# POST-IRRADIATION EXAMINATION OF TWO GENTILLY-2 BUNDLES TO INVESTIGATE THE EFFECT OF PRESSURE-TUBE DIAMETRAL CREEP ON FUEL PERFORMANCE

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## ABSTRACT

Two bundles, discharged in 1997 from the Gentilly-2 Nuclear Generating Station, were selected for post-irradiation examination to investigate the effect of pressure-tube diametral creep on fuel performance. The bundles were irradiated in a pressure tube that had experienced relatively high diametral creep (maximum = 2.5%); these operated at peak outer-element linear powers of 48 and 52 kW/m to bundle-average burnups of 179 and 163 MWh/kgU, respectively.

Bundle orientation in the channel was determined from bearing-pad wear marks on individual elements. Residual sheath strain, fission-gas release and $UO_2$ grain growth were measured on elements located at the top and bottom of each bundle. All observed performance parameters were within the expected range, and there was no apparent difference between elements irradiated at the top and bottom of the bundle/channel. It is concluded that pressure-tube diametral creep had no measurable impact on the performance of these bundles.

## 1. INTRODUCTION

Reactor ageing leads to pressure tube (PT) diametral creep, resulting in a slightly larger PT inner diameter. It has been postulated that such creep may result in higher coolant flow over the top of the fuel (resulting in less flow across the bottom), causing temperature differences between the top and bottom fuel elements in the channel. A significant temperature differential might cause the bottom elements to have a higher FGR, $UO_2$ grain growth and sheath strain than the top elements. Such an effect might have performance, safety and licensing implications.

Under the initiative of the CANDU* Owners Group (COG), two bundles irradiated in the Gentilly-2 Nuclear Generating Station were examined in the hot cells at AECL - Chalk River Laboratories. The bundles were irradiated in a PT that had experienced relatively high diametral creep (peak = 2.5% at axial position 9), and operated at peak outer-element linear powers

* CANDU: CANada Deuterium Uranium; registered trademark of Atomic Energy of Canada Limited.

(OELP's) of 48 and 52 kW/m to bundle-average burnups of 179 and 163 MWh/kgU, respectively.

The primary objective of the post-irradiation examination (PIE) was to investigate whether PT diametral creep has any effect on fuel performance. In particular, PIE activities focused on looking for performance variations resulting from creep-induced coolant flow increases across the top of the bundles. The investigation first determined bundle orientation in the channel, and then looked for "top-" vs. "bottom-of-channel" variations in performance parameters such as residual sheath strain, fission-gas release (FGR) and $UO_2$ grain growth.

## 2. MANUFACTURING DATA AND IRRADIATION HISTORY

The bundles were of standard CANDU-6 37-element geometry; their uranium mass was 19.3 kg. Both bundles were manufactured by GE Canada in Peterborough, Canada. Bundle OY291C1 was irradiated in axial position 7 of the channel, where 2.09% local diametral creep strain was measured in 1997. It operated at a peak OELP of 52 kW/m to a bundle-average burnup of 163 MWh/kgU. Bundle KY689C1 was initially irradiated in axial position 1 of the channel (0.52% local diametral creep) and then in position 9, which had the highest local diametral creep strain of 2.47%. It achieved a bundle-average burnup of 179 MWh/kgU with a peak OELP of 48 kW/m. Figures 1 and 2 illustrate the power history of Bundles OY291C1 and KY689C1, respectively.

## 3. PIE RESULTS

The PIE included: 1) bearing-pad wear mapping to determine bundle orientation in the channel, 2) element profilometry and residual sheath-strain calculations, 3) element puncture and internal gas analysis, and 4) ceramographic and metallographic examination.

Throughout this paper, the term "reference end" refers to the end of the bundle/element associated with the manufacturer's monogram (stamped on the endplate). It is not known whether the reference end resided upstream or downstream during the irradiation.

### 3.1 Bearing-Pad Wear Mapping

All bearing pads from both bundles were examined using an in-cell stereomicroscope, and each pad was mapped for wear and any abnormal features.

The top surface of the bearing pads on elements 6 to 14 from Bundle OY291C1 were wear-free, indicating that these elements resided at the top portion in the channel. Light wear marks were observed on the bearing pads of the remaining elements. The bearing pads on elements 1 and 18 exhibited the greatest amount of wear and refueling (sliding) scratches, indicating that they resided at or near the bottom (6 o'clock) of the channel. Using a similar method, it was determined that elements 12 and 13 from Bundle KY689C1 resided near the bottom of the channel.

## 3.2 Element Profilometry

The top and bottom outer elements from each bundle were profiled after bundle disassembly. Element diameters were measured using a dual-transducer profilometer. The mid-pellet sheath strain ($\delta$) is defined as:

$$\delta = (d_1 - d_0)/d_0 \qquad (1)$$

where $d_0$ and $d_1$ denote sheath outside-diameter before and after irradiation, respectively. The uncertainty in the calculation is ± 0.1%.

The strains for the elements from Bundles OY291C1 and KY689C1 ranged from 0.0% to 0.2% and 0.0% to 0.1%, respectively (Table 1). The average ridge height (measured at the pellet interfaces) for the elements from Bundles OY291C1 and KY689C1 was about 25 and 10 μm, respectively. No significant differences were observed in sheath strain and ridge height between the top and bottom elements from both bundles. The observed strains are within the range expected for CANDU commercial power-reactor fuel [1].

## 3.3 Element Puncture and Internal-Gas Analysis

Gas puncture was performed on the top and bottom elements from both bundles. Internal gases were collected and their volumes were determined. The gas samples were analyzed using a mass spectrometer.

FGR from Bundles OY291C1 and KY689C1 ranged from 2.1% to 2.4% and from 0.1% to 0.2%, respectively (Table 2). The higher FGR observed in Bundle OY291C1 is consistent with its higher peak OELP (52 kW/m vs. 48 kW/m). The FGR is within the range expected for CANDU commercial power-reactor fuel [1].

FGR in the top and bottom elements from Bundle KY689C1 was low and exhibited no dependence on element location in the bundle. The top elements (elements 9 and 10) and bottom elements (elements 1 and 18) from Bundle OY291C1 exhibited a similar FGR (top vs. bottom: 2.1-2.2% vs. 2.1-2.4%).

## 3.4 Metallography and Ceramography Examination

Elements 9 (top) and 18 (bottom) from Bundle OY291C1 and elements 3 (top) and 12 (bottom) from Bundle KY689C1 were examined destructively. The elements were sectioned at the midplane and examined using an in-cell optical microscope; examinations included sheath metallography and $UO_2$ pellet ceramography.

## 3.5 Sheath Metallography

Sheath metallography examinations included:

1. oxide-thickness measurements on the sheath outside (OD) and inside (ID) surfaces,
2. CANLUB retention behaviour, and
3. sheath hydride and deuteride (H/D) density.

### 3.5.1 Sheath Oxidation

A continuous oxide layer was observed on the sheath OD and on the top of the appendages. For both bundles, elements at the top position exhibited a slightly thinner oxide layer on the sheath OD than did elements at the bottom (Table 3). The oxide layer on the top element 9 from Bundle OY291C1 was 1-2 μm, which is slightly thinner than that on the bottom element 18 (2-3 μm). Similarly, the oxide layer was slightly thinner on the top element 3 (1-3 μm) than on the bottom element 12 (3-4 μm) from Bundle KY689C1. All of the observed sheath-oxide thicknesses were within the range typically observed in CANDU power-reactor fuel [2].

Oxide was not discernible on the sheath ID.

### 3.5.2 CANLUB Retention

The average CANLUB thickness observed was about 10 μm for both bundles (Table 4). The graphite layer was distributed along the sheath ID, $UO_2$ pellet surface and/or between the sheath and the pellets.

Elements 9 (top) and 18 (bottom) from Bundle OY291C1 showed similar CANLUB retention behaviour. Most of the graphite layer was adhering to the pellet surface. CANLUB retention for both elements ranged from 97% to 99%. This behaviour is typical of that observed in CANDU power-reactor fuel irradiated to burnups < 400 MWh/kgU [3].

For Bundle KY689C1, element 3 (top) and element 12 (bottom) exhibited similar CANLUB retention behaviour. About 46-52% of the coating was adhering to the pellet surface; ~ 30% of the coating was in the pellet-sheath gap. About 18-24% of the CANLUB was unaccounted for, and very little CANLUB (≤ 1%) was adhering to the sheath ID. The CANLUB retention for both elements ranged from 76% to 82%. This behaviour is typical of that observed in CANDU power-reactor fuel irradiated to burnups < 400 MWh/kgU [3].

### 3.5.3 Sheath Hydride/Deuteride Density

All of the examinations were performed at the element midplane, through the sheath braze heat-affected zone (HAZ). The samples were examined using an optical microscope to investigate the sheath H/D density.

The H/D densities in all samples were very low. Figures 3 and 4 show typical micrographs of the elements from Bundle OY291C1 at the top and bottom positions; both samples exhibited similar H/D distributions.

The H/D pickup in the sheath as-received zone (ARZ, cold-worked $\alpha$ microstructure) is significantly lower than in the HAZ (prior-$\beta$ microstructure). This is typical of that observed in CANDU power-reactor fuel irradiated to burnups of ~ 200 MWh/kgU [4].

### 3.5.4 $UO_2$ Pellet Ceramography

Ceramographic examination was performed at the periphery, mid-radius and centre of the fuel pellets. $UO_2$ grain size was determined using the average-linear-intercept method (ASTM standard [5]). Fuel-pellet cross-section crack patterns were examined.

Cross-section samples at the midplane of elements 9 (top) and 18 (bottom) from Bundle OY291C1 were examined. Table 5 lists the results of the grain-size measurements. The two elements exhibited very similar microstructures; grain growth was observed only in the central region of both samples. The grain-growth factors (central/periphery grain-size ratio) for the two elements were identical (~ 3).

Cross-section samples at the midplane of elements 3 (top) and 12 (bottom) from Bundle KY689C1 were examined. There was no distinguishable difference in microstructure between the two elements. No evidence of grain growth was observed in the pellet centre regions (Table 5).

The cracking patterns and grain growth observed are typical of those observed in CANDU fuel operating at maximum powers of ~ 50 kW/m to burnups of ~ 200 MWh/kgU [6].

## 4. DISCUSSION

The main objective of this PIE was to investigate whether the aforementioned postulated top/bottom creep effect exists in operating CANDU reactors. This was accomplished by comparing performance parameters (e.g., FGR, sheath strain and pellet grain growth) for the top and bottom fuel elements from the bundles discharged from a fuel channel that experienced significant diametral creep (maximum = 2.5%).

For comparison, the performance parameters of the top and bottom elements from both bundles are listed in Table 6. The top and bottom elements from each bundle exhibited very similar irradiation behaviour, and all the performance parameters are within the range expected based on past investigations of CANDU fuel behaviour [1-4, 6].

The FGR, sheath strain and $UO_2$ grain growth are all temperature-related fuel-performance parameters; the results listed in Table 6 suggest that the temperature difference between the top and bottom elements from both bundles is negligible. It is concluded that PT diametral creep (up to 2.5%) has no measurable effect on fuel performance.

## 5. CONCLUSIONS

Bundles OY291C1 and KY689C1 achieved reported bundle-average burnups of 163 MWh/kgU and 179 MWh/kgU and peak OELP's of 52 and 48 kW/m, respectively. The main conclusions of our investigations are:

1. The top and bottom elements from both bundles exhibited very similar irradiation behaviour, indicating that PT diametral creep (up to 2.5%) has no significant effect on fuel performance.

2. All fuel-performance parameters, including residual sheath strain, FGR, pellet grain growth, CANLUB retention, sheath OD and ID oxidation behaviour, sheath H/D density and pellet radial-crack patterns, were within the expected range for similarly operated CANDU power-reactor fuel.

## 6. ACKNOWLEDGEMENTS

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## 7. REFERENCES

1. PURDY, P.L., MANZER, A.M., HU, R.H., GIBB, R.A. and KOHN, E., Assessments of Sheath Strain and Fission-Gas Release Data from 20 Years of Power Reactor Fuel Irradiations, Proc. Fifth Int. Conf. CANDU Fuel, 1997, Toronto, Ontario, Canada, Canadian Nuclear Society, Toronto (1997), Vol. 2, 134-147.

2. COLEMAN, C.E., HOLT, R.A. and CHEADLE, R.A., Zirconium Alloy Fuel Cladding, in The Physical Metallurgy of Zirconium Alloys, A Series of Lectures Prepared by CHEADLE, R.A. et al., CRNL-1208, (1974) 166-168.

3. FLOYD, M.R., LEACH, D.A., MOELLER, R.E., ELDER, R.R., CHENIER, R.J. and O'BRIEN, D., Behaviour of Bruce NGS-A Fuel Irradiated to a Burnup of ~ 500 MWh/kgU, Proc. Third Int. Conf. CANDU Fuel, 1992, Pembroke, Ontario, Canada, Canadian Nuclear Society, Toronto (1992), 2.44-2.49.

4. GRAHAM, N.A., NOVAK, J. and SEJNOHA, R., Behaviour of Braze Heat-Affected Zone in CANDU Fuel Sheaths, Proc. 11th CNS Conf., 1990, Toronto, Ontario, Canada, Canadian Nuclear Society, Toronto (1990), 6.5-6.9.

5. ASTM Standard, E-112-82, 1982.

6. HASTINGS, I.J. and HATTON, G.C., Microstructures in $UO_2$ Fuel from CANDU Reactors, AECL report PP-35/1 (1980).


TABLE 1: MID-PELLET SHEATH-STRAINS AND RIDGE-HEIGHTS

| Bundle | Elements | Position | Mid-Pellet Sheath Strain (%) | Average Ridge Height (μm) |
|---|---|---|---|---|
| OY291C1 | 9, 10 | Top | 0.1-0.2 | 25 |
| | 1, 18 | Bottom | 0.0-0.2 | 25 |
| KY689C1 | 3, 4 | Top | 0.0-0.1 | 10 |
| | 12, 13 | Bottom | 0.0-0.1 | 10 |

TABLE 2: FISSION-GAS RELEASE MEASUREMENTS

| Bundle | Elements | Position | FGR (%) |
|---|---|---|---|
| OY291C1 | 9, 10 | Top | 2.1-2.4 |
| | 1, 18 | Bottom | 2.1-2.2 |
| KY689C1 | 3 | Top | 0.2 |
| | 12 | Bottom | 0.1 |

TABLE 3: SHEATH OD OXIDE-THICKNESSES

| Bundle | Elements | Position | Oxide Thickness (μm) |
|---|---|---|---|
| OY291C1 | 9 | Top | 1-2 |
| | 18 | Bottom | 2-3 |
| KY689C1 | 3 | Top | 1-3 |
| | 12 | Bottom | 3-4 |

TABLE 4: CANLUB RETENTION SURVEY

| Bundle | Element | Position | CANLUB Retention (%) | CANLUB Average Thickness (μm) |
|---|---|---|---|---|
| OY291C1 | 9 | Top | 97 | 9 |
| | 18 | Bottom | 99 | 9 |
| KY689C1 | 3 | Top | 76 | 9 |
| | 12 | Bottom | 82 | 9-10 |

TABLE 5: GRAIN-SIZE MEASUREMENTS

| Bundle | Element | Position | Periphery (μm) | Mid-Radius (μm) | Centre (μm) |
|---|---|---|---|---|---|
| OY291C1 | 9 | Top | 6 | 7 | 18 |
| | 18 | Bottom | 5 | 6 | 14 |
| KY689C1 | 3 | Top | 8 | 9 | 9 |
| | 12 | Bottom | 9 | 8 | 10 |

TABLE 6: COMPARISON OF FUEL PERFORMANCE BETWEEN TOP AND BOTTOM ELEMENTS FROM BUNDLES OY291C1 AND KY689C1

| Performance Parameters | Bundle OY291C1 | | Bundle KY689C1 | |
|---|---|---|---|---|
| | Top | Bottom | Top | Bottom |
| Sheath Strain (%) | 0.2 | 0.1 | 0.1 | 0.1 |
| FGR (%) | 2.3 | 2.2 | 0.2 | 0.1 |
| Grain Growth Factor | 3 | 3 | 1 | 1 |

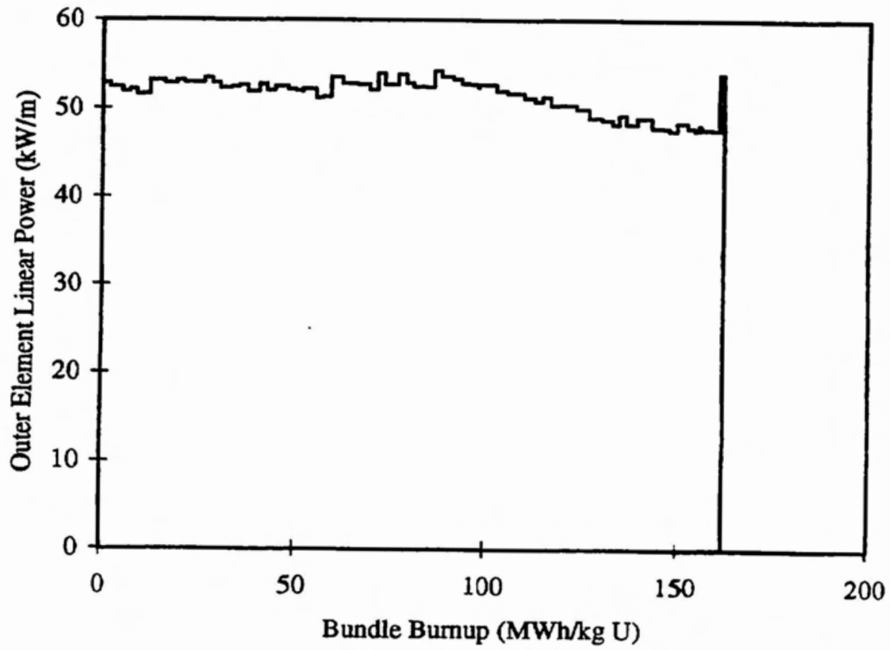


FIGURE 1: POWER HISTORY OF BUNDLE OY291C1.

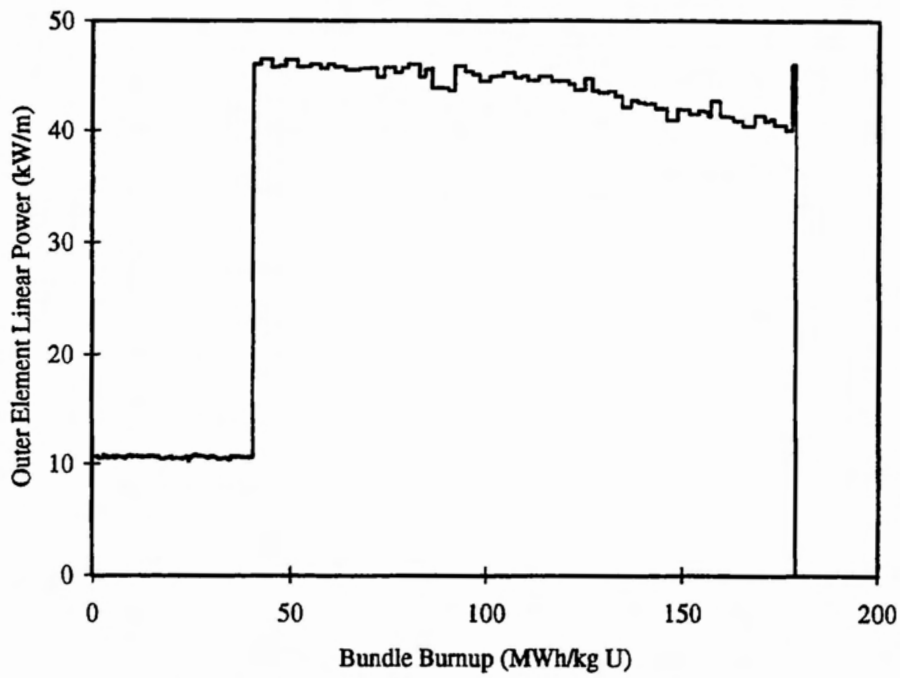


FIGURE 2: POWER HISTORY OF BUNDLE KY689C1.

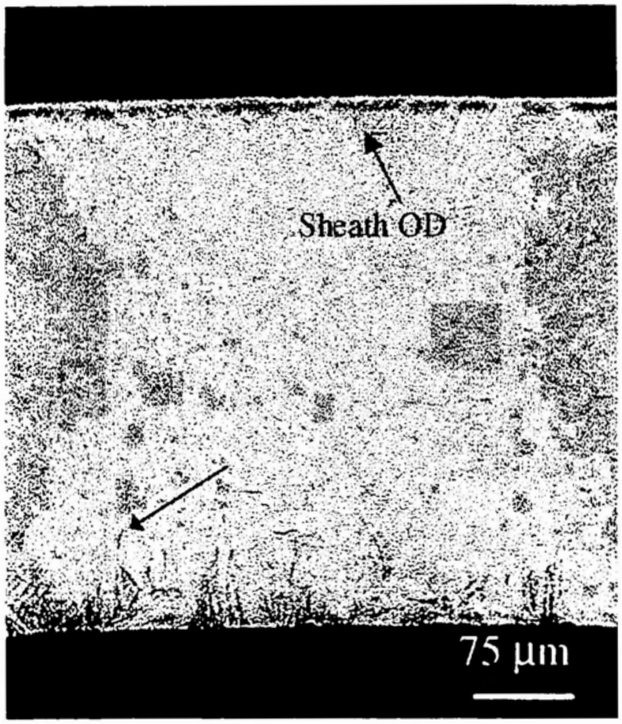


FIGURE 3: TYPICAL SHEATH H/D DISTRIBUTION (ARROW) IN HAZ OF ELEMENT 18 (BOTTOM POSITION) FROM BUNDLE OY291C1.

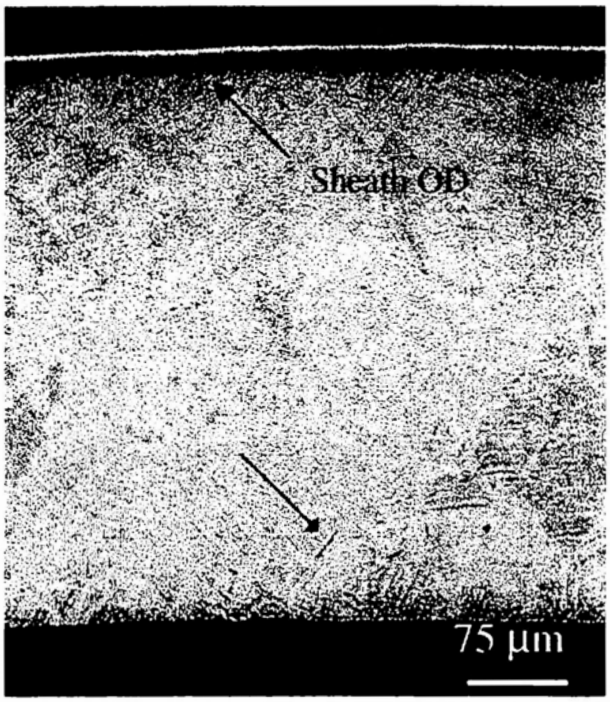


FIGURE 4: TYPICAL SHEATH H/D DISTRIBUTION (ARROW) IN HAZ OF ELEMENT 9 (TOP POSITION) FROM BUNDLE OY291C1.