EXPLICIT CORE-FOLLOW SIMULATIONS FOR A CANDU®6 REACTOR FUELLED WITH RECOVERED-URANIUM CANFLEX® BUNDLES

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ABSTRACT

Recovered uranium (RU) is a by-product of many light-water reactor (LWR) fuel recycling programs[1]. After fission products and plutonium (Pu) have been removed from spent LWR fuel, RU is left. A fissile content in the RU of 0.9 to 1.0% makes it impossible for reuse in an LWR without re-enrichment, but CANDU reactors have a sufficiently high neutron economy to use RU as fuel.

Explicit core-follow simulations were run to analyse the viability of RU as a fuel for existing CANDU 6 cores. The core follow was performed with RFSP, using WIMS-AECL lattice properties. During the core follow, channel powers and bundle powers were tracked to determine the operating envelope for RU in a CANFLEX bundle.

The results show that RU fits the operating criteria of a generic CANDU 6 core and is a viable fuel option in CANDU reactors.

1 INTRODUCTION

The recovered-uranium (RU) fuel considered in this report is typical of that from reprocessed spent light-water reactor (LWR) fuel. The isotopic specification used for modeling RU is given in Table 1. It is very similar to slightly enriched uranium (SEU) fuel, but with higher concentrations of ^{234}U and ^{236}U than the concentrations found in enriched fuel derived directly from natural uranium.

The use of RU fuel in CANDU reactors potentially offers economic, environmental and public acceptance benefits. RU can be used to flatten the channel power across the core to increase reactor power in new reactor designs or in existing designs where sufficient heat removal capacity exists. RU fuel will have burnups of about 14000 MW·d/Mg (U), reducing the quantity of spent fuel. Depending on RU pricing, the annual fuelling costs can be reduced. The high neutron efficiency of CANDU reactors and the neutronic characteristics of RU make it possible to extract twice the energy from RU compared to re-enriching it as a fuel for LWRs. AECL is collaborating with KAERI and BNFL to develop a CANFLEX bundle with RU fuel and AECL has had a joint program with COGEMA to study RU. These programs are relatively recent and definitive results are several years away.

We have completed a 500 full-power day (FPD) core-follow simulation of RU fuel in a CANFLEX bundle using a 2-bundle-shift refuelling scheme. A core follow is a long series of simulations of a reactor operating history, modelling successive time steps of a few FPD in each time step. In each step, a number of channels are refuelled just as the fuelling engineers at a site would do in their normal production runs. We used the finite-core code RFSP[(2)] in our core follow.

The data to model the CANFLEX bundle were extracted from the latest CANFLEX fuel bundle drawing and are current as of June 1996. The mass of uranium metal per bundle is 18.674 kg.

The analysis shows that RU fuel is expected to perform well in a CANDU 6 core without any modifications. Our core follow was able to maintain an equilibrium core with acceptable channel powers, bundle powers, linear-element-power and power-boost envelopes and reasonable zone fills.

2 METHOD OF ANALYSIS

The first step in simulating this core follow was creating the fuel model. WIMS-AECL[(3)] with the ENDF/B-V nuclear data library was used to construct fuel tables for use with RFSP. The reactor core calculations were then done using RFSP version 2-12HP. To facilitate the decisions that must be made during refuelling, an automated method was used to do most of the editing and calculations required to perform the steps described below.

Refuelling started with a quasi-equilibrium core generated with a patterned-random fuel-age distribution calculated from the time-average irradiation distribution. This unflattened core uses the same channel power distribution as a natural uranium CANDU 6 core.

Once a generic CANDU 6 model was created in RFSP using RU fuel, the sequence of calculations used to produce the individual 2-FPD steps of the core follow are

1. A FORTRAN code ranks each channel in the core by its suitability for refuelling, according to bundle power and burnup data from RFSP for that channel and its nearest neighbours.

2. Eight channels are selected from the rankings and an RFSP input is created to refuel those channels over a period of 2 FPD.

3. RFSP is run with the input from step 2, and the calculated bundle powers and burnups are saved for later use.

4. The RFSP output is checked against acceptance criteria (defined below) and channels or groups of channels that fail to meet these criteria are excluded from the rankings of suitable channels to be refuelled.

5. If the acceptance criteria in step 4 are met, the process is repeated at the next time step, and steps 1 through 4 are repeated. If the criteria are not met, the channels excluded from the suitability list are replaced, and steps 3 and 4 are repeated.

Typically this process requires a few iterations at each time step.

In our simulations, typically a few of the initial channel choices from step 2 produced channel powers that were above the acceptance criterion. It is impossible, with a new fuel type, to predict with certainty what a refuelled channel's power will be before the simulation is run.

The criteria used to determine whether a given set of refuellings was acceptable are simplified from those that a refuelling engineer at a site would apply, but still provide a good set of rules for selecting channels. The acceptance criteria used here include

1. Maximum channel power must be lower than 7100 kW, to provide margin below the 7300 kW license limit.

2. Maximum bundle power must be comfortably lower than the 37-element bundle license limit of 935 kW (e.g. ≤880 kW). Limits for CANFLEX bundles have not been finalized yet although they are expected to be higher.

3. Average zone controller fill should be in the operating range of 0.3 to 0.7.

4. Individual zone controller fills should be in the range of 0.05 to 0.9.

Fuel performance is a major point of interest in this study. To examine the likelihood of fuel failure, the individual bundle powers were extracted for each simulation. The power boost that each bundle sees between successive simulations was calculated. The bundle powers and power boosts were then converted to linear-element powers and linear-element power boosts using element power vs. irradiation data given by WIMS-AECL. Graphing the linear-element powers vs. burnup gives a way of comparing the results to SCC threshold values that would be indicative of fuel-element failure.

In order to be a non-trivial candidate for fuel failure, a fuel element must exceed both the stress-corrosion cracking (SCC) linear-element power threshold and the SCC linear-element power-boost threshold. If a fuel element exceeds both limits, then it is considered to have a 0.1%

chance of failing. The odds of a failure occurring in an element that does not exceed both SCC limits are insignificant.

3 RESULTS OF SIMULATIONS

The first and most crucial result of the simulations is that an equilibrium core was able to be refuelled and maintained for 500 FPD without exceeding the channel-power and bundle-power targets, or causing uncontrollable tilts. Average zone fills were kept between 0.3 and 0.7 for all simulations, and individual zone controllers did not reach their minimum or maximum limits.

The average refuelling rate was 7.8 bundles/FPD (3.9 channels/FPD). Knowing the mass of uranium per bundle and the fission power of the core, this refuelling rate is equivalent to an average exit burnup of 334.6 MW·h/kg (U) [13940 MW·d/Mg (U)].

Figure 1 shows the power-boost envelope for the entire simulation period. Each dot on the graph represents the maximum-linear-element power from a bundle. Every bundle that saw a power boost greater than 20 kW at any time in the core follow is represented.

We do not approach the SCC power-boost threshold until high burnup values are reached. At these values, the trend of the threshold is unknown.

Figure 2 shows the linear-element powers plotted vs. burnup. The range of concern in Figure 1 is the burnup interval of 250 to 300 MW·h/kg (U). Figure 2 clearly shows that the elements in this range do not come close to approaching the SCC element-power threshold limit. The large margin between the CANLUB element-power threshold and the bundle-maximum linear-element powers suggests that, even with power boosts occurring at burnups between 250 and 300 MW·h/kg (U), caused by a 2-bundle shift, there is no fuel failure expected.

Of importance is that none of the linear-element powers were above 44 kW/m which suggests very low fission gas release[4]. This will have beneficial implications for both normal operating conditions (lower chance of fuel-element failure) and under postulated accident scenarios (less free inventory available for release).

Also of interest is the axial power shape that results from the use of RU fuel. Figure 3 shows the time-average axial powers for a high-power, inner-core channel and a low-power, outer-core channel. The power peaking towards the inlet end has positive implications on the critical channel power (CCP) values.

Comparisons of other core-follow results with time-average results can be found in Table 2, and Figures 4 through 6 show some of the operating parameters during the core-follow simulation.

4 DISCUSSION AND CONCLUSIONS

The results of the 500-FPD core follow show that RU CANFLEX fuel containing 0.96% ^{235}U by weight used with a 2-bundle-shift refuelling scheme would be a satisfactory fuel in an equilibrium CANDU 6 core. It would not cause excessive channel or regional overpowers, or significant risk of fuel element failure in spite of its high burnup and slight enrichment relative to natural-uranium fuel.

Fuel performance analysis suggests that, while this fuel would experience positive linear-element power boosts at burnups in the range of 250 to 300 MW·h/kg (U), there is no significant risk of fuel-element failures. Indeed, the large margin of linear-element powers to the CANLUB threshold suggests that this fuel will perform well.

Future analysis of recovered uranium is expected to study a 4-bundle-shift refuelling scheme and to analyze the transition fuelling when converting a natural-uranium core to a recovered-uranium core.

REFERENCES:

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3. J.V. DONNELLY, "*WIMS-CRNL: A User's Manual for the Chalk River Version of WIMS*", Atomic Energy of Canada Limited Report, AECL-8955 (1986)
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TABLE 1. ISOTOPIC CONCENTRATION OF RECOVERED-URANIUM FUEL.

Isotope	% by mass
^{234}U	0.016
^{235}U	0.96
^{236}U	0.275
^{238}U	98.75

TABLE 2. COMPARISON OF TIME-AVERAGE AND CORE-FOLLOW VALUES

	Time Average	Core Follow
Exit Burnup [MW·h/kg]	339	335
Feed Rate [channels/FPD]	4.1	3.9
Feed Rate [bundles/FPD]	8.2	7.8
Max. Channel Power [kW]	6820	7098
Ave. Max. Channel Power [kW]	na	7021
Max. Bundle Power [kW]	771	857

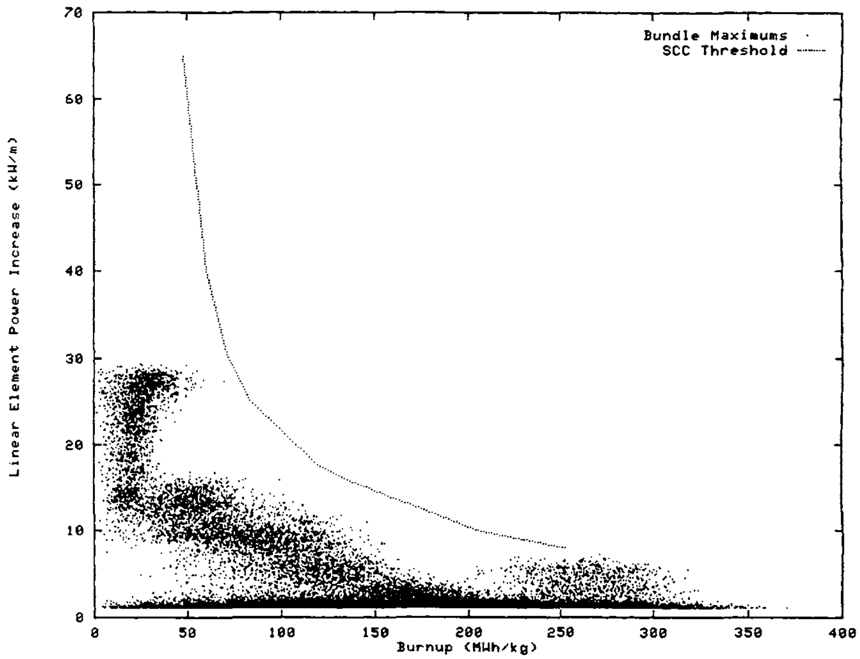

FIGURE 1. POWER BOOST ENVELOPE WITH STRESS-CORROSION CRACKING THRESHOLD

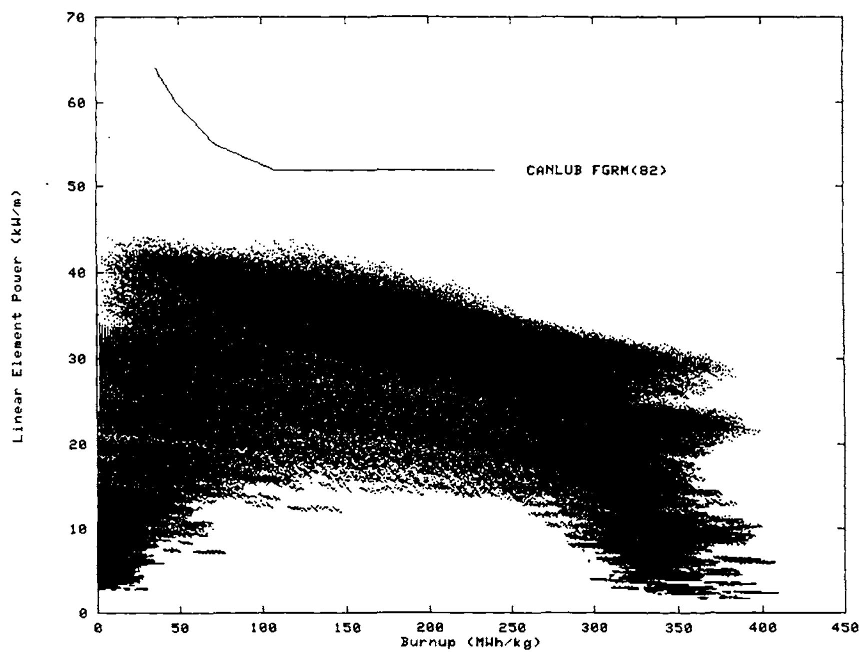

FIGURE 2. BUNDLE-MAXIMUM LINEAR-ELEMENT POWERS vs. BURNUP FOR RU CANFLEX FUEL USING A 2-BUNDLE SHIFT

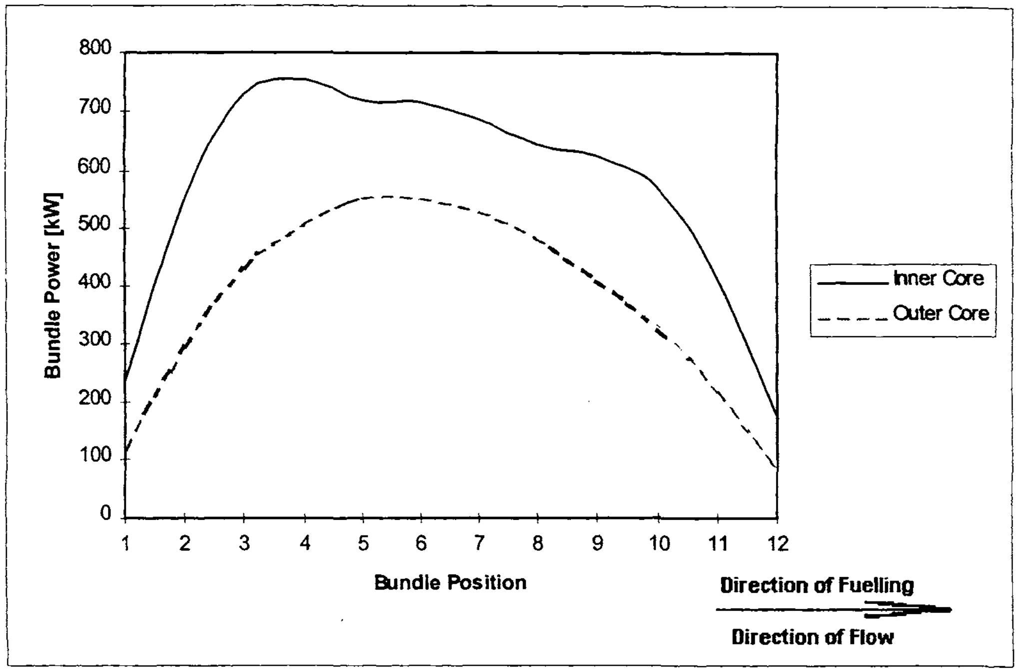

FIGURE 3. TYPICAL AXIAL POWER DISTRIBUTION (time-average data)

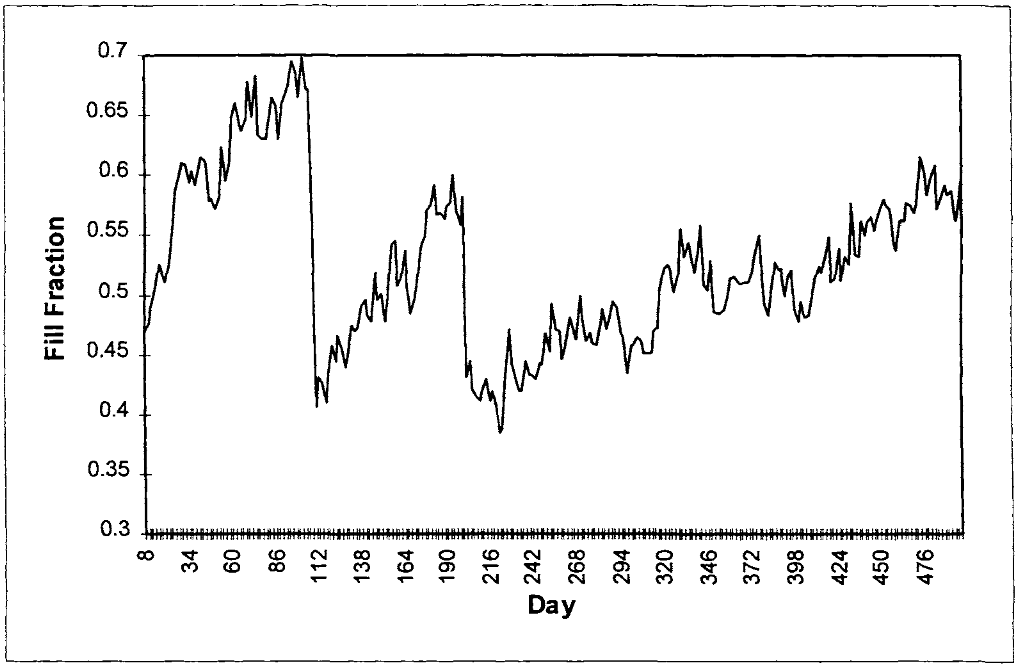

FIGURE 4. AVERAGE ZONE FILLS OVER THE 500 FPD CORE FOLLOW

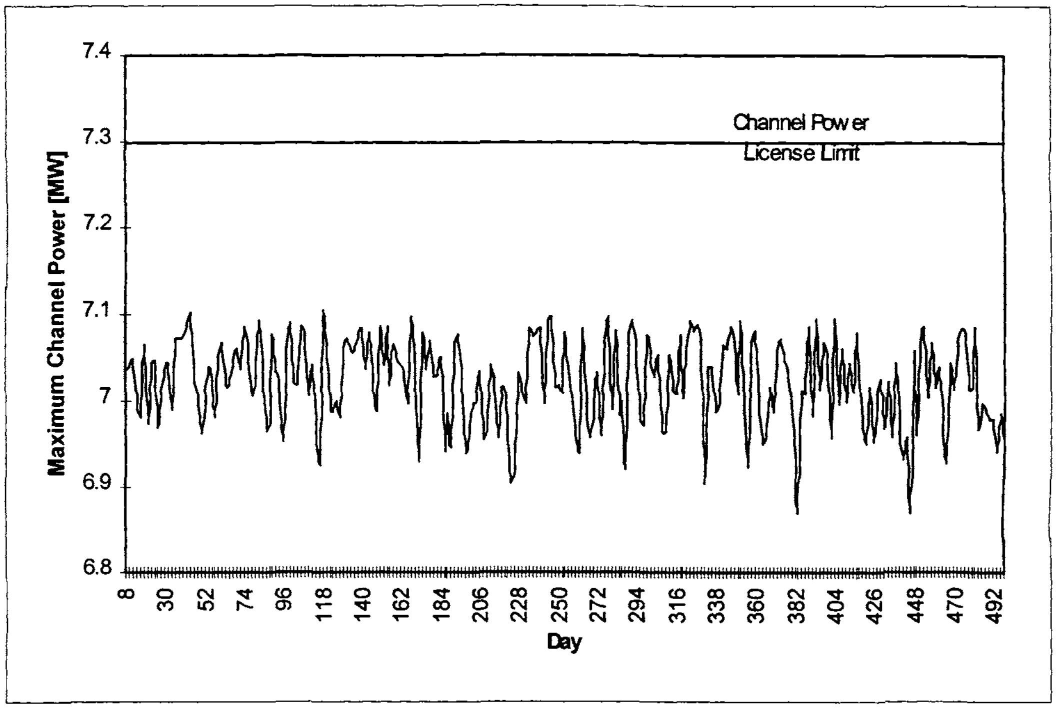

FIGURE 5. MAXIMUM CHANNEL POWERS OVER THE 500 FPD CORE FOLLOW

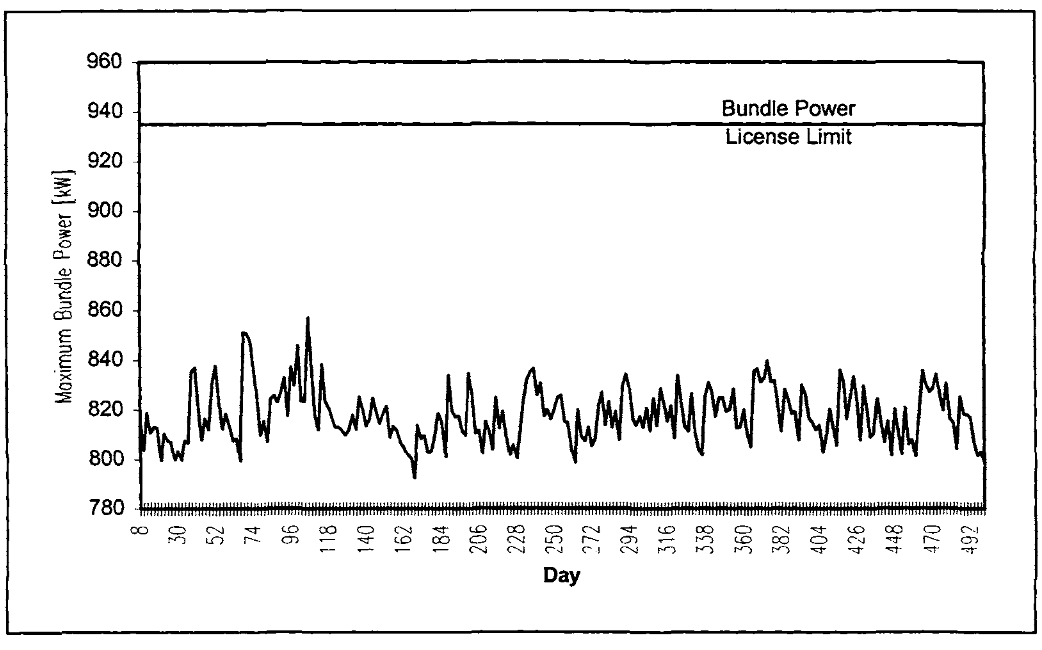

FIGURE 6. MAXIMUM BUNDLE POWERS OVER THE 500 FPD CORE FOLLOW