Comparison of Calculated and Measured Fine-Structure Reaction Rate Data from CANFLEX-RU in ZED-2

M.B. Zeller and **J.E. Atfield**
AECL Chalk River Laboratories, Chalk River, Ontario, Canada

Abstract

This paper describes an experiment performed in ZED-2 to provide data appropriate for validating lattice code predictions for qualification of CANFLEX-RU fuel in CANDU®. The experiment involved the measurement of fine-structure reaction rates in a CANFLEX-RU demountable bundle.

Experimental results are compared to calculations using the lattice code WIMS-IST.

1. Introduction

Recovered Uranium (RU) is derived from the reprocessing of spent Light Water Reactor (LWR) fuel. It is slightly enriched (~0.9 wt% U^{235} in total U) and a fuel cycle based on it using the CANFLEX® [1] fuel carrier is referred to as CANFLEX-RU [2].

The use of RU in CANDU represents a major departure from Natural Uranium (NU). For example, if the RU feed stock is not blended down the burn-up is at least doubled compared to NU, resulting in a much larger change in properties between fresh and discharged fuel. In addition, bundle radial power variations and end-flux peaking are more pronounced.

In a previous paper [2] we describe some of the history of the experimental program on CANFLEX- RU. Briefly, the test bundles were assembled at Chalk River in the Advanced CANDU Fuel Development Laboratory and the reactor-physics experiments were performed using Chalk River's ZED-2 reactor [3].

This paper presents results from fine structure measurements using a CANFLEX-RU demountable bundle and includes analyses and a discussion of these results. The experimental test components are as follows:

1) Capture-rate measurements using the materials Cu^{63}, U^{238}, Mn^{55}, Lu^{176}, In^{115} and Au^{197}.
2) Fission-rate measurements using the materials U^{235} and Pu^{239}.

Note that a companion paper at these proceedings describes End Flux Peaking measurements using CANFLEX-RU [4].

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 the ZED-2 reactor.

ZED-2 is a critical facility designed for studying the physics of heavy-water moderated lattices of natural uranium and other fuels. The reactor is made critical by pumping

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heavy water moderator into the calandria and power is controlled by adjusting the moderator level. The reactor is described in more detail in References [2] and [3].

3. Fine-Structure Reaction-Rate Measurements in CANFLEX-RU

3.1 Description of the CANFLEX-RU Test Assemblies

The RU was derived from spent LWR fuel. The uranium product used for the pellet manufacture was obtained from the UO_3 stockpile at Sellafield's Thermal Oxide Reprocessing Plant (THORP). The U^{235} content is 0.96 wt% of total uranium. Note that this U^{235} content is slightly higher than is typical for RU.

Figure 1 shows a plan view of a bundle inside a test assembly and Figure 2 shows an assembly side view. RU pellets were sheathed in Zircaloy-4 to form elements that were assembled into 43-element bundles. The bundle geometry is CANFLEX except that there were no appendages attached to the elements. Zircaloy-wire clips were used to centre the bundles inside the ZED-2 CANDU-type channel assemblies.

The demountable bundle is similar to the other 35 welded bundles. It is comprised of two welded bundle halves that allow for the removal of seven demountable elements located across the bundle diameter.

The demountable-element end caps have welded spigots for positioning the elements in the test bundle. The end caps are removable to allow for loading activation foils between the pellets in the elements.

3.2 Experimental Set Up

Only seven CANFLEX-RU test assemblies were available for this experiment (five bundles per assembly). A non-uniform critical lattice (see Figure 3) was used for the irradiation. The seven centre sites comprised the test region. The centre site contained the demountable bundle. The test region was surrounded by 48 NU driver assemblies.

The demountable bundle was loaded with activation foils containing the following detector materials: Cu, Au-Al alloy, In-Al alloy, Lu-Mn-Al alloy, natural-uranium metal, U^{235}-Al alloy, and Pu^{239}-Al alloy.

Stringers were positioned interstitially between the centre site and the two adjacent sites located east and west in the test region. The stingers were used to position non-fissile/fissionable activation foils at cell-boundary locations.

Two of each of the In-Al, Cu, Au-Al, and Lu-Mn-Al foils were taped to the outside of the calandria tube (CT), on the east and west side, and on the stringers. The stringers also positioned copper foils axially along the length of the test assemblies. The stringers axial Cu-capture data were used to adjust all of the activation data measured in the test region to a common elevation above the reactor floor.

An aluminum frame was attached to the centre site to position copper-wire sections radially into the moderator in two directions. One arm of the frame pointed northward towards the cell boundary separating two adjacent sites. Another arm pointed in a direction towards the centre of one of the adjacent sites. A third arm positioned wire sections along the cell boundary of the centre site. Figure 4 shows the frame details.

Two rotating aluminum reference wheels were positioned in the heavy-water reflector, well separated from the lattice (see Figure 3). One of the wheels had two of each type of activation foil and wire positioned around its perimeter. With this arrangement all of the activation foils and wire sections experienced the same time-average flux in a well-thermalized spectrum during the irradiation. The activation data measured on this wheel were used to normalize the activation data measured in the centre test region.

A second wheel, located directly above the first wheel, was used to measure the cadmium ratio for gold activation in the reference spectrum.

4. Results

4.1 Preliminary Comments

The properties of the detector materials are as follows:

- One-upon-v absorbers
  - Cu^{63}, Mn^{55}, U^{235}
- Epithermal resonance absorbers
  - Au^{197} (4.916 eV resonance), In^{115} (1.457 eV resonance)
- Thermal resonance absorbers
  - Pu^{239} (0.296 eV resonance), Lu^{176} (0.141 eV resonance).

Activation data and reaction-rate ratios (normalized to the reference-wheel spectrum) are compared to code predictions. The copper-capture data comparison was used to test the ability of the code to predict the neutron density distribution across the test cell. The spectrum indicator ratios (see Section 4.2) were used to test the ability of the code to predict the change in energy spectrum across the cell.

4.2 Comparison of Activation Data to WIMS-IST

Figure 5 shows the Cu-wire activation data obtained from the frame work (see Figure 4). As described in Section 3.2, data were obtained in two radial directions in the moderator, and along the cell boundary.

Figure 6 compares the frame work data to WIMS-IST [5] predictions. Also included is a comparison of the Cu-foil activation data obtained from the demountable bundle, the calandria tube, and the stringers. One concludes that there is good agreement between the code prediction and measurement of neutron-density spatial distribution in the CANFLEX-RU lattice cell.

Table 1 lists the measured spectrum indicator ratios and Calculation-over-Experiment (C-upon-E) ratios. The measured relative conversion ratios (U^{238} capture/U^{235} fission) are in good agreement with calculation, as are the Pu^{239}/U^{235} fission ratios.

The relative conversion ratio data and the In^{115}/Cu^{63} capture ratio data, indicate that the code correctly predicts epithermal flux distributions in the fuel.

The Pu^{239}/U^{235} fission ratios and the Lu^{176}/Mn^{55} capture ratios, measured in the fuel, indicate that the code correctly predicts spectrum temperature changes in the fuel.

The calculated Au^{197}/Cu^{63} capture ratios are consistently high, by about four percent, relative to experiment. Additional corrections may be required to these data to account for gap effects and/or foil self-shielding effects.

5. Conclusion

This paper has presented an analysis of fine-structure reaction-rate measurements using a CANFLEX-RU demountable bundle; the measurements are compared to predictions of the lattice code WIMS-IST. The analysis concludes that the comparison agrees, within a few percent, with measured neutron-density spatial distributions and spectrum indicator ratios in a CANFLEX-RU lattice cell.

6. References

[1] A.D. Lane et. al., “The CANFLEX Fuel Bundle: An Economic and Pragmatic Route to the Use of Advanced Fuel Cycles in CANDU Reactors”, Proc. 8th KAIF/KNS/OKAEA Annual Conference, 1993 April, pp. 435-444

[2] J.E. Atfield and M.B. Zeller, “Physics Experiments in the ZED-2 Reactor using CANFLEX-RU, Thirty-First Annual Conference of the Canadian Nuclear Society, Montreal, PQ, Canada, 2010 May.

[3] “ZED-2”, AECL Report, AECL-2132, 1964.

[4] J.E. Atfield and M.B. Zeller, “End-Flux Peaking Experiments in the ZED-2 Reactor using CANFLEX-RU”, Current Proceedings.

[5] J.D. Irish and S.R. Douglas, “Validation of WIMS-IST”, Twenty-Third Annual Conference of the Canadian Nuclear Society, Toronto, Ontario, Canada. 2002 June.

Table 1:
Comparison of Measured Spectrum-Indicator Ratios to WIMS-IST Calculations

Location	Lu^{176}/Mn^{55} Capture Ratio		Au^{197}/Cu^{63} Capture Ratio		In^{115}/Cu^{63} Capture Ratio	
	Experiment	C upon E	Experiment	C upon E	Experiment	C upon E
Centre Element	1.270	1.029	1.697	1.043	2.134	0.989
Inner Ring	1.277	1.013	1.687	1.034	2.087	0.991
Intermediate Ring	1.234	1.015	1.627	1.047	1.951	0.996
Outer Ring	1.170	1.020	1.578	1.045	1.800	0.991
Calandria Tube	1.098	1.073	1.492	1.012	1.666	0.945
Cell Boundary	1.035	1.012	1.377	1.051	1.498	0.983
Wheel	1.000	1.000	1.000	1.000	1.000	1.000

Location	U^{238}/U^{235} Conversion Ratio		Pu^{239}/U^{235} Fission Ratio	
	Experiment	C upon E	Experiment	C upon E
Centre Element	1.531	1.024	1.226	0.993
Inner Ring	1.501	1.018	1.176	1.027
Intermediate Ring	1.431	0.994	1.180	1.001
Outer Ring	1.356	0.984	1.137	1.009
Wheel	1.000	1.000	1.000	1.000

Note: Experimental spectrum-indicator-ratio uncertainties approximately ± 2%

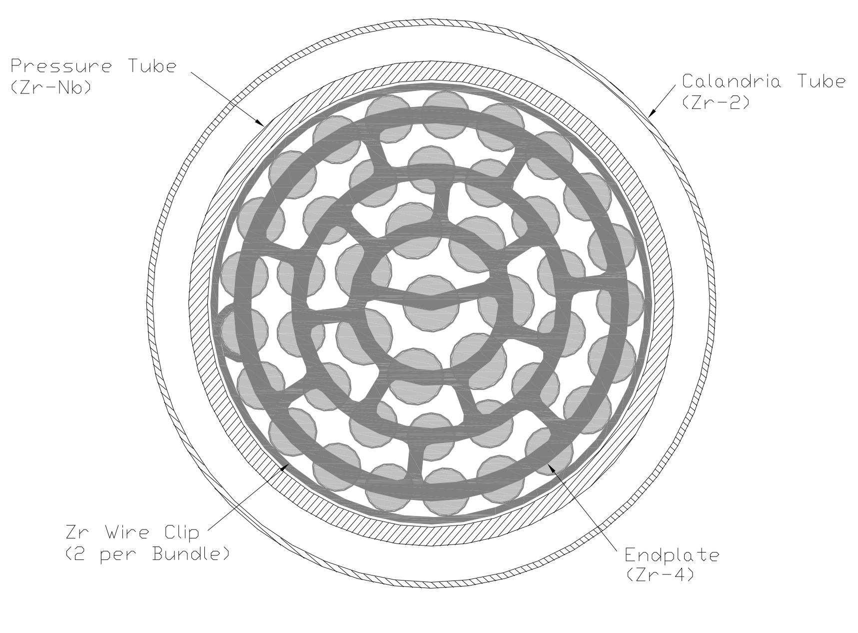

Figure 1 Top view of CANFLEX-RU in a CANDU-type Channel

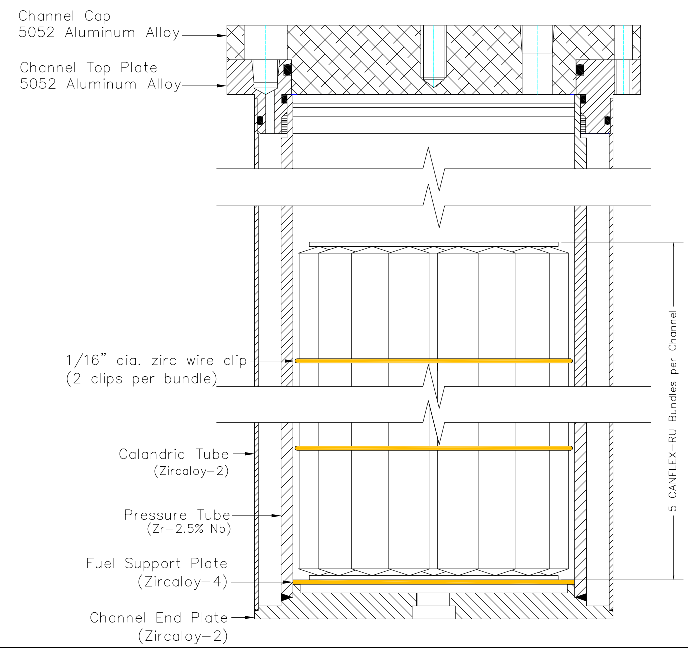

Figure 2 Side view of CANFLEX-RU in a CANDU-type Channel

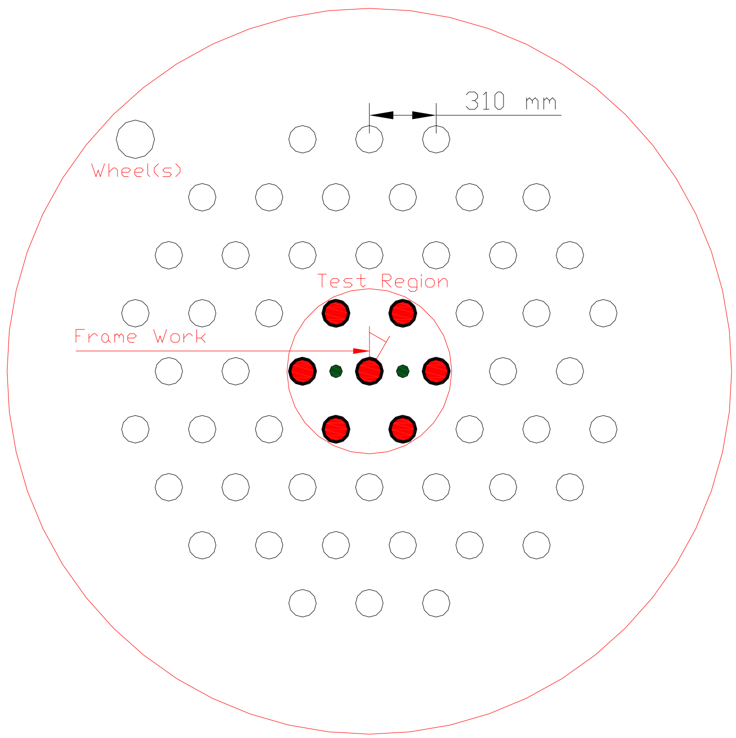

Figure 3 Top View Test Lattice

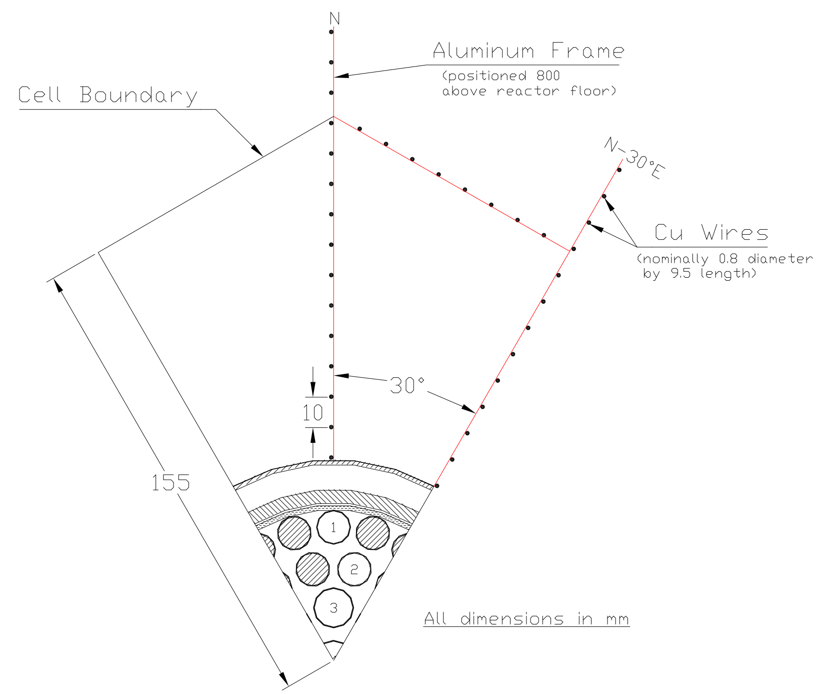

Figure 4 Frame Work Details

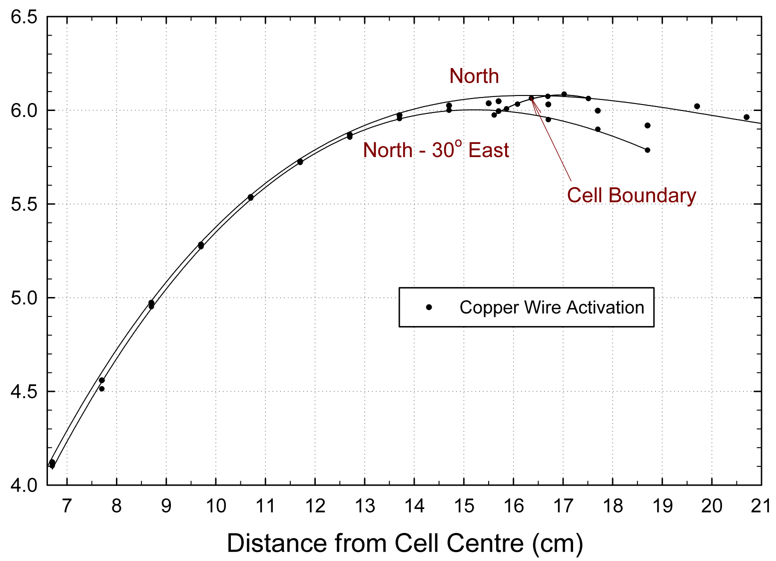

Figure 5 Frame Work Activation Data

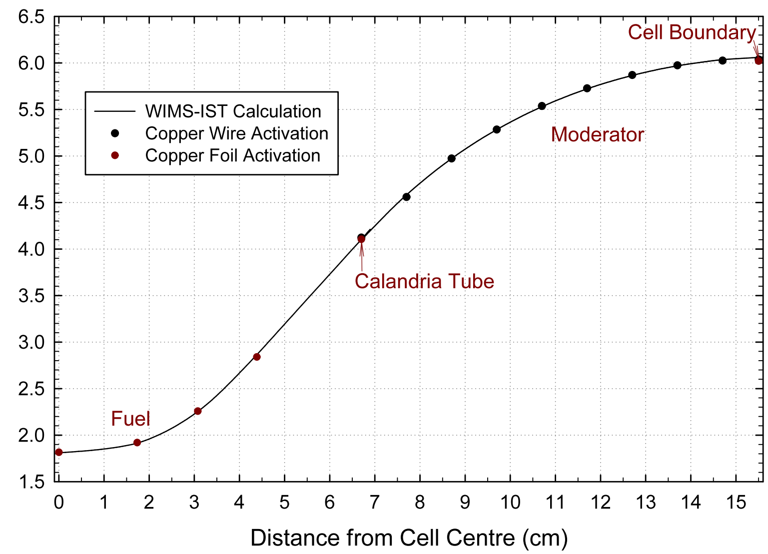

Figure 6 Comparison of Cu Activation Data to WIMS-IST