# PERFORMANCE OF TWO CANDU-6 FUEL BUNDLES CONTAINING CANLUB AND NON-CANLUB PRODUCTION ELEMENTS

by

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## ABSTRACT

As part of the CANDU® Owners Group (COG) Safety and Licensing Program, two CANDU-6 standard production fuel bundles were purposely manufactured containing up to six standard fuel elements that did not have a CANLUB coating on the inside sheath surface, and irradiated in the Point Lepreau Generating Station (PLGS). The primary objective of the program was to determine if the fuel performance of the CANLUB and non-CANLUB elements were comparable, in order to determine whether CANLUB has a detrimental effect on fuel centreline temperature.

The bundles were irradiated with declining power histories in PLGS in 1996-1997, achieving calculated maximum outer-element linear powers of about 48 kW/m, and bundle-average burnups of about 200 MWh/kgU. The bundles were transferred to Chalk River Laboratories for post-irradiation examination. The performance of the CANLUB and non-CANLUB elements was comparable, and within the range expected for CANDU fuel irradiated within the normal operating envelope. Temperature-sensitive parameters such as $UO_2$ grain growth and fission-gas release were similar in both types of elements, indicating that the CANLUB layer had no detrimental effect on centreline temperature.

## 1. INTRODUCTION

The specification for CANDU fuel elements requires a graphite layer, known as CANLUB, on the inside sheath surface. The purpose of the CANLUB layer is to mitigate stress-corrosion cracking of the sheath following a power ramp [1]. Post-irradiation examination (PIE) has shown that fuel incorporating CANLUB coatings has less oxidation on the inside sheath surface than uncoated fuel [2]. It appears that the CANLUB layer in some way prevents the Zircaloy sheath from being oxidized. This raises questions about what happens to fission-liberated oxygen in CANLUB-coated fuel. One possibility is that the excess oxygen remains in the $UO_2$ and diffuses along the thermal gradient [3, 4] to the centre of the pellet, decreasing the fuel thermal conductivity and raising centreline temperatures [5, 6, 7]. To address this potential concern, COG, in cooperation with PLGS, completed an investigation to empirically demonstrate the effect of the CANLUB coating on parameters that are sensitive to centreline temperature.

To achieve this goal, two CANDU-6 standard production fuel bundles were manufactured, having some outer and intermediate elements without CANLUB coatings on the inside sheath surface. The bundles were irradiated in PLGS during 1996-1997, and were subsequently examined in the hot-cell facilities at AECL Chalk River. This paper presents the results of the investigation.

## 2. FUEL DESCRIPTION

Two bundles were manufactured to meet the design specifications of standard CANDU-6 (37-element, natural $UO_2$) fuel. Normally, all elements of a CANDU-6 fuel bundle contain a graphite coating (CANLUB) on the inner sheath surface. Selected elements on the outer and intermediate rings of these two fuel bundles were substituted with elements that did not contain the CANLUB coating on the inner sheath surface during the fabrication process. The locations of the non-CANLUB coated elements in the two bundles are shown in Figure 1

## 3. IRRADIATION HISTORY

The two bundles were irradiated in PLGS from 1996 June to 1997 June, in channels K08 and M15. Each bundle was initially irradiated in axial position 5 to a burnup of about 40 MWh/kgU, and then shifted to axial position 7 for the duration of its irradiation. The bundles achieved maximum outer-element linear powers of 47-48 kW/m and bundle-average discharge burnups of 199-202 MWh/kgU (see Figures 2 and 3). The intermediate elements achieved maximum powers of 39 kW/m.

## 4. POST-IRRADIATION EXAMINATION RESULTS

The following PIE was performed on the bundles and on selected elements:

- bundle and element visual examination,
- bundle profilometry,
- element profilometry,
- fission-gas analysis, and
- ceramographic and metallographic examination.

The highlights of the PIE results are presented below.

### 4.1 Bundle and Element Visual Examination

Both bundles were in good condition, with no unusual features found on the end plates or outer elements. Typical features that were observed included handling scratches, abrasions, variations in the zirconium-oxide shading, stains,.and white deposits. Minimal wear was found on the bearing pads and spacer pads. The visual appearance of the CANLUB and non-CANLUB elements were comparable.

### 4.2 Bundle Profilometry

The outer elements of both bundles were profiled while still assembled in the bundle, using a dual-transducer profilometer that was equipped with a digital data acquisition and control system [8]. The bundle was rotated so that each element was profiled at the 3 o'clock position, thus minimizing gravity effects on the measurements. The bundle-element bow profiles shown in Figure 4 indicate that the two bundles conformed to the shape of the pressure tube (i.e., the elements at the top of bundle bowed inward, the elements at the bundle sides bowed outward, and the bottom elements had a "W" shape). Typical axial bundle-element profiles for elements at the 12, 3, 6, and 9 o'clock positions are shown in Figure 5. The bundle-element bow at the centre-bearing pad ranged from -0.7 to +1.0 mm. The bundle-element bow profiles are comparable to that previously observed for 37-element bundles irradiated within the normal operating envelope [9].

### 4.3 Element Profilometry

All non-CANLUB and adjacent CANLUB elements from each bundle were profiled after bundle disassembly. Element diameters were measured to ± 0.01 mm, using a dual-transducer profilometer [8].

#### 4.3.1 Residual Sheath Strain

Residual sheath strain was calculated at the mid-pellet and pellet interface locations, using the following equation:

$$\%\ \text{Residual Sheath Strain} = 100 \times \frac{(d_p - d_i)}{d_i} \qquad (1)$$

where $d_p$ is the post-irradiation element outside diameter (OD), and $d_i$ is the as-manufactured element OD. A positive value indicates tensile strain, while a negative value indicates a compressive strain. The mid-pellet and pellet-interface residual sheath strain results are summarized in Table 1.

The residual sheath strain for non-CANLUB elements was slightly lower (by about 0.1%) than for the CANLUB elements. The reason for this appears to be the larger diametral clearance in the uncoated elements afforded by the lack of the CANLUB interlayer. A recent study has shown that residual sheath strain decreases by about 0.05% per 0.01 mm increase in diametral clearance [10]. The lack of a CANLUB layer is equivalent to an increase in diametral clearance, if all other fabrication parameters remain constant. The CANLUB thickness specification is 3-20 μm, and the typical thickness is 10 μm. This is equivalent to an increase in diametral clearance of 0.02 mm, which is expected to result in a 0.1% decrease in sheath strain, as observed. All observed residual sheath strains are within the range that is expected for CANDU commercial power-reactor fuel irradiated within the normal operating envelope [11].

4.3.2 Pellet-Interface Ridge Height

Measurements of the pellet-interface ridge height for the CANLUB and non-CANLUB elements are summarized in Table 2. There is no difference in the ridge heights of the CANLUB and non-CANLUB element, within measurement uncertainties.

## 4.4 Fission-Gas Release

Gas-puncture analysis was performed on two outer and one intermediate non-CANLUB and CANLUB elements from each bundle. Gas composition was measured for one outer CANLUB and non-CANLUB element from each bundle, from which the fission-gas release (FGR) was determined. The gas puncture and FGR results are summarized in Table 3.

The outer element FGR ranged from 2% to 3% for both bundles, and is within the range expected for similarly-operated commercial power reactor [11]. The average gas volume collected from the CANLUB and the non-CANLUB elements were comparable (5 to 7 mL for outer elements). The percent FGR for the two element types was comparable and within the range of measurement uncertainty.

## 4.5 Metallographic and Ceramographic Examination

A continuous layer of oxide (1-2 μm in thickness) was found on the outside sheath surface of the CANLUB and non-CANLUB elements. On the inside sheath, the non-CANLUB elements had patches of oxide (4-8 μm in thickness) that covered about 10 to 20 percent of the inside sheath surface, while the CANLUB elements had little or no discernible oxide. The observed oxidation on the internal surface of non-CANLUB elements is directly related to the absence of the CANLUB coating, which seems to prevent the Zircaloy sheath from gettering oxygen that is liberated during fissioning [2].

The $UO_2$ microstructure was examined at five radial locations, for a selection of outer and intermediate CANLUB and non-CANLUB elements. All the elements exhibited similar microstructural features; gas bubbles and solid fission products (i.e., white spherical precipitates) were observed at the pellet centre. Grain growth was seen at the pellet central region of the outer elements only. No grain growth was evident for the intermediate elements, which operated at lower power. Typical $UO_2$ microstructures for the CANLUB and non-CANLUB elements are shown in Figure 6.

The $UO_2$ grain size was similar for the CANLUB and non-CANLUB outer and intermediate elements. The outer elements had some grain growth in the central region, and the grain growth factor was about 2. No grain growth was observed at the pellet mid-radius or periphery in the outer elements.

These $UO_2$ microstructural features and grain growth are typical of those observed in CANDU fuel operating at a maximum power of 47-48 kW/m to burnups of about 200 MWh/kgU [12].

## 5. SUMMARY AND CONCLUSIONS

The fuel performance of CANLUB and non-CANLUB elements simultaneously operating to maximum powers of 47-48 kW/m and bundle-average burnups of about 200 MWh/kgU has been shown to be comparable, and within the range expected for CANDU fuel irradiated within the normal operating envelope. There is no evidence to indicate that the CANLUB layer has a detrimental effect on centreline temperature. Temperature sensitive parameters, including FGR and $UO_2$ grain growth, are comparable. Differences in sheath strain are accounted for by the larger diametral clearance afforded by the lack of a CANLUB interlayer. In conclusion, the use of CANLUB appears to have no detrimental effect on fuel performance, while at the same time decreasing the risk of sheath defects from stress-corrosion cracking.

## 6. ACKNOWLEDGEMENTS

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Table 1. Residual Sheath Strain Summary

| Channel - Element Ring | Average Residual Sheath Strain (%) ± 1 Standard Deviation of the Average | |
|---|---|---|
| | Non-CANLUB Elements | CANLUB Elements |
| **Mid-Pellet Residual Sheath Strain** | | |
| K05 - Outer | 0.09 ± 0.03 | 0.22 ± 0.04 |
| K05 - Intermediate | -0.01 ± 0.01 | 0.08 ± 0.08 |
| M15 - Outer | 0.16 ± 0.06 | 0.22 ± 0.06 |
| M15 - Intermediate | -0.04 ± 0.09 | 0.13 ± 0.03 |
| **Pellet-Interface Residual Sheath Strain** | | |
| K05 - Outer | 0.50 ± 0.05 | 0.63 ± 0.05 |
| K05 - Intermediate | 0.19 ± 0.01 | 0.28 ± 0.08 |
| M15 - Outer | 0.44 ± 0.07 | 0.52 ± 0.09 |
| M15 - Intermediate | 0.11 ± 0.10 | 0.28 ± 0.04 |

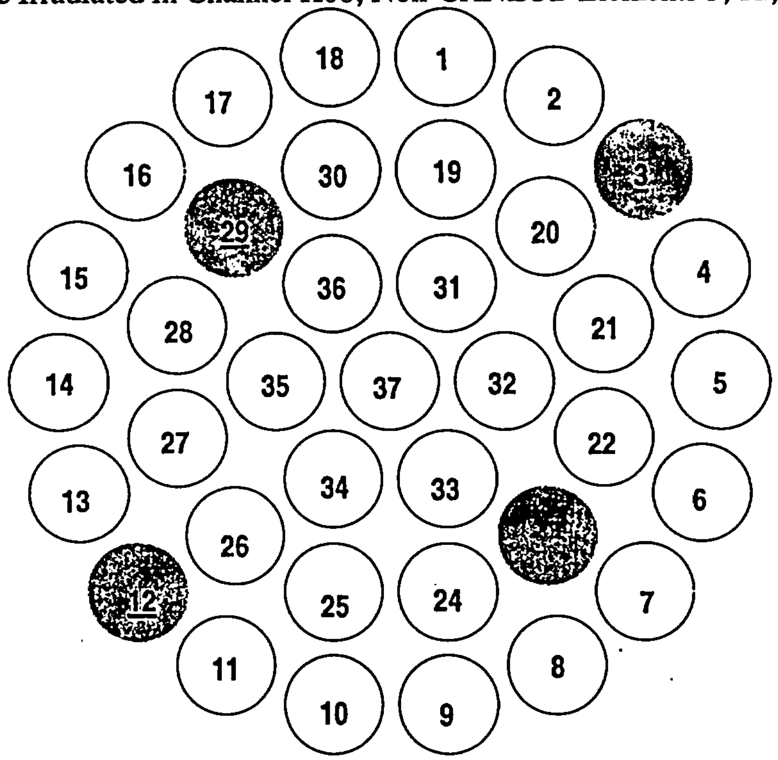
Table 2. Pellet-Interface Ridge Height Summary

| Channel - Element Ring | Average Pellet-Interface Ridge Height (mm) ± 1 Standard Deviation of the Average | |
|---|---|---|
| | Non-CANLUB Elements | CANLUB Elements |
| K05 - Outer | 0.026 ± 0.001 | 0.027 ± 0.001 |
| K05 - Intermediate | 0.013 ± 0.000 | 0.013 ± 0.001 |
| M15 - Outer | 0.019 ± 0.000 | 0.019 ± 0.002 |
| M15 - Intermediate | 0.010 ± 0.001 | 0.009 ± 0.001 |

TABLE 3. Gas Puncture and Fission-Gas Release Summary

| Channel - Element # - Type | Gas Volume at STP* (mL) | % Fission Gas Release (Kr +Xe) |
|---|---|---|
| Outer Elements | | |
| K05-03-NC | 5.4 | 1.9% ± 0.2% |
| K05-04 | 5.7 | 2.1% ± 0.2% |
| K05-12-NC | 5.1 | |
| K05-13 | 5.0 | |
| M15-02-NC | 6.1 | 2.4% ± 0.3% |
| M15-03 | 6.5 | 2.7% ± 0.3% |
| M15-08-NC | 7.2 | |
| M15-09 | 7.0 | |
| Intermediate Elements | | |
| K05-23-NC | 2.1 | |
| K05-24 | 2.0 | |
| M15-20 | 2.0 | |
| M15-21-NC | 2.0 | |
| NC = Non-CANLUB<br>*Uncertainty (2σ) is 3%<br>*STP = standard temperature (0°C) and pressure 101.325 kPa | | |

Bundle Irradiated in Channel K08; Non-CANLUB Elements 3, 12, 23, 29




Bundle Irradiated in Channel M15; Non-CANLUB Elements 2, 8, 14, 21, 25, 29

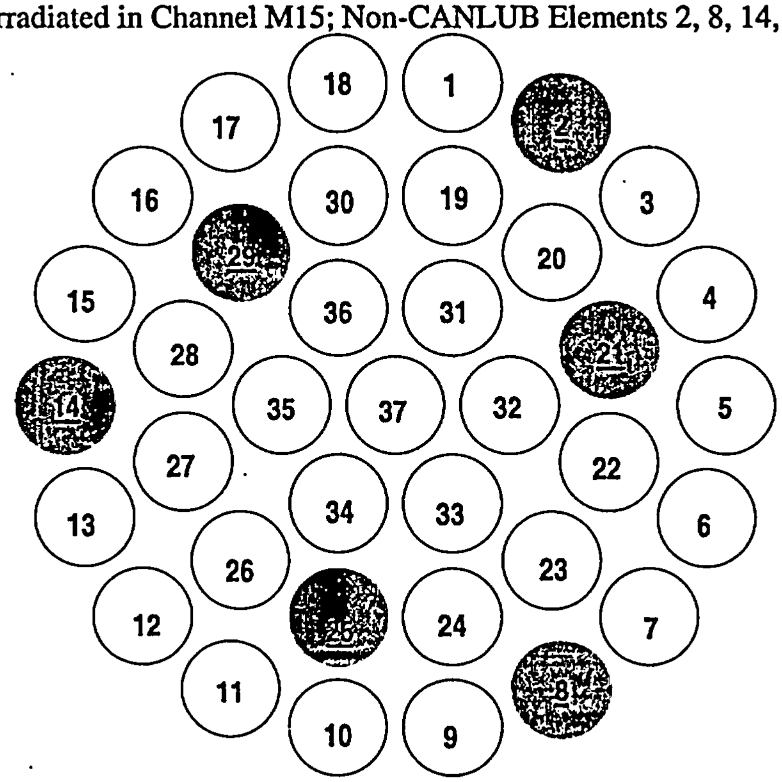



**Figure 1. Non-CANLUB Element Locations as View From the Bundle Monogram End**

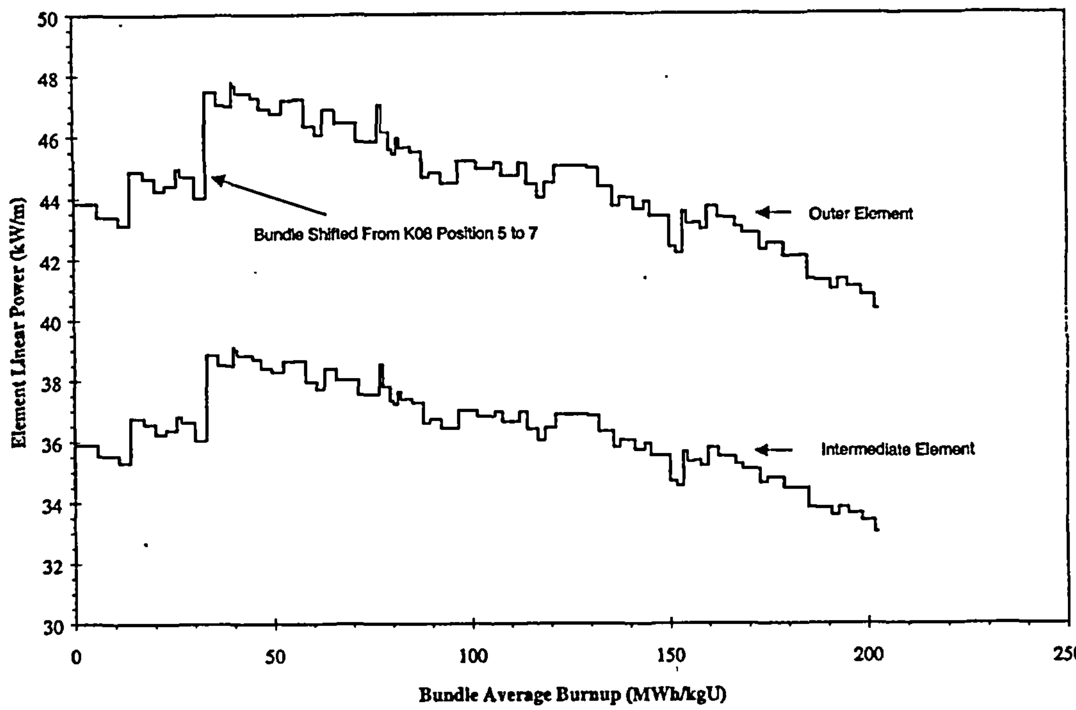



**Figure 2.** **Power History for Bundle Irradiated in Channel K08**

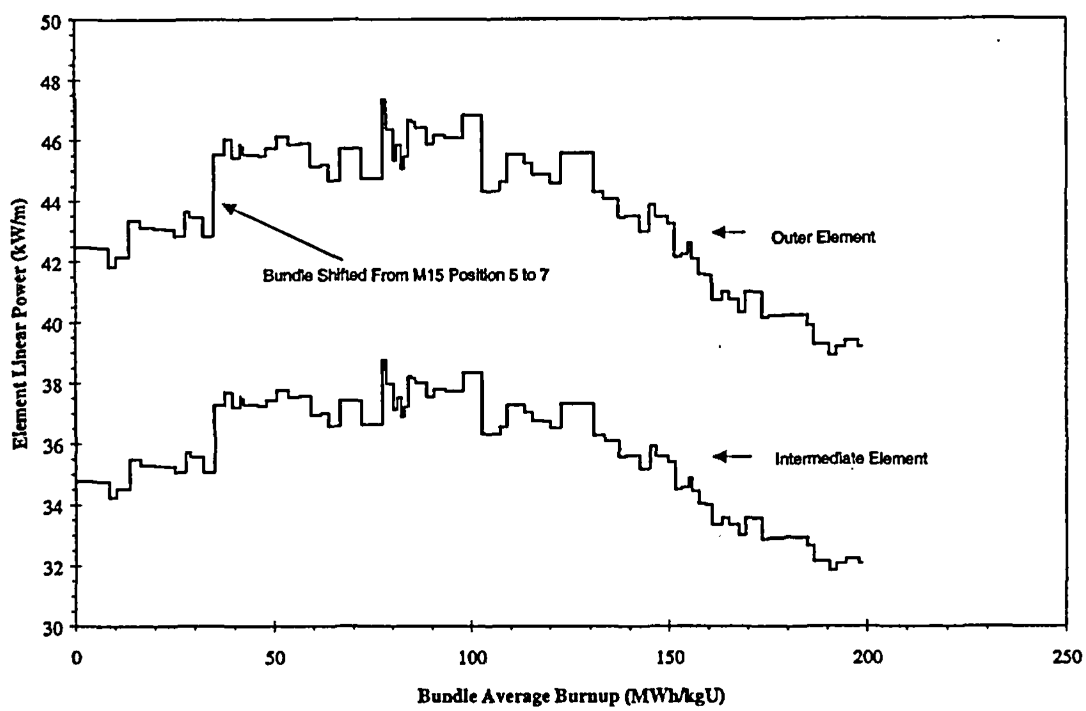



**Figure 3.** **Power History for Bundle Irradiated in Channel M15**

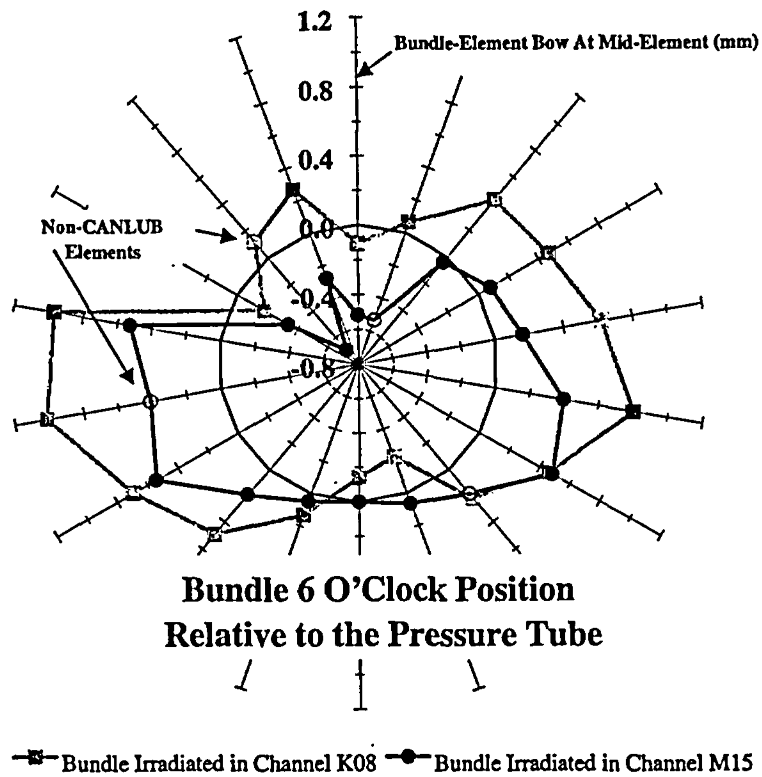



**Figure 4.** **Bundle-Element Bow Profiles**

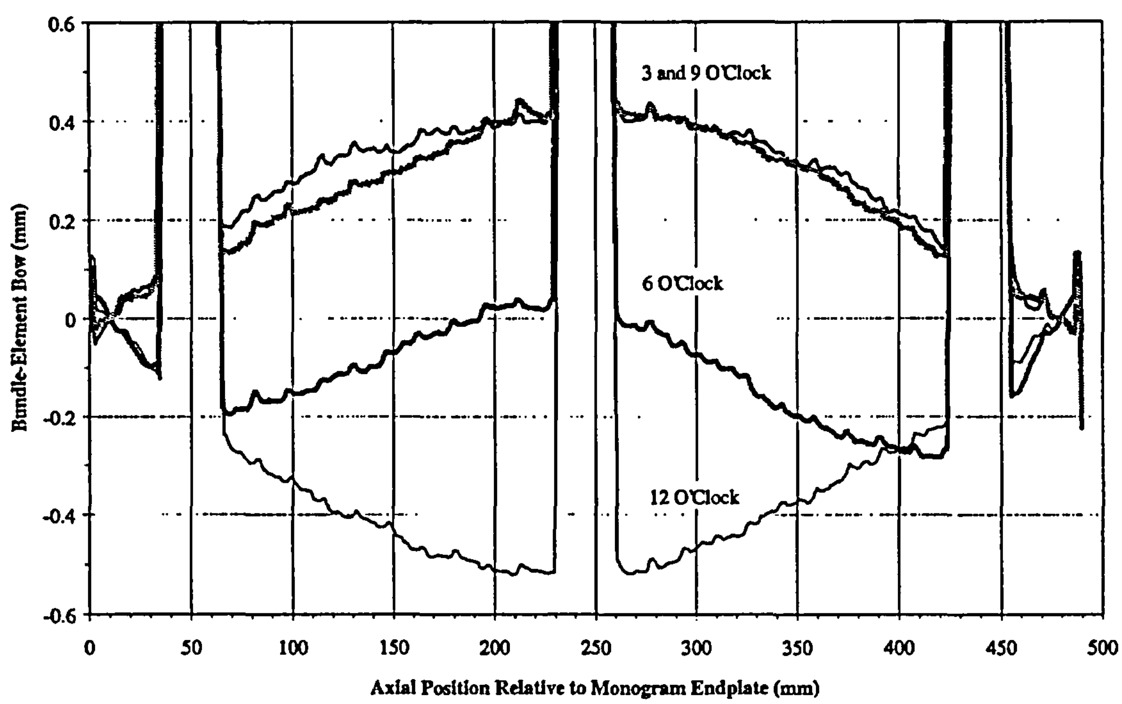
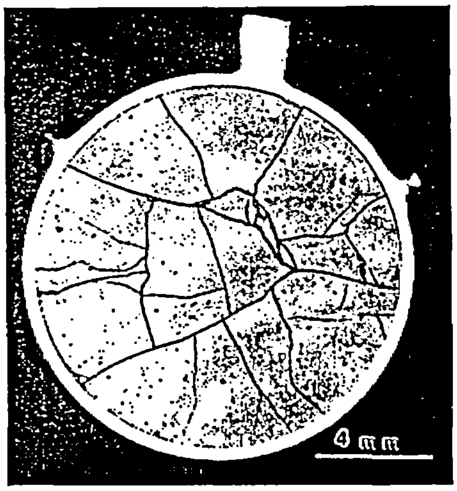
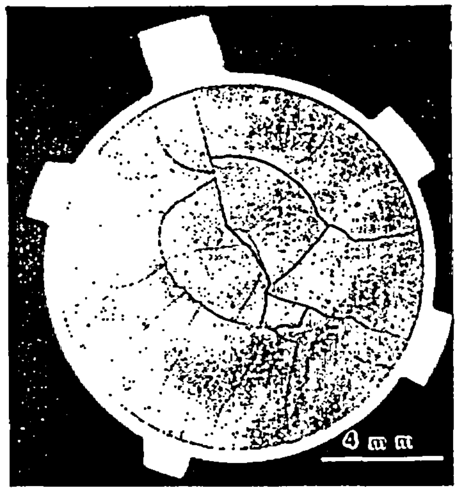


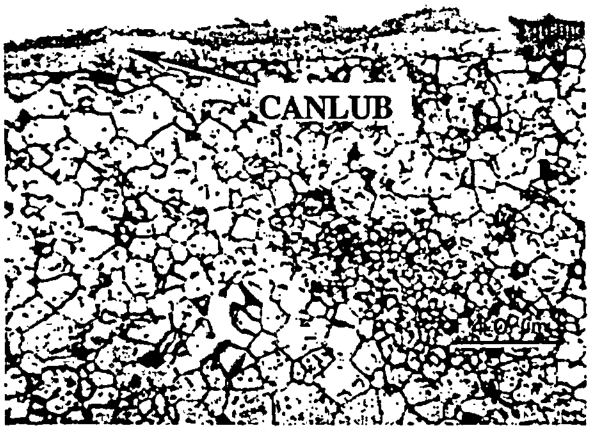

**Figure 5.** **Typical Axial Bundle-Element Bow Profiles (Labels Indicate Position of Elements Relative to The Fuel Channel; E.G., 6 O'clock = Bottom)**



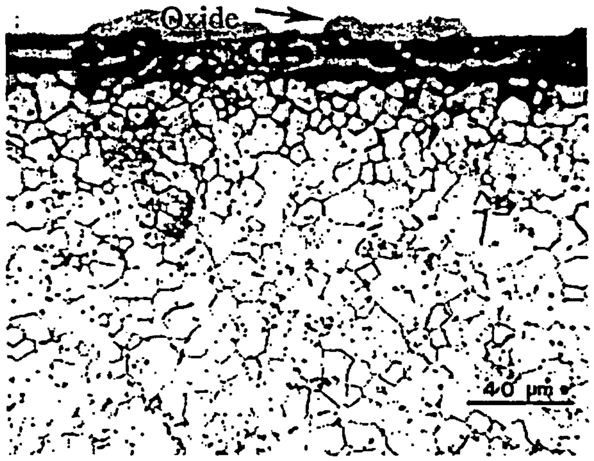

**As-Polished CANLUB Element**



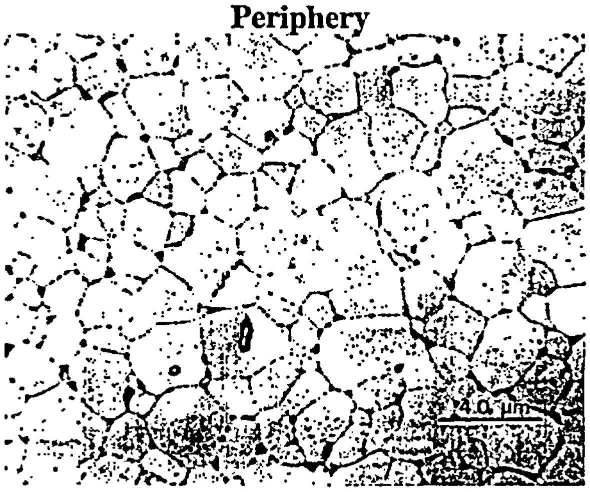

**As-Polished Non-CANLUB Element**



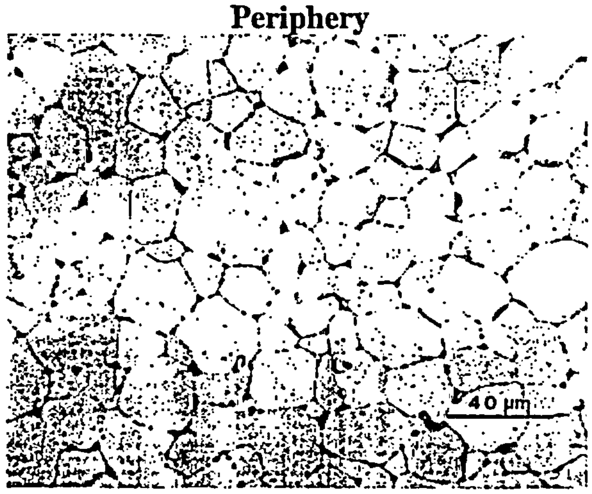

**Microstructure at CANLUB Element Periphery**




**Microstructure at Non-CANLUB Element Periphery**




**Microstructure at CANLUB Element Centre**




**Microstructure at Non-CANLUB Element Centre**

**Figure 6. Typical Microstructural Features**