End-Flux Peaking Experiment in the ZED-2 Reactor using CANFLEX-RU

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Abstract

This paper describes an end-flux peaking experiment performed in the Zero Energy Deuterium reactor (ZED-2) that provides data appropriate for validating code predictions used for qualification of CANFLEX-RU[1] fuel in CANDU®[2]. The experiment involved the substitution of 7 channels of CANFLEX-RU test assemblies into a natural uranium driver lattice, with a 'demountable' CANFLEX-RU bundle positioned in the centre of the central RU channel. Copper foils positioned between adjacent fuel pellets within the demountable bundle were used to derive end-flux peaking factors appropriate for CANFLEX-RU fuel.

Experimental results are presented and compared to predictions from the reactor physics code MCNP.

1. Introduction

Recovered Uranium (RU) fuel is derived from reprocessing spent Light Water Reactor (LWR) fuel, resulting in a slight net enrichment in ^{235}U (~0.9 wt% U^{235} in total U). A fuel cycle based on recycling LWR fuel through a CANDU reactor provides increased fuel economy. Additionally, the RU enrichment will increase the core-average discharge burn-up relative to Natural Uranium (NU) fuel, resulting in a decrease in spent fuel volume. The CANFLEX® design can accommodate these increased burn-ups, and a fuel cycle based on RU with the CANFLEX fuel carrier is referred to as CANFLEX-RU. The features of CANFLEX-RU combine to produce a cost effective fuel cycle for CANDU.

A previous paper [1] describes some of the history behind the reactor physics experimental program on CANFLEX-RU, and contains further information on the RU fuel and fuel cycle.

CANFLEX-RU bundles were assembled for testing in the ZED-2 [2] reactor. The ZED-2 experimental test components include Coolant Void Reactivity (CVR) measurements [1], Fuel Temperature Coefficient (FTC) measurements [1], fine-structure reaction-rate measurements, and end-flux peaking measurements. This paper presents results from the end-flux peaking measurements and includes analyses and a discussion of those results. Note that a companion paper at these proceedings describes fine-structure reaction rate measurements using CANFLEX-RU [3].

2. ZED-2 reactor

A significant component of the validation of the CANDU reactor physics lattice codes is based on comparison of code predictions to measurements performed in ZED-2.

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[1] CANFLEX® (CANDU FLEXible fuelling) is a registered trademark of AECL and the Korea Atomic Energy Research Institute (KAERI). These experiments used CANFLEX bundles containing Recovered Uranium (RU) fuel (CANFLEX-RU bundles).
[2] CANDU® (CANada Uranium Deuterium) is a registered trademark of AECL.

The ZED-2 calandria vessel, as shown in Figure 1, is a cylindrical tank with a 3.36 m inner diameter and 3.33 m depth. It is surrounded by graphite blocks arranged with an average thickness of ~60 cm radially and 90 cm below the tank. Fuel assemblies are hung vertically from beams located above the calandria.

The reactor is made critical by pumping heavy water moderator into the calandria, and power is controlled by adjusting the moderator level. Typical moderator critical levels range from 150 to 250 cm above the calandria floor. The maximum power is about 200 watts (nominal), corresponding to an average neutron flux of about 10^9 n/cm^2/s.

3. Measuring End-Flux Peaking Factors

3.1 Methodology

The end-flux peaking factors presented here are based on measured copper activation ratios. Because the core is not infinite, each measured activity is multiplied by $A(z_0)/A(z)$ to correct the data to a common elevation z_0 in the lattice (See section 3.2.3). After applying this correction, the measured end-flux peaking factor is calculated as

$$\text{Measured end-flux peaking factor} = \frac{E_{0\,cm}}{E_{10-25\,cm}} \qquad \text{Eq. 1}$$

where $E_{0\,cm}$ is the activity measured at the end of the fuel stack (adjacent to the pellet end-stop) and $E_{10\text{-}25\,cm}$ is the average measured activity at the axial centre of the bundle, away from end-flux peaking effects.

3.2 Experimental Set-up

3.2.1 Lattice Description

Figure 2 is a top view of the lattice used for the study. It comprised 55 assemblies arranged hexagonally with a 31-cm centre-to-centre spacing. The outer 48 sites were occupied by reference assemblies, each comprising five 28-element fuel bundles[3] within aluminum channels. The seven centre sites were occupied by the CANFLEX-RU test assemblies, as depicted in Figure 3 and Figure 4. The seven test assemblies each contained five CANFLEX-RU bundles (35 bundles total) with Zr-Nb Pressure Tubes (PTs) and Zircaloy-2 Calandria Tubes (CTs). The radial dimensions of the PTs and CTs (referred to as CANDU-type channels in this paper) are identical to those of the CANDU-6 PT and CT. The assemblies have bottom openings that allow heavy water to enter the pressure tubes as moderator is pumped into the ZED-2 calandria.

Although the test-fuel bundle geometry is CANFLEX, there are no appendages attached to the fuel sheaths (*i.e.*, no spacers and bearing pads). The absence of bearing pads necessitated the use of zirconium-wire clips (two clips per bundle) to centre the bundles in the channel PTs (see also Figure 3 and Figure 4).

[3] The 28-element fuel bundles are representative of 28-element production fuel, but lack any appendages, and are bolted together with two aluminum endplates.

3.2.2 Demountable Bundle

A special demountable bundle was fabricated for these tests so that copper activation foils could be placed within specific elements of the bundle. The bundle has essentially the same dimensions and element configuration as rest of the CANFLEX-RU bundles, but is modified to have seven removable elements located along an approximate diameter of the bundle. These elements are each outfitted with a resistance-welded endcap and removable endcap, providing access for loading activation foils between the fuel pellets. The bundle halves are held together with two zirc-wire clips fitted around the outer fuel elements.

Figure 5 shows a plan view of the assembled bundle depicting the location of the seven removable elements, as well as the zirc clips.

Copper foils were loaded within each demountable element, from the fuel end-stop of the resistance-welded endcap to the bundle mid-plane. Prior to loading the demountable bundle, the copper foils were wrapped in aluminum to prevent their contamination by the fuel. The aluminum was removed before counting copper activities.

3.2.3 Core Axial Flux Measurements

Copper foils were suspended axially within the lattice along the cell boundary of the central lattice site (See Figure 2) using “stringers”. The stringers consisted of aluminum backing plates to which the foils were attached, connected by zirconium wires. These foils were positioned at 10 cm axial intervals at locations from 15 cm above the calandria floor to the moderator surface.

These foils were used to measure the core axial flux profile. A cosine function was fitted to the measured axial flux:

$$A(z)=A_0\cos\left(\alpha\left(z-Z_{max}\right)\right) \qquad \text{Eq. 2}$$

where:

- $A(z)$ is the fitted activity at elevation z above the reactor floor,
- A_o is the normalization constant,
- α is the square root of the axial buckling, and
- Z_{max} is the axial position of maximum flux.

As discussed in Section 3.1, the fitted activity derived from Eq. 2 is used to correct the activities measured within the demountable bundle to a common elevation.

4. Results

The copper activation data measured on the ”stringers” located at the cell boundary of the central lattice site are listed in Table 1 and shown in Figure 6. The parameters for the cosine fit are listed in Table 2.

Table 3 lists the relative activation data obtained from the demountable bundle, corrected to a common elevation of z_0 = 85.0 cm. The measured end-flux peaking factors are listed in Table 3.

5. Comparison to MCNP

MCNP [6] was used to calculate the axial flux profile within a CANFLEX-RU bundle to compare against the experimental results, including calculation of end-flux peaking factors. The MCNP model consisted of single bundle within a channel, surrounded by moderator. The model extended to reflective boundaries at the perimeter of the hexagonal lattice cell on the sides, and to periodic boundaries at the outer edges of the bundle endplates on the top and bottom. This represents an infinite lattice of CANFLEX-RU assemblies, but the error introduced by this approximation has been found to be negligible. Figure 7 compares the MCNP results to the experiment, and Table 4 lists calculation to measurement (C upon E) ratios for the end-flux peaking factors in each of the seven elements.

6. Comparison of End-Flux Peaking in RU vs. NU fuel

The end-flux peaking factors measured in the CANFLEX-RU bundles are compared to those previously measured for 37-Element NU fuel [7] in Table 5. The results show an increase in end-flux peaking for the CANFLEX-RU fuel (3-5%). This result is consistent with the increased atom density of ^{235}U in the RU fuel, resulting in a larger total absorption cross-section of thermal neutrons compared to the NU fuel.

7. Conclusions

End-flux peaking experiments were conducted using CANFLEX-RU fuel bundles in ZED-2. The results show that there is a slight enhancement of end-flux peaking (3-5%) in the CANFLEX-RU fuel as compared to NU fuel, as expected for the higher enrichment in RU fuel. Agreement between the experimental results and MCNP predictions are within ~1-2%, where past experience indicates uncertainties in the experimental data are also ~1-2% due to counting statistics and foil positioning. This shows that there is good agreement between calculation and experiment.

8. References

[1] J.E. Atfield and M.B. Zeller, "Physics Experiments in the ZED-2 Reactor using CANFLEX-RU", 31st Annual Conference of the Canadian Nuclear Society, Montreal, Quebec. 2010 May.

[2] "ZED-2", AECL Report, AECL-2132, 1964.

[3] M.B. Zeller and J.E. Atfield, "Comparison of Calculated and measured Fine-Structure Reaction Rate Data from CANFLEX-RU in ZED-2", Current Proceedings.

[4] M.B. Zeller et al., "Void-Reactivity Measurements in the ZED-2 Reactor using the Substitution Method", Fifteenth Annual Conference of the Canadian Nuclear Society, Montreal, PQ, Canada. 1994 June.

[5] M.B. Zeller et al., "High Temperature Physics experiments using UO_2 and Simulated Irradiated CANDU-Type Fuel in the ZED-2 Reactor", Twenty-First Annual Conference of the Canadian Nuclear Society, Toronto, Ontario, Canada. 2000 June.

[6] "MCNP – A General Monte Carlo N-Particle Transport Code", Version 5 Los Alamos National Laboratory Report, LA-UR-03-1987, 2003 April.

[7] P.M. French, "Measurements of Bundle End Flux Peaking Effects in 37-Element CANDU PHW Fuel", AECL Report, AECL-5968, 1977 October.

9. Acknowledgements

The authors acknowledge the contribution of our technologist Greg Morin in planning and performing the experiments.

Table 1: Axial Flux Measurements at Centre Lattice Site Boundaries

Elevation (cm)	**Relative Flux (West Boundary)**	**Relative Flux (East Boundary)**
175.0	**0.0690**	**0.0694**
165.0	**0.2523**	**0.2520**
155.0	0.4110	0.4105
145.0	0.5508	0.5495
135.0	0.6781	0.6782
125.0	0.7873	0.7901
115.0	**0.8789**	**0.8834**
105.0	0.9398	0.9460
95.0	0.9827	0.9839
85.0	1.0000	1.0000
75.0	0.9908	0.9949
65.0	**0.9609**	**0.9603**
55.0	0.8997	0.9007
45.0	0.8124	0.8151
35.0	0.7139	0.7127
25.0	**0.6074**	**0.6063**
15.0	**0.5094**	**0.5087**

Note: Values in bold are close to the core axial boundaries or bundle-to-bundle junctions, and were not used for cosine fit to the data.

Table 2: Cosine Fit Parameters for Axial Flux Profile

A_0	α(m^{-1})	z_{max}(m)
1.0037 ± 0.0007	0.01606 ± 0.00002	83.51 ± 0.07

Table 3: Measured Relative Flux within Demountable Elements

Elevation (cm)	Element #1	Elevation (cm)	Element #2	Elevation (cm)	Element #3	Elevation (cm)	Element #4	Elevation (cm)	Element #5	Elevation (cm)	Element #6	Elevation (cm)	Element #7
0.00	1.4931	0.00	1.2557	0.00	1.1046	0.00	1.0494	0.00	1.0702	0.00	1.2566	0.00	1.4863
1.05	1.3662	1.05	1.1140	1.05	0.9662	1.05	0.9197	1.05	0.9385	1.00	1.1142	1.05	1.3590
2.10	1.3329	2.10	1.0634	2.10	0.9204	2.10	0.8724	2.05	0.8827	2.00	1.0575	2.10	1.3245
3.10	1.3078	3.15	1.0453	3.10	0.8970	3.10	0.8453	3.05	0.8656	3.05	1.0388	3.10	1.3087
4.15	1.3000	4.20	1.0329	4.15	0.8770	4.15	0.8260	4.10	0.8497	4.10	1.0230	4.15	1.2971
5.15	1.2852	5.20	1.0217	5.15	0.8739	5.15	0.8176	5.15	0.8355	5.15	1.0195	5.15	1.2928
6.20	1.2847	6.25	1.0202	6.20	0.8664	6.20	0.8115	6.20	0.8314	6.20	1.0112	6.20	1.2875
7.20	1.2779	7.25	1.0132	7.25	0.8632	7.20	0.8115	7.20	0.8413	7.20	1.0076	7.25	1.2831
8.25	1.2814	8.25	1.0116	8.30	0.8590	8.25	0.8047	8.25	0.8355	8.25	1.0032	8.25	1.2696
9.25	1.2714	9.30	1.0061	9.30	0.8591	9.30	0.8020	9.25	0.8304	9.25	1.0016	9.30	1.2753
10.30	1.2699	10.35	1.0023	10.40	0.8550	10.35	0.8018	10.30	0.8296	10.30	0.9983	10.30	1.2709
11.30	1.2667	11.40	1.0074	11.40	0.8536	11.40	0.8000	11.30	0.8309	11.35	0.9968	11.35	1.2714
12.35	1.2612	12.45	1.0041	12.45	0.8561	12.40	0.8014	12.35	0.8274	12.35	0.9937	12.35	1.2690
13.40	1.2551	13.45	1.0062	13.45	0.8532	13.45	0.8028	13.40	0.8333	13.40	0.9964	13.40	1.2606
14.40	1.2514	14.50	1.0003	14.55	0.8548	14.50	0.8019	14.40	0.8317	14.45	0.9945	14.50	1.2636
15.45	1.2568	15.55	1.0006	15.55	0.8542	15.55	0.8011	15.40	0.8343	15.50	0.9933	15.50	1.2618
16.50	1.2580	16.55	1.0022	16.60	0.8504	16.55	0.7997	16.45	0.8366	16.50	0.9901	16.50	1.2538
17.50	1.2495	17.60	1.0009	17.65	0.8514	17.60	0.7994	17.45	0.8369	17.55	0.9885	17.55	1.2586
18.55	1.2566	18.65	1.0046	18.70	0.8499	18.65	0.7977	18.50	0.8387	18.55	0.9895	18.55	1.2577
19.55	1.2507	19.65	1.0013	19.70	0.8519	19.65	0.7966	19.50	0.8392	19.60	0.9907	19.60	1.2598
20.60	1.2451	20.70	0.9978	20.75	0.8543	20.70	0.7961	20.55	0.8406	20.65	0.9907	20.65	1.2601
21.60	1.2518	21.70	0.9990	21.80	0.8512	21.75	0.8007	21.55	0.8403	21.65	0.9888	21.65	1.2592
22.65	1.2497	22.75	0.9966	22.80	0.8522	22.75	0.7991	22.60	0.8457	22.70	0.9887	22.70	1.2655
23.65	1.2501	23.75	1.0004	23.85	0.8486	23.75	0.7996	23.60	0.8482	23.70	0.9893	23.70	1.2632
24.70	1.2479	24.80	0.9965	24.90	0.8484	24.80	0.8001	24.60	0.8482	24.75	0.9900	24.75	1.2628
25.70	1.2482	25.85	1.0014	25.95	0.8501	25.80	0.7999	25.70	0.8494	25.80	0.9877	25.80	1.2607
End-flux Peaking Factors:													
	1.1904		1.2540		1.2961		1.3120		1.2768		1.2671		1.1773

Table 4: Comparison between Calculated and Measured End-flux Peaking Factors

Element #	**End-flux Peaking Factors:**		**C Upon E**
	Experiment	**MCNP**	
1	1.1904	1.1613	0.9756
2	1.2540	1.2467	0.9942
3	1.2961	1.3124	1.0125
4	1.3120	1.3272	1.0116
5	1.2768	1.3044	1.0216
6	1.2671	1.2595	0.9940
7	1.1773	1.1668	0.9911

Table 5: Comparison of End-flux Peaking in CANFLEX-RU and 37-Element NU Fuel Bundles

Element #	**Average End-flux Peaking Factors**		**Ratio:**
	CANFLEX-RU	**37-Element NU**	
1 and 7	1.1838	1.1420	1.0366
2 and 6	1.2606	1.2050	1.0461
3 and 5	1.2865	1.2460	1.0325
4	1.3120	1.2680	1.0347

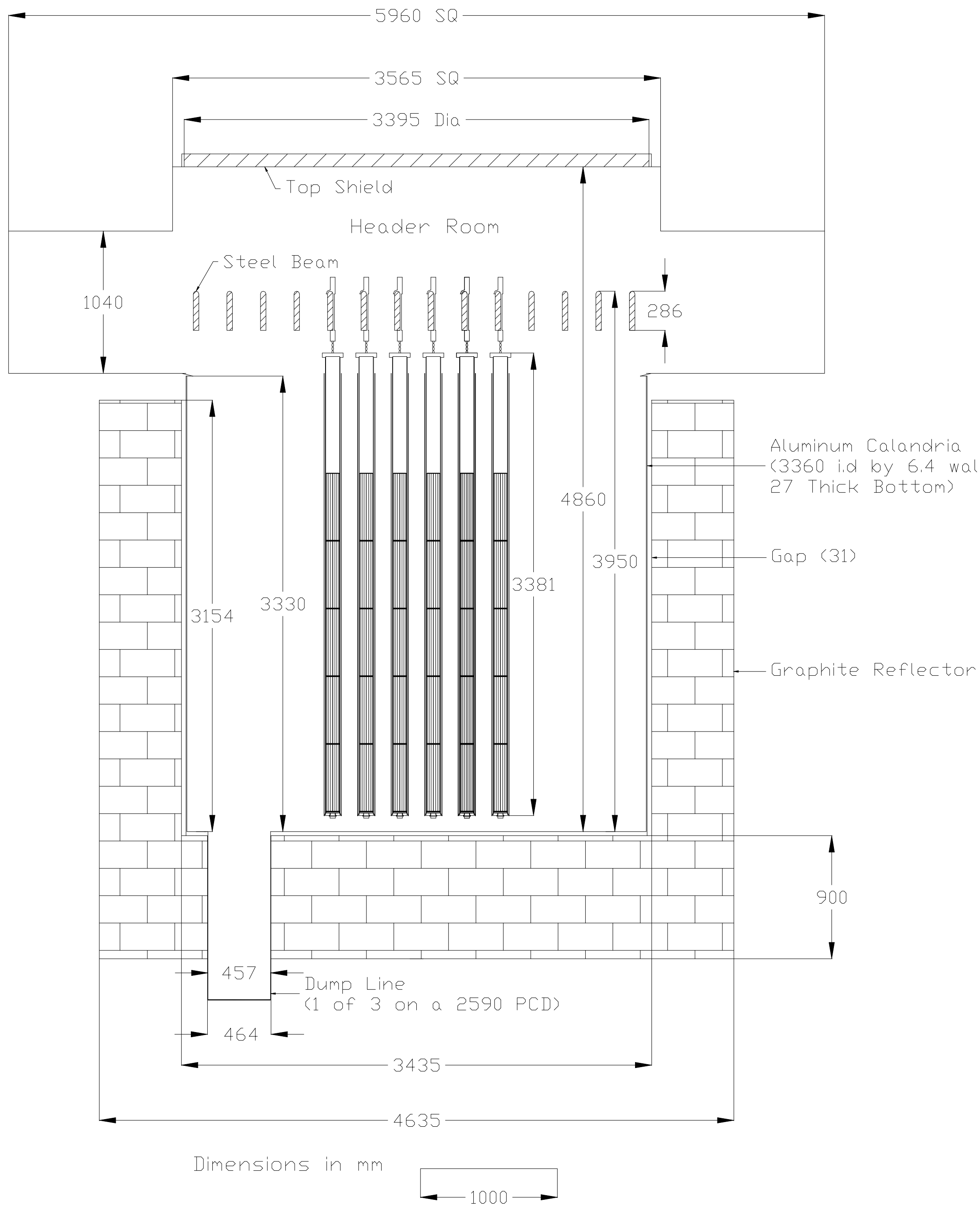

Figure 1 ZED-2 Reactor—Vertical Cross Section

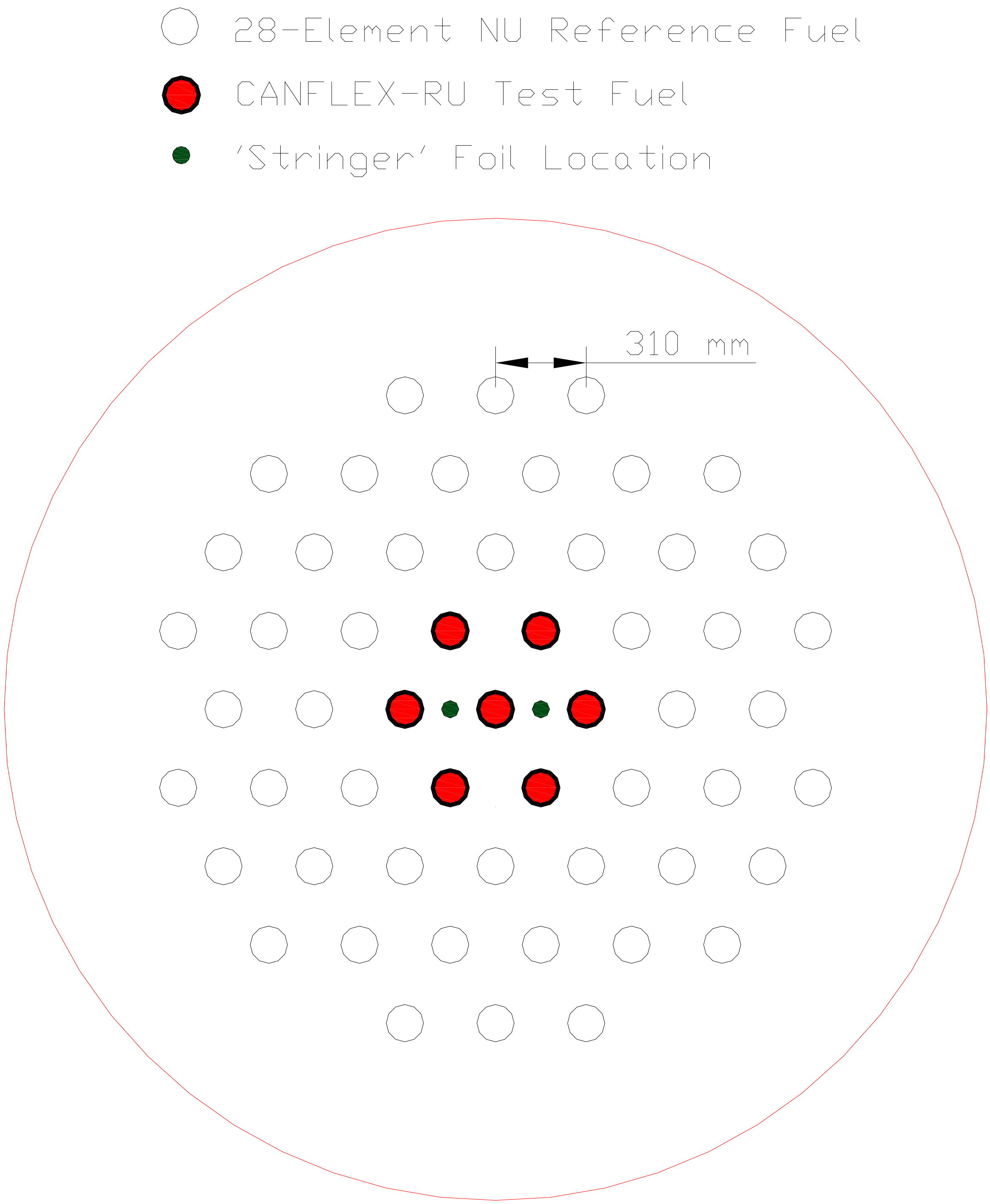

Figure 2 Top View of Test Lattice

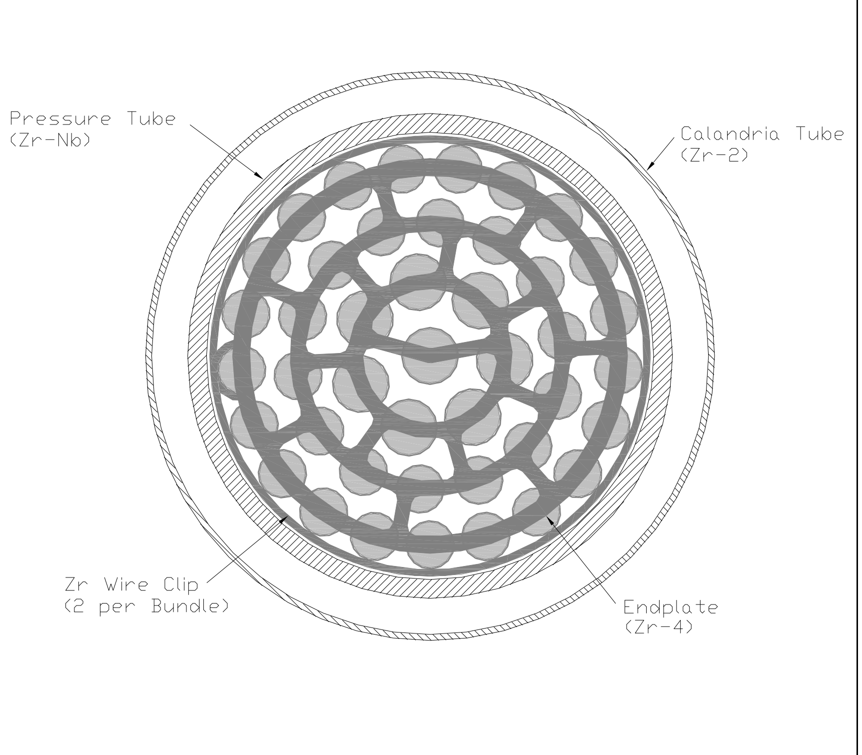

Figure 3 Top view of CANFLEX-RU in a CANDU-type Channel

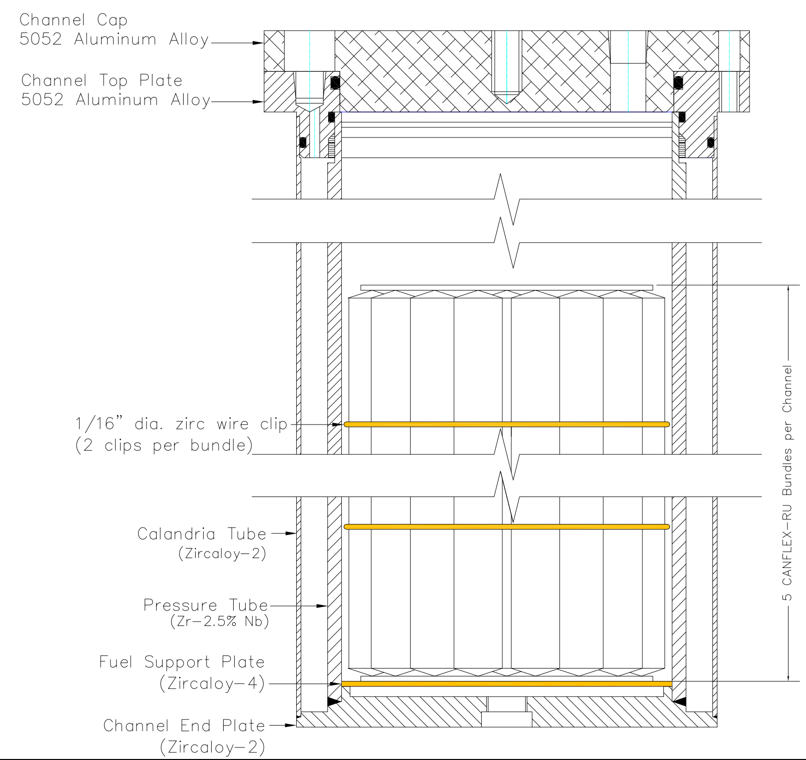

Figure 4 Side view of CANFLEX-RU in a CANDU-type Channel

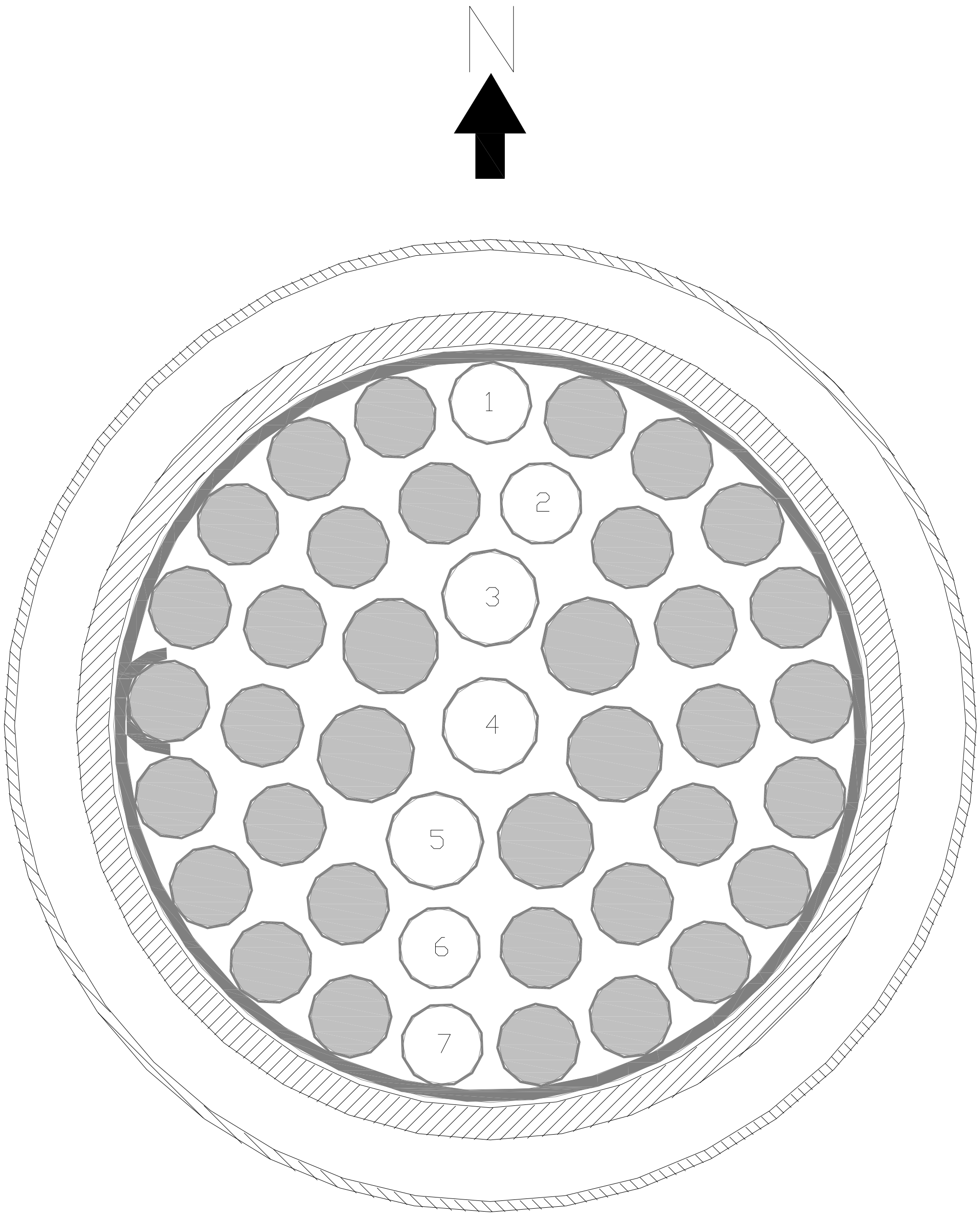

Figure 5 Location of Demountable Elements

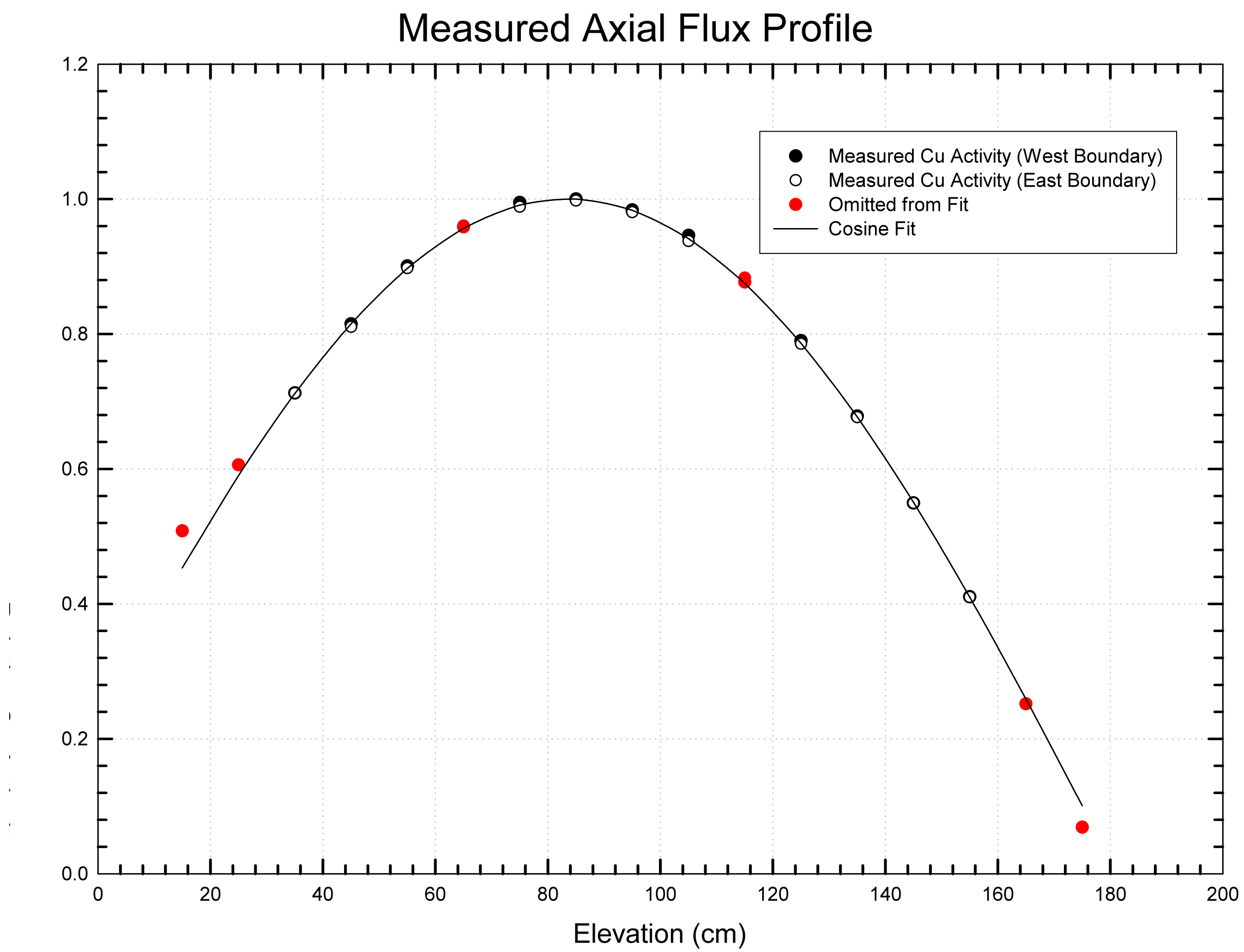

Figure 6 Axial Flux Profile of Experiment

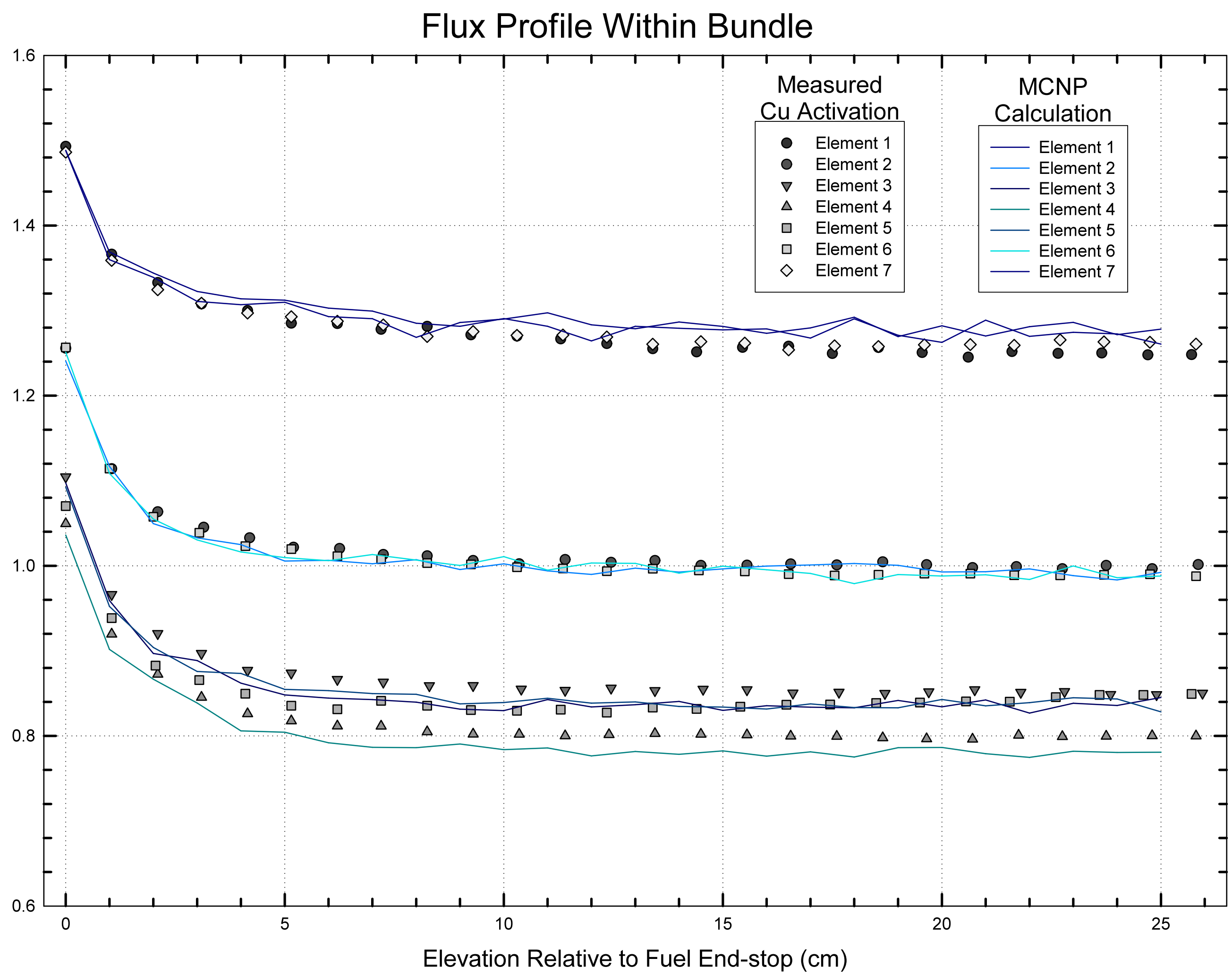
Flux Profile Within Bundle
Measured Cu Activation
Element 1
Element 2
Element 3
Element 4
Element 5
Element 6
Element 7
MCNP Calculation
Element 1
Element 2
Element 3
Element 4
Element 5
Element 6
Element 7
1.6
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
25
Elevation Relative to Fuel End-stop (cm)

Figure 7 End-Flux Peaking Measurements and Calculations