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AXIAL GAS FLOW IN IRRADIATED PWR FUEL RODS

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September 1977

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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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TREE-NUREG-1158

AXIAL GAS FLOW IN IRRADIATED
PWR FUEL RODS

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Errata to TREE-NUREG-1158, "Axial Gas Flow in Irradiated PWR Fuel Rods", September 1977, Sig. J. Dagbjartsson, Beverly A. Murdock, Dennis E. Owen, Philip E. MacDonald. Please insert attachment (Table A-VA) after page 59 of Appendix A of TREE-NUREG-1158.

1. On page 59, the statement "(Table I of the main text)" should read, "(Table A-VA)".
2. On page 59, the statement "... Table I probably represents ..." should read, "... Table A-VA probably represents ...".
3. On page 3, the statement "... Figure A-3 and Table A-II show ..." should read, "... Figure A-3 and Table A-VA show ...".
4. On page x, insert the words "Table V-VA. Assembly B05 Power Histories, page 59A."

Attachment:
As stated

**AXIAL GAS FLOW IN IRRADIATED
PWR FUEL RODS**

by

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September 1977

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[a] On assignment for Gesellschaft für Kernforschung, Germany.

ABSTRACT

Transient and steady state axial gas flow experiments were performed on six, irradiated, commercial pressurized water reactor fuel rods at ambient temperature and 533 K. Laminar flow equations, as used in the FRAP-T2 and SSYST fuel behavior codes, were used with the gas flow results to calculate effective fuel rod radial gaps. The results of these analyses were compared with measured gap sizes obtained from metallographic examination of one fuel rod. Using measured gap sizes as input, the SSYST code was used to calculate pressure drops and mass fluxes and the results were compared with the experimental gas flow data.

SUMMARY

Fuel rod behavior is being studied in the Thermal Fuels Behavior Program conducted by EG&G Idaho, Inc., as part of the Nuclear Regulatory Commission's Water Reactor Safety Research Fuel Behavior Program [1]. Experimental data for verification of analytical models developed to predict the behavior of light water nuclear fuel rods under normal and postulated accident conditions are being obtained from a variety of in-reactor and out-of-reactor experiments. This report describes a series of axial gas flow experiments performed on six, irradiated, commercial fuel rods. The experiments were performed with the rods attached to a gas manifold and flow measuring system, using compression fittings at the ends and at intermediate locations along the length of the rods. Gas was then introduced into the rods at various pressures and flow rates. The experiments consisted of transient flow tests in which rapid rod depressurization was monitored as a function of time, and steady state flow tests in which rod differential pressure was measured between several axial pressure taps at constant gas mass flow. The experiments were conducted at ambient temperature and at 533 K using both helium and argon gas.

One fuel rod was sectioned and metallographic measurements were made of the fuel-to-cladding radial gap as a function of azimuthal position. The radial gaps varied from 9 to 55 μm , depending on azimuthal and axial location. Radial gaps varied as much as 43.5 μm at a single transverse location.

High magnification photographs of the major fuel cracks were obtained on five transverse sections. The number of major cracks per section varied from 3 to 13, and their size varied from narrow fissures (0.5 μm wide) to large cracks (130 μm wide). Grinding and repolishing the sample revealed that the pattern of the fuel rod was substantially altered over < 1 mm axial distance and was completely changed over approximately 1 cm. The fuel rod gas paths were extremely tortuous.

The gas flow equations used in the fuel behavior models, FRAP-T2 and SSYST, were used to calculate local effective radial gaps for three fuel rods from the gas flow experimental data. The results indicated rod average effective radial gaps of 25, 30, and 35 μm . Local effective radial gaps as a function of rod axial position were calculated for two fuel rods from the steady state experimental data. The analysis indicated a larger gap at the ends of the rod (which operated at lower power) than at the center. The central effective radial gap was 50 to 70% of the gap at the rod ends.

Statistical analysis of the gap size calculations revealed that larger gaps were calculated for helium than for argon and for ambient temperature than for 533 K. Further analysis revealed that deviations from laminar flow were partly responsible for this unexpected gap behavior, presumably due to flow turbulence caused by pellet edges and fragments. In the turbulent regime, flow is proportional to gas density. A correction to the Reynolds number (a measure of turbulent flow) was devised to account for this effect.

Other work had shown that the Hagen number (a measure of gas-to-wall friction) was not constant as assumed, but was a strong function of gap size. A Hagen number correction function was also applied to the gas flow analysis. These corrections increased the calculated rod average effective radial gap by 20 to 30%.

An averaging technique was applied to the metallographic gap and fuel crack measurements to assess their relative contribution to the axial gas flow. The results showed that the contribution of fuel cracks to the total gas flow varied widely, reflecting large local variations in the crack size and pattern. The calculated effective radial gap sizes (from the gas flow data) lie between the measured radial gap sizes and the measured effective radial gaps (radial gap plus fuel cracks).

The gas flow experimental results were compared with the results calculated by the SSYST code in order to verify that the code equations, which are based on theoretical gas flow behavior, approximate actual gas flow. Agreement was good between the predicted and experimental results for both the transient (depressurization) tests and the steady state (pressure differential) tests, though the code overpredicted the total gas mass flow by about 70% for the latter.

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AXIAL GAS FLOW IN IRRADIATED PWR FUEL RODS

I. INTRODUCTION

Fuel rod behavior studies are being conducted as part of the Thermal Fuels Behavior Program at the Idaho National Engineering Laboratory (INEL). This program is conducted by EG&G Idaho, Inc., as part of the Nuclear Regulatory Commission's Water Reactor Safety Research Fuel Behavior Program^[1]. Experimental data for verification of analytical models developed to predict the behavior of light water nuclear fuel rods under normal and postulated accident conditions are being obtained from a variety of in-reactor and out-of-reactor experiments. This report describes a series of out-of-reactor experiments designed to study the nature of the axial flow of gases contained within a fuel rod (filled with gases during fabrication and with fission gases released during operation). An analysis of the experimental results is presented in three steps. First, laminar flow theory is combined with the experimental results to calculate the effective gap size for gas flow within the tested fuel rods. In the second step, flow paths (annular gap and fuel cracks) measured metallographically are combined and compared with those calculated using the mass flow and pressure drop data. In the final step the measured gap sizes are used as input to appropriate computer modules and predicted mass fluxes and pressure drops are compared with the measured values.

Axial gas flow within a fuel rod may have an important bearing on fuel rod behavior during a severe transient such as a loss-of-coolant accident (LOCA). In a design basis LOCA, a brittle fracture of the primary reactor coolant pipe is assumed to occur. The rapid loss of coolant can cause a sudden fuel rod temperature rise resulting in decreased cladding strength and an increase in rod internal pressure. The rod internal pressure (ranging from a few MPa to > 10 MPa, depending on fuel burnup and fission gas release) may exceed the coolant pressure and cause ballooning of the weakened cladding. Axial gas flow can prevent or assist cladding ballooning in a LOCA, depending on whether gas flow is fast or slow and at what time during the LOCA event ballooning occurs. If ballooning occurs early in the LOCA and if gas flow from the fuel rod plenum to the ballooning region is slow, the emergency cooling systems may cause the cladding temperature to be lowered before the ballooning region becomes pressurized, thus stopping the ballooning prior to failure.

Ballooning may also occur in the reflood phase of a LOCA. During reflood the emergency core cooling systems flood the core with water which flows upward (in most pressurized water reactors) through the core, cooling the lower portion of the rods first. In this case, the axial gas flow to the lower portion of the rod must be rapid in order to relieve the pressure on the ballooning region. If the LOCA and other reactor transients are to be analyzed, the nature of fuel rod axial gas flow must be understood.

Axial gas flow experiments performed to date have used simulated fuel pellets in unirradiated rods^[2,3]. The experimental work reported herein is the first to use irradiated, commercial fuel rods. In this report the experimental procedures, results, and analyses for transient and steady state gas flow experiments at ambient temperature and 533 K are presented. Experimental data are compared with results obtained from current gas flow models and with the results of metallographic measurements of fuel gas paths.

The experimental description and typical results are presented in Section II; Section III contains the results of the metallographic examination of one of the experimental fuel rods. Analysis of the gas flow data and comparison of the data with the metallographic results and the gas flow model may be found in Section IV. Section V contains the conclusions.

II. EXPERIMENT DESCRIPTION AND TYPICAL RESULTS

Axial gas flow experiments were performed on six, irradiated commercial fuel rods. The fuel rods used in these experiments were pressurized water reactor (PWR) rods irradiated in the Carolina Power and Light H. B. Robinson 2 reactor^[a]. The fuel rods consisted of UO₂ pellets clad in zircaloy-4 sheathing. The rods were 3.86 m long and had an outside diameter of 1.07 cm. The six rods (Rods K-7, K-4, L-4, M-4, H-1, and K-9) used for the axial gas flow experiments were removed from Assembly B05. The assembly average burnup was 28 026 MWd/tU and the peak burnup was 31 364 MWd/tU. The assembly was removed from the reactor in May 1974 and had cooled for 21 months prior to the axial gas flow experiments. Preirradiated fuel rod dimensions and the results of postirradiation characterizations are presented in Appendix A. Appendix A Figure A-3 and Table A-II show the location of the rods in Assembly B05 and the PDQ-7^[b] calculated power history for the assembly.

The gas flow apparatus consisted of an irradiated fuel rod to which a gas supply, gas manifold, and a number of absolute pressure transducers had been attached. For the elevated temperature tests the fuel rod was placed in a clamshell furnace and the gas was preheated. Figure 1 shows the apparatus being bench tested using a simulated fuel rod.

This section describes the apparatus and test procedures for both transient and steady state gas flow tests and presents typical experimental results.

[a] H. B. Robinson 2 is a 655 MW electrical (2192 MW thermal) three-loop PWR, which began operation in March 1971. The core, which operates at an average temperature of 575 K, consists of 157 fuel assemblies, each containing 204 fuel rods.

[b] A three-dimensional diffusion theory code.

Fig. 1. Gas flow apparatus.

1. TRANSIENT TESTS

The transient tests were performed on all six rods by pressurizing the fuel rod at ambient temperature to a fixed pressure of approximately 6.89 MPa with argon gas, then opening a quick-acting valve and monitoring depressurization with time. For the transient tests, the fuel rods were equipped with compression tee fittings at the top and bottom ends, which were held onto the rod by indexing blocks as shown in Figure 2.

Approximately 0.16 m was cut from the top of the rod, leaving 1.27 cm of the plenum. A compression tee fitting with an internal volume approximately equal to that of the plenum was attached to the top of the rod. An absolute pressure transducer was connected to the tee at the top of the rod.

The bottom end cap was cut from the rod just above the end cap weld. The rod was pushed tight into the bottom end compression tee fitting and sealed. Valve V1 at the bottom of the rod was closed, Valve V2 at the top of the rod opened, and the rod pressurized until slight bowing was observed at approximately 6.9 MPa. Valve V2 was then closed and the pressurized system checked for leaks by monitoring the absolute pressure transducer. Valve V1 was then opened to atmospheric pressure and the pressure drop at the top of the rod was recorded as a function of time. The time required for the rods to depressurize to ambient pressure varied from 240 to 480 s. The tests were repeated three times on each rod, except for Rod K-7. About 180 mm of fuel was lost from Rod K-7 during handling; therefore, this rod was tested only once.

Typical results from the transient tests are shown in Figure 3. Only one curve is shown for each rod because the three duplicate tests gave virtually identical results.

Fig. 2 Schematic of the transient test apparatus.

Fig. 3. Results of transient flow tests on six, irradiated PWR fuel rods.

2. STEADY STATE TESTS

The following steady state flow tests were run on fuel Rods K-4, M-4, and L-4:

- (1) Ambient temperature argon tests (Rods K-4, M-4, and L-4)
- (2) Ambient temperature helium tests (Rods K-4, M-4, and L-4)
- (3) 533 K argon tests (Rods K-4 and M-4)
- (4) 533 K helium tests (Rods K-4, M-4, and L-4).

The steady state apparatus utilized compression fittings mounted over laser-punctured holes in the fuel rod. All of the fittings, including those at the top and bottom of the rod, were connected by tubing to a manifold as shown in Figure 4. A differential pressure transducer was placed between the top of the rod and the manifold. This transducer enabled the differential pressure between the top of the rod and any of the pressure taps, or the bottom of the rod, to be recorded.

The fuel rod was pressurized by a gas cylinder located outside the hot cell (Figure 4). A metering valve (Valve V.1) was slowly opened until the required differential pressure was established between the ends of the rod. Gas flowed from the metering valve at the bottom of the rod through approximately 4.6 m of copper tubing to a three-way valve (Valve V.4) outside the hot cell, which routed the gas back into the cell or to a flow measuring tank.

Fig. 4 Schematic of the steady state test apparatus.

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The gas flow along the entire rod was measured by monitoring the tank pressure rise for ten minutes. The flow rate of the gas was calculated from the ideal gas law, knowing the volume filled, the pressure increase in that volume, the elapsed time, and the gas temperature. Through use of the gas manifold, the differential pressure was measured between the top of the rod, each of the eight intermediate pressure taps, and the bottom of the rod, in turn. The gas flow rate along the entire rod was remeasured at the conclusion of the test.

An example of the data, obtained from Rod K-4, is shown in Figure 5 and Table I.

The detailed results of these experiments, in both tabular and graphical form, are presented in Appendix B. The experiments yielded a family of pressure versus axial position curves for various gas test conditions and rod differential pressures. A unique axial gas mass flow rate, W , applies to each curve.

Fig. 5 Typical results of steady state flow tests.

TABLE I

STEADY STATE GAS FLOW RESULTS FOR FUEL ROD K-4
(Test Conditions: Argon Gas, Ambient Temperature)

Pressure Tap									
Outlet	1	2	3	4	5	6	7	8	Inlet
Pressure Tap Location (cm from Bottom of Rod)									
(Bottom) 1.3	53.3	88.9	124.5	160.0	195.6	231.1	266.7	302.3	(Top) 307.1
Pressure (MPa)									
2.18	2.26	2.27	2.36	---	2.68	2.80	2.93	3.06	3.10
1.98	2.06	2.23	2.47	---	3.13	3.39	3.62	3.85	3.93
3.48	3.50	3.61	3.78	---	4.27	4.47	4.66	4.86	4.93
5.16	5.16	5.20	5.28	---	5.49	5.58	5.68	5.78	5.83

Average Pressure [(P ₀ +P ₉)/2] (MPa)	Differential Pressure, ΔP P ₉ -P ₀ (MPa)	Mass Flow Rate (mol/min)
2.64	0.92	0.023
2.95	1.95	0.059
4.21	1.45	0.059
5.50	0.66	0.041

III. DESTRUCTIVE EXAMINATION

Fuel Rod K-4 underwent sectioning and metallographic examination in order to obtain direct measurements of the gas flow paths within the rod. This information was needed to compare the size of the actual gas flow paths within the rod with the gap sizes predicted by fuel rod gas flow models. Such comparisons are helpful in understanding the influence of different types of gas paths on total axial gas flow.

1. SECTIONING AND METALLOGRAPHIC EXAMINATION

Fuel Rod K-4 was cut into sections for ease of handling. Immediately after sectioning and prior to any handling, each section was photographed to document the fuel crack pattern. Figure 6 illustrates the fuel crack pattern at several locations. Most of the major cracks are radially oriented and the fuel has fractured into roughly equal-sized, wedge-shaped pieces.

Two of the sections were each epoxy encapsulated in 19.1-mm OD stainless steel tubes, previously marked to indicate the metallographic sample location, sample number, and fuel rod orientation. After an overnight cure at ambient temperature, a vent was made at the bottom of each section by sawing approximately halfway through the fuel rod diameter. A pressure fitting was attached to the top of each section and epoxy was injected into the rod at 1.4 MPa until it emerged through the vent. After an overnight cure, the sections were cut with a diamond saw, ground, and final polished with 0.5- μ m diamond grit, using water and paraffin oil lubricants.

Figure 7 is the metallography cutting diagram. All samples, except Sample D-6, are transverse sections. All transverse sections were 1.27 cm long and were polished on the bottom surface. The dimensions shown in Figure 7 indicate the approximate distance from the bottom of the rod to the surface examined. Sample D-6 was a longitudinal metallographic sample, 1.57 cm long.

Typical results of the transverse metallographic examination are shown in Figures 8 through 10. View (a) in each case is the original metallographic surface. The major fuel cracks are apparent and the majority are radial, interconnected, and intersect the fuel-cladding gap. View (b) in each case is the polished fuel surface a small distance from the original metallographic plane. View (b) was obtained by either grinding an additional increment from the original plane and repolishing the surface or turning the sample over and polishing the top surface. In Figures 8 through 10, View (b) is 0.20 mm, 0.45 mm, and 1.0 cm, respectively, from the original plane. These figures reveal that the fuel crack pattern is retained over a distance of 0.20 mm, substantially altered over 0.45 mm, and completely changed over 1.0 cm. Thus, the resultant fuel rod gas paths were extremely tortuous. (The large areas of missing fuel in Figure 8 are the result of sample preparation and do not represent gas paths in the intact fuel rod.)

(a) 3.01 m from bottom of rod
1 cm

(b) 1.77 m from bottom of rod
1 cm

(c) 0.78 m from bottom of rod
1 cm

Fig. 6 Fuel crack pattern observed after sectioning.

Fig. 7 Metallography sectioning diagram for fuel Rod K-4.

Fig. 8 Transverse metallographic Sample E-1.

Fig. 9 Transverse metallographic Sample D-1.

Fig. 10 Transverse metallographic Sample D-3.

Sample D-6, the longitudinal metallographic sample, is shown in Figure 11. Total fuel crack length may be long (up to 9 mm in this case), but the crack paths are contorted. The result is a tortuous, interconnected network of fuel cracks.

Additional photomicrographs are provided in Appendix C.

(a) 2.87 to 2.89 m from bottom of rod, 0 to 180 degrees

(b) 2.87 to 2.89 m from bottom of rod, 180 to 360 degrees

Fig. 11 Longitudinal metallographic Sample D-6.

2. FUEL-CLADDING GAPS

Fuel-cladding radial gaps were measured on seven transverse metallographic samples as follows. An arbitrary zero-degree point was selected on each sample. A 100x photograph of the radial gap was taken at 30-degree intervals around the mount, and an average measured gap was obtained at each location. The results are shown in Table II.

Local gaps varied as much as 43.5 μm in Sample E-5, and as little as 10 μm in Sample D-2. Contrary to what might be expected, the average gap size going from Sample D-1, near the high power region of the rod, to Sample E-5, near the low power fuel column end, does not continually increase.

TABLE II
METALLOGRAPHIC MEASUREMENT OF AVERAGE RADIAL GAP

Metallographic Sample	Average Radial Gap (μm)												Average for Sample
	Orientation (degrees)												
	0	30	60	90	120	150	180	210	240	270	300	385	
E-1	18.0	25.0	37.5	[a]	[a]	23.5	24.5	35.0	[a]	37.5	47.5	32.5	31.2
E-2	32.5	20.0	20.0	40.0	55.0	20.0	20.0	27.5	22.5	[a]	35.0	27.5	29.1
E-5	10.0	15.0	25.0	22.0	52.5	9.0	12.5	20.0	25.0	14.0	70.0	27.5	25.2
D-1	37.5	25.0	25.5	25.0	35.0	32.5	30.0	30.0	30.0	35.0	35.0	25.0	30.5
D-2	15.0	18.0	10.0	17.5	20.0	15.0	10.0	10.0	15.0	10.0	13.0	20.0	14.5
D-3	25.0	27.5	27.5	27.5	30.0	18.5	30.0	20.0	20.0	30.0	40.0	30.0	27.2
D-5	20.0	20.0	10.0	10.0	28.0	10.0	35.0	28.0	18.0	22.5	15.0	7.0	18.6

[a] Missing fuel prevented gap measurement.

3. FUEL CRACK SIZES

Five metallographic samples were analyzed to determine the sizes of the major cracks present. The major cracks were identified in photographs (as in Figure 8). Composite photographs at 100x magnification were then taken of each crack and the size was measured from the photographs. Table III summarizes the results of these measurements.

Crack length varied from quite short (1.1 mm) to full pellet diameter (9.3 mm). Average crack width varied from tight fissures (0.5 μm) to substantial cracks (130 μm). The number of major cracks in a sample tended to be larger near the fuel center (13 cracks in Sample D-3) than at the top of the fuel column (three cracks in Sample E-5). This trend would be expected as a result of higher power and, therefore, larger thermal gradients in the rod center.

TABLE III
METALLOGRAPHIC MEASUREMENT OF FUEL CRACKS

<u>Metallographic Sample</u>	<u>Number of Major Cracks</u>	<u>Crack Dimensions</u>	
		<u>Length (mm) [a]</u>	<u>Average Width (μm)</u>
E-5	3	9.4	100.0
		4.9	50.0
		4.5	40.0
D-1	11	5.1	15.0
		5.8	80.0
		4.1	10.0
		3.8	15.0
		4.0	110.0
		2.4	10.0
		3.6	10.0
		4.7	130.0
		5.4	50.0
		2.6	20.0
		3.6	10.0
E-1	6	9.4	40.0
		4.7	70.0
		3.5	10.0
		4.4	10.0
		4.0	20.0
		3.4	10.0
E-2	8	2.7	0.5
		2.6	30.0
		5.1	25.0

TABLE III (continued)

Metallographic Sample	Number of Major Cracks	Crack Dimensions	
		Length (mm) [a]	Average Width (μm)
D-3 (continued)		3.8	15.0
		4.7	20.0
		9.4	15.0
		3.8	40.0
		3.5	8.0
D-3	13	9.4	30.0
		4.6	20.0
		8.9	60.0
		2.8	20.0
		3.7	20.0
		2.9	0.5
		4.0	20.0
		2.7	8.0
		4.7	15.0
		1.1	25.0
		4.5	30.0
		4.1	15.0
		1.9	25.0

[a] Crack length is measured in the radial direction.

IV. ANALYSIS OF THE EXPERIMENTAL RESULTS

Results obtained from current models for transient axial gas flow (contained, for example, in the fuel rod behavior codes FRAP-T2^[4] and SSYST^[5]) have previously been compared with experimental data from unirradiated and simulated fuel rods^[3]. Although these analyses based on unirradiated and simulated fuel rods have been useful, similar analyses of gas flow experiments using irradiated fuel rods are necessary to assess the influence of cracked fuel pellets and small, irregular gaps on internal gas flow.

The analysis of these experiments was carried out in three steps. First, the laminar flow theory utilized in the FRAP-T2 and SSYST-1 computer models was combined with the experimental results to calculate the effective gap size for gas flow within the tested fuel rods. The deviation from the laminar flow theory observed elsewhere^[6] was used to correct the calculated effective gap sizes.

In the second step, the flow paths (annular gap and fuel cracks) measured in the metallographic examination were combined and averaged to obtain an effective gap size for axial gas transport. The effective gaps calculated in the first step through use of the computer code models were then compared with those obtained through averaging the metallographic data.

In the final step, the measured gap sizes were used as input for the appropriate module of the SSYST code system to calculate the pressure drops and mass fluxes under conditions, both steady state and transient, used in the gas flow experiments. Additional SSYST calculations were carried out to investigate the influence of the gas flow resistance on the ballooning behavior of a PWR fuel rod under LOCA conditions.

1. CALCULATION OF EFFECTIVE GAP SIZES FROM THE GAS FLOW EXPERIMENTAL RESULTS

In this section the local effective gap sizes for the gas flow fuel rods are calculated using theoretical gas flow equations employed in fuel rod behavior models. A statistical test is performed to assess the influence of gas species and pressure on the results. Several corrections to the results are employed to account for the effect of nonideal gas flow.

1.1 Analytical Models

The analytical models used for transient axial gas flow simulation in FRAP-T2 and SSYST are very similar, although independently developed. In both models the following assumptions are made:

- (1) Laminar compressible flow
- (2) Variable temperature along the flow path
- (3) Ideal gas law is valid
- (4) Viscosity of gas is dependent on temperature and gas composition.

The only differences exist in the assumptions of the gap geometry (tubular gap in FRAP-T2, plane gap in SSYST) and in the pressure drop as a function of distance from the gas plenum to the assumed balloon area.

The mass flow rate, W , through a constant gap between two nodes at pressure P_1 and P_2 , respectively, is calculated using the following equation:

$$W = \frac{\pi}{Ha} \bar{D} D_H^3 \frac{P_1^2 - P_2^2}{2\eta R T L} \quad (1)$$

where

- $\bar{D}$ = the mean diameter between fuel surface and inside of cladding
- D_H = hydraulic diameter = the diametral gap size for an annular gap
- η = gas viscosity
- R = universal gas constant
- T = absolute temperature
- L = flow path length
- Ha = Hagen number = 64 for tubular gap; 96 for plane gap (the Hagen number is a measure of the friction between the gas and the gas path).

For the basic analysis of the steady state experiments, Equation (1) was used and a Hagen number of 96 was assumed. During the steady state gas flow experiments the mass flow rate was measured with constant known pressures at the top and bottom of the fuel rod. If $\bar{D}$ is assumed to be approximately equal to the fuel diameter, the only remaining unknown in Equation (1) is the hydraulic diameter, D_H . Because of fuel fracture and relocation, the flow path cannot be assumed to be annular. Thus, the term "effective gap" is used for one half of the effective hydraulic diameter.

Rearranging Equation (1) to obtain the effective gap, Δr , results in the expression

$$\Delta r^3 = \frac{W}{\bar{r}} \frac{12 R \eta T \Delta Z}{\pi (p_1^2 - p_2^2)} \quad (2)$$

where

ΔZ = effective flow path length

$\bar{r}$ = $\bar{D}/2$.

1.2 Average Effective Radial Gap

Equation (2) was used to calculate the average effective radial gap, as a function of rod axial position, for fuel Rods K-4, L-4, and M-4. The following values of the equation parameters were used:

W (mol/s)	=	as measured
η (centipoise)	=	0.0194 for helium (ambient)
	=	0.0285 for helium (533 K)
	=	0.0222 for argon (ambient)
	=	0.0345 for argon (533 K)
$\bar{r}$	=	4.66×10^{-3} m
T	=	298 K or 533 K
P	=	(MPa) - as measured
R	=	$8.314 \text{ J K}^{-1} \text{ mol}^{-1}$
ΔZ	=	3.65 m (total fuel length).

The data are plotted in Figures 12, 13, and 14. All of the data fit well into fairly tight scatter bands, indicating an average effective radial gap of approximately 25, 35, and 30 μm for fuel Rods K-4, L-4, and M-4, respectively. Whereas Rods K-4 and M-4 show only a slight dependence of effective radial gap width on mass flow rate, the results for Rod L-4 indicate a significant decrease in the average gap at low mass flow rates. This decrease in gap size at low flows may result from experimental error, since no physical reason could be found for this behavior. The results for Rod L-4 and the points in parentheses on Figures 12 and 14 were excluded from further analysis.

Fig. 12 Average effective radial gap for fuel Rod K-4.

Fig. 13 Average effective radial gap for fuel Rod L-4.

Fig. 14 Average effective radial gap for fuel Rod M-4.

1.3 Local Gap as a Function of Axial Position

The pressure measurements at different axial positions along the rod during the steady state tests permit the calculation of local gaps using Equation (2). Figure 15 shows the local effective radial gap plotted as a function of distance from the bottom of Rod M-4. The results clearly show a varying effective radial gap along the rod. The gap size is in the 40- through 50- μm range at the ends (about one half as large as the as-fabricated gap), but is only about 25 μm in the center. Similar results are shown in Figure 16 for Rod K-4; however, in this case the results are the average of all tests in a series. The results are in general agreement with expected fuel behavior; that is, the radial gap is less in the higher power center region of the rod where the fuel cladding creep collapse is greater than at the rod ends.

Profilometer measurements of fuel rods from the same bundle (Appendix A) show a decrease in rod outside diameter varying from approximately 25 μm at the ends, to 100 μm in the center region of the rods. In addition, the rods showed significant ovality, small at the bottom and increasing to 500 μm at the top. Qualitatively, these results are in agreement with the gas flow experiments.

1.4 Corrections to the Calculated Gap Size

The local and average effective radial gap calculated from the experimental pressure and flow data showed considerable scatter (Figures 15 and 16). The scatter may have resulted from systematic effects. For example, the fuel rod pressure level may have had an influence on the gap size because of the elastic expansion of the cladding tube. Use of the expansion formula

Fig. 15 Local effective radial gap along Rod M-4 from steady state data.

Fig. 16 Local effective radial gap along Rod K-4 from steady state data.

$$\frac{d(\Delta r)}{dP} = \frac{r_c^2}{Ed} \quad (3)$$

where

E = modulus of elasticity

d = cladding thickness

r_c = cladding radius

with an elastic modulus of ($7.0 \times 10^{10} \text{ N/m}^2$) for the cladding, results in a gap increase of only about $1 \mu\text{m}$ for a 1.38-MPa pressure increase.

The different thermal expansions of the fuel and cladding will result in approximately a $1.2\text{-}\mu\text{m}$ smaller radial gap at 533 K than at ambient temperature. These effects are small with respect to the scatter in the effective radial gaps calculated from the gas flow data and can be neglected.

1.5 Statistical Analysis of the Calculated Average Gap Sizes

Statistical analysis of the calculated effective average gap sizes for fuel Rods K-4 and M-4 were performed in order to study possible systematic effects.

A statistical t-test^[7] was employed to determine whether differences in effective gap width could be seen for helium versus argon, for ambient temperature versus 533 K, and for average pressure above 2.76 MPa versus 2.76 MPa pressure.

The results of this analysis are summarized in Table IV. First, the random errors originating from the measurements are low enough to permit the discovery of small systematic effects. However, the significant differences observed were not those expected. No obvious reason exists for predicting larger gaps with helium than with argon. Secondly, the gap calculated from the measurement at 533 K was expected to be smaller, not larger, than the gap at ambient temperature. On the basis of these results, apparently some systematic effect was not taken into account in the calculations. Possible effects are discussed in the following subsections.

1.5.1 Gap Dependence on Reynolds Number. The Reynolds number is a quantity proportional to gas density and gas velocity, and inversely proportional to gas viscosity. If the Reynolds number exceeds a critical value, the flow has become turbulent and the gas flow equations used previously no longer apply. During experimental and analytical work performed at the Nuclear Research Center, Karlsruhe, Germany^[3] in gas flow tests using simulated fuel pellets, a significant difference was found to exist between the measured and calculated mass flow rates for Reynolds numbers greater than 100. Measured rates were lower than expected for Reynolds numbers greater than this value. This effect is believed to be due to the pellet edges and fragments causing turbulence, which increases the apparent

TABLE IV
RESULTS OF STATISTICAL TESTS PERFORMED ON
THE CALCULATED EFFECTIVE RADIAL GAPS

Rod K-4						
	Gas		Temperature		Pressure	
	Helium	Argon	Ambient	533 K	2.76 MPa	>2.76 MPa
Average Gap (μm)	24.92	23.95	24.18	24.95	24.43	24.36
Significance	$\Delta r_{\text{He}} > \Delta r_{\text{Ar}}$		$\Delta r_{\text{amb}} < \Delta r_{533}$		None	
Rod M-4						
Average Gap (μm)	31.45	29.54	29.99	31.36	30.73	30.29
Significance	$\Delta r_{\text{He}} > \Delta r_{\text{Ar}}$		$\Delta r_{\text{amb}} < \Delta r_{533}$		None	

flow resistance. This effect has not been analyzed quantitatively nor implemented in the transient fuel rod behavior codes, FRAP-T2 and SSYST.

The apparent increase in flow resistance with Reynolds number helps to explain even the relatively small scatter shown in Figures 12 and 14. The Reynolds number is higher for argon flow than for helium, and higher at room temperature than at 533 K. These facts are consistent with the conclusions of Table IV. When the data, normalized to 2.76 MPa and ambient temperature and corrected for cladding elastic and thermal expansion, are plotted versus Reynolds number (Re) in Figures 17 and 18, a significant decrease in apparent gap width is seen at the higher Reynolds numbers, indicating higher flow resistance.

A correction for the deviation from laminar flow (as indicated by the Reynolds number) was devised. By drawing smooth curves through the points of Figures 17 and 18 and cubing the deviation from the laminar flow, the correction function $[f(\text{Re})]$ shown in Figure 19 was obtained. This function represents the ratio of laminar to partially turbulent mass flow rate at the given Reynolds number.

The effective radial gaps for fuel Rods K-4 and M-4 were recalculated using the function of Figure 19 to correct for deviation from laminar flow. The results are plotted in Figure 20 versus the average pressure level at which the experiments were performed. The expected slope for Rod K-4 was calculated using Equation (3).

1.5.2 Influence of the Gap Size on the Hagen Number. The data analyses of Subsections 1.2 and 1.3 were performed using Equations (1) and (2) and a Hagen number of 90. Recent Karlsruhe work^[3] conducted at ambient temperature on simulated fuel rods

Fig. 17 Corrected gap for Rod K-4 versus Reynolds number.

Fig. 18 Corrected gap for Rod M-4 versus Reynolds number.

Fig. 19 The function $f(Re)$ versus Reynolds number for Rods K-4 and M-4.

Fig. 20 Corrected gap versus average pressure.

(zircaloy tubes loaded with either Al_2O_3 pellets or a solid stainless steel rod) showed that the Hagen number is a strong function of the gap size, as shown in Figure 21. Therefore, if hydraulic diameters of about $50 \mu\text{m}$ in these fuel rods were assumed, a Hagen number of 230 would result. Thus, a significant correction to gap size must be applied. This correction factor, calculated from Equation (1), is

$$f(\text{Ha}) = \sqrt[3]{\frac{230}{96}} = 1.34. \quad (4)$$

As a result of these corrections, the effective average gap size for fuel Rods K-4 and M-4 would be about $30 \mu\text{m}$ and $37 \mu\text{m}$, respectively. These numbers are uncertain, however, due to the expected irregularities in the gas flow paths. These irregularities will be considered in Section 2.3.

1.5.3 Application of the Correction Functions to the Local Effective Radial Gap. The two correction functions described previously, $f(\text{Re})$ and $f(\text{Ha})$, should be applied to the local effective gap. The application of the function $f(\text{Re})$, however, does not result in a significant decrease in the broad scatter band observed in Figures 15 and 16. Multiplying the local effective gap results, however, by $f(\text{Ha})$ would increase the local effective radial gap by approximately 30%.

Fig. 21 Hagen number as a function of hydraulic diameter.

2. ANALYSIS OF THE DESTRUCTIVE EXAMINATION RESULTS

This section applies the results of the direct metallographic measurement of fuel gas paths to the analysis of fuel rod axial gas flow. This analysis will have major uncertainties however, since:

- (1) The mass flow is proportional to the third power of the gap size. Thus, irregularities in the gap geometry have a strong influence on the gas flow rate. The metallographic examination has shown that the gap (and crack) geometry may change markedly over small distances due to fuel relocation.
- (2) The geometry of the annular gap flow paths changes only in the direction normal to the gas flow direction, whereas the fuel crack gas paths change both in length and width along the fuel rod axis.

2.1 Averaging the Measured Gap Sizes

One purpose of the destructive examination of fuel Rod K-4 was to determine the validity of the effective gaps calculated from the gas flow data. Therefore, the gas paths observed and measured on the photomicrographs must be averaged to obtain an effective flow area for comparison with that calculated from the gas flow data.

The averaging procedure was based on the hypothesis that the total gas flow penetrates through many parallel paths of different breadth (b_i), width (d_i), and length (ΔZ_i) and that the assumptions of Equation (1) are valid. This procedure results in an expression for the total mass flux

$$W_{\text{tot}} = \frac{4(P_1^2 - P_2^2)}{\eta R T} \sum_{i=1}^I \frac{b_i d_i^3}{Ha_i \Delta Z_i} \quad (5)$$

Equating the right side of Equations (1) and (5), and recalling that $\Delta r = D_H/2$, results in the following equation for the average effective gap:

$$\frac{\overline{\Delta r}^3}{Ha} = \frac{\Delta Z}{2\pi \bar{r}} \sum_{i=1}^I \frac{b_i d_i^3}{Ha_i \Delta Z_i} \quad (6)$$

The averaging procedure is to be performed over the flow paths present in one cross section of the rod, assuming that they are unaltered in a ΔZ long section of the rod.

2.2 Effective Annular Gap Sizes

As discussed in Section III-3, 100x photographs of the fuel-cladding gaps were used to measure the average gap size every 30 degrees on seven transverse metallographic sections. The results are plotted in Figure 22 assuming a linear change in gap size between the measured values. In order to obtain an effective annular gap for the entire rod, the averaging procedure of Equation (6) must be applied. The expression may be simplified in this case by considering

- (1) The flow path length, ΔZ_i , is constant = ΔZ
- (2) A constant annular gap over a 30-degree arc, thus, the gap breadth reduces to $b_i = \frac{\pi \bar{r}}{6}$
- (3) The Hagen number for the individual flow paths is constant, $Ha_i = Ha$.

The result is the simplified expression

$$\overline{\Delta r} = \sqrt[3]{\sum_{i=1}^{12} \frac{(\Delta r_i)^3}{12}} \quad (7)$$

Fig. 22 Measured annular gap size around the circumference of Rod K-4.

for the average annular gap in a specific fuel rod cross section. The result of this averaging procedure for fuel Rod K-4 is given in Table V.

TABLE V
MEASURED EFFECTIVE ANNULAR AVERAGE GAP
IN DIFFERENT SECTIONS OF ROD K-4

Measurement or Calculation	Metallographic Sample						
	E-5	E-2	E-1	D-5	D-3	D-2	D-1
Distance from Bottom of Rod (m)	3.52	3.27	3.22	2.66	2.46	2.36	2.26
Effective Annular Gap (μm)	31	34	34	21	28	15	31

Metallographic Samples E-5, E-2, and E-1 were sectioned from the fuel rod between the top end and pressure Tap 8, and Samples D-5, D-3, D-2, and D-1 were taken between pressure Taps 7 and 5. According to the gas flow experiment analysis results shown in Figure 16, an effective gap size of about $30\ \mu\text{m}$ should exist between the top of the rod and pressure Tap 8, and about $20\ \mu\text{m}$ between pressure Taps 7 and 5. However, considering the correction function $f(H_a)$ discussed in Subsection 1.5.2 these values must be increased to 38 and $29\ \mu\text{m}$, respectively. These final values are larger than the results in Table V, indicating that some gas flow must have occurred through the fuel cracks.

2.3 Influence of Fuel Cracks on the Gas Flow

The metallography of transverse and longitudinal samples clearly indicated that numerous axial gas flow paths existed within the fuel. A quantitative estimate of the contribution of fuel cracks to gas flow cannot be made because of the complexity of the crack patterns. However, an upper limit estimate of the contribution of the fuel cracks to the total equivalent gap size can be estimated. This estimate has been obtained by using the cross-sectional area of the major fuel cracks (from Table III) and applying the averaging procedure of Equation (6) and the assumptions of Equation (1).

The results of this analysis are combined in Table VI with the results of Table V. The calculated effective annular gap (line 2 in the table) was obtained by multiplying the results shown in Figure 16 by the correction function $f(H_a)$. The effect was to increase the results by 20 to 40%.

The results of the gas flow experiment analysis (Table VI, line 2) are bracketed by the measured gas paths (Table VI, lines 3 and 5). The measured contribution of the fuel cracks (Table VI, line 4) varies widely, as would be expected. Fuel fracture and relocation will

TABLE VI

COMPARISON OF CALCULATED AND MEASURED EFFECTIVE ANNULAR GAPS IN ROD K-4

Measurement or Calculation	Metallographic Sample						
	E-5	E-2	E-1	D-5	D-3	D-2	D-1
Distance from bottom of rod (measured, m)	3.52	3.27	3.22	2.66	2.46	2.36	2.26
Total effective annular gap (calculated, from the gas flow data, μm)	36-41	36-41	36-41	29-31	29-31	29-31	29-31
Effective annular gap (measured from the photomicrographs, μm) (contribution of radial gaps only)	31	34	34	21	28	15	31
Effective annular gap (measured from the photomicrographs, μm) (contribution of fuel cracks only)	70	25	42	33	17	28	87
Total effective annular gap (measured from the photomicrographs, μm) (sum of radial gap and fuel cracks)	72	38	48	35	30	30	88

sometimes produce unusually large fissures in the fuel (some of these may be seen in the photomicrographs in Figures 8, 9, and 10) which will result in large gas mass flow through these regions.

The total effective annular gap (Table VI, line 5) is not simply the sum of the radial gap (Table VI, line 3) and the fuel cracks (Table VI, line 4), due to the third power effect on the mass flow.

Large variations occur in the measured contributions of fuel cracks to the radial gap. These variations, and the extremely tortuous and ever-changing nature of the fuel crack gas paths, means that direct metallographic measurement of cracks to obtain their contribution to axial gas transport is inaccurate and potentially misleading. To determine the effective crack flow path by calculating it from the gas flow experimental analysis and the average effective annular gap may be a more accurate approach.

3. UTILIZATION OF THE RESULTS FOR CODE VERIFICATION

The purpose of this experiment was to provide axial gas flow data on actual irradiated fuel rods. The data by itself, however, is only of limited utility since it is based on a vanishingly small percentage of actual commercial fuel rods and is taken after the fact; that is, after reactor discharge. The real value of these experiments lies in confirming or improving gas flow models upon which some reactor safety margins are based. Whereas earlier sections have used the gas flow model to improve understanding of the experimental results, this section will use these results to verify the predictive ability of the codes.

In the fuel behavior codes FRAP-T2 and SSYST, Equation (1) is used to describe the axial gas flow through a fuel rod. The codes differ in the assumed Hagen number (64 and 96, respectively); thus, calculations based on the same fuel geometry should only vary by a factor of 1.5.

The SSYST gas flow module (ODRUSPA) was chosen for data analysis since it could be easily modified to accept the axial gas flow experimental data; whereas, the utilization of FRAP-T2 would have required a significant programming effort. Their fundamental similarity, however, means that the analysis is applicable to either code.

The analysis was performed using the steady state and transient gas flow results for Rod K-4 and the average effective gap size (as calculated in Section 2.2) from the experimental results.

3.1 Comparison of Measured and Calculated Results for Steady State Flow

The calculated and experimental pressure drops as a function of rod axial position for fuel Rod K-4 are shown in Figure 23. The gap size used in the calculation varied with axial position and was the average of the local gap shown in Figure 16. Where the slope of the

Fig. 23 Pressure drop along Rod K-4.

calculated curve is larger or smaller than the slope of the experimental curve, the average gap value used was smaller or larger, respectively, than the actual average effective radial gap.

The calculated mass flow, W_{calc} , however, is about 70% higher than the actual mass flow rate, W_{exp} . Equation (1) shows that the mass flow rate is proportional to the third power of the radial gap. Therefore, small errors in the local gap used in the calculation can contribute to substantial variations in the calculated mass flow rate.

3.2 Simulation of a Transient Gas Flow Experiment

The ODRUSPA module was used to simulate a transient gas flow test using the average local radial gap calculated for fuel Rod K-4. Figure 24 shows the resultant plot of plenum pressure versus time. The excellent agreement indicates that the fuel behavior code SSYST (and FRAP-T2) satisfactorily models transient axial gas flow in a fuel rod.

Fig. 24 Plenum pressure decay for Rod K-4.

3.3 Importance of the Gas Flow on LOCA Consequences

The reason for this study, as discussed in the introduction, is the possibility of a significant influence of axial gas flow on fuel rod ballooning behavior during a LOCA. This influence is shown quantitatively in Figure 25 for one case, assuming a heatup rate of about 10 K/s and internal rod pressure (at operating temperature) of 13.0 MPa. The fuel rod simulated had a geometry similar to the H. B. Robinson fuel rods. The power distribution was chosen to cause ballooning about 0.4 m in length in the central region of the fuel rod cladding. The maximum hoop strain is plotted versus time in Figure 25 for different radial gap sizes. The curve on the left represents the case of no pressure drop along the rod during

Fig. 25 Influence of gap size on the pressure history of a ballooning fuel rod.

ballooning and assumes the plenum pressure is constant. The other curves take into account nonzero pressure drop along the rod and a plenum volume of 50 cm^3 . The curve on the right (gap size, $9 \mu\text{m}$) approximates the case of a closed gap during normal operations. Therefore, the actual case must be between this curve and the curve on the left (constant pressure = 13.0 MPa). From Figure 25 the conclusion can be reached that for high burnup rods in which the gap is closed during normal operations, the ballooning process might be considerably delayed due to gas flow resistance. Also evident is the fact that the total strain is significantly influenced, as shown by the ϵ_U -values which denote the total circumferential strain at failure [8].

During normal operation, a fresh PWR fuel rod may have an effective radial gap in the range 30 to $70 \mu\text{m}$, depending on axial location and power shape. This gap increases 10 to $20 \mu\text{m}$ during cladding heating, following the departure from nucleate boiling during a LOCA. Thus, the radial gap in a fresh rod is so large that gas pressure rapidly equalizes.

For high burnup rods, however, cladding creepdown plus fuel swelling and relocation can result in quite small gaps. Under these circumstances the gas flow equation can predict a significant pressure gradient within a ballooning fuel rod. Additional gas flow experiments which better simulate very small gaps in high burnup fuel rods may be required to verify these predictions.

V. CONCLUSIONS

Transient (rapid depressurization) and steady state (differential pressure as a function of mass flow) axial gas flow experiments have been conducted on high burnup, irradiated PWR fuel rods. Analyses of these results employing the analytical gas flow expressions used in two major fuel behavior codes (FRAP-T2 and SSYST), when corrected for nonideal gas behavior, resulted in calculated effective fuel rod gaps which were close to those measured directly using metallographic techniques.

The gas flow module of SSYST (and by similitude, FRAP-T2) calculates transient axial gas flow accurately in the range of gap sizes of 20 to 50 μm , even though large local variations in gap size and fuel crack gas paths exist.

The code also accurately predicts the differential pressures along a fuel rod under steady state gas flow conditions, though the total gas mass flow, being a strong function of local gas path variations, is overpredicted by the current code. For small gaps, significant pressure gradients may be present in the rod during a LOCA and, consequently, ballooning may be delayed substantially.

These gas flow experiments were conducted on actual, full-length irradiated fuel rods with high exposure, fragmented fuel containing large local gas path variations. However, the radial gaps in these experiments, at both ambient and 533-K temperatures, may have been substantially larger than the actual gaps present in the operating fuel rod due to the absence of nuclear heating. Thus, the conclusion that gas pressures rapidly equalize in these rods must be tempered by the possibility that the gas paths were atypical of operating fuel. Additional experiments on actual, irradiated, high-exposure fuel with smaller radial gaps, achieved perhaps by externally pressurizing the rod to induce additional cladding creepdown, would be valuable.

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APPENDIX A

PREIRRADIATION DATA AND POSTIRRADIATION CHARACTERIZATION

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APPENDIX A

PREIRRADIATION DATA AND POSTIRRADIATION CHARACTERIZATION

Postirradiation fuel rod characterization studies have been performed on 15 H. B. Robinson pressurized water reactor (PWR) fuel rods at Battelle Columbus Laboratories (Rods A-1, A-8, C-8, D-4, D-9, F-8, G-8, H-6, H-10, H-13, K-8, M-12, O-14, P-4, and P-8), and three rods (F-7, F-9, and G-6) at Argonne National Laboratory.

This appendix discusses the results of the following nondestructive and destructive examinations: visual examination, eddy current inspection, profilometry, gamma scanning, burnup, fuel and cladding microstructure, plenum gas measurements, and fast neutron dosimetry. Preirradiation fabrication data for the H. B. Robinson rods are shown in Table A-I.

TABLE A-I

PREIRRADIATION FABRICATION DATA FOR THE
H. B. ROBINSON PWR FUEL RODS

Outside diameter	1.07 cm
Diametral gap	165 μ m
Cladding thickness	0.62 mm
Cladding material	Zircaloy-4
Overall length	3.86 m
Pellet diameter	0.93 cm
Pellet length	1.52 cm
Fuel stack length	3.65 m
Plenum length	17.35 cm
End cap length	1.75 cm
Fuel pellet material	UO ₂ sintered
Density (% of theoretical)	92 (10.08 g/cm ³)
Fuel enrichment (wt%)	3.10

1. VISUAL EXAMINATION

The 15 H. B. Robinson fuel rods sent to Battelle Columbus Laboratories were visually examined at 3.2x using a Lenz Model 8700/A stereoviewer^[A-1]. The rods appeared in good condition. Slight fretting wear was observed at grid locations on several rods. Crud deposits were sparse, except at the top. Most of the rods had heavy deposits of a dark, flaky crud starting at 3.35 m from the bottom of the rod. The crud persisted, in decreasing quantities, to the tops of the rods. Crud deposits in other regions of the rods were patchy. Rod bowing was not detected.

2. EDDY CURRENT INSPECTION

The 15 (Battelle Columbus Laboratories) rods were inspected by an eddy current system that was designed to detect the wide variety of defects and anomalies that can occur in fuel rods during service^[A-1].

Only one fuel rod provided an eddy current signal response indicating a defect. The eddy current scan on this rod indicated an anomaly 7.6 cm long, located in the fuel cladding 2.13 m from the bottom of the rod. The signal was a type infrequently observed on fuel rods; it was quite different than the signal caused by pits, holes, and internal hydriding of the cladding. The signal indicated that the defect was on the cladding interior. Its cause is unknown.

3. PROFILOMETRY

Spiral profilometry traces were run on the 15 Battelle Columbus Laboratories rods for diametral measurements and for detection and characterization of local cladding anomalies such as blisters, depressions, and ovality^[A-1, 2, 3]. Just prior to being loaded into the profilometer, each rod was wiped with an acetone-soaked Shurwipe towel to remove loose material.

The major profilometry observations were tubing ovality and cladding creepdown, as evidenced by a reduction in average cladding diameter. Typical measurements at preselected positions along the fuel rod length as well as measurements at the position of maximum cladding ovality are presented in Table A-II. Maximum ovality in 14 of the 15 rods occurred in the upper 2.67 to 3.56 m of the fuel rod length and ranged from 0.22 to 0.48 mm. This upper region was also a region of considerable crud deposition. Rod K-8 exhibited relatively uniform ovality and was the only H. B. Robinson fuel rod in which the maximum ovality (0.28 mm) occurred outside the upper 2.67- to 3.56-m region. The maximum ovality for this rod occurred about 33 cm from the bottom of the rod. As compared with a nominal

TABLE A-II
RESULTS OF PROFILOMETRY MEASUREMENTS

Rod	Rod Position (cm from bottom of fuel rod)	Total Ovality (mm)	Rod Diameter (cm)		
			Maximum	Average	Minimum
A-1	5.1	0.079	1.072	1.068	1.064
	91.4	0.099	1.065	1.060	1.055
	180.3	0.119	1.066	1.060	1.054
	269.2	0.068	1.064	1.061	1.058
	340.4 ^[a]	0.277	1.080	1.067	1.053
	370.8	0.018	1.072	1.071	1.070
A-8	5.1	0.063	1.073	1.070	1.066
	91.4	0.038	1.062	1.060	1.058
	180.3	0.102	1.065	1.060	1.054
	269.2	0.198	1.071	1.061	1.051
	316.2 ^[a]	0.483	1.087	1.063	1.039
	370.8	0.0051	1.072	1.072	1.071
D-9	5.1	0.020	1.070	1.069	1.068
	91.4	0.185	1.071	1.062	1.053
	180.3	0.061	1.064	1.061	1.058
	269.2	0.218	1.071	1.060	1.049
	273.1 ^[a]	0.422	1.082	1.061	1.040
	370.8	0.020	1.073	1.072	1.071
F-8	5.1	0.020	1.068	1.067	1.066
	91.4	0.053	1.062	1.060	1.057
	180.3	0.043	1.062	1.060	1.058
	269.2	0.094	1.065	1.060	1.055
	339.3 ^[a]	0.325	1.084	1.068	1.052
	370.8	0.033	1.072	1.070	1.068
G-8	5.1	0.063	1.072	1.069	1.065
	91.4	0.046	1.064	1.062	1.056
	180.3	0.043	1.064	1.062	1.056
	269.2	0.030	1.064	1.062	1.061

TABLE A-II. (continued)

Rod	Rod Position (cm from bottom of fuel rod)	Total Ovality (mm)	Rod Diameter (cm)		
			Maximum	Average	Minimum
G-8 (continued)	317.1 ^[a]	0.295	1.079	1.065	1.050
	348.7 ^[a]	0.295	1.083	1.068	1.053
	370.8	0.020	1.073	1.072	1.071
H-6	5.1	0.107	1.072	1.067	1.062
	91.4	0.201	1.070	1.060	1.050
	180.3	0.208	1.071	1.061	1.050
	269.2	0.343	1.078	1.061	1.044
	318.5 ^[a]	0.475	1.088	1.062	1.038
	370.8	0.015	1.072	1.072	1.071
H-10	5.1	0.020	1.072	1.071	1.070
	91.4	0.188	1.071	1.061	1.052
	180.3	0.046	1.063	1.061	1.058
	269.2	0.185	1.070	1.060	1.050
	337.8 ^[a]	0.325	1.084	1.067	1.051
	370.8	0.119	1.080	1.074	1.068
H-13	5.1	0.041	1.068	1.066	1.064
	91.4	0.119	1.064	1.058	1.052
	180.3	0.056	1.061	1.059	1.056
	269.2	0.175	1.068	1.059	1.051
	313.2 ^[a]	0.388	1.080	1.061	1.041
	370.8	0.020	1.071	1.070	1.069
M-12	5.1	0.068	1.071	1.068	1.064
	91.4	0.132	1.067	1.060	1.054
	180.3	0.091	1.065	1.060	1.056
	269.2	0.226	1.072	1.061	1.050
	322.8 ^[a]	0.477	1.088	1.064	1.040
	370.8	0.0051	1.071	1.071	1.071
O-14	5.1	0.061	1.072	1.070	1.066
	91.4	0.140	1.071	1.064	1.057

TABLE A-II (continued)

Rod	Rod Position (cm from bottom of fuel rod)	Total Ovality (mm)	Rod Diameter (cm)		
			Maximum	Average	Minimum
O-14 (continued)	180.3	0.104	1.067	1.064	1.056
	269.2	0.132	1.070	1.063	1.056
	320.0 ^[a]	0.279	1.079	1.065	1.051
	370.8	0.020	1.074	1.073	1.072
P-4	5.1	0.015	1.072	1.066	1.065
	91.4	0.068	1.062	1.059	1.055
	180.3	0.038	1.061	1.059	1.057
	269.2	0.142	1.068	1.061	1.054
	348.7 ^[a]	0.323	1.080	1.064	1.048
	370.8	0.043	1.070	1.068	1.066
P-8	5.1	0.074	1.071	1.071	1.063
	91.4	0.096	1.064	1.060	1.055
	180.3	0.025	1.061	1.060	1.059
	269.2	0.213	1.070	1.059	1.048
	336.0 ^[a]	0.300	1.081	1.066	1.051
	370.8	0.020	1.071	1.070	1.070
D-4	5.1	0.107	1.070	1.064	1.057
	91.4	0.107	1.064	1.059	1.053
	180.3	0.163	1.066	1.058	1.050
	269.2	0.142	1.067	1.065	1.053
	287.0 ^[a]	0.460	1.083	1.060	1.037
	370.8	0.030	1.071	1.070	1.068
C-8	5.1	0.104	1.074	1.070	1.064
	91.4	0.028	1.064	1.062	1.061
	180.3	0.079	1.067	1.063	1.059
	269.2	0.191	1.073	1.064	1.054
	345.0 ^[a]	0.371	1.085	1.066	1.047
	370.8	0.071	1.073	1.070	1.066
K-8	5.1	0.081	1.075	1.071	1.067
	33.0 ^[a]	0.279	1.080	1.063	1.049

TABLE A-II (continued)

Rod	Rod Position (cm from bottom of fuel rod)	Total Ovality (mm)	Rod Diameter (cm)		
			Maximum	Average	Minimum
K-8 (continued)	91.4	0.132	1.066	1.063	1.060
	180.3	0.134	1.071	1.064	1.057
	269.2	0.134	1.071	1.064	1.057
	370.8	0.058	1.077	1.074	1.071

[a] Maximum ovality.

preirradiation diameter of 1.07 cm, the average diameter of the 15 irradiated fuel rods over the central fuel region was about 1.06 cm. The average cladding diameter at the ends of the rods was 1.069 cm. Cladding diameter extremes of 1.088 and 1.037 cm were measured.

A typical portion of a profilometer scan over an extremely oval section of Rod A-8 is shown in Figure A-1. Rod A-8 was also profiled without rod rotation, at 0 and 90 degrees with respect to the rod axis, to obtain linear, rather than spiral traces. Portions of both the spiral and linear scans are shown in Figure A-2. Several observations can be made by comparing the spiral and linear traces. One is that changes in orientation of the major axis of ovality occur by two means; either by simple rotation around the axis of the rod, or by going through a minimum in ovality (the rod is round at this point). The other observation is of a fairly regular periodic ovality, of less than 0.025 mm in dimension, that overlies the major ovality variations. The significance of this ovality form is unknown.

Fig. A-1 Portion of H. B. Robinson Rod A-8 profilometry chart showing extreme ovality.

Fig. A-2 Illustrations of spiral and linear profilometry scans for H. B. Robinson Rod A-8.

4. BURNUP ANALYSES

Burnup analyses were performed at Battelle Columbus Laboratories and Argonne National Laboratory. Results of Nd-148 mass-spectrometric burnup measurements at three axial positions for fuel Rods F-7 and P-8 are presented in Table A-III. The burnup to gamma scan intensity (BU:GSI) ratio is quite constant except for that from the one sample from Rod F-7, which was taken very close (0.64 cm) to the bottom of the rod. This discrepancy results from distortions in the neutron energy spectrum at the reactor core periphery, causing relative Nd-148 enrichment at that location. The constancy of the BU:GSI ratio (except at the fuel periphery) permits direct calculation of the burnup from the gamma scan intensity values (discussed in the next section).

TABLE A-III
BURNUP ANALYSES FOR FUEL RODS F-7 AND P-8

Rod	Sample Identity	Distance From Rod Bottom (m)	Burnup (at%)	Burnup (MWd/tU)	Relative Gamma Scan Intensity (GSI)	BU:GSI Ratio ^[a]
F-7	a	0.006	1.26	12 100	11.2	0.113
	b	0.569	3.14	30 150	51.0	0.062
	c	0.930	3.12	29 950	52.9	0.059
P-8	a	0.305	2.56	24 570	43.0	0.059
	b	1.740	3.22	30 920	54.5	0.059
	c	2.019	2.88	27 620	48.5	0.059

[a] BU = Burnup in at%.

5. GAMMA SCAN RESULTS AND CORRELATION WITH AXIAL GAS FLOW RODS

The 15 H. B. Robinson fuel rods at Battelle Columbus Laboratories were gamma scanned to measure the gross gamma activity (>0.5 MeV) along the length of the rods and thereby provide a relative measure of fuel burnup along the rods^[A-1]. The average and peak-to-average gamma intensities for each rod are tabulated in Table A-IV. The values do not include the depressed gamma activity levels in the region of the fuel-assembly grid spacers or the lower values associated with pellet interfaces.

Fuel Rod F-7 was gamma scanned at Argonne National Laboratory^[A-4]. The results were typical of the Battelle scans.

TABLE A-IV

SUMMARY OF GAMMA SCAN OBSERVATIONS

Rod	Fuel Stack Height ^[a] (cm)	Average Gamma Intensity (arbitrary units)	Peak-to-Average	Number of Gaps ^[b] (>0.762 mm)	Comments
A-1	364.82	43.9	1.24	8	Several large gaps at top end of rod (cracked pellet fragments)
A-8	364.34	44.4	1.24	8	---
C-8	364.97	48.4	1.26	6	Several large gaps at top end of rod (cracked pellet fragments)
D-4	365.91	46.0	1.25	8	
D-9	363.07	47.6	1.22	5	---
F-8	365.61	44.6	1.23	7	Several large gaps at top end of rod (cracked pellet fragments)
G-8	364.64	45.5	1.24	3	---
H-6	390.37	44.5	1.25	9	Several large gaps at top end of rod (cracked pellet fragments)
H-10	364.49	43.9	1.25	3	---
H-13	362.43	49.0	1.22	4	---

TABLE A-IV (continued)

Rod	Fuel Stack Height ^[a] (cm)	Average Gamma Intensity (arbitrary units)	Peak-to-Average	Number of Gaps ^[b] (≥ 0.762 mm)	Comments
K-8	363.55	45.6	1.21	2	One large (5.08 mm) gap 91.4 cm from bottom of rod
M-12	365.13	47.5	1.21	11	---
O-14	363.37	45.6	1.22	8	---
P-4	363.22	45.0	1.22	8	---
P-8	366.09	46.8	1.21	4	Several large gaps at top end of rod (cracked pellet fragments)

[a] Fuel stack height including all gaps.

[b] Interpellet, low activity regions are not considered gaps.

Figure A-3 shows a map of Assembly B05 indicating the location of the axial gas flow rods, the gamma scanned rods, the guide tubes (no control rods were present in this assembly; thus, these tubes were water-filled), and the instrumentation tube. The average gamma scan intensities are shown adjacent to indicated rods. (Rod F-7 was scanned at Argonne National Laboratory using a different scale factor than for the other rods scanned at Battelle Columbus Laboratories. Thus, no average value is shown.) These average values may be intercompared and used to estimate average gamma scan intensities (and to estimate average burnup and power) for the axial gas flow rods.

Comparison of the average gamma scan intensities for fuel Rods K-8, M-10, F-8, and H-6, located symmetrically around instrumentation tubes, shows that the values are reasonably close, indicating approximate quarter-assembly symmetry, with a slight peaking toward the top of the assembly. This peaking is confirmed by comparing the gamma intensity for Rods A-8 and P-8. A peaking factor exists for rods adjacent to the water-filled guide tubes due to increased water moderation. This factor may be estimated by comparing the gamma intensity for Rod C-8 with that for Rods P-8 and A-8, and that for Rod H-13 with that for Rods H-6 and H-10. The result is a peaking factor of 10% for rods adjacent to guide tubes.

If quarter-bundle symmetry is assumed, a 3% peaking factor occurs in the top half of the assembly, and a 10% peaking factor occurs for rods adjacent to guide tubes. Average gamma scan intensities and average burnups (assuming a BU:GSI ratio of 0.059) were estimated for the six axial gas flow rods and are listed in Table A-V.

Gas flow fuel Rod K-4, having undergone destructive examination, is the best characterized of the gas flow rods. Accordingly, its gamma scan is of interest. Of those rods which were gamma scanned, fuel Rod C-8 has the average gamma intensity closest to that of Rod K-4 (< 1% difference), and may be considered comparable. The gamma scan for Rod C-8 is shown in Figure A-4. The depressions are due to assembly spacers.

The powers at which the axial gas flow rods, particularly Rod K-4, operated are also of interest. In-core, monitor-adjusted, $P_{DQ}/[a]$ calculated, peak assembly and average assembly powers were 326.44 and 219.49 W/cm respectively, during Cycle I (October 1971 to March 1973, 0 to 18 600 MWd/tU). During Cycle II (May 1973 to May 1974, 18 600 to 28 026 MWd/tU), the peak and average powers were calculated to be 244.42 and 180.77 W/cm, respectively. The average assembly power over both cycles was 200.13 W/cm. Figures A-5 and A-6 show the assembly axial power profile at the beginning of Cycle I and the end of Cycle II, respectively. Figure A-5 shows the assembly axial power profile when the average power was 200.46 W/cm, very close to the actual average of 200.13 W/cm.

[a] A three-dimensional diffusion theory code.

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Fig. A-3 Diagram of Assembly B05 from H. B. Robinson 2 reactor.

TABLE A-V
ESTIMATED AVERAGE GAMMA
INTENSITY AND BURNUP FOR THE
AXIAL GAS FLOW RODS

<u>Rod</u>	<u>Average Gamma Intensity</u>	<u>Average Burnup (%)</u>
K-7	44.7	2.64
K-9	44.7	2.64
H-1	45.6	2.69
M-4	46.7	2.76
L-4	47.9	2.83
K-4	48.1	2.84

Fig. A-4 Gamma scan of fuel Rod C-8.

The average gamma scan intensity for all of the rods listed in Table A-IV is 45.6. On the basis that this sampling is representative of the assembly, the assembly average gamma intensity also equals 45.6. The power profile of any of the axial gas flow rods can thus be estimated by factoring Figure A-7 by the ratio of the average gamma scan intensity of the fuel rod of interest (from Table A-V) to the estimated assembly average gamma intensity of 45.6.

Fig. A-5 Assembly B05 axial power profile at the beginning of Cycle I.

Fig. A-6 Assembly B05 axial power profile at the end of Cycle II.

The PDQ-7-calculated power history for the assembly (Table I of the main text) indicated an assembly average burnup of 28 026 MWd/tU. Whereas, the burnup and gamma scan analysis indicated an assembly average burnup of 25 828 MWd/tU, $\left[\left(45.6 \text{ avg. GSI} \right) \left(0.059 \right) \frac{\% \text{BU}}{\text{GSI}} \text{ Ratio} \right] \left(9600 \frac{\text{MWd/tU}}{\% \text{BU}} \right)$ or about 8% less than the PDQ calculation. This discrepancy may be primarily due to errors in the measured burnup; however, the reader concerned with detailed irradiation histories (for example, for code calculations) should realize that Table I probably represents an upper limit to the power history.

Fig. A-7 Assembly B05 average axial power profile.

6. FUEL AND CLADDING MICROSTRUCTURE

During the examination to characterize the fuel crack pattern, the metallographic mounts were etched to reveal the fuel and cladding microstructure. Fuel grain pullout occurred on most metallographic samples near the fuel periphery. At low magnification this region appears as a dark band on the outer edge of the mount (for example, Figures 9 and 10 from the main text). Figure A-8 shows this region, 500x, in comparison with the intact fuel grain structure at the center of the specimen. The reason for this localized pullout is unknown, but it has been observed to be reduced if kerosene is substituted for alcohol in the metallographic preparation [A-5]. The kerosene may be a better lubricant or it may exhibit different chemical behavior. Migration of volatile fission product cesium to the fuel periphery and collection at the grain boundaries could be responsible. The cesium would react with alcohol, perhaps loosening the grain structure, but would not react with dry kerosene.

Very little grain growth was observed in the UO_2 fuel. Average fuel grain size varied from $7\text{ }\mu\text{m}$ in Sample D-1 near the peak power region, to $4\text{ }\mu\text{m}$ in Sample E-5 near the top of the rod.

The zircaloy-4 cladding retained the as-fabricated, stress-relieved microstructure throughout its length. Low hydride concentrations were observed in the cladding, as shown in Figure A-9; the hydride platelets were primarily circumferentially oriented. Cladding oxide thickness varied from 5.5 to $7\text{ }\mu\text{m}$ on the interior and from 11 to $16\text{ }\mu\text{m}$ on the exterior, as shown in Figure A-10.

Center of fuel

20 μ m

Edge of fuel

20 μ m

Fig. A-8 Fuel microstructure in Sample D-4.

Typical cladding hydride

20 μ m

Fig. A-9 Cladding hydride in Sample E-2.

Fig. A-10 Cladding oxide thickness.

7. PLENUM GAS MEASUREMENTS

Internal gas quantity and void volume were measured for 15 rods by Battelle Columbus Laboratories[A-1], and on the 6 axial gas flow rods by the Idaho National Engineering Laboratory. Table A-VI presents the gas quantity, void volume, and calculated gas pressure for the Battelle Columbus Laboratories rods. Rod H-6 had an internal pressure less than half the value of the other rods. Table A-VII lists the gas puncture data for the 6 axial gas flow rods.

TABLE A-VI

FISSION GAS PUNCTURE DATA FOR THE
BATTELLE COLUMBUS LABORATORIES RODS

Rod	Gas Quantity (cm ³) (STP)		Rod Void Volume (cm ³)	Internal Gas Pressure (MPa)
	First Expansion	Second Expansion		
P-8	387.9	387.4	24.53 ± 0.13	1.54
H-10	255.2	355.0	24.67 ± 0.21	1.41
F-8	355.7	355.4	22.73 ± 0.15	1.53
P-4	378.4	377.8	24.17 ± 0.20	1.53
H-13	361.2	360.6	25.04 ± 0.21	1.41
M-12	377.8	376.9	25.30 ± 0.17	1.46
O-14	374.0	373.2	24.56 ± 0.20	1.49
H-6	160.8	160.8	26.34 ± 0.17	0.60
D-9	354.6	353.7	24.98 ± 0.16	1.39
G-8	372.9	372.1	23.52 ± 0.22	1.55
A-8	359.4	358.2	24.98 ± 0.12	1.40
A-1	386.4	385.1	26.14 ± 0.14	1.44
K-8	387.6	377.9	25.23 ± 0.18	1.52
D-8	384.6	374.5	24.11 ± 0.16	1.58
D-4	369.9	369.9	27.16 ± 0.21	1.38

TABLE A-VII

FISSION GAS PUNCTURE DATA FOR THE AXIAL GAS FLOW RODS

Composition of Internal Gas (mol %)								
Rod	H ₂	He	N ₂ + CO	O ₂	Ar	CO ₂	Kr	Xe
K-4	<0.01	97.66	0.02	<0.01	1.31	0.01	0.10	0.89
M-4	<0.01	97.64	0.05	<0.01	1.29	<0.01	0.10	0.89
L-4	0.03	97.00	0.10	0.04	1.33	0.03	0.16	1.31
H-1	<0.01	98.31	0.01	<0.01	0.67	<0.01	0.11	0.87
K-9	<0.01	98.26	0.04	0.01	0.71	0.01	0.10	0.86
K-7	<0.01	98.09	0.06	<0.01	0.98	0.01	0.09	0.76

Xe and Kr Isotopic

Rod	Kr-83	Kr-84	Kr-85	Kr-86	Xe-128	Xe-130	Xe-131	Xe-132	Xe-134	Xe-136
K-4	11.7	31.1	6.1	51.1	---	0.13	8.33	20.61	28.02	42.91
M-4	11.6	30.9	6.3	51.2	---	0.13	8.40	20.48	28.25	42.74
L-4	11.5	31.3	6.5	50.7	0.07	0.16	7.81	20.66	28.44	42.86
H-1	11.5	31.1	6.2	51.2	---	0.13	7.37	20.91	28.69	42.90
K-9	12.7	31.2	5.8	50.3	0.05	0.14	8.44	20.55	28.33	42.49
K-7	11.7	31.3	6.2	50.8	---	0.15	8.47	20.54	28.41	42.42

Internal Gas Pressures and Gas volumes

Rod	Volume of Total Gas Std (cm ³)	Void Volume (cm ³)	Internal Pressure (MPa)
K-4	366.2 ± 3.7	20.6 ± 0.5	1.80
M-4	368.1 ± 3.7	22.7 ± 0.3	1.64
L-4	380.0 ± 0.8	24.5 ± 0.3	1.57

TABLE A-VII (continued)

Internal Gas Pressures and Gas Volumes (continued)			
Rod	Volume of Total Gas Std (cm ³)	Void Volume (cm ³)	Internal Pressure (MPa)
H-1	276.1 ± 3.8	26.2 ± 0.3	1.52
K-9	375.1 ± 3.8	23.3 ± 0.4	1.63
K-7	373.7 ± 3.7	23.7 ± 0.3	1.60

8. FAST NEUTRON DOSIMETRY

Three, 1.59-cm-long zircaloy cladding rings were used for fast neutron dosimetry analysis at Battelle Columbus Laboratories^[A-3]. The cladding rings enclosed the fuel submitted for burnup analysis. The samples were taken from three regions of interest along the rod. Sample 1 was taken from the bottom of the rod in a low-flux region, Sample 2 from the center of the rod in a region of unperturbed flux, and Sample 3 from a grid spacer region. The samples were chemically analyzed for Mn-54 activity. The fast neutron flux was then calculated for the Fe-54 (n,p), Mn-54 reaction. The fast neutron flux and fluence, along with the fuel burnup results obtained, at the same locations in the fuel rod, are shown in Table A-VIII. Comparison of data for the three sample regions indicates some notable

TABLE A-VIII

FAST NEUTRON DOSIMETRY RESULTS

Sample	Rod P-8 Cladding Sample Location (cm from bottom of rod)	Burnup (MWd/tU)	Average Fast Neutron Flux >1 MeV (n/cm ² -s)	Fast Neutron ^[a] Fluence >1 MeV (n/cm ²)
1	30.0 to 31.5	24 570	5.5 x 10 ³	3.8 x 10 ²¹
2	173.7 to 175.5	30 920	6.3 x 10 ¹³	4.4 x 10 ²¹
3	201.0 to 202.4	27 620	6.2 x 10 ¹³	4.3 x 10 ²¹

[a] Time of irradiation = 799 equivalent full power days.

differences between the fast neutron dosimetry results and the burnup results. The latter were shown to be proportional to the gamma scan intensity and provide a relative measure of the thermal neutron fluence, as discussed previously. Burnup was depressed in the region of the grid as well as at the bottom of the fuel rod. The fast fluence shows a negligible influence of the grid and a lesser reduction at the bottom of the rod.

9. REFERENCES

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- A-2. *Progress on Evaluating Strength and Ductility of Irradiated Zircaloy During July through September 1975*, BMI-1938 (September 1975).
- A-3. *Evaluating Strength and Ductility of Irradiated Zircaloy, Quarterly Progress Report for October through December 1975*, BMI-1942 (December 1975).
- A-4. *Light-Water Reactor Safety Research Program: Quarterly Progress Report July – September 1975*, ANL-75-72 (September 1975).
- A-5. *Light-Water Reactor Safety Research Program: Quarterly Progress Report for April through June 1976*, ANL-76-87 (June 1976).

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APPENDIX B

STEADY STATE GAS FLOW RESULTS

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APPENDIX B

STEADY STATE GAS FLOW RESULTS

The detailed results of the steady state axial gas flow experiments are presented in this appendix. The data are organized as follows:

- (1) Table B-I: steady state gas flow results for fuel Rod K-4.
Figures B-1 through B-9: graphical gas flow results for fuel Rod K-4.
- (2) Table B-II: steady state gas flow results for fuel Rod M-4.
Figures B-10 through B-17: graphical gas flow results for fuel Rod M-4.
- (3) Table B-III: steady state gas flow results for fuel Rod L-4.
Figures B-18 through B-23: graphical gas flow results for fuel Rod L-4.

TABLE B-I

STEADY STATE GAS FLOW RESULTS FOR FUEL ROD K-4

Pressure Tap										Average Pressure (MPa)	Differential Pressure (MPa)	Flow Rate (mol/min)	
0	1	2	3	4	5	6	7	8	9				
Bottom	Location (cm from bottom of rod)									Top			
1.3	53.3	88.9	124.5	160.0	195.6	231.1	265.7	302.3	307.1				
Pressure (MPa)													
Argon, ambient temperature													
2.18	2.26	2.27	2.36	--	2.67	2.80	2.93	3.06	3.10	2.64	0.92	0.023	
1.87	1.94	2.06	2.23	--	2.77	2.98	3.17	3.36	3.43	2.65	1.57	0.038	
1.98	2.07	2.23	2.47	--	3.14	3.39	3.61	3.85	3.93	2.95	1.95	0.059	
1.51	1.70	2.01	2.39	--	3.28	3.59	3.88	4.16	4.24	2.87	2.74	0.076	
3.73	3.73	3.79	3.88	--	4.15	4.27	4.38	4.51	4.55	4.14	0.83	0.033	
3.49	3.50	3.61	3.78	--	4.27	4.47	4.66	4.86	4.93	4.21	1.45	0.059	
3.10	3.17	3.34	3.58	--	4.30	4.59	4.85	5.12	5.20	4.15	2.11	0.085	
2.89	2.99	3.24	3.60	--	4.58	4.93	5.24	5.58	5.69	4.28	2.81	0.114	
5.16	5.16	5.21	5.27	--	5.49	5.58	5.68	5.78	5.83	5.50	0.66	0.041	
4.73	4.77	4.86	5.02	--	5.51	5.72	5.92	6.13	6.20	5.47	1.48	0.082	
4.27	4.34	4.52	4.77	--	5.57	5.89	6.18	6.48	6.58	5.43	2.32	0.117	
3.98	4.08	4.32	4.68	--	5.70	6.10	6.45	6.81	6.93	5.45	2.95	0.146	
Helium, ambient temperature													
2.39	2.40	2.45	2.52	--	2.75	2.86	2.96	3.06	3.10	2.75	0.71	0.026	
2.01	2.05	2.17	2.35	--	2.85	3.05	3.23	3.43	3.48	2.75	1.47	0.054	
1.69	1.79	2.01	2.29	--	2.58	3.27	3.50	3.75	3.83	2.76	2.14	0.071	
1.42	1.62	1.93	2.30	--	3.18	3.49	3.77	4.05	4.14	2.78	2.72	0.087	
3.73	3.74	3.78	3.86	--	4.11	4.22	4.32	4.44	4.48	4.11	0.74	0.040	
3.51	3.52	3.64	3.79	--	4.24	4.44	4.64	4.83	4.89	4.21	1.88	0.076	
3.14	3.25	3.42	3.66	--	4.34	4.61	4.87	5.14	5.23	4.19	2.08	0.109	
2.73	2.89	3.15	3.49	--	4.43	4.79	5.11	5.44	5.55	4.14	2.82	0.141	
5.27	5.27	5.30	5.36	--	5.53	5.61	5.77	5.81	5.93	5.60	0.66	0.056	
4.77	4.84	4.99	5.09	--	5.55	5.75	5.95	6.15	6.24	5.50	1.48	0.109	
4.42	4.54	4.69	4.88	--	5.57	5.84	6.11	6.38	6.48	5.45	2.06	0.149	
4.06	4.18	4.39	4.71	--	5.66	6.03	6.38	6.74	6.86	5.32	2.80	0.198	

TABLE B-I (continued)

Pressure Tap										Average Pressure (MPa)	Differential Pressure (MPa)	Flow Rate (mol/min)	
0	1	2	3	4	5	6	7	8	9				
Bottom	Location (cm from bottom of rod)									Top			
<u>1.3</u>	<u>53.3</u>	<u>88.9</u>	<u>124.5</u>	<u>160.0</u>	<u>195.6</u>	<u>231.1</u>	<u>266.7</u>	<u>302.3</u>	<u>307.1</u>				
Pressure (MPa)													
Argon, 533 K													
2.39	--	2.41	--	--	2.64	2.83	2.95	3.03	3.10	2.74	0.72	0.007	
2.21	--	2.39	--	--	2.96	3.16	3.34	3.48	3.58	2.90	1.38	0.017	
1.37	--	--	--	--	3.23	3.43	3.75	3.96	4.14	2.75	2.76	0.029	
3.73	--	3.81	--	--	4.04	4.19	4.31	4.40	4.48	4.10	0.75	0.015	
3.43	--	3.69	--	--	4.16	4.34	4.55	4.71	4.82	4.13	1.40	0.023	
2.88	--	3.69	--	--	4.66	4.83	5.21	5.47	5.65	4.27	2.78	0.043	
Helium, 533 K													
2.35	--	2.41	--	--	2.52	2.77	2.91	2.97	3.07	2.71	0.71	0.011	
1.99	--	2.18	--	--	2.90	2.89	3.14	3.24	3.44	2.72	1.45	0.023	
1.39	--	2.06	--	--	2.97	3.38	3.75	3.93	4.17	2.79	2.78	0.043	
3.69	--	3.75	--	--	3.82	4.10	4.31	4.37	4.51	4.10	0.82	0.009

Fig. B-1 Internal pressure versus distance from bottom of Rod K-4 (Argon, 2.76 MPa, ambient temperature).

Fig. B-2 Internal pressure versus distance from bottom of Rod K-4 (Argon, 4.14 MPa, ambient temperature).

Fig. B-3 Internal pressure versus distance from bottom of Rod K-4 (Argon, 5.52 MPa, ambient temperature).

Fig. B-4 Internal pressure versus distance from bottom of Rod K-4 (Helium, 2.76 MPa, ambient temperature).

Fig. B-5 Internal pressure versus distance from bottom of Rod K-4 (Helium, 4.14 MPa, ambient temperature).

Fig. B-6 Internal pressure versus distance from bottom of Rod K-4 (Helium, 5.52 MPa, ambient temperature).

Fig. B-7 Internal pressure versus distance from bottom of Rod K-4 (Argon, 2.76 MPa, 533 K).

Fig. B-8 Internal pressure versus distance from bottom of Rod K-4 (Argon, 4.14 MPa, 533 K).

Fig. B-9 Internal pressure versus distance from bottom of Rod K-4 (Helium, 2.76 MPa, 533 K).

TABLE B-II

STEADY STATE GAS FLOW RESULTS FOR FUEL ROD M-4

Pressure Tap										Average Pressure (MPa)	Differential Pressure (MPa)	Flow Rate (mol/min)	
0	1	2	3	4	5	6	7	8	9				
Bottom	Location (cm from bottom of rod)									Top			
1.3	53.3	88.9	124.5	160.0	195.6	231.1	266.7	302.3	307.1				
Pressure (MPa)													
Argon, ambient temperature													
2.30	2.35	2.42	2.56	--	2.79	--	2.95	3.01	3.03	2.67	0.73	0.039	
2.02	2.10	2.30	2.59	--	3.02	--	3.29	3.40	3.44	2.74	1.42	0.078	
1.62	1.86	2.14	2.55	--	3.14	--	3.49	3.63	3.69	2.65	2.07	0.108	
1.34	1.79	2.19	2.73	--	3.47	--	3.88	4.04	4.12	2.73	2.77	0.131	
3.76	3.78	3.87	4.00	--	4.23	--	4.39	4.45	4.48	4.12	0.72	0.055	
4.06	4.13	4.28	4.55	--	5.01	--	5.31	5.43	5.48	4.77	1.41	0.125	
3.16	3.16	3.56	--	4.29	4.65	--	5.05	5.20	5.27	4.22	2.12	0.154	
2.77	2.93	3.39	--	4.36	4.80	--	5.30	5.50	5.58	4.18	2.81	0.199	
Helium, ambient temperature													
2.36	2.41	2.48	2.61	--	2.83	2.85	2.98	3.04	3.07	2.72	0.70	0.044	
1.93	2.00	2.18	--	2.72	2.96	--	3.25	3.36	3.41	2.68	1.48	0.106	
1.64	1.78	2.12	--	2.81	3.18	3.53	3.54	3.69	3.76	2.70	2.12	0.155	
1.39	1.75	2.18	--	3.11	3.50	3.84	3.93	3.40	4.17	2.79	2.78	0.204	
3.76	3.80	3.85	--	4.09	4.22	4.29	4.37	4.43	4.47	4.12	0.71	0.047	
3.40	3.54	3.69	--	4.14	4.36	4.62	4.64	4.75	4.81	4.10	1.41	0.128	
3.11	3.25	3.50	--	4.21	4.54	4.92	4.93	5.09	5.17	4.14	2.06	0.216	
2.73	2.96	3.33	--	4.32	4.75	5.04	5.24	5.44	5.53	4.13	2.80	0.298	
5.23	5.27	5.34	--	5.56	5.68	5.80	5.83	5.90	5.93	5.58	0.70	0.049	

TABLE B-II (continued)

Pressure Tap										Average Pressure (MPa)	Differential Pressure (MPa)	Flow Rate (mol/min)
0	1	2	3	4	5	6	7	8	9			
Location (cm from bottom of rod)										Average Pressure (MPa)	Differential Pressure (MPa)	Flow Rate (mol/min)
Bottom									Top			
1.3	53.3	88.9	124.5	160.0	195.6	231.1	266.7	302.3	307.1			
Pressure (MPa)												
Argon, 533 K												
2.39	2.46	2.56	--	2.81	2.85	--	3.05	3.10	3.14	2.76	0.74	0.002
2.05	2.14	2.30	--	2.81	3.04	--	3.25	3.35	3.43	2.74	1.38	0.024
1.73	1.91	2.28	--	2.95	3.25	--	3.54	3.70	3.78	2.76	2.04	0.043
1.36	1.72	2.19	--	3.12	3.43	--	3.86	3.95	4.15	2.76	2.79	0.064
3.79	4.01	4.05	--	4.19	4.27	--	4.37	4.42	4.46	4.13	0.67	0.007
3.46	3.58	3.73	--	4.18	4.41	--	4.63	4.76	4.82	4.14	1.37	0.043
Helium, 533 K												
2.48	--	--	--	--	2.95	--	3.08	--	3.17	2.83	0.70	0.020
2.07	--	2.53	--	--	3.07	--	3.34	--	3.48	2.78	1.41	0.046
1.51	--	2.29	--	--	3.65	--	4.04	--	4.27	2.90	2.76	0.080
3.84	--	3.92	--	--	4.30	--	4.45	--	4.55	4.20	0.71	0.033
3.40	--	3.63	--	--	4.36	--	4.62	--	4.79	4.10	1.39	0.065
2.88	--	3.47	--	--	4.68	--	5.36	--	5.65	4.27	2.78	0.125

Fig. B-10 Internal pressure versus distance from bottom of Rod M-4 (Argon, 2.76 MPa, ambient temperature).

Fig. B-11 Internal pressure versus distance from bottom of Rod M-4 (Argon, 4.14 MPa, ambient temperature).

Fig. B-12 Internal pressure versus distance from bottom of Rod M-4 (Helium, 2.76 MPa, ambient temperature).

Fig. B-13 Internal pressure versus distance from bottom of Rod M-4 (Helium, 4.14 MPa, ambient temperature).

Fig. B-14 Internal pressure versus distance from bottom of Rod M-4 (Argon, 2.76 MPa, 533 K).

Fig. B-15 Internal pressure versus distance from bottom of Rod M-4 (Argon, 4.14 MPa, 533 K).

Fig. B-16 Internal pressure versus distance from bottom of Rod M-4 (Helium, 2.76 MPa, 533 K).

Fig. B-17 Internal pressure versus distance from bottom of Rod M-4 (Helium, 4.14 MPa, 533 K).

TABLE B-III

STEADY STATE GAS FLOW RESULTS FOR FUEL ROD L-4

Pressure Tap										Average Pressure (MPa)	Differential Pressure (MPa)	Flow Rate (mol/min)
0	1	2	3	4	5	6	7	8	9			
Bottom	Location (cm from bottom of rod)								Top			
1.3	53.3	88.9	124.5	160.0	195.6	231.1	266.7	302.3	307.1			
Pressure (MPa)												
Argon, ambient temperature												
2.35	2.39	2.46	2.55	2.66	2.85	2.86	2.96	3.05	3.10	2.72	0.76	0.055
2.04	2.13	2.29	2.49	2.70	2.97	3.08	3.23	3.37	3.44	2.74	1.41	0.122
1.75	1.94	2.21	2.51	2.82	--	3.36	3.54	3.74	3.82	2.79	2.08	0.173
1.38	1.74	2.15	2.53	2.93	--	3.58	3.80	4.04	4.14	2.76	2.76	0.219
3.74	3.79	3.86	3.94	4.04	--	4.24	4.32	4.41	4.45	4.10	0.70	0.073
3.40	3.49	3.65	3.85	4.07	--	4.48	4.65	4.83	4.89	4.15	1.50	0.172
2.67	2.96	3.30	3.69	4.11	--	4.67	--	5.35	5.45	4.06	2.78	0.301
5.16	5.32	5.32	5.40	--	--	5.45	5.69	5.82	5.86	5.51	0.70	0.090
Helium, ambient temperature												
2.43	2.47	2.55	2.64	2.74	2.86	2.93	3.02	3.10	3.14	2.79	0.71	0.043
2.11	2.20	2.36	2.55	2.77	3.01	3.13	3.27	3.43	3.48	2.79	1.37	0.149
1.40	1.78	2.19	2.58	3.18	3.38	3.57	3.81	4.05	4.14	2.76	2.74	0.322
3.80	3.83	3.90	3.98	4.08	4.20	4.25	4.36	4.45	4.48	4.14	0.68	0.036
3.40	3.57	3.69	3.84	4.04	4.29	4.41	4.56	4.74	4.79	4.10	1.39	0.193
2.75	3.07	3.37	3.78	4.17	4.34	4.46	4.81	5.35	5.52	4.13	2.76	0.489
Helium, 533 K												
2.32	2.03	2.13	2.22	2.35	2.51	2.55	2.62	2.73	2.76	2.39	0.74	0.002
2.34	2.19	2.34	2.51	2.74	--	3.09	3.22	3.38	3.44	2.74	1.41	0.036
1.40	1.77	2.13	2.56	2.96	--	3.52	3.75	4.02	4.14	2.76	2.74	0.133
3.30	3.85	3.92	4.01	4.12	--	4.21	4.35	4.50	4.55	4.17	0.74	0.001
3.25	3.40	3.52	3.69	3.92	--	3.98	4.26	4.59	4.69	3.97	1.43	0.036
2.89	3.12	3.41	3.81	4.25	4.41	4.52	4.87	5.45	5.65	4.27	2.76	0.176

Fig. B-18 Internal pressure versus distance from bottom of Rod L-4 (Argon, 2.76 MPa, ambient temperature).

Fig. B-19 Internal pressure versus distance from bottom of Rod L-4 (Argon, 4.14 MPa, ambient temperature).

Fig. B-20 Internal pressure versus distance from bottom of Rod L-4 (Helium, 2.76 MPa, ambient temperature).

Fig. B-21 Internal pressure versus distance from bottom of Rod L-4 (Helium, 4.14 MPa ambient temperature).

Fig. B-22 Internal pressure versus distance from bottom of Rod L-4 (Helium, 2.76 MPa, 533 K).

Fig. B-23 Internal pressure versus distance from bottom of Rod L-4 (Helium, 4.14 MPa, 533 K).

APPENDIX C

ADDITIONAL METALLOGRAPHY

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APPENDIX C

ADDITIONAL METALLOGRAPHY

Figures C-1 through C-4 are photomicrographs illustrating the fuel crack patterns in fuel Rod K-4.

(a) 2.36 m from bottom of rod

(b) 2.37 m from bottom of rod

Fig. C-1 Transverse metallographic Sample D-2.

(a) 2.66 m from bottom of rod

(b) 2.68 m from bottom of rod

Fig. C-2 Transverse metallographic Sample D-2.

(a) 3.51 m from bottom of rod

(b) 3.52 m from bottom of rod

Fig. C-3 Transverse metallographic Sample E-5.

Fig. C-4 Transverse metallographic Sample E-2.

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