Recent Irradiations And Pie Supporting The Development Of Advanced CANDU UO_2 Fuel Technology

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ABSTRACT

Since 1994, AECL has undertaken several irradiation tests in the U1 and U2 loops of the NRU reactor, including post-irradiation examination (PIE) in the Chalk River hot cell facilities.

Advanced CANDU® UO_2 fuel technology development over the past 10 years can be categorized in three broad areas: (i) development of the 43-element CANFLEX fuel bundle, (ii) extended-burnup technology, and (iii) low-void-reactivity fuel (LVRF) technology.

This paper reviews irradiations and PIE supporting the development of advanced fuel technologies in these broad areas.

NRU LOOP TEST FACILITIES

The tests described in this paper were conducted in the U1 and U2 loop facilities in the NRU reactor. These loop facilities comprise three test sections, each containing a vertically oriented fuel carriage containing six full-size CANDU fuel bundles. The centre element is removed from each bundle to facilitate mounting on a tie rod. The axial flux in each test section is cosine-shaped, and can be varied by up to 25%, depending on the loading of driver fuel adjacent to the loop sites. The combination of varied loop fuel enrichment and flux is used to simulate powers achieved in commercial CANDU power reactors. For example, refuelling power ramps are simulated via irradiating bundles in low-flux axial positions 1 or 6, and relocating them to high-flux positions 3 or 4. The U1

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and U2 loops are light water cooled, having conditions (temperature, pressure and chemistry) simulating that in CANDU commercial power reactors. Coolant temperatures are typically in the range of 260-305 ^{o}C at pressures of 9.5-10.9 MPa. Underwater visual inspections take place in the NRU irradiated fuel bay.

TYPICAL PIE ACTIVITIES

Following irradiation in the NRU loops, fuel is examined in the hot cell facilities at Chalk River Laboratories. Typical non-destructive examinations include:

- visual examination of both intact and disassembled bundles
- dimensioning of bundles and elements (sheath diameter, element bow, element length and endplate distortion)
- axial gamma scanning (illustrates axial burnup gradients, end-of-life fuel power gradients, end-flux peaking, fission-product segregation and pellet dish filling).

Typical destructive examinations include:

- internal gas analyses (determining internal gas volume and composition, % fission-gas release (FGR) and internal void volume)
- sheath hydrogen (H) and deuterium (D) analyses
- sheath metallography (examining microstructure and oxidation)
- pellet ceramography (examining microstructure and determining grain growth)
- chemical burnup measurement.

CANFLEX FUEL BUNDLE DEVELOPMENT AND QUALIFICATION

The qualification of the 43-element CANFLEX fuel bundle included irradiation testing and PIE under tests designated as BDL-437, BDL-440 and BDL-443. These tests included operation over a wide range of powers and burnups that bounded the high-power envelope for UO_2 fuel cycles and simulated power ramps encountered during refuelling operations. AECL has also developed a demountable CANFLEX fuel bundle for use in test irradiations in the NRU reactor. This technology is presently being demonstrated in the DME-222 irradiation test. Highlights of the BDL-437, BDL-440, BDL-443 and DME-222 tests are given below.

BDL-437 CANFLEX Irradiation Tests.

BDL-437 bundles are of the CANFLEX Mk III design (having an earlier CHF-enhancing button design) and contain 2.5 wt.% ^{235}U UO_2 fuel pellets. Bundles AJK and AJN were irradiated in the U1 and U2 loops during 1994-1997 at very high powers (significantly exceeding those typical of CANDU UO_2 fuel cycles). Figure 1 shows that AJK and AJN achieved outer element sustained maximum powers of 70-73 kW/m and burnups of 372-555 MWh/kgU. PIE was conducted on bundles AJK and AJN, which confirmed that there were no fuel failures or unexpected behaviour. The performance of these CANFLEX fuel bundles is similar to that observed in 37-element fuel operating at similar linear element ratings. The BDL-437 irradiation tests demonstrate that the CANFLEX bundle is capable of withstanding high power operation (>70 kW/m) to extended burnup (> 550 MWh/kgU).

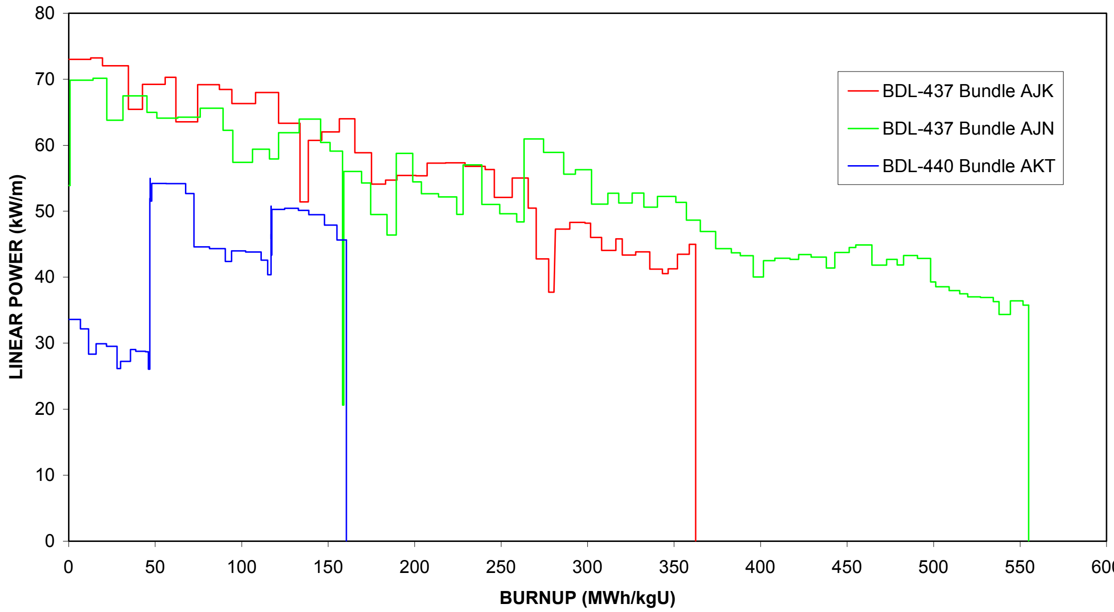

FIGURE 1: OUTER ELEMENT POWER HISTORIES FOR BDL-437 and BDL-440 BUNDLES AJK, AJN and AKT

BDL-440 CANFLEX Irradiation Tests.

BDL-440 bundle AKT is of the CANFLEX Mk IV design and contains 1.85 wt.% ^{235}U UO_2 fuel pellets. Bundle AKT was irradiated in the U2 loop during 1998-1999 under power ramp conditions. Figure 1 shows that the outer elements of AKT sustained power ramps to 59 kW/m and 55 kW/m at burnups of 51 MWh/kgU and 127 MWh/kgU (respectively).

PIE was conducted on bundle AKT, which confirmed that there were no fuel failures or unexpected behaviour. The performance of CANFLEX bundle AKT is similar to that observed in 37-element fuel operating at similar linear element ratings. The BDL-440 irradiation test demonstrates that the CANFLEX bundle is capable of withstanding power ramps typical of a natural UO_2 fuel cycle.

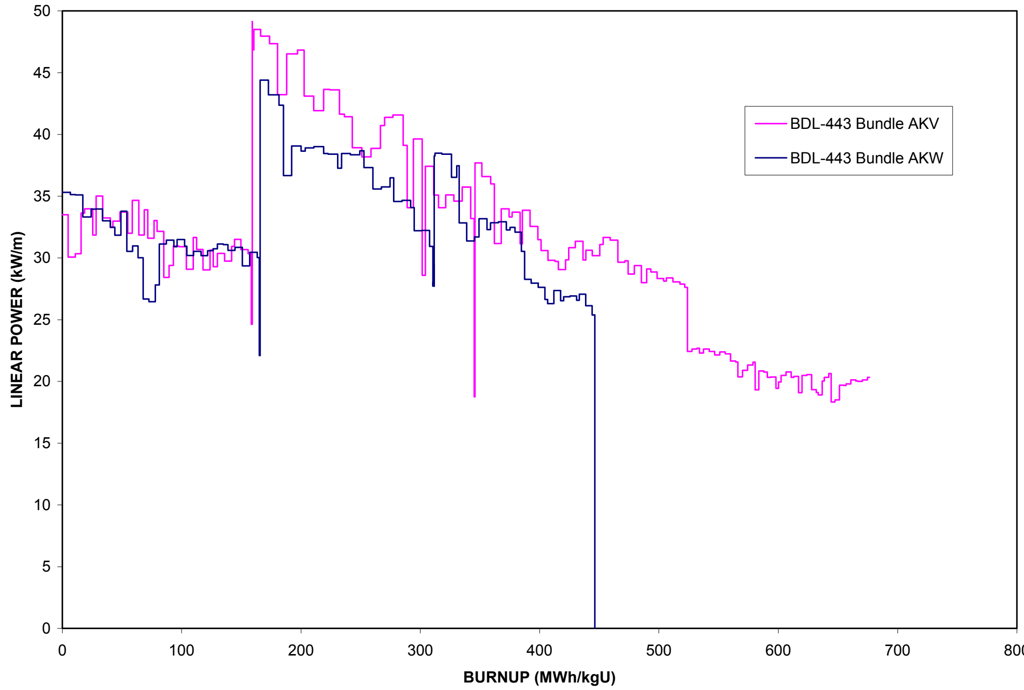

FIGURE 2: OUTER ELEMENT POWER HISTORIES FOR BDL-443 BUNDLES AKV and AKW (IRRADIATION OF AKV IS CONTINUING TO 1000 MWh/kgU)

BDL-443 CANFLEX Irradiation Tests.

BDL-443 bundles are of the CANFLEX Mk IV design and contain 1.65 wt.% ^{235}U UO_2 fuel pellets. Bundles AKV and AKW were irradiated in the U1 and U2 loops during 1999-2003 to outer element burnups of approximately 450 MWh/kgU (Figure 2). The irradiation of AKV is presently being extended to 1000 MWh/kgU (675 MWh/kgU as of 2005 September), to support extended burnup applications. The irradiation of bundles AKV and AKW simulate power ramps representative of 2-bundle shifts with extended burnup SEU fuel (Table 1). PIE of bundle AKW is pending.

TABLE 1: POWER RAMP DATA FOR BDL-443 BUNDLES AKV AND AKW

Bundle	Ramp Burnup (MWh/kgU)	Initial Power* (kW/m)	Final Power (kW/m)	ΔP (kW/m)
AKV	159	30	49	19
	345	33	38	5
AKW	165	30	44	14
	311	31	38	7

*Note: Initial power is the power at the end of the pre-ramp irradiation.

FIGURE 3: THE CANFLEX DEMOUNTABLE BUNDLE SHOWING DEMOUNTABLE OUTER AND INNER ELEMENTS

CANFLEX Demountable Bundle Development (DME-222).

Demountable element bundles facilitate the removal/replacement of individual elements at different stages of irradiation to study performance as a function of burnup. The standard demountable 37-element geometry bundle has only demountable 13.1 mm diameter outer elements and has been utilized successfully in irradiation tests in the NRU reactor for many years (e.g., DME-214 and DME-217 tests described later in this paper).

AECL has designed and developed a new CANFLEX demountable bundle. The CANFLEX demountable bundle (Figure 3) incorporates demountable outer elements (11.5 mm in diameter), as well as demountable inner elements (13.5 mm in diameter). Out-reactor vibration testing and pressure-drop measurements were completed successfully in 2000, as part of bundle qualification for NRU irradiation. During 2003, an in-reactor demonstration of the CANFLEX demountable bundle commenced under the DME-222 test. This test is taking place in five stages to 50, 150, 300, 500 and 700 full-power days (FPD) to demonstrate the suitability of the DME bundle for a range of test conditions. Special tooling was developed for handling, disassembly and reassembly of the bundle in the NRU irradiated fuel bay and CRL hot cells. Testing to 50 FPD was completed in 2003 and followed by complete disassembly and visual examination in the hot cells. No evidence of unusual fretting wear was observed. Testing to 150 FPD was completed in 2004 and followed by complete underwater disassembly and visual examination in the NRU irradiated fuel bay. No evidence of unusual fretting wear was observed.

CANFLEX demountable bundles will be used in new experimental fuel tests scheduled to commence in 2005/2006.

EXTENDED BURNUP TECHNOLOGY DEVELOPMENT

An extensive review of extended-burnup CANDU fuel performance was presented at the 7th CANDU Fuel Conference (2001) [1]. This paper focuses on recent irradiation tests and PIE supporting extended-burnup technology, including DME-217, BDL-445 and BDL-448.

Pellet Geometry Tests (DME-217).

The DME-217 test utilized demountable 37-element geometry bundle technology having demountable 13.1 mm diameter outer elements (1.4 wt.% ^{235}U). The primary objective of the DME-217 test was to study the effect of pellet geometry and internal void volume on key performance parameters, such as fission-gas release and sheath strain as a function of burnup. This understanding is important in optimizing the fuel element design for extended burnup fuel performance and for power ramp performance.

The DME-217 test comprises elements having pellets of varied length and chamfer angle/depth (at the pellet ends). DME-217 elements were irradiated during 1998-2002 at sustained maximum powers of 61 kW/m to burnups of approximately 200, 500 and 700 MWh/kgU (Figure 4). Since 2002, selected elements have continued irradiation to 1000 MWh/kgU.

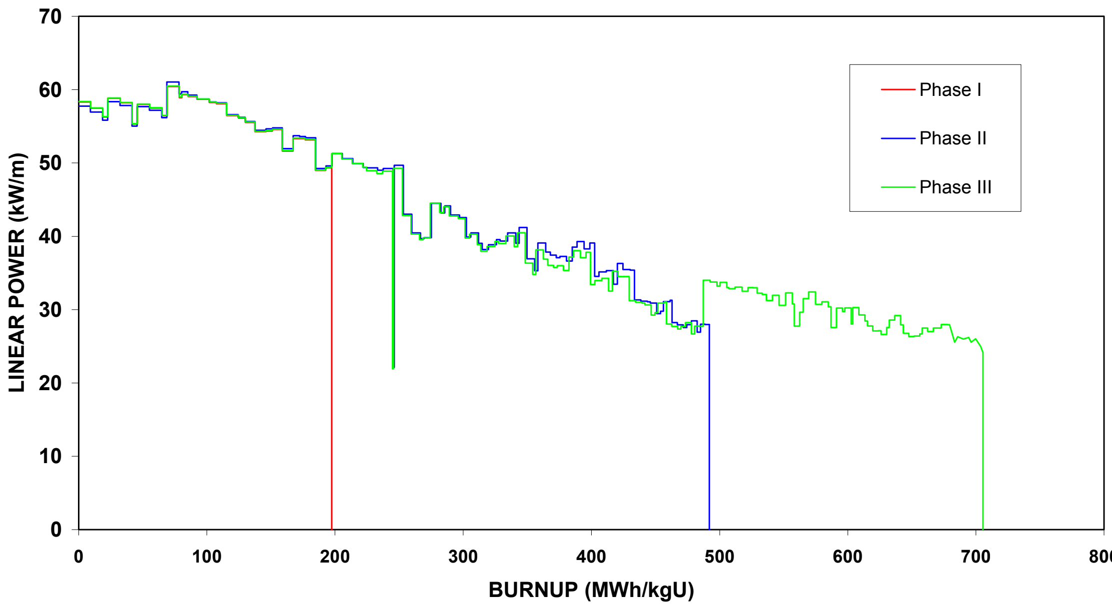

FIGURE 4: DME-217 POWER HISTORIES SHOWING ELEMENTS IRRADIATED TO ~ 200, 500 & 700 MWh/kgU (Phases I, II & III)

Power-Ramp Tests (BDL-445).

The BDL-445 experiment was designed to better define power ramp defect thresholds at extended burnup, to validate a new stress corrosion cracking (SCC) threshold prediction method [2], and to investigate the SCC behaviour of a new pellet design. BDL-445 bundles are of the CANFLEX Mk IV design and contain outer elements with varying pellet enrichments to facilitate achieving varying ramp powers within the same bundle. Bundles AMF, AMH and AMK have seven outer elements each of 1.3, 1.4 and 1.5 wt.% ^{235}U. Bundles AMJ and AML have seven outer elements each of 1.6, 1.8 and 2.0 wt.% ^{235}U. BDL-445 utilized one of the advanced pellet geometries used in the DME-217 experiment. This advanced pellet design reduces pellet-interface ridge strains, and reduces internal gas pressure (increased internal void space). The BDL-445 irradiation commenced in 2001 and is continuing.

The five BDL-445 bundles were initially irradiated at low, pre-ramp powers of 18-35 kW/m to outer element burnups of 100-210 MWh/kgU. Bundles AMF, AMH, and

AMJ were power ramped to sustained maximum powers of 39-50 kW/m. No failures occurred, as predicted by the new methodology. Bundle AML will be ramped to above the predicted defect threshold to sustained maximum powers of 55-64 kW/m (at burnups of 100-120 MWh/kgU). Ramp powers for bundle AMK will be selected based upon results from the ramp test of bundle AML.

Beyond the BDL-445 test, another series of power ramp tests is in the planning stages to further optimize the pellet shape for enhanced power-ramp (SCC) and extended burnup performance.

Power Envelope Tests (BDL-448).

The BDL-448 test comprises two CANFLEX Mk IV bundles with an advanced pellet design. The test was initiated in 2004 to demonstrate operation typical of extended burnup SEU fuel cycles. The first bundle (designated “ANS”) is simulating a high power envelope, gradually increasing in power from 42-59 kW/m to a burnup of 260 MWh/kgU, then declining to a power of 40 kW/m at a burnup > 700 MWh/kgU. The second bundle (ANT) will undergo a power ramp before continuing irradiation to a high burnup.

LVRF TECHNOLOGY DEVELOPMENT

Several tests have been completed in support of LVRF technology development, including the DME-214 demountable elements and four prototype bundle tests under BDL-436, BDL-438 and BDL-439. The highlights of the DME-214, BDL-436, BDL-438 and BDL-439 tests are summarized below. A new CANFLEX demountable bundle is expected to commence irradiation during 2005/2006 and includes the irradiation of elements with Dy-doped fuel at fission powers of up to 25 kW/m to burnups of 200 MWh/kgU.

LVRF Demountable Element Tests (DME-214).

The DME-214 test comprised the fabrication, irradiation and PIE of standard 13.1 mm diameter demountable elements. Twenty-one DME-214 elements were fabricated containing depleted uranium (DU, 0.3 wt.% ^{235}U) and natural uranium (NU) UO_2 fuel pellets, having varying dysprosium (Dy) contents of 0-15% (100% x wt.Dy/wt.U). The DME-214 elements were irradiated during 1994-1998 at fission powers of 2-24 kW/m to burnups of 7-249 MWh/kgU. All elements experienced gradually increasing powers (with increasing burnup), as a result of the burnout of Dy (Figure 5). Fifteen DME-214 elements were examined in the hot cells following irradiation. Performance was benign, as expected given the low operating powers.

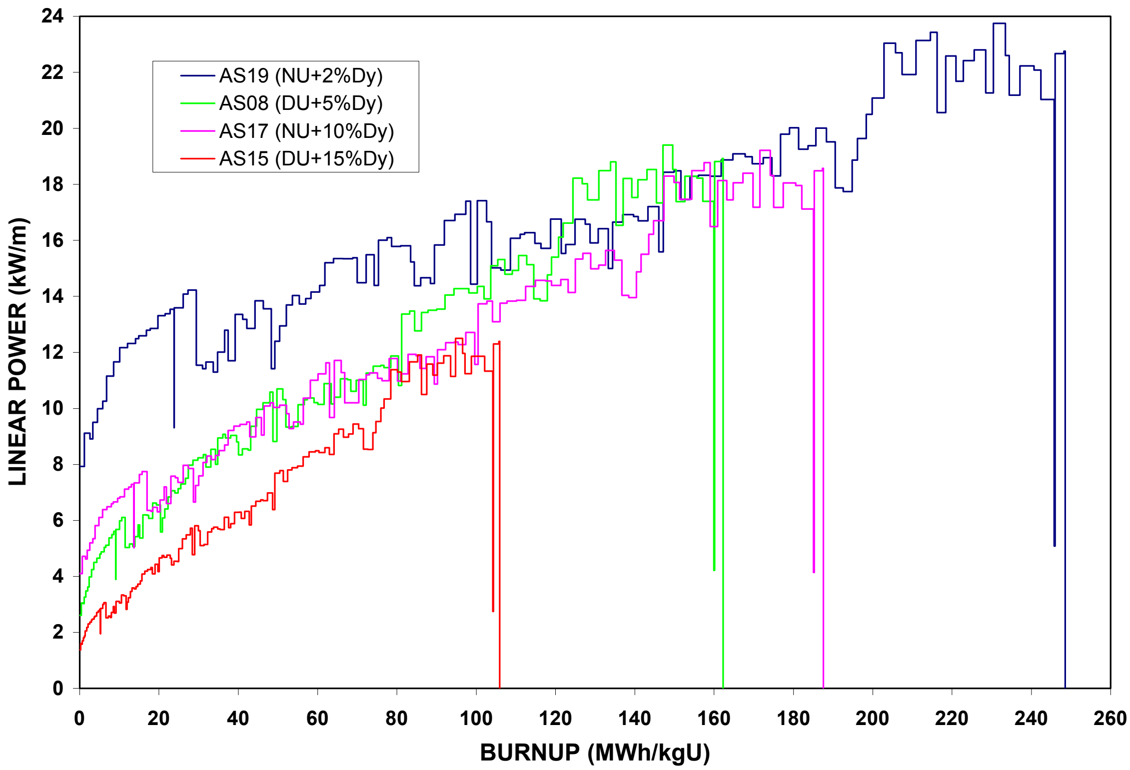

FIGURE 5: POWER HISTORIES FOR LVRF DEMOUNTABLE ELEMENTS AS08, AS15, AS17 AND AS19 (DME-214)

LVRF Prototype Bundle Irradiations (BDL-436, BDL-438 and BDL-439).

Four LVRF bundles were irradiated in the U1 and U2 loops between 1994 and 1998. Table 2 gives design and operating data for the tests known as BDL-436 (CANDU-6 geometry bundle AHX), BDL-438 (CANDU-6 geometry bundle AJR) and BDL-439 (CANFLEX Mk IV bundles AKK and AKG). These bundles contained 1.32-2.67% SEU UO_2 fuel pellets in the outer and intermediate rings and NU or DU UO_2 fuel pellets with 1.88-2.00% Dy in the inner ring.

The SEU-bearing outer elements achieved sustained maximum powers up to 68 kW/m and burnups of 324 MWh/kgU. Sheath strain and FGR were as expected based on other experience with UO_2 and Dy-bearing fuel elements. Dimensional measurements (including element lengths, element bowing and endplate distortion) were conducted; in spite of large radial power gradients, dimensional changes in the bundles were similar to those observed in other CANDU fuel bundles irradiated in NRU and CANDU power reactors.

TABLE 2: DESIGN AND OPERATING DATA FOR LVRF BUNDLES

Experiment	Bundle	Element	Type	Power (kW/m)	Burnup (MWh/kgU)
BDL-436	AHX	Outer	1.87% SEU	68	318
		Intermediate	1.32% SEU	35	185
		Inner	DU+2%Dy	11	55
BDL-438	AJR	Outer	1.35% SEU	59	324
		Intermediate	1.92% SEU	50	261
		Inner	DU+2%Dy	14	70
BDL-439	AKK	Outer	2.08% SEU	36	175
		Intermediate	2.67% SEU	28	132
		Inner	NU+1.88%Dy	9	31
	AKG	Outer	2.08% SEU	51	181
		Intermediate	2.67% SEU	41	138
		Inner	NU+1.88%Dy	16	33

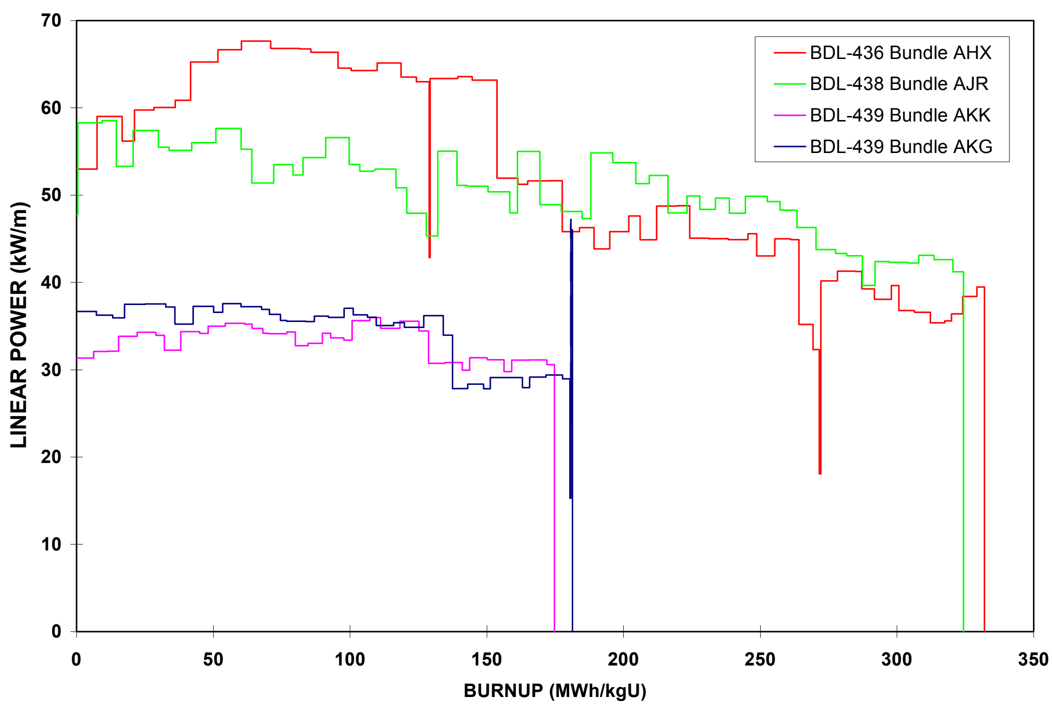

FIGURE 6: OUTER ELEMENT POWER HISTORIES FOR LVRF PROTOTYPE BUNDLES AHX, AJR, AKK AND AKG.

BDL-439 bundle AKG was power ramped from 29 kW/m to 51 kW/m at a burnup of 181 MWh/kgU (Figure 6). Three outer elements experienced SCC failures approximately 7.5 hours after the ramp. This experience has contributed to improved understanding of SCC defect thresholds at burnups > 150 MWh/kgU.

SUMMARY

In the past 10 years, AECL has conducted irradiation tests and PIE supporting the development of advanced CANDU UO_2 fuel technology. This has included:

- development and qualification of the 43-element CANFLEX fuel bundle under high power, high burnup and power ramp conditions
- extended burnup technology development, including testing of advanced pellet designs
- low-void-reactivity fuel technology development, including prototype bundle irradiations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of numerous AECL staff that have contributed to the success of the irradiations and PIE reviewed in this paper. This includes staff from the Reactor Core Technology Division (Fuel Development Branch, Fuel Design Branch and Reactor & Radiation Physics Branch), Thermalhydraulics Branch, NRU Operations and Nuclear Facilities Operations (hot cells).

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