentric test section showed a similar discontinuity in temperature. All this, in turn, implies that the total cladding elongation is the result of a wide variety of forces operating between pellet and cladding; these forces are as yet largely unpredictable. Since the total cladding elongation measurement yields insufficient information to build a reliable predictive model, it should be used only for code verification and not for model building.

However, some conclusions have been made from the input required to produce the curves in Figure 3.17:

TABLE 3.2. SLIPR Results, Case 1

Oversize Pellet										
LHR W/cm	T _{CL} °C	h _g W/cm ² -°C	h _{solid} W/cm ² -°C	PCF ^(a) Kg/cm ²	Friction Force Kg	Axial Heat Flux W/cm	Gap μm			
50	415	0.166	0.039	44	155	1.92	7.6			
100	549	0.223	0.092	108	378	2.21	7.6			
150	683	0.275	0.139	170	594	2.78	7.6			
175	750	0.299	0.162	201	701	2.56	7.6			
175	752	0.300	0.163	202	704	3.31	7.6			
200	820	0.324	0.185	233	813	3.14	7.6			
Test Pellets										
LHR W/cm	T _{CL} °C	h _g W/cm ² -°C	Reference Axial Force Kg	Final Axial Force Kg	Slip μm	Relocation μm	Δr _{fuel} ^(b) μm	Δr _{clad} μm	ΔL _{clad} ^(c) μm	Gap μm
50	600	0.052	358	155	65.3	73.7	2.53	0.68	12.2	21.7
100	800	0.081	474	378	31.0	68.1	6.32	1.67	29.9	14.3
150	1050	0.093	625	594	10.2	53.2	10.17	2.63	47.1	13.2
175	1100	0.112	643	643	0.0	53.5	11.00	2.85	51.0	10.5
175	1225	0.091	740	704	11.9	40.7	12.27	3.12	55.8	14.4
200	1285	0.106	765	765	0.0	39.9	13.37	3.39	60.6	11.9

elastic modulus factor = 0.06

minimum gap = 7.6 μm

friction factor = 0.8

(a) Pellet-Cladding Interfacial Pressure

(b) Δr = change in radius

(c) ΔL = change in length

TABLE 3.3. SLIPR Results, Case 2

Oversize Pellet

LHR W/cm	T _{CL} °C	h _g W/cm ² -°C	h _{solid} W/cm ² -°C	PCF ^(a) Kg/cm ²	Friction Force Kg	Axial Heat Flux W/cm	Gap μm
50	370	0.308	0.000	0	0	2.42	5.0
100	474	0.213	0.024	26	74	2.94	5.0
150	658	0.312	0.111	133	378	2.98	5.0
175	723	0.340	0.136	166	471	2.77	5.0
175	725	0.341	0.137	167	474	3.51	5.0
200	790	0.368	0.163	200	568	3.36	5.0

Test Pellets

LHR W/cm	T _{CL} °C	h _g W/cm ² -°C	Reference Axial Force Kg	Final Axial Force Kg	Slip μm	Relocation μm	Δr _{fuel} ^(b) μm	Δr _{clad} μm	ΔL _{clad} ^(c) μm	Gap μm
50	600	0.052	0	0	0.0	76.5	0.00	0.00	0.00	22.1
100	800	0.080	148	74	19.6	74.5	0.93	0.33	5.88	14.5
150	1050	0.093	344	344	0.0	60.0	4.41	1.52	27.22	13.2
175	1100	0.112	367	367	0.0	61.0	4.71	1.62	29.04	10.6
175	1225	0.091	493	474	5.1	47.7	6.18	2.10	37.54	14.4
200	1285	0.106	524	524	0.0	47.4	6.87	2.32	41.56	11.9

elastic modulus factor = 0.08

minimum gap = 5.0 μm

friction factor = 0.65

(a) Pellet-Cladding Interfacial Pressure

(b) Δr = change in radius

(c) ΔL = change in length

FIGURE 3.17. Comparison of Experimental and Calculated Strain

- The fuel modulus of elasticity ranges from 1/12 to 1/16 of the MATPRO⁽¹²⁾ values for polycrystalline solid UO_2 for these loading conditions. ^(a)
- The friction factor between pellet and cladding ranges from 0.65 to 0.80 for these loading conditions. This is not unreasonable since some galling of the cladding may be expected to occur with sliding at these pressures.
- The effective gap size at contact varied from 5.0 to 7.6 μm for the two cases. This distance is highly dependent on the profiles of the fuel and cladding. Its major effect here is to influence the point of first contact.

Note in Tables 3.2 and 3.3 that the fuel radial deflection is three to four times that for the cladding. This is a result of the reduced effective fuel modulus of elasticity. MATPRO values for the fuel elastic modulus

(a) This agrees with other work performed at PNL; this will be discussed in detail in future reports.

produce cladding radial strains that are two to four times greater than those for the fuel. Note also that fuel relocation is about an order of magnitude greater than the radial elastic deflections for fuel and cladding.^(a) This indicates it is incorrect to assume no fuel relocation; however, this does not affect the conclusion regarding the dependence of gap conductance on the fill gas composition. That conclusion was reached solely on the basis of gap size, not gap radial location. When gap location is taken into account, the minor change in radial heat flux is much less than the uncertainty in gap conductance.

The axial heat transfer observed between oversize and test pellets at each converged step is seen to be less than 5% of the linear heat rating. The uncertainty in linear power is about $\pm 5\%$, so the axial heat transfer is shown to be negligible. This result was also reached by a method explained in Reference 7.

In conclusion, the behavior of rod 4 can be modeled. The phenomena of pellet - cladding contact, fuel and cladding diameter changes, and slippage, can be shown calculationaly to have occurred. However, the model to date is only an estimate, and some of the conclusions must be verified independently before proceeding with the work. It is evident that more work is required in the areas of effective fuel modulus, friction factors, and minimum effective gap at contact.

3.3 ECCENTRIC ANALYSIS

Besides studying the effects of xenon fill gas, the second major design objective for rod 4 is to obtain a comparison of thermal response between concentric and eccentric fuel regions. To accomplish this, as described in Section 2, the fuel region containing the lower thermocouple was mechanically constrained to full eccentricity.

(a) Relocation calculated in Tables 3.2 and 3.3 decreases with increasing power because, as calculated here, it is not totally separated from fuel thermal expansion. An overall average initial relocation for this rod is about 45% of the initial cold gap.

Figures 3.18 and 3.19 compare the upper and lower thermocouple response as a function of linear power for assemblies IFA-431 and IFA-432, respectively. The most important item of note from these figures is that, for equivalent power, the lower thermocouple consistently registered lower temperatures.

FIGURE 3.18. Comparison of Upper and Lower Centerline Temperature Response, Rod 4, IFA-431

FIGURE 3.19. Comparison of Upper and Lower Centerline Temperature Response, Rod 4, IFA-432

If the temperature-power data for the lower region of rod 4 is subjected to the same concentric analysis assumptions that were applied to the upper region, azimuthal averages of the gap conductance and radial gap may be obtained. Figure 3.20 compares such gap conductance for the upper and lower regions of rod 4 at equivalent local powers. Figure 3.21 provides the same

FIGURE 3.20. Comparison of Inferred Gap Conductance for Concentric and Eccentric Regions of Rod 4

FIGURE 3.21. Comparison of Inferred Gap Size for Concentric and Eccentric Regions of Rod 4

comparison for the azimuthal average physical radial gaps. Figures 3.20 and 3.21 show that the eccentric fuel region of rod 4 experienced higher azimuthal average gap conductance, due to a smaller azimuthal average radial gap, than did the concentric region. More specifically, at 200 W/cm, the azimuthal average gap conductance is ~17% greater and the azimuthal average radial gap is ~25% lower for the eccentric region than the concentric region.

It is useful to analyze the eccentric region of rod 4 based upon concentric assumptions in order to estimate the azimuthal average gap conditions that exist because of the eccentric geometry. However, concentric analysis provides little information as to the actual geometry and corresponding temperature distribution. Even when two-dimensional analysis is used, difficulties still exist because, as Williford stated previously: "The basic problem of the eccentric case is the lateral force equilibrium of an asymmetrically loaded, statically indeterminate column with thermally dependent geometry."⁽⁷⁾ Thus, there is a problem in estimating cladding diametral reduction, fuel relocation, fuel - cladding contact area, and fuel - cladding contact pressure.

It is necessary to shift to two-dimensional analysis (using the code CRAKR)⁽¹³⁾ in order to estimate possible fuel - cladding geometries which will reproduce the observed fuel centerline temperatures. This report examines three situations and develops solutions which satisfy the experimental fuel centerline temperatures. Because this is strictly a thermal analysis, the radial size rather than the radial position, of the gap is the important variable; therefore, the fuel radii are based on thermal expansion alone. The three situations that were investigated are:

Case A: Nonrestricted lateral movement of the fuel; during relocation or cladding diametral reduction, the fuel will remain in point contact with the cladding (full eccentricity), but no solid conductance will be assumed.

Case B: Slightly restricted lateral movement of the fuel; point contact between fuel and cladding resulting in interfacial pressure and solid conductance.

Case C: Strongly restricted lateral movement of the fuel; the fuel and cladding are in contact over 96° of arc. A maximum gap is maintained opposite the center point of contact and the gap is smoothly varied from maximum to minimum (contact).

These three cases represent varying degrees, and most likely extremes, of fuel - cladding response to the forces present in the eccentric region of rod 4.

An important assumption which must be input into CRAKR is a value for the solid conductance between the fuel and cladding. For IFA-431, it will be assumed that the contact conductance between the eccentric test pellet and cladding is the same as the conductance between the oversize pellet and cladding above the concentric test section, as calculated by SLIPR. For IFA-431 then, the assumed contact conductance at 200 W/cm is $0.163 \text{ W/cm}^2\text{-}^\circ\text{C}$. Because rod 4 of IFA-432 had smaller oversize pellets, it is expected to have lower contact conductance. A value of $0.1 \text{ W/cm}^2\text{-}^\circ\text{C}$ is assumed for the IFA-432 solid conductance. Table 3.4 lists additional assumptions used in the CRAKR analysis.

TABLE 3.4. Eccentric Analysis Assumptions

	<u>IFA431</u>	<u>IFA432</u>
Linear Power, W/cm	200	200
Centerline Temperature, °C	1280	1440
Fuel Radius Due to Thermal Expansion, cm	0.5395	0.5402
Solid Conductance, $\text{W/cm}^2\text{-}^\circ\text{C}$	0.163	0.100
Minimum Gap at Contact, μm	7.6	7.6

Table 3.5 summarizes the results obtained from the three eccentric geometries that were considered. Several features are worth noting:

- There is close agreement for the azimuthal average gap conductance between eccentric Cases A and B and the concentric analysis. The eccentric cases, however, predict larger azimuthal average radial gaps.

TABLE 3.5. Eccentric Analysis Results

	IFA-431				IFA-432			
	Concentric	Case A	Case B	Case C	Concentric	Case A	Case B	Case C
Centerline Temperature (°C)	1280	1280	1279	1289	1440	1438	1434	1456
Azimuthal Average Gap Conductance (W/cm ² -°C)	0.112	0.111	0.119	0.138	0.090	0.093	0.096	0.113
Maximum Gap Conductance (W/cm ² -°C)	--	0.166	0.313	0.309	--	0.170	0.261	0.255
Minimum Gap Conductance (W/cm ² -°C)	--	0.078	0.075	0.052	--	0.057	0.055	0.042
Azimuthal Average Radial Gap (μm)	10.8	14.0	14.5	19.8	14.6	21.0	21.4	30.6
Maximum Radial Gap (μm)	--	20.4	21.4	38.0	--	34.4	36.4	65.0
Maximum/Minimum Fuel Surface Temperature (°C)	806/806	945/693	965/595	1122/539	932/932	1142/726	1155/668	1323/603
Maximum/Minimum Cladding Inner Temperature (°C)	280/280	281/271	282/271	289/266	280/280	285/269	293/269	291/265

- Inclusion of solid conductance over a substantial area, Case C, produces significant increases in the azimuthal average gap conductance and azimuthal average radial gap, while maintaining the same centerline temperature.
- All three eccentric cases display significant azimuthal variation for fuel and cladding temperatures. However, Case C with its extensive fuel - cladding contact produces the most extreme temperature variations.

Cases B and C for IFA-432 were also run with a solid conductance of $0.2 \text{ W/cm}^2\text{-}^\circ\text{C}$. This was done to check the effect of assuming a specific value of solid conductance. Table 3.6 shows that there is little effect when the amount of fuel - cladding contact is minimal (Case B). However, as the area of fuel - cladding contact increases (Case C), the assumed solid conductance has a larger effect.

TABLE 3.6. Effect of Assumed Solid Conductance for IFA-432

	Case B		Case C	
	$\frac{h_g^{(a)}}{h_g} = 0.1$	$\frac{h_g^{(a)}}{h_g} = 0.2$	$\frac{h_g^{(a)}}{h_g} = 0.1$	$\frac{h_g^{(a)}}{h_g} = 0.2$
Centerline Temperature ($^\circ\text{C}$)	1434	1442	1456	1454
Azimuthal Average Gap Conductance ($\text{W/cm}^2\text{-}^\circ\text{C}$)	0.096	0.099	0.113	0.132
Maximum Gap Conductance ($\text{W/cm}^2\text{-}^\circ\text{C}$)	0.261	0.347	0.255	0.339
Minimum Gap Conductance ($\text{W/cm}^2\text{-}^\circ\text{C}$)	0.055	0.054	0.042	0.039
Azimuthal Average Radial Gap (μm)	21.4	22.2	30.6	35.0
Maximum Radial Gap (μm)	36.4	37.4	65.0	76.0
Maximum/Minimum Fuel Surface Temperature ($^\circ\text{C}$)	1155/668	1165/622	1323/603	1363/540
Maximum/Minimum Cladding Inner Temperature ($^\circ\text{C}$)	293/269	298/269	291/265	294/264

(a) h_g is solid conductance, $\text{W/cm}^2\text{-}^\circ\text{C}$

As noted in Table 3.5, the assumption of fuel - cladding eccentricity results in azimuthal variations of the fuel surface and cladding inner surface temperatures. Also, Figure 3.22 shows that the degree of azimuthal temperature variation is dependent upon the degree of fuel - cladding contact. Assuming that azimuthal temperature variations are important to fuel integrity, this example shows that while eccentricity reduces fuel centerline temperatures, it also produces azimuthal temperature variations that may affect cladding integrity during postulated off-normal conditions.

FIGURE 3.22. Azimuthal Variation in Temperature for Rod 4, IFA-431 at 200 W/cm

4.0 CONCLUSIONS

This report has investigated the BOL behavior of rod 4 of the fuel assemblies IFA-431 and IFA-432. These two rods were designed to investigate the effects of xenon fill gas upon heat transfer across the fuel - cladding gap, and the effects of an eccentric fuel - cladding geometry relative to the standard assumption of concentric geometry. Following analysis of IFA-432 data and re-analysis of IFA-431 data, the conclusions reported for the preceding work remain unchanged.⁽⁷⁾ The major conclusions that have been reached as a result of these two studies are:

- Higher fuel centerline temperatures were observed in the two xenon-filled rods than the helium-filled rods. This is attributed to approximately equal reductions in gap conductance and gas thermal conductivity for the xenon rods.
- Better heat transfer was observed in the two xenon rods than was initially predicted. It was concluded that this was due to radial gap reductions that were greater than expected, and not to the effect of xenon upon heat transfer being less than anticipated.
- Fuel - cladding eccentricity results in reduced fuel centerline temperatures relative to concentric geometries at equivalent local power. This temperature reduction is due to increased azimuthal average gap conductance. However, eccentricity also produces azimuthal temperature variations which may be of importance.

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APPENDIX

DETERMINATION OF OPERATING GAP CONDITIONS USING CONCENTRIC ASSUMPTIONS

DETERMINATION OF OPERATING GAP CONDITIONS
USING CONCENTRIC ASSUMPTIONS

The gap conditions which are present in an operating fuel rod may be inferred from the measured fuel centerline and coolant temperatures, the linear power, and the initial fuel and cladding specifications. More specifically, the gap conditions are inferred from the gap temperature drop and the use of several assumptions. In turn, the gap temperature drop is found from the difference between the inner cladding temperature and the fuel surface temperature.

The method presented here assumes that the fuel and cladding are concentric and that a one-dimensional (radial) analysis is adequate. Realizing that the true experimental geometries are rarely perfectly round, smooth, and concentric, all results from this analysis (particularly the gap temperature drop, operating gap size, and gap conductance) should therefore be assumed to be azimuthal averages.

The inner cladding temperature is found by summing the bulk coolant temperature and the water film and cladding temperature drops. The water film temperature drop is found by:

$$\Delta T_F = \frac{q}{\pi d_{co} h_F}$$

where: ΔT_F = water film temperature drop, °C

q = linear power, W/cm

d_{co} = cladding outer diameter, cm

h_F = water film heat transfer coefficient, W/cm²-°C

The cladding temperature drop is found by:

$$\Delta T_C = \frac{q \ln (d_{co}/d_{ci})}{2\pi K_C}$$

where: ΔT_c = cladding temperature drop, °C

d_{ci} = cladding inner diameter, cm

K_c = cladding average thermal conductivity, W/cm²-°C

The fuel surface temperature is determined by the conductivity integral method:

$$\int_{T_S}^{T_{CL}} K_F(T) dT = \frac{qF}{4\pi}$$

where: T_{CL} = fuel centerline temperature, °C

T_S = fuel surface temperature, °C

K_F = fuel thermal conductivity, W/cm-°C

F = flux depression factor

This resulting fuel surface temperature is dependent upon the choice of fuel thermal conductivity. During the preirradiation characterization of the fuel used in these assemblies, ⁽⁴⁾ thermal conductivity was determined based on diffusivity measurements. This conductivity is higher than Lyon's results for 95% TD UO₂ ⁽¹⁴⁾, and based on experimental data, concluded to be too high for in-reactor analysis. Therefore, for this report, the assumed fuel thermal conductivity is Lyon's equation:

$$K_F(T) = \frac{38.24}{(402.4 + T)} + 6.1256 \times 10^{13} (T + 273)^3$$

where T is in °C. The assumed flux depression factor ($F = 0.835^{(a)}$) was taken from the results of a THERMOS ⁽¹⁵⁾ calculation based upon a central hole and UO₂ enrichment of 10% ²³⁵U.

(a) Applicable only to IFA-431 and IFA-432.

Once the gap temperature drop has been determined, it becomes possible to make some inferences about the operating gap conditions of gas thermal conductivity, gap width, and average gap diameter, through the use of the following relationship:

$$\Delta T_g = \frac{q}{\pi d_g h_g} \quad (A-1)$$

where: ΔT_g = gap temperature drop, °C
 d_g = average gap diameter, cm
 h_g = gap conductance, W/cm²-°C

For the purposes of this analysis, the gap conductance is considered to be a single parameter which is useful for characterizing the heat transfer across the gap. Although the gap conductance is used to characterize the gap heat transfer, that heat transfer is actually determined by the gas mixture, gap width, and the average gap diameter, and the analysis may be performed without reference to gap conductance. Thus, the gap conductance, if no fuel - cladding contact is assumed, is the sum of gas conduction and radiation across the gap:

$$h_g = \frac{K_g}{G_p + TJ} + h_r \quad (A-2)$$

where: K_g = gas thermal conductivity, W/cm-°C
 G_p = physical gap width, cm
 TJ = sum of temperature jump distances at fuel and cladding surfaces, cm
 h_r = radiative heat transfer, W/cm²-°C

and:

$$h_r = \frac{\sigma (T_s^2 + T_c^2) (T_s + T_c)}{\frac{d_{ff}^2}{d_{cf}^2} \left(\frac{1}{E_c (T_c)} - 1 \right) + \frac{1}{E_f (T_s)}} \quad (A-3)$$

where: σ = Stefan-Boltzman constant, $5.6732 \times 10^{-12} \text{ W/cm}^2\text{-}^\circ\text{K}^4$
 T_s = fuel surface temperature, $^\circ\text{K}$
 T_c = inner cladding temperature, $^\circ\text{K}$
 d_{ff} = operating fuel diameter, cm
 d_{cf} = operating cladding inner diameter, cm
 E_c = cladding emissivity = $f(T_c)$
 E_f = fuel emissivity = $f(T_{FS})$

Inserting Equations A-2 and A-3 into Equation A-1, it may be concluded that there are essentially two unknowns, gas thermal conductivity and physical geometry, and only one equation. Thus, a range of conditions may exist which will satisfy the observed gap temperature drop. However, it is possible to make some assumptions that will limit the range of solutions.

The gas thermal conductivity may be determined fairly easily. Since the fuel surface and cladding inner surface temperatures have already been evaluated, the normal procedure is to assume a gas composition and then evaluate its thermal conductivity at the average gap temperature. As it is the BOL conditions which are of interest in this report, it may be assumed that the initial fill gas compositions are still present in the rods. Therefore, the gas thermal conductivity is assumed known for each situation of interest.

The corresponding geometry presents a more difficult situation. As seen in the following equation:

$$\Delta T_g = \frac{q}{\pi d_g \left(\frac{K_g}{G_p + TJ} + h_r \right)} \quad (A-4)$$

both the physical radial gap (G_p) and the average gap diameter (d_g) are required. Once the gas thermal conductivity has been determined, examination of Equation A-4 shows that the radial gap becomes the controlling factor. The operating radial gap may then be determined from Equation A-4 by assuming either the fuel diameter or the inner cladding diameter, and then adjusting the other until the equation is satisfied. Because the average gap diameter changes very little for a specific fuel rod, the estimate for the radial gap is essentially independent of the fuel and cladding diameters.

The combined effects of gap size and gas mixture upon heat transfer across the gap may now be summarized as the gap conductance, Equation A-2.

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