

PHYSICS CHARACTERISTICS OF A CANDU-600 WITH REPOSITIONED ADJUSTER RODS
FUELLED WITH MOX OR NATURAL URANIUM

P.G. BOCZAR

AECL Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario

ABSTRACT

Repositioning the adjuster rods in 4 axial banks in future CANDU-600 reactors would permit the flexibility of grading the inner and outer banks to achieve optimal flattening of the axial power distribution for any particular fuel. With the 4 banks identical, acceptable axial power profiles can be achieved for both MOX and natural uranium fuels. Future work is to be directed at assessing the impact of lower zone controller and shutoff rod worth in the configuration of reactivity devices considered here, and if necessary, in identifying means of increasing their worth.

INTRODUCTION

The use of high burnup fuels in a CANDU reactor necessitates changes in fuel management and/or changes in the location of reactivity devices. This paper explores the potential of relocating reactivity devices in future CANDU reactors to allow the use of both natural uranium (NU) and mixed plutonium-UO₂ fuel (MOX), while maintaining the benefits of a simple push-through fuelling scheme employing the same bundle-shift throughout the core. Another paper in this session (1) examines the possibility of using fuel management alone to enable the use of enriched fuels in existing CANDU's. The problems associated with the use of higher burnup fuel in a CANDU reactor are mostly generic, and while this paper focuses on MOX fuel giving a burnup of about 21 MWd/kg, the conclusions also apply to low enrichment uranium and thorium fuels.

Calculations were performed using the fuel management code FMDP (2), which solves for the neutron flux in three dimensions using finite-difference diffusion theory, and accounts for axial fuel management explicitly. For MOX fuel, cell parameters were obtained from the lattice code WIMS (3), with incremental cross sections for reactivity devices from the 3-dimensional transport code SHETAN (4), which was modified to interface with WIMS. For NU fuel, an existing data base was employed, based on the lattice code POWDERPUFS-V (5), with incremental cross sections from MULTICELL (6). The reactor model was based on a CANDU-600 reactor.

INCENTIVE FOR RELOCATING ADJUSTER RODS

Most of the important physics characteristics of MOX fuel, such as cross sections and reactivity, show a much larger variation with burnup than in NU fuel. This has important implications in axial fuel management. Since MOX fuel has a much larger initial reactivity, and change in reactivity over burnup than does NU fuel, in order to limit the increase in channel power upon refuelling it is necessary to reduce the number of fresh bundles added to a channel

during refuelling from that normally employed for NU fuel. In this study, a 2-bundle-shift bidirectional fuelling scheme was employed throughout the MOX core, and an 8-bundle-shift fuelling scheme in the NU core.

In the current CANDU design, with a 2 bundle-shift fuelling scheme, the axial power profile with MOX fuel in the absence of adjuster rods peaks at bundle position 3 (in the refuelling direction), and then decreases monotonically to the discharge end of the channel (Figure 1). This is in contrast to NU fuel where the power peaks near the center of the channel when an 8-bundle-shift fuelling scheme is employed. The presence of adjuster rods in a NU core flattens the axial power profile, while in a MOX core the adjuster rods produce a severe drop in the power of nearby bundles, and the resultant axial power profile is an asymmetric double hump. Moreover, since the relative thermal flux at the adjuster rod locations is lower in the MOX core than in the NU core, the adjuster rod worth is reduced, and there is only about 15 minutes xenon override time in the MOX-fuelled core compared to the 30 minutes obtained in a NU core.

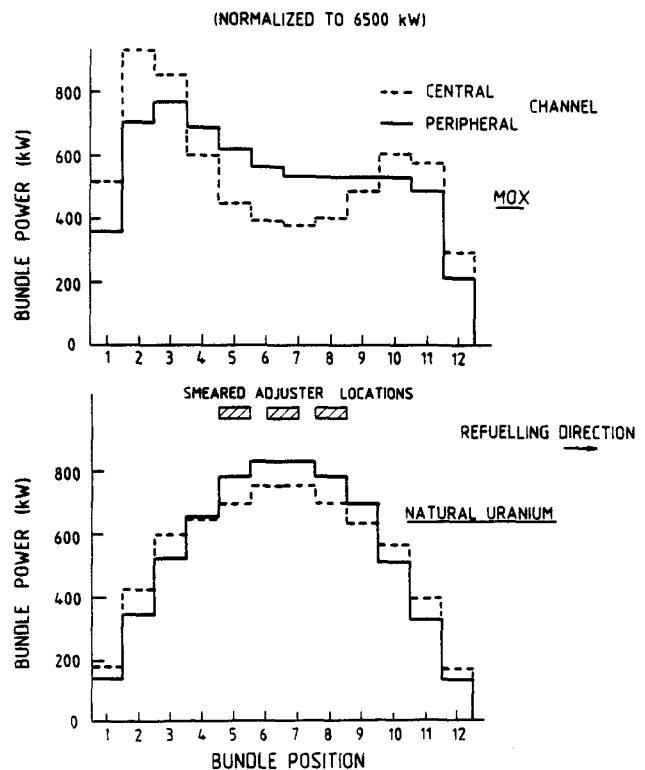


FIGURE 1: AXIAL POWER PROFILES IN CURRENT CANDU

CANDU-600 WITH REPOSITIONED ADJUSTER RODS

One way to increase the adjuster rod worth and improve the axial power profile for MOX fuel in future reactors is to reposition the adjuster rods, by moving the outer adjuster rod banks towards the channel ends. Figure 2 is a top view of the reactor showing the locations of reactivity devices in the present CANDU-600, and an alternative arrangement in which 28 adjuster rods have been positioned in approximately 4 axial banks. The zone controller locations have been kept unchanged, and mechanical control absorbers and shutoff rods have been located so as not to conflict with other devices. In each of the outer adjuster rod banks, 2 adjuster rods have been displaced inward one bundle pipe length to accommodate the emergency discharge pipes.

This arrangement of adjuster rods provides the flexibility of varying the relative strengths of the inner and outer banks to provide the optimal flattening of the axial power profile for any particular fuel. With NU fuel, removing the outer adjuster rod banks altogether and sizing the remaining rods to give the required xenon override time results in an axial power distribution which is flatter than in the standard CANDU-600. With MOX fuel, the optimal flattening giving 30 minutes xenon override time is achieved with the outer banks stronger than the inner banks, in which case the axial power profiles with and without adjuster rods are very similar. With the 4 adjuster rod banks identical, the strength of the adjusters can be chosen to give the required worth for both NU and MOX fuels, and the resultant power profiles are good, though not optimal, for both fuels. This is the reference case which will be used for the remainder of this paper. Figure 3 illustrates typical axial power profiles for adjuster bank gradings which are near optimum for either NU or MOX fuel, and for the reference case which has identical banks axially.

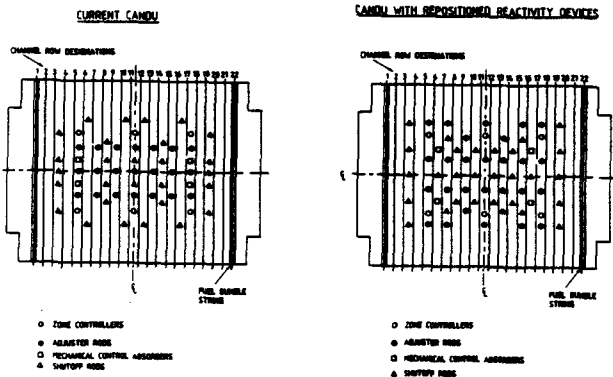


FIGURE 2: TOP VIEWS OF REACTOR

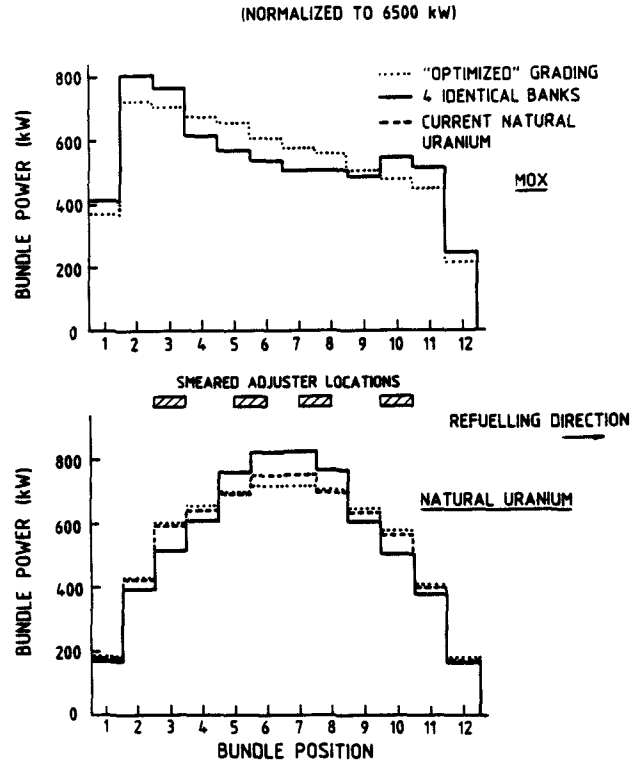


FIGURE 3: AXIAL POWER PROFILES WITH REPOSITIONED ADJUSTER RODS

The time-averaged characteristics of the reference MOX and NU cores with adjuster rods repositioned in 4 identical banks are compared to the standard NU CANDU-600 in Table 1. In each case, the irradiation distribution has been adjusted to achieve criticality. In the MOX core, 3 radial irradiation zones were used compared to 2 in the NU cores, enabling a flatter radial channel power distribution to be achieved, and an 8% reduction in maximum channel power. The maximum bundle power is 9% lower in the MOX-fuelled core than in the NU cores. The refuelling machine usage, taking into account the refuelling rate and the capacity of the fuelling machines, is lower in the MOX than in the NU core.

The worth of reactivity devices is generally smaller with MOX fuel than with NU fuel, reflecting the greater blackness of the MOX fuel, and differences in the axial flux distributions. However the adjuster rods now give approximately 30 minutes xenon override time in both MOX and NU cores. As the increase in reactivity upon refuelling and the consequent power ripple are only slightly larger in the MOX core than in the NU core, refuelling has not been identified as a problem. Further simulations are, however, required to characterize the zone controller system with respect to bulk and spatial control.

TABLE 1: FM DP TIME-AVERAGED RESULTS

	CANDU-600 Reference	Repositioned Adjuster Rods	
	Net U	MOX	Net U
k_{eff}	0.9999	0.9990	0.9985
Maximum Channel Power (MW)	6525	6070	6564
Maximum Bundle Power (MW)	813	750	831
Burnup (MWD/kg)*	6.4	21.3	6.4
Refuelling Rate (cb/day)	2.3	2.6	2.3
(bdl/day)	18.2	5.2	18.2
Reactivity Decay Rate (mk/day)	-0.391	-0.480	-0.409
Adjuster Rod Worth (mk)	16.9	11.2	16.7
Zone Control Worth (mk)			
Full	7.0	5.3	6.5
Nominal	4.1	3.2	4.1
Mechanical Control Absorber Worth (mk)	10.8	9.0	14.6
Shutoff Rod Worth (mk)	82	38	76

* Nominal values. Actual burnup depends on details of the model.

The mechanical control absorbers are provided for the initiation of a rapid power reduction, and for overriding the reactivity increase following a power reduction. In a NU core, the largest reactivity increase follows a hot shutdown for fresh fuel with boron in the moderator, and the mechanical control absorbers provide sufficient depth for this case. In an equilibrium MOX core, the reactivity increase following a hot shutdown is only about 2 mk, based on point calculations with WIMS, and for this situation, the reactivity worth of the mechanical control absorbers is more than sufficient.

The shutoff rods must provide sufficient static reactivity to keep the reactor shut down in its most reactive state, and the dynamic reactivity and insertion rate must limit the power pulse during a LOCA to an acceptable level. For NU fuel the static reactivity must exceed the reactivity increase following a cold shutdown with xenon decay, about 55 mk. For a MOX-fuelled core at equilibrium, the most reactive state is a hot shutdown with xenon decay, about 35 mk. The static shutoff rod worth with both fuels exceeds the estimated required worth, although the margin for the MOX core is small. A dynamic simulation is required to determine whether the dynamic worth of the shutoff rods in the MOX core is sufficient. Additional shutoff rod worth with MOX fuel can be achieved by placing the shutoff rods in the high flux position approximately 3 bundle lengths from the channel ends. For example, by switching the location of the outermost adjuster rods with the shutoff rods between channel rows 7/8 and 15/16 (see Figure 2), the shutoff rod worth increases to 46 mk, with only a small effect on the axial power profile and adjuster rod worth.

Finally, a 75 day time-dependent refuelling simulation was carried out for the MOX-fuelled core using the SIMULATE module in FM DP, starting from a random distribution of channel ages. From this simulation, the average maximum channel and bundle powers are 6550 kW and 850 kW, respectively. The average maximum channel power in the MOX-fuelled core is approximately 7% lower than in a NU core, and the average maximum bundle power is comparable to that in NU. Defining the channel overpower as the fractional difference in the power of a channel at a point in time from its time-averaged power, and defining the channel power peaking factor (CPPF) as the maximum overpower averaged over time, the CPPF for the MOX-fuelled core is 14%, compared to approximately 10% for a NU core. Analysis of the power and power boost histograms from the point of fuel performance indicates that the defect probability is below the 1% threshold even with the effects of end-flux peaking included.

SUMMARY

Repositioning the adjuster rods in 4 axial banks in future CANDU-600 reactors would permit the flexibility of grading the inner and outer banks to achieve optimal flattening of the axial power distribution for any particular fuel. With the 4 banks identical, acceptable axial power profiles can be achieved for both MOX and NU fuels, with 30 minutes xenon override time. Future work is to be directed at assessing the impact of the lower zone controller and shutoff rod worths in the configuration considered here, and if necessary, in identifying means of increasing their worths.

ACKNOWLEDGMENTS

Helpful discussions with J.V. Donnelly during the course of this work are gratefully acknowledged. S. Wall assisted in the refuelling simulations. Finally the continuing assistance of AECL - CANDU Operations personnel in the use of FM DP is appreciated.

REFERENCES

- (1) CHAN, P.S.W. and DASTUR, A.R., "Checkerboard Fuelling - The Key to Advanced Fuel Cycles in Operating CANDU", to be published in Proc. of Sixth Annual Conf. of the Canadian Nuclear Society, 1985.
- (2) WIGHT, A.L. and SIBLEY, R., AECL Unpublished Report, 1977.
- (3) DONNELLY, J.V., "Progress in the Development of WIMS at Chalk River", to be published in Proc. of Sixth Annual Conf. of the Canadian Nuclear Society, 1985.
- (4) CHOW, H.C. and Roshd, M.H.M., "SHETAN - a Three-Dimensional Integral Transport Code for Reactor Analysis", AECL-6878, 1980.
- (5) TIN, E.S.Y. and LOKEN, P.C., AECL Unpublished Report, 1979.
- (6) DASTUR, A.R. and BUSS, D.B., "MULTICELL - a 3-D Program for the Simulation of Reactivity Devices in CANDU Reactors", AECL-7544, 1983.