A Comparison of Reactivity Parameters of CANDU Fuel Bundles over Fuel Lifetime

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*(Dated: **18 August 2017)***

Two important parameters for safety analysis of CANDU fuel are the coolant void reactivity (CVR) and the adjuster rod reactivity worth near the fuel. In this study the CVR and adjuster rod worth of two CANDU fuel designs, the standard 37 element natural uranium bundle and the 43 element CANDU Flexible Fuelling (CANFLEX) bundle containing slightly enriched uranium are compared over the useful life of the fuel. Analysis of the neutron multiplication factor of each bundle found that the useful life of the CANFLEX fuel is approximately 32 days longer than the standard CANDU fuel. The plutonium peak, a well-known trait of natural uranium CANDU fuel, was not observed in CANFLEX fuel design. It was found that the presence of a burnable neutron absorber in the centre pin of the CANFLEX fuel reduces CVR by approximately 55%, from about 16.2 mk for the natural uranium fuel to 7.0 mk for CANFLEX before irradiation. The worth of adjuster rods near CANFLEX fuel was found to vary by approximately 5 mk over the life of the fuel. Adjuster rods became more effective as the CANFLEX fuel was irradiated. Standard CANDU fuel exhibits different behaviour. The adjuster rod reactivity becomes less negative for the first 100 days of the fuel cycle before dropping to within 1 mk of the fresh fuel reactivity worth at the end of the useful life. The standard CANDU fuel bundle is a safer design during normal operating conditions, while the CANFLEX fuel bundle is safer during a loss of coolant accident.

PACS numbers: 2028

Keywords: Lattice physics, CANDU, CVR, Reactivity worth, Fuel Cycle

I. INTRODUCTION

Worldwide goals to reduce greenhouse gas emissions and protect the climate will require significant use of non-carbon emitting electricity production. Nuclear power is the second largest non-emitting source of electricity in Canada, representing 16% of total electricity production. In Ontario, nuclear energy accounts for nearly 60% of total electricity production[1].

Nuclear energy production in Canada relies on the CANDU (Canada Deuterium Uranium) reactor design. The defining features of the CANDU design are the use of heavy water (D_2O) as a moderator, a separated neutron moderation and fuel coolant system and the use of natural uranium as fuel. The concentration of the fissile isotope which releases energy in the reactor core, Uranium-235, in natural uranium is 0.71%. A typical pressurized water reactor (PWR) or boiling water reactor (BWR) uses light water (H_2O) as a simultaneous coolant and moderator. The fuel used in a PWR or BWR is typically enriched to up to 5% U-235.

To support the safe use of nuclear energy in electricity generation it is critical to understand how a nuclear reactor will behave in accident scenarios. One of the most significant accidents that can occur in a nuclear power plant is a loss of coolant accident (LOCA), where the fluid used to remove heat from the fuel becomes unavailable. This accident is more dangerous in CANDU reactors because of the separated coolant and moderation systems. In the event of a loss of coolant, neutron moderation is not lost, which allows the fission reactor to continue[2]. The loss of neutron absorption in the coolant increases the rate of fissions in the fuel. The result is an increase in heat production as capacity for heat removal decreases, creating a dangerous situation where fuel damage can rapidly occur.

In this study, the Monte Carlo reactor physics program Serpent[3] was used to test the properties of two CANDU fuel materials and geometries. The standard CANDU fuel bundle, containing 37 pins of natural uranium (NU) and a proposed design of the CANFLEX (CANDU Flexible Fueling)[4] 43 element slightly enriched uranium (SEU) fuel bundle were compared. The tests examined the fuel's behaviours under two conditions: a loss of coolant accident and in the presence of a CANDU control rod, as well as the base case of a cooled fuel bundle without an adjuster rod. The impact of the loss of coolant, also known as coolant void reactivity (CVR) was measured by comparing the voided fuel assembly to the base case. The impact of the adjuster rod, also referred to as the adjuster rod's reactivity worth, was measured by comparing the rod in simulation and the base case. The properties of the fuels were analyzed over the entire expected life cycle of the fuel to determine how the behaviour of the fuel in each situation changes over time.

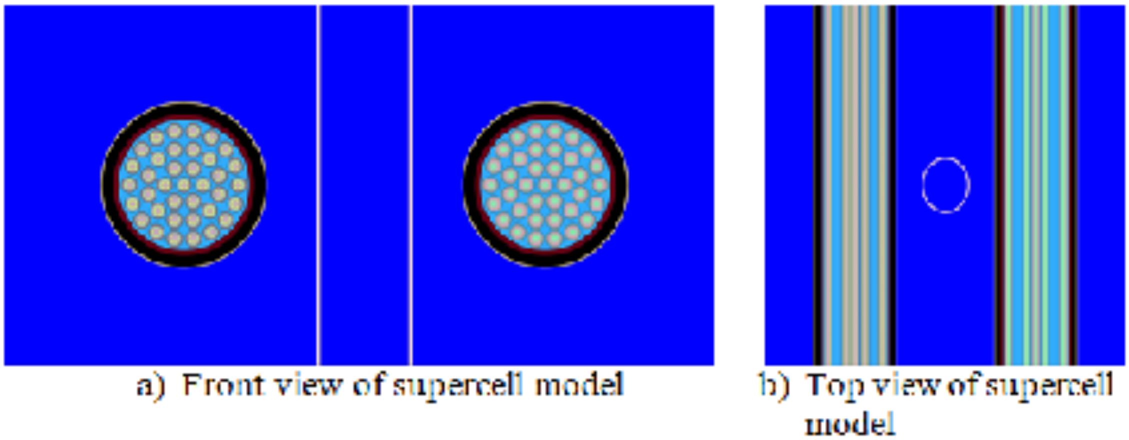

Figure 1: The geometry of the supercell model is shown. The stainless steel adjuster rod, filled with moderator in the center, sits between the fuel bundles.

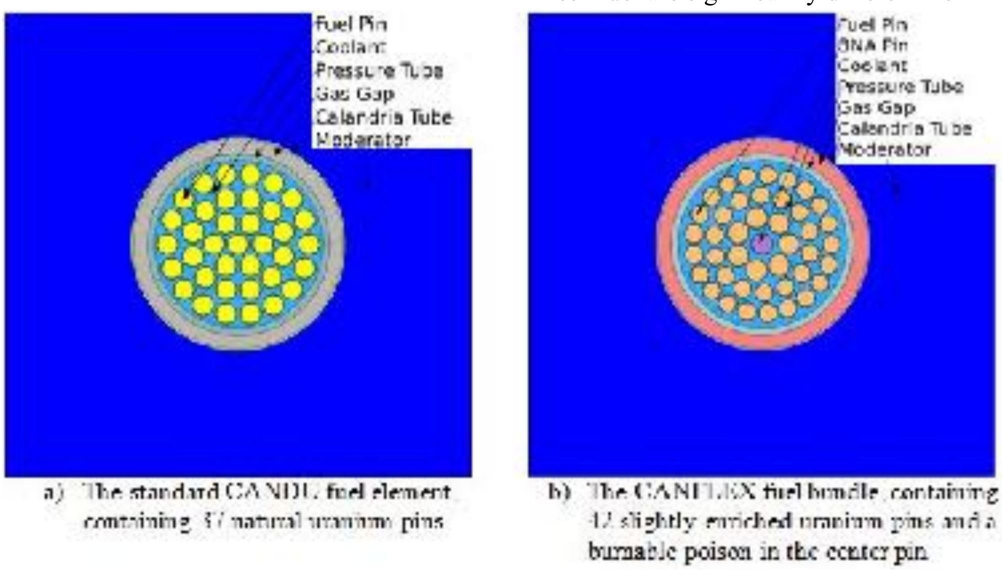

Figure 2: The two fuel bundles tested in the study are shown.

The coolant void reactivity of CANDU fuel bundles has been measured by many researchers using different tools [2,5–8]. The worth of CANDU adjuster rods has also been predicted by previous researchers for a standard CANDU fuel bundle [9,10]. The properties of the CANFLEX bundle have not been studied as thoroughly in either case. Historically, researchers have examined the properties of both fuel types at the fresh fuel state, before irradiation within the core. In this study, I examine how the key safety parameters CVR and adjuster rod worth change over the fuel's life in the core to determine whether this simplification is valid or not.

Unlike PWRs and BWRs, CANDU reactors are refueled on a daily basis. In a CANDU reactor, approximately 18 bundles of new fuel are inserted into the core each day[11]. The high refueling rate of CANDU reactors makes the difference in properties of fresh and spent fuel particularly important. If the reactivity parameters of fresh fuel are significantly different from that of spent fuel refueling the reactor will introduce perturbations which must be counted by the reactor regulating system.

This study will determine two things:

1. Which fuel design is safer during regular CANDU operating conditions?
2. Which fuel design is safer during a loss of coolant accident?

II. MODELLING METHODS

A. Full Model Geometry

A 3D model of a CANDU cell was generated using Serpent 2.1.26. Front and top cuts of the model are shown in Figure 1. The model, referred to as a supercell, contains an adjuster rod containing 304L stainless steel centered between two fuel bundles (the tested bundle designs are shown in Figure 2). The supercell is 57.15 cm (two CANDU lattice pitches) wide, 28.575 cm (one lattice pitch) high and 49.53 cm (one fuel bundle length) deep. Each edge of the supercell was modelled in Serpent with periodic boundary conditions.

B. Natural Uranium Bundle

The standard CANDU fuel assembly is a 37-element bundle containing a center pins with rings of 6, 12 and 18 pins surrounding it. The fuel pins are surrounded by a zirconium cladding and held in place by end plates, which were not modelled in this test. The entire fuel assembly is surrounded by a pressure tube which allows coolant to flow over the fuel pins. The pressure tube is enclosed in a calandria tube, with an annulus of gas, often carbon dioxide, used to separate the tubes and prevent heat transfer from the coolant. Moderator surrounds the calandria tube. The modelled cell, including moderator, is 28.575 cm wide, 28.575 cm high and 49.53 cm long. The natural uranium bundle is shown in Figure 2a).

C. Slightly Enriched Uranium Bundle

The CANFLEX SEU fuel bundle was designed to fit within the existing CANDU pressure and calandria tubes. The bundle contains 42 pins of uranium enriched to 1% U-235 in rings of 7, 14 and 21 pines surrounding a center pin which contains a mixture of 85% NU and 15% dysprosium. The dysprosium acts as a burnable neutron absorber (BNA) as is intended to lower the reactivity of the bundle when the coolant is voided[9]. The center pin and first ring are larger in diameter than the outer two rings of fuel pins[4]. The 43-element SEU bundle is shown in Figure 2b).

D. Burnup Calculations

Burnup calculations were performed using a Dell XPS 8900 desktop computer. The burnup of the bundles was calculated using steps of 0.5 MWd/kg(U). The bundles were burned at a constant power level of 600 kW each (1200 kW for the entire supercell) with the adjuster rod removed and coolant present.

III. RESULTS

A. K_{eff} Throughout the Fuel Cycle

The neutron multiplication factor of a fuel bundle is a measure of how effective the bundle is at sustaining a chain reaction. It is the ratio of neutrons produced to neutrons lost in the supercell. A critical reactor has a neutron multiplication factor, k_{eff} equal to 1.
Figure 3 shows the evolution of k_{eff} for the two fuel types against the total number of days in the core. It was found that the SEU fuel bundle's k_{eff} only remains above 1.0 for approximately 32 days longer than the NU fuel bundle. The k_{eff} of the NU fuel bundle drops below 1.0 after 7.5 MWd/kg burnup (at 248 full power days). The SEU k_{eff} drops below 1.0 at 4.5 MWD/kg burnup, after 281full power days. Although the SEU bundle is able to remain critical for a longer time than the NU bundle, it was expected that the SEU bundle would be able to reach higher burnup. It was found that the burnable neutron absorber in the center pin of the SEU bundle significantly lowers the exit burnup obtainable with the fuel.

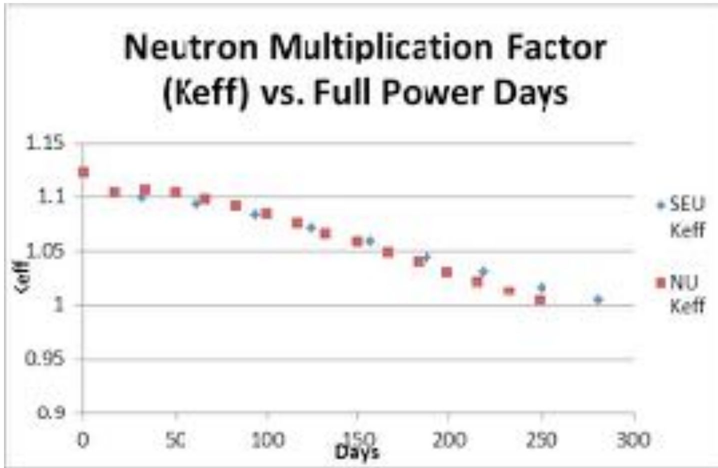

Figure 3: The evolution of k_{eff} for the SEU and NU fuel bundles is shown. Both bundles are considered spent when k_{eff} is no longer greater than 1.0. The plutonium peak in k_{eff} is seen for the NU bundle at approximately 50 days. The SEU fuel bundle does not exhibit a peak in k_{eff}.

The SEU fuel bundle does not exhibit the peak in neutron multiplication factor that is typical of NU fuel. Standard CANDU fuel elements see a decline in k_{eff} immediately after entering the core, followed by a peak after approximately 50 full power days, due to the increasing isotopic density of Plutonium in the fuel. After this peak, the k_{eff} of the NU fuel decreases at a near linear rate. The SEU fuel bundle does not have a peak in k_{eff}. The reactivity decreases also decreases at a near linear, but slower rate. The plutonium buildup causes the NU bundle to have a higher k_{eff} than the SEU fuel for the first 130 days of irradiation and a lower k_{eff} afterwards.

B. Coolant Void Reactivity and Control Rod Worth

Values of CVR and adjuster rod worth throughout the fuel cycle are shown in Table I. End of cycle is determined as the last burnup step with a k_{eff} greater than 1.0. Calculations of the reactivity effect of coolant voiding and adjuster rod insertion were performed using Equation 1. The variable k_{base} refers to the k_{eff} of the base case while k_{test} refers to k_{eff} in the test case.

$$\Delta\rho = 1000 * \left(\frac{1}{k_{base}} - \frac{1}{k_{test}}\right) [mk] \quad (1)$$

A negative reactivity implies a decreasing reaction rate. It is desirable for adjuster rods to have a very negative reactivity. Ideally, CVR would be as close to zero as possible.

Table I: A summary of the coolant void reactivity worth and adjuster rod worth calculated during the study is shown for the beginning, middle and end of the fuel cycle.

Natural Uranium			Slightly Enriched Uranium		
Burnup (MWd/ kg)	CVR (mk)	Rod Worth (mk)	Burnup (MWd/ kg)	CVR (mk)	**Rod Worth (mk)**
0	16.192 ± 0.003	-75.55 ± 0.02	0	7.033 ± 0.002	-68.38 ± 0.02
1.0	14.689 ± 0.003	-72.58 ± 0.02	1.0	6.091 ± 0.002	-68.46 ± 0.02
2.0	13.682 ± 0.003	-71.36 ± 0.02	2.0	5.755 ± 0.002	-68.59 ± 0.02
3.0	13.177 ± 0.003	-71.06 ± 0.02	3.0	5.582 ± 0.002	-70.14 ± 0.02
4.0	12.906 ± 0.003	-72.03 ± 0.02	4.0	4.990 ± 0.002	-72.35 ± 0.03
5.0	12.684 ± 0.003	-72.74 ± 0.02	4.5	5.461 ± 0.002	-73.39 ±0.03

As expected, the CVR of the SEU fuel bundle is lower than the NU bundle at all points in the fuel cycle. The behaviour of CVR in both bundles is similar. The CVR starts slightly higher than average but falls to a resting point. The CVR of the SEU bundle is lower by approximately 55% due to the dysprosium in the centre pin. The insertion of fresh fuel into a previous spent fuel channel increases CVR in both cases by about 23%. In absolute values, relative to spent fuel, CVR is 3.75 mk higher for fresh NU fuel and 1.57 mk higher for fresh SEU fuel. The lower CVR of the SEU bundle coupled with the additional fuel pins (which give a larger surface area for heat transfer) make the SEU fuel bundle a more accident safe design.

It was found that the reactivity worth of control rods is 5.0 mk more negative for spent SEU fuel than fresh. Regular refuelling of CANDU bundles introduces positive reactivity to the core, which is controlled by the reactor regulating system with a mixture of adjuster rods and liquid zone controllers. When SEU fuel bundles are replaced in the core the positive reactivity added will

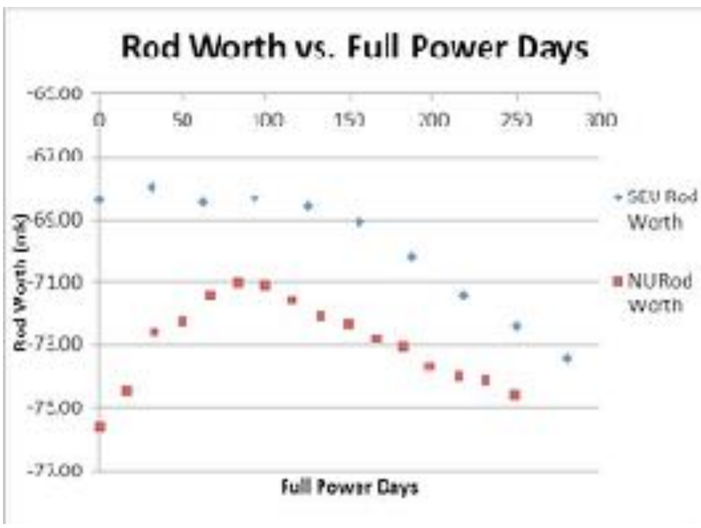

Figure 4: The reactivity worth of adjuster rods as fuel is irradiated is shown.

also include the lost control rod worth. This could lead to an unstable and potentially dangerous transient period following the insertion of new SEU fuel. It has been shown that the standard NU bundle exhibits the opposite phenomenon, as adjuster rods are approximately 1.0 mk more negative near fresh fuel. The adjuster rod worth's through the full fuel cycle are shown in Figure 4.

The adjuster rods exhibit different behaviour near each fuel bundle. For the NU bundle, the adjuster rods are least effective between 50 and 100 days in the core. At this minimum, the rods are approximately 4.55 mk less negative. As the NU fuel continues to be irradiated, the adjuster rod worth approaches the initial worth. For the SEU fuel the rods are initially worth about -68.5 mk. The adjust rod becomes slightly less negative, reaching -67.9 mk within 50 days of irradiation. The adjuster rod worth near the SEU fuel begins to decrease almost linearly after 100 days of irradiation. The final adjuster rod worth is -73.4 mk.

IV. CONCLUSIONS

Through comparison of the reactivity parameters of the standard 37-element natural uranium CANDU bundle and the 43-element CANFLEX bundle fuelled with slightly enriched uranium I have shown two weaknesses in the CANFLEX bundle. Despite enrichment to 1% U-235 (0.3% higher than natural uranium) the SEU bundle is expected to be useful in the CANDU core for only an additional 32 days, largely due to the presence of burnable poison in the centre pin. Secondly, due to the 5 mk change in adjuster rod worth between fresh and spent SEU fuel, refuelling options in CANDU reactors will become less safe. The loss of control rod reactivity worth and simultaneous insertion of positive reactivity in the form of new fuel creates a far riskier fuelling scenario than the standard CANDU fuel bundle.

Despite these weaknesses, it was found that the CANFLEX bundle's CVR is approximately 55% lower than the standard CANDU fuel bundle. Lower CVR and better heat transfer properties suggest the CANFLEX bundle is significantly safer in a loss of coolant accident.

It was determined that the standard CANDU fuel bundle is a safer fuel design during regular operating conditions to the high frequency of refuelling in a CANDU reactor. The less significant transient and power change in the vicinity of fresh fuel drives this decision. During a loss of coolant accident the CANFLEX bundle is the safer fuel design.

Notes and references

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