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A Preliminary Assessment of the Adjuster Rod Depletion Effect in the CANDU Reactor

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1. Introduction

A refurbishment program is underway to extend the lifetime of the Wolsong-1 CANDU reactor, which will be shutdown in April, 2009. Major reactor components such as the pressure tube are to be replaced and it is expected that the CANDU reactor can be operated for additional 25~30 years. Meanwhile, all the reactivity devices including the adjuster rods (ADJ) are supposed to be continuously used without any change. In the CANDU reactor, 21 stainless steel (SS) ADJs are used to control the core power distribution and compensate for some reactivity loss during several abnormal cases. The ADJs are normally fully inserted and the SS absorber should undergo a slow depletion through neutron irradiation for a long time. In April, 2009, the accumulated FPY (Full Power Day) of Wolsong-1 is about 23 years.

Depletion of ADJs should result in a smaller ADJ worth and a higher fuel burnup and the core power distribution should also be affected by the ADJ depletion. In this work, the effects of the ADJ depletion have been assessed in terms of ADJ worth, time-average core characteristics.

2. ADJ Depletion Calculation

Currently, the CANDU core is analyzed by the WIMS-AECL/DRAGON/RFSP code system [1,2,3]. The lattice parameters are calculated by the WIMS-AECL/DRAGON codes in advance the 3-D core analysis is performed with the RFSP code. For an accurate evaluation of the ADJ depletion, each ADJ should be depleted with the position-dependent neutron fluxes calculated by RFSP. Unfortunately, the current RFSP code does not provide the flux level of the ADJ region. Therefore, in this work, a rather simple ADJ depletion calculation is done with the ORIGEN2.2 code [4] by assuming that all the 21 ADJs are in the same condition for a preliminary assessment.

Basically, the CANDU reactor is always in an equilibrium condition due to the on-power refueling and the ADJ depletion is very slow. Thus, it can be reasonably assumed that each ADJ is subject to a very similar neutron field during the whole operation period. In addition, the radial power distribution is rather flat in the CANDU core. Consequently, the simple 0-D ORIGEN calculation is expected to provide reliable ADJ composition as a function of irradiation time.

In the ORIGEN depletion calculation, the most important parameter is the neutron flux level of the ADJ zone. Also, the cross section data for the depletion calculation should be accurate. The HELIOS code [5] was used to renew the public cross section library of ORIGEN2.2 and calculate the average neutron flux of the core. Based on the average core power density, a total neutron flux of 3.2×10^{14} n/cm$^2\cdot$sec was obtained with the 190-group HELIOS calculation of the standard fuel lattice.

Table 1 shows the major ADJ compositions depending on the irradiation period. Fe-56 is the main isotope of the ADJ and decreases significantly with irradiation due to the high absorption cross-section. As a result, Fe-57 builds up substantially.

Table 1 Time-dependent ADJ Composition (wt%)

Isotope	0 Year (Fresh)	10 Years	23 Years	30 Years	40 Years
Fe-56	**63.71**	**59.69**	**54.40**	**51.72**	**48.10**
Cr-52	15.40	15.13	14.73	14.52	14.24
Fe-57	**1.47**	**6.19**	**11.30**	**13.64**	**16.52**
Ni-58	6.97	6.09	5.07	4.59	3.99
Ni-60	2.68	3.08	3.69	3.93	4.21
Fe-54	4.06	3.81	3.48	3.31	3.09
Cr-54	0.43	1.27	2.05	2.38	2.80

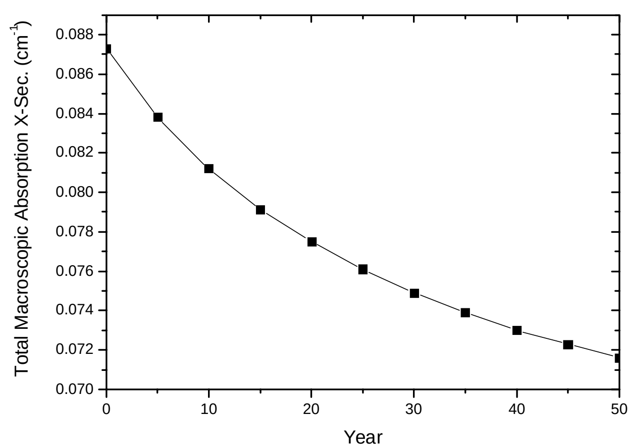

Fig. 1. Total Macroscopic Absorption Cross-section of the ADJ

Figure 1 shows the total macroscopic absorption cross-section of the ADJ as a function of time. It is clear that the absorption cross section of ADJ monotonically decreases with irradiation. It is mainly due to the conversion of Fe-56 to Fe-57, which has a smaller capture cross section than Fe-56. Figure 1 indicates that the worth of ADJs should decreases with the irradiation time.

3. Reactor Core Simulation

Once the ADJ compositions are identified, the rector core simulation can be done in a standard procedure. First, the lattice calculations are performed with the WIMS-AECL/DRAGON codes for various configurations including ADJ-inserted one. And the core characteristics are analyzed by the steady-state RFSP calculation.

Table 2 summarizes the effects of the ADJ depletion in the CANDU core. The worth of ADJ was evaluated with an instantaneous core condition of Wolsong-1 and the core characteristics are analyzed for the time-average core of Wolsong-1.

The reactivity worth of the ADJs decreases noticeably as the irradiation time increases, as expected in Fig. 2. In the current Wolsong-1 reactor, the total worth of ADJs needs to be ~15 mk for their appropriate role [6]. Table 2 shows that the worth of ADJs is slightly smaller than the design target when the ADJs are depleted for 23 years.

The time-average core calculation results show that the maximum channel power (MCP) is hardly affected by the ADJ depletion. This is because the zone-average discharge burnup is adjusted for an appropriate power distribution in the time-average core analysis. On the other hand, it is noted that the maximum bundle power (MBP) slightly increases with the ADJ depletion. In addition, the dwelling time (DT) and average fuel discharge burnup increase slightly as the irradiation time increases.

Table 2. Total ADJ Reactivity Worth and Time-Average Core Calculation Results

Total ADJ reactivity worth					
	0 Year	10 Year	23 Year	30 Year	40 Year
Unrodded	1.0138	1.0138	1.0138	1.0138	1.0138
Rodded	0.9977	0.9983	0.9988	0.9990	0.9993
Worth (mk)	15.88	15.27 (-0.61)*	14.75 (-1.13)*	14.55 (-1.33)*	14.22 (-1.66)*
Time-average core calculation					
K-eff	0.9991	0.9994	0.9994	0.9994	0.9995
MCP(kW)	6623.0	6635.9	6633.2	6629.4	6634.5
MBP(kW)	803.5	806.8	809.2	809.9	811.7
DT(day)	193.3	194.3	195.6	196.2	196.7
Avg burnup (MWD/tU)	7172.1	7207.4	7256.0	7280.0	7298.9

*Difference in worth, mk

In this work, an approximate flux level (3.2×10^{14} n/cm^2·sec) was used to determine the ADJ composition as a function of time. Table 3 shows the variation of the cell-average total neutron flux of the ADJ-inserted regions in the time-average RFSP core analysis. Also, neutron flux in the ADJ region was also estimated based on the RFSP and HELIOS results. It should be noted that the actual neutron flux of the ADJ region is significantly higher than $3.2\text{x}10^{14}$ n/cm^2·sec, which was used in the current work. Therefore, it should be considered that the current analysis under-estimates the effects of ADJ depletion.

Table 3. Neutron flux in ADJ-inserted regions (RFSP calculation), 10^{14} n/cm^2·sec

Time	0	10	23	30	40
Min.	3.90 (3.3)*	3.95 (3.4)*	4.00 (3.4)*	4.02 (3.4)*	4.04 (3.4)*
Max.	4.82 (4.1)*	4.87 (4.1)*	4.90 (4.2)*	4.91 (4.2)*	4.93 (4.2) *

*Estimated flux in ADJ region

4. Conclusions

In the refurbished CANDU reactor, the impact of the ADJ depletion is not negligible. The core simulation shows that there is a chance to violate the design target of the total reactivity worth of the depleted ADJ. And, the time-average core calculation results indicate that the MBP of the refurbished CANDU reactor slightly increases with ADJ depletion. In addition, ADJ depletion for 23 years results in a noticeable increase in the fuel discharge burnup, which will also change the safety-related physics parameters of the CANDU core. Therefore, the depletion effect of the ADJ should be considered in the core design and safety analysis of the refurbished CANDU reactor.

References

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