Effects of Fill Gas Composition and Pellet Eccentricity

by
R. E. Williford
C. R. Hann

July 1977

Report to
Fuel Behavior Research Branch
Division of Reactor Safety Research
U.S. Nuclear Regulatory Commission

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SUMMARY

This report presents data and an analysis showing that when the operating pellet-cladding gap size of contemporary UO_2 fuel rods is carefully considered, the gap conductances are closely proportional to the thermal conductivities of the fill gases.

Pellet-cladding gap eccentricity is shown to raise the gap conductance appreciably in cases of high thermal gradients across the gap. Ignoring the azimuthal heat flow can lead to an underestimation of the thermal time constant of the rod, resulting in a slower calculated thermal response during power transients.

The data for this report were obtained during the startup of the NRC-RSR/BPNL^(a) test assembly IFA-431 in the Halden Boiling Water Reactor in Norway.

One rod in this fuel assembly was designed to evaluate the effects of xenon fill gas and pellet column eccentricity. The rod was backfilled with xenon at room temperature and one atmosphere. Instrumented portions of the rod were mechanically constrained with oversized pellets and molybdenum rods to ensure a concentric geometry in the upper portion of the rod and an eccentric geometry in the lower portion. (See page 6).

At 200 W/cm, where the radial hot gaps were approximately 0.019 mm, the calculated gap conductance of the helium-filled Rod 3 was $1.5 \text{ W/cm}^2 \text{ }^\circ\text{C}$ (+50%/-25%) whereas that of the concentric section of the xenon-filled Rod 4 was $0.09 \text{ W/cm}^2 \text{ }^\circ\text{C}$ ($\pm 11\%$). The calculated gap conductance in the eccentric section of the xenon rod was 25-50% higher than in the concentric section. Ignoring azimuthal heat flow in the eccentric xenon case and using a concentric approximation yields a 7-24% underestimation of the gap conductance and thermal time constant of the rod.

(a) Nuclear Regulatory Commission-Reactor Safety Research/Battelle, Pacific Northwest Laboratories.

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INTRODUCTION

Previous experiments have indicated that gap conductances are not as sensitive to different fill gas compositions as some models would predict. In particular, Cohen et al.,⁽¹⁾ Horn⁽²⁾ and Lawrence et al.⁽³⁾ have reported that large portions of xenon must be mixed with helium before significant changes in gap conductance can be detected. In addition, analytical work had indicated that asymmetric pellet cladding gap geometries could have a significant effect on fuel temperatures and gap conductances.⁽⁴⁾ The experimental resolution of the above was considered in the design of the NRC-RSR/BPNL Halden assemblies IFA-431 and IFA-432.

These two well-characterized,⁽⁵⁾ virtually identical Boiling Water Reactor (BWR) six-rod assemblies, have been undergoing irradiation in the Halden Boiling Water Reactor (HBWR) in Norway. The objective of these assemblies is to establish a sound data base with reference points for the verification of the NRC fuel performance codes GAPCON-THERMAL-2⁽⁶⁾ and FRAP-S.⁽⁷⁾ These codes are used as independent checks of vendor codes during licensing procedures.

These experiments will span the normal operating range of contemporary water reactor fuels with many points that can be cross correlated and will provide internal checks of data consistency.

EXPERIMENT DESIGN

IFA-431 was successfully discharged in February 1976, after reaching its goal burnup of 4300 MWd/MTM. IFA-432, in a separate channel, will remain in the core until it reaches its goal burnup of 20,000 MWd/MTM late in 1977.

The HBWR uses natural circulation of heavy water for cooling. Reactor operating data are shown in Table 1.

TABLE 1. Operating Data for the HBWR

Power Level	12 MW
Reactor Pressure	500 psi (34 atm)
Heavy Water Saturation Temp.	464°F (240°C)
Plenum Inlet Temp.	459°F (237°C)
Thermal Flux	$\sim 3 \times 10^{13}$ n/cm ² -sec
Fast Flux (>1 MeV)	$\sim 5 \times 10^{11}$ n/cm ² -sec
Average Fuel Power Density	14.8 W/g

The assembly and channel configurations are shown in Figure 1. Design parameters and instrumentation for both assemblies are shown in Table 2.

Test parameters include pellet-cladding gap size, fill gas composition, fuel density and stability, linear heat rating, and burnup. Each assembly is instrumented with two fuel centerline thermocouples and one cladding elongation sensor per rod, pressure transducers, and neutron detectors. Data is recorded every 15 min by a computer-controlled acquisition system. This data is then sent to Battelle, Pacific Northwest Laboratories, where it is analyzed, and appropriate corrections (e.g., axial flux shape and radial flux tilt) are made.

FIGURE 1. Schematic of Instrumented Fuel Assembly--IFA-431

TABLE 2. 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	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	10.858	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

The comprehensive design of the test is evident from the purposes of the individual rods:

- Rod 1 simulates a typical BWR-6 fuel rod and serves as a reference standard.
- Rod 2 simulates instantaneous densification with a 0.015-in. cold diametral gap.
- Rod 3 has a small cold diametral gap, and its high gap conductance provides an internal, independent check on rod linear heat ratings through both steady-state and transient analysis.⁽⁸⁾
- Rods 5 and 6 provide further fuel density and stability data.

These rods have helium at one atmosphere as an initial fill gas. The fuel in all rods consists of flat-ended, 0.5-in.-long, sintered UO_2 pellets that have been enriched to 10 wt% ^{235}U .

Figure 2 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 composition 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 concentrically and 10% near the bottom eccentrically with respect to the cladding. The "oversized" pellets are from Rod 3 of each respective assembly. They have flats ground on the periphery to allow axial fill gas communication.

FIGURE 2. Schematic of Rod 4 Fuel Column

ANALYSIS

STARTUP HISTORY FOR IFA-431

IFA-431 experienced its first rise to power on June 8, 1975. The fuel centerline temperature histories and inferred gap conductances for Rods 1, 3 and 4 are shown in Figures 3 and 4, respectively.

As the assembly rose to power, higher-than-usual fuel temperatures occurred in Rod 4 because of the xenon fill gas. The radial thermal expansion of the oversized pellets in Rod 4 caused them to contact the cladding at relatively low power. With further increases in power, the smaller-diameter pellets in Rod 4 expanded axially against the oversized pellets. The resulting axial tensile strain in the cladding then reduced the operating radial hot gap to nearly half that calculated from free thermal expansion of the smaller pellets alone. This effect can be seen in Figure 3 when the pretest calculation is compared with the data. The model for the pretest calculation did not include the oversized pellets.

FIGURE 3. Startup Temperature History for IFA-431

FIGURE 4. Startup Gap Conductance History for IFA-431

When the axial thermal expansion forces overcame the friction forces between the oversized pellets and cladding in Rod 4, the fuel column slipped axially with respect to the cladding. The sudden increase in the gap size resulted in an accompanying increase in fuel centerline temperature. This is also shown in Figure 3.

The axial forces quickly reached equilibrium, and the cladding began necking down again (Figure 5). The nearly vertical high-temperature sections of the Rod 4 curves in Figure 3 represent a power plateau lasting approximately 12 hr (also see Appendix A). During this time, axial slipping, cladding recovery and plastic flow of the fuel allowed the gap to widen and the temperature to rise (Figure 6). Calculations based on conservation of volume showed that the decrease in gap size due to plastic flow of the fuel was negligible. The decrease in cladding elongation accompanying the increase in gap size is shown in Figure 7.

FIGURE 5. Schematic of Rod 4 Pellet-Cladding Interaction

FIGURE 6. Fuel Temperatures in Rod 4 During June 8, 1975 Startup

FIGURE 7. Rod 4 PCI During Startup

Fuel temperatures are very sensitive to changes in gap dimensions in rods backfilled with a gas of low thermal conductivity. In order to complete the original objectives and provide a basis for further study, it was necessary to further quantify the operating gap size.

DETERMINATION OF GAP SIZE FOR THE CONCENTRIC CASE

Figure 8 is a flow chart of the analysis procedure. All available pre-irradiation characterization data were input for the analysis.⁽⁵⁾ The general approach was to build a tool to quantify the gap sizes.

The operating gap conductances and associated uncertainties were calculated with HGAP, a code written for the uncertainty analysis⁽⁹⁾ of these tests. This code uses the $\int K(T)dT$ method to calculate the fuel surface temperature and the gap conductance, and it then applies these in a first order Taylor series propagation of errors routine.

FIGURE 8. Flow Chart of Analysis Procedure

Two codes were used to establish a basis for concentric conditions with no PCI: GAPCON-THERMAL-2⁽⁶⁾ and TRUMP.⁽¹⁰⁾ TRUMP is a finite difference heat transfer code that can accommodate complex three-dimensional geometries and temperature-dependent material properties.

The development of GAPCON-3⁽¹¹⁾ proceeded simultaneously. Rod 4 was used to test the thermomechanical models of this code. Although GAPCON-3 contained a first approximation fuel creep package and no fuel-cladding axial slippage routine at the time of these calculations, the temperature and geometric results were quite encouraging (see page 16). The code verified the cladding necking phenomenon for Rod 4 and closely simulated the mechanical response of Rod 3.⁽¹²⁾

DETERMINATION OF GAP SIZE FOR THE ECCENTRIC CASE

At the outset, let us define radial hot gap and gap conductance for the eccentric case. The eccentric radial hot gap refers to the radial hot gap if the fuel and cladding were concentric. That is, the gap volume is the same, but the fuel and cladding centers do not coincide. The eccentric gap conductance is just the azimuthal average of the local gap conductance at each gap node (see Figure 10).

The concentric solution was used as a first estimate of the gap size for the eccentric case, but it was necessary to determine the amount of contact between fuel and cladding that occurred in this case. Three more variables were added to the gap size variable of the concentric case:

- the azimuthal angle of contact between fuel and cladding,
- the pressure of contact and resulting solid-solid contact conductance, and
- the effective distance for conduction through the gas in the area of contact.

The basic problem of the eccentric case is the lateral force equilibrium of an asymmetrically loaded, statically indeterminate column with thermally dependent geometry⁽¹³⁾ (see Figure 9). A three-dimensional finite element or finite difference model would be very large and would still include

FIGURE 9. Schematic of Eccentric Portion of Rod 4

uncertainties in the mechanical properties and surface profiles of the Zirc-aloy cladding and UO_2 fuel pellets. At the heart of the problem is the interface between mechanical and thermal models: the lateral force between cladding and fuel is pressure times area. In the concentric case the contact area of the pellet and the pressure may be found easily. The contact area is difficult to define in the eccentric case; thus, there is an unknown pressure term in the solid-solid contact conductance model and in the equation for the effective distance for conduction through the gas.⁽¹⁴⁾

The eccentric problem was solved using the steady-state points on the power plateau of the Rod 4 curves in Figure 3. The constant temperatures at the ends of the curves indicated that the gap sizes had approached stable values for these thermal conditions. GAPCON-3 calculations using a complete axial model of Rod 4 predicted an effective 0.030-mm (0.0012-in.) radial hot gap for the eccentric case during the power plateau at 145 W/cm. The TRUMP model shown in Figure 10 was used to establish the eccentric contact conditions shown in Table 3. There was good agreement between data for June 8 and the analysis, which established a basis for further calculations. The

FIGURE 10. TRUMP mesh for Xenon-Filled Rod (Eccentric Case)

TABLE 3. Solutions for Eccentric Portion of Fuel Column^(a)

Data		Calculations							
Power (W/cm)	Date	Fuel Centerline Temperature (°C)	Fuel Centerline Temperature (°C)	H_{solid} (W/cm ² °C)	Included Angle (Deg)	Contact Conditions			
						Pressure		Radial	Hot Gap
						(psi)	(kg/cm ²)	(mils)	(mm)
145	June 8	1150	1152	0.0712	100	705	49.5	1.20	0.030
200	June 20	1285	1255	0.0084	168	83	5.8	0.73	0.019
200	June 20	1285	1277	0.1381	100	1314	92.4	0.80	0.020
200	June 20	1285	1336	0.0712	120	705	49.5	0.90	0.023

(a) H_{solid} = solid-solid contact conductance

contact pressure for this base case was the same as that calculated by GAPCON-3 for the contact pressure between the oversized pellets and the cladding.

By assuming that the cladding deformed in a similar manner over both the eccentric and concentric pellet sections, the analysis could proceed in an iterative manner for the eccentric case. The target was the 1285°C eccentric fuel centerline temperature at 200 W/cm observed during the second power ramp of IFA-431, which occurred on June 20, 1975, after an 11-day shutdown. Changes in the fuel during this time were minimal (see Figures 11 and 12)

FIGURE 11. Rod 4, Upper Thermocouple, IFA-431

FIGURE 12. Rod 4, Lower Thermocouple, IFA-431

and can be explained by the small amount of relocation that had lowered the fuel centerline temperature by approximately 30°C and 40°C at the upper and lower thermocouple locations, respectively. Thermal radiation across cracks in the fuel should account for changes in fuel thermal conductivity. The gap sizes at the crossover points are expected to be very similar for both ramps. In the first ramp, the cladding elongation and temperatures had reached asymptotic values, indicating that a stable gap size had been achieved at those powers. The oversized pellets had become locked into their positions (with respect to the cladding) at power during the first ramp, and subsequent cool-down of the rod created axial gaps between the oversized pellets and the smaller test pellets. The presence of these gaps was verified by the post-irradiation examination gamma scan (Figure 13). In the second ramp, the axial expansion of the fuel column was insufficient to contact the oversized pellets, and no diameter reduction of the cladding had yet occurred at 200 W/cm. Using a two-dimensional TRUMP model (Figure 10), a range of solutions for the 200 W/cm case was found. These varied from low contact pressure and high contact area to high pressure and low area (see Table 3). The high pressure was assumed to be limited by the maximum calculated value of contact pressure for the oversized pellets (approximately 1400 psi). Again, the contact pressure associated with the best solution was approximately the same as that calculated by GAPCON-3 for the oversized pellets and cladding interface.

FIGURE 13. Rod 4 Axial Gamma Scan

RESULTS

Figures 14 and 15 show the fuel centerline temperatures and gap conductances, respectively, versus gap size for the concentric and eccentric cases of the xenon-filled rod. These curves represent beginning-of-life (BOL) conditions and were calculated with a contiguous fuel pellet model.

The dashed lines in Figures 14 and 15 show the effects of eliminating from the calculations variations in the fuel and cladding roundnesses, but still including the surface roughnesses. These calculations provide a check on the shape of the solid curves above a gap size of 0.01 mm. The nearly vertical portions of the solid curves between 0.25 and 0.35 mils (0.006 to 0.009 mm) show the expected effects of increasing pellet-cladding contact pressure.

FIGURE 14. Fuel Centerline Temperature Versus Hot Gap as a Function of Gap Geometry for a Xenon-Filled Rod Operating at 200 W/cm

FIGURE 15. Calculated Gap Conductance at 200 W/cm Versus Hot Gap as a Function of Fill Gas and Fuel Column Eccentricity

Rod 1, the standard for the assembly, had a 0.08 mm radial hot gap, a centerline temperature of 750°C, and a gap conductance of approximately 0.30 W/cm² °C at 200 W/cm. The cold pellet-cladding gap in Rod 4 was the same as Rod 1. However, on startup the complex geometry of Rod 4 caused extensive pellet-cladding interaction. Its operating hot gap was reduced to a value comparable to that of Rod 3.

Three comparisons may be made at this point:

- If the eccentricity in the xenon case is ignored and a comparison is made between xenon and helium cases based on cold gap sizes, the difference in the gap conductances is only a factor of 2 to 3.
- If eccentricity in the xenon case is taken into account but the comparison is still based on cold gap sizes, the difference in gap conductances is a factor of 4 to 5.
- If eccentricity is taken into account and the comparison is based on the operating hot gap sizes, the conclusion is that the ratios of the gap conductances are indeed proportional to the ratios of the thermal conductivities of the fill gases. Thus there is an order of magnitude difference in the gap conductances between xenon and helium filled rods.

Comparing the concentric and eccentric portions of the xenon-filled rod, we see that eccentricity has increased the gap conductance by 25-50% in the range of these data. For purposes of comparison and to provide perspective for the reader, Rod 4 with a 0.02 mm radial hot gap is thermally equivalent to a helium-filled rod with an approximately 0.3 mm (0.012 in.) radial hot gap.

STORED ENERGY CONSIDERATIONS

This section further demonstrates the importance of considering eccentricity in the analysis of fuel rods with large thermal gradients across the pellet-cladding gap. If the centerline temperature and power are used to calculate gap conductances without considering eccentricity, the results are likely to be in error. For example, the same three 200 W/cm eccentric cases in Table 3 were checked under this assumption (Table 4). The symmetric model ignored azimuthal heat transfer, while the asymmetric model (TRUMP) included it. The gap conductance in the asymmetric case is 17% higher on the average than in the symmetric case, but the volume averaged fuel temperature is increased only 1%. The reason for this is illustrated in Figure 16. The decrease in the volume average temperature on the contact side of the fuel is nearly equal to the increase on the open side of the gap. The net fuel volume average temperature remains nearly unchanged. Aside from the underestimation of the gap conductances, this has further implications.

The temperature history of the fuel during a power drop can be represented by:

$$T = T_{ss} e^{-\alpha t}$$

where

$$\alpha = \frac{HA}{\rho VC_p}$$

is the rod thermal time constant based on averaged properties, and:

T = Fuel centerline temperature ($^{\circ}\text{C}$)

T_{ss} = Initial steady-state fuel centerline temperature ($^{\circ}\text{C}$)

t = Time (sec)

H = Gap conductance ($\text{W}/\text{cm}^2 \text{ } ^{\circ}\text{C}$)

A = Area of gap normal to heat flow (cm^2)

ρ = Fuel density (gm/cm^3)

V = Fuel volume (cm^3)

c_p = Fuel specific heat capacity at constant pressure ($\text{W-sec}/\text{gm } ^{\circ}\text{C}$)

TABLE 4. Calculated Effects of Asymmetry in the Xenon-Filled Rod at 200 W/cm

Centerline Temperature (°C)	$H_{\text{gap}}, (\text{W/cm}^2 \text{ } ^\circ\text{C})$		Volume Average Fuel Temperature (°C)	
	Symmetric	Asymmetric	Symmetric	Asymmetric
1255	0.107	0.115	1046	1053
1277	0.104	0.129	1065	1088
1336	0.097	0.116	1114	1128

FIGURE 16. Effects of Calculational Model on Fuel Volume Average Temperature

Increasing the gap conductance, H , in the numerator and leaving the denominator unchanged (since the temperature of the fuel is unchanged) will result in an underestimation of the thermal response of the rod. In other words, the rod will respond faster than the calculations indicate. This should be considered a boundary case, since the thermal gradients in the xenon rod are higher than normal operating values.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this analysis:

- Quantification of hot gap size is necessary to assess the effects of fill gas composition and eccentricity on gap conductance.
- The helium-filled concentric versus xenon-filled concentric cases showed that the ratio of their respective gap conductances was proportional to the ratio of the thermal conductivities of the associated gases when the hot gap sizes are the same.
- Eccentricity in the xenon case increased the gap conductance by 25-50% at 200 W/cm.
- The importance of pellet-cladding eccentricity increases as the thermal gradient across the gap increases.
- Ignoring azimuthal heat flow causes an underestimation of the gap conductance and the rod thermal response time for rods with large radial thermal gradients across the gap.

Two recommendations may also be made concerning extension of the analysis into the normal operating life of a UO_2 fuel rod:

- Further study of IFA-431 would help in assessing the effects of fuel relocation on the parameters fill gas composition and eccentricity, and vice versa. The fuel-cladding geometries ensured by mechanical constraints, the high fuel temperatures, and the sensitivity of these temperatures with respect to gap size all contribute to provide useful boundary cases for gap closure studies.
- This analysis should be applied to IFA-432, which also had a xenon rod. However, the design power for this assembly was 50% higher than for IFA-431. Once the operating hot gap size is determined, minimum values of the gap conductance at higher powers may be calculated.

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APPENDIX A

Startup History IFA-431

Rods 1, 3, 4

FIGURE A-1. IFA-431 Rod Power History During Startup Period (June 8, 1975)

FIGURE A-2. Fuel Temperatures in the Upper Ends of Rods 1, 3 and 4 During Startup Period (June 8, 1975)

APPENDIX B

Uncertainties

UNCERTAINTIES IN EXPERIMENTAL GEOMETRY

Uncertainties in experimental geometry were investigated under the following classifications:

- axial heat conduction caused by the oversized pellets
- effects of fuel and cladding roundness and roughness on small gap sizes
- boundary cases representing the effects of circumferential cool-down cracks in the pellets.

The code TRUMP was used for these calculations. The results are summarized in Table B-1. All are compared to concentric results at the proper gap sizes. The axial model used is shown in Figure B-1. The roundness check used a stepwise model of pellet and cladding surface waviness with an amplitude of ± 0.00015 in. (0.0038 mm), azimuthal increments of 12° , and a mean gap of 0.00065 in. (0.017 mm); see Figure B-2. The circumferential crack models consisted of moving the shown percentages of the hot gap to 75% of the fuel radius to simulate cracks formed during cool-down (Figure B-3).

TABLE B-1. Uncertainties in Experimental Geometry^(a)

Case	mils	mm	Centerline Temperature (°C)	H_{gap} , W/cm ² °C	% Change From Concentric Case	
					Centerline Temperature	H_{gap}
Axial	0.85	0.022	1556	0.0738	+ 1.7	-5.4
Roundness	0.65	0.017	1328	0.0958	- 3.8	+3.0
13% Crack	0.70	0.018	1455	0.0906	+ 2.5	-3.0
50% Crack	0.40	0.010	1349	0.1311	+20.5	-0.1

(a) H_{gap} = Gap conductance

The results generally compare well with the temperature and gap conductance uncertainties of $\pm 3\%$ and $\pm 11\%$, respectively. The axial case showed only small deviations. The temperature change in the roundness case was

NODES		
MATERIAL	RADIAL	AXIAL
Tc	1	10
UO ₂	18	10
Xe	1	10
Zry-2	3	10

FIGURE B-1. TRUMP Model for Axial Heat Conduction Test

NODES		
MATERIAL	RADIAL	AZIMUTHAL
Tc	1	30
UO ₂	18	30
Xe	1	30
Zry-2	3	30

FIGURE B-2. TRUMP Model to Test Effects of Roundness

NODES		
MATERIAL	RADIAL	AZIMUTHAL
Tc	1	30
UO ₂	18	30
Xe	1	30
Zry-2	3	30

FIGURE B-3. TRUMP Model to Test Effects of Circumferential Cracks in the Fuel

slightly higher because of the small gap size investigated. Roughness was not a significant factor until pellet-cladding contact occurred (Figures 14 and 15). The 13% and 50% circumferentially cracked pellet cases, representing cool-down cracks, showed varying results (Table B-1). The small crack (0.0025 mm wide) showed little change from the reference concentric case, but the temperature change of the 50% crack (0.01 mm wide) case was large. The small change in gap conductance for the 50% crack case was caused by the fuel surface temperature remaining nearly unchanged from the reference concentric case. The simulated crack acted as a thermal barrier affecting only the interior temperature distribution. This is contrary to the results of M. D. Freshley of Battelle Northwest who found (February 1977) no significant thermal changes caused by a fabricated annular gap within a duplex pellet assembly. Note that the emissivity of the fuel is not well characterized at the interior fuel temperatures of the xenon-filled rod, where radiation heat transfer should be significant.

UNCERTAINTIES IN CALCULATIONS

Uncertainties in the radial hot gap sizes can be found by projecting the fuel centerline temperature plus the uncertainties onto the desired curve (see Figure 14) and then moving from these points down to the abscissa. Thus a temperature of $1490^{\circ}\text{C} \pm 3\%$ corresponds to a $0.020^{+0.0015}_{-0.0018}$ mm ($0.0008^{+0.00006}_{-0.00007}$ in.) radial hot gap. The uncertainties in radial hot gap sizes deduced by this method are approximately $\pm 8\%$ for the range studied. Uncertainties in the deduced gap conductances for the helium and both xenon cases were calculated at $^{+50\%}_{-25\%}$ and $\pm 11\%$, respectively.⁽⁹⁾

APPENDIX C

TRUMP Solution for the Eccentric Case
at 200 W/cm

TABLE C-1. TRUMP Solution for the Eccentric Case at 200 W/cm

Fuel Center Temperature = 1277°C

Included Angle of Node (Degrees)	Fuel Surface Temperature (°C)	Clad ID Temperature (°C)	Q at Clad ID (W/cm ²)				Gap Conductance (W/cm ² °C)	Q at Clad OD (W/cm ²)	Gap x 10 ³ (cm)
			Gas	Rad	Solid	Total			
0-12	1075	272	33.31	13.49	0	46.80	0.0583	38.80	3.368
12-24	1071	272	33.17	13.34	↓	46.51	0.0582	38.68	3.363
24-36	1062	272	33.52	12.98		46.50	0.0589	38.69	3.288
36-48	1048	272	34.28	12.43		46.71	0.0602	38.79	3.150
48-60	1029	272	35.19	11.71		46.90	0.0620	38.87	2.984
60-72	1006	272	35.72	10.85		46.57	0.0634	38.73	2.834
72-84	975	272	36.34	9.82	↓	46.16	0.0657	38.56	2.656
84-96	934	272	37.64	8.55		46.19	0.0698	38.80	2.398
96-108	880	273	40.04	7.04		47.08	0.0776	40.26	2.000
108-120	803	277	50.16	5.23	↓	55.39	0.1053	46.35	1.320
120-132	723	281	56.29	3.73	0	60.02	0.1358	53.61	0.940
132-144	619	294	45.65	2.22	44.85	92.72	0.2853	70.60	0.800
144-156	591	293	40.91	1.91	41.17	83.99	0.2818	69.63	0.800
156-168	578	291	39.09	1.78	39.70	80.57	0.2807	67.07	0.800
168-180	574	290	38.36	1.73	39.16	79.25	0.2790	66.09	0.800
Means	864	278	39.31	7.79	10.99	58.09	0.1295	48.23	2.100
Percents			68%	13%	19%				

Clad OD = 0.5151 in.

Clad ID = 0.4320 in.

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