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RECALCULATION OF POWER COSTS FOR THE CANDU REACTOR

by

C.-F. G. Hsi and M. Benedict

Massachusetts Institute of Technology
Nuclear Engineering Department

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Recalculation of Power Costs for CANDU Reactor

1. Introduction

Report NYO-9715 "The Effect of Fuel and Poison Management on Nuclear Power Systems" developed a new code for fuel cycle analysis and illustrated its application to the CANDU heavy water, natural uranium reactor. Since the work was done, three important changes in nuclear fuel costs have occurred.

1. The cost of natural UO_2 in Canada has decreased.
2. The cost of fabricating UO_2 fuel for CANDU has decreased.
3. The price of slightly enriched UF_6 set by USAEC was lowered on July 1, 1962.

The purpose of this report is to recompute the cost of power for CANDU, using the same technical specifications and cost bases as were used in NYO-9715, except the three cost reductions noted above. No new fuel cycle calculations were made, and no reoptimization of fuel management was attempted.

Fuel management cases considered in the present report are: (1) continuous bidirectional movement, (2) batch irradiation, and (3) discontinuous out-in movement, each at four different U-235 enrichments.

Two alternative methods of preparing fuel for the reactor were considered:

1) Obtaining natural uranium in Canada at the Canadian price and slightly enriched uranium from USAEC at the current price scale.
2) Preparing slightly enriched uranium by blending natural UO_2 from Canada with UO_2 containing 3.2 weight % U-235 obtained from the USAEC. This is the optimum enrichment for blending under the cost assumptions of this report.

Two alternative methods of treating spent fuel from the reactor were considered:

1) Fuel stored at the reactor site indefinitely without reprocessing for plutonium recovery.
2) Fuel shipped to reprocessing plant, reprocessed, and the recovered plutonium sold to USAEC.

2. Cost Bases

The cost bases are the same as those given in NYO-9715, Table 4.2, pp. 106-108, except the following changes are made:

1) cost of natural UO_2 = \$13.55/kg U
2) cost of fuel fabrication = \$42.78/kg U

These costs (supplied by AECL) are based on a cost of \$22.86/lb UO_2 for fabricated natural UO_2 fuel elements of 0.60 inch diameter for the CANDU reactor, of which \$5.50/lb UO_2 is the cost of the ceramic grade powder in finished fuel, taking into account a 1.5% loss of UO_2 during fabrication. These costs are the projected costs for future CANDU type reactors. (1)

The costs of enriched UF_6 are calculated from the price scale published in the U. S. Federal Register on May 29, 1962. Those values used in this report are:

1.0 a/o U-235:	\$46.60/kgU
1.3 a/o:	\$74.15/kgU
1.5 a/o:	\$93.45/kgU
1.75 a/o:	\$118.39/kgU
3.2 w/o:	\$276.40/kgU

The optimum enrichment for blending is 3.2 w/o U-235, based on a price of \$13.55/kg U for natural UO_2, and a price of \$12.50/kg U for conversion of UF_6 to UO_2. The procedure used for determining the optimum enrichment is described on pp. 111-113 of NYO-9715.

(1) Private communication, W. B. Lewis to M. Benedict

3. Results

The results of the recalculation are given in Tables 1, 2, and 3. The method of calculation is described in NYO-9715, p. 104, ff. Sample calculations are given in NYO-9715, Appendix C, and also at the end of this report. Two important points should be noted:

1) Some of the cost estimates were made in the U. S., while others were made in Canada. No distinction is made between the possible difference in value of the currencies in the two countries.

2) The variation of fuel cycle cost with U-235 enrichments is strongly dependent on the effective parasitic neutron absorption cross-section of the reactor (see Report No. AECL-651). This study was made for one fixed reactor design only, and thus did not consider the effect of variation of parasitic cross-section. Also a thermal neutron cross-section of 0.212 barn was used for zirconium, while a more recent value (December, 1959) of 0.263 was given by Report No. AECL-961, Appendix 3. A lower value of parasitic absorption tends to favor natural uranium fueled reactors. Also, the effects of variation in interest rate or capital costs were not considered.

From Tables 1, 2, and 3 it can be seen that fuel reprocessing is often not economically worthwhile, and that the maximum saving from reprocessing for the cases considered is 0.06 mill/kwhr. In fact, for the costs assumed in this report, reprocessing is only worthwhile when the amount of plutonium in the spent fuel is more than 45.8 kg/10,000kg initial U. For total burnup of over 20,000 $\frac{\text{MWD}}{\text{Tonne U}}$, the amounts of Pu-239, 240, and 241 are closely in equilibrium with the amount of U-238. The maximum concentration of total plutonium, for the cases considered, is 56.6 kg/10,000kg initial U, at a burnup of 21920 $\frac{\text{MWD}}{\text{Tonne U}}$. Thus the savings from reprocessing is very limited. Furthermore, these calculations were based on a price of $9500/kg Pu, which was thought to be consistent for the price given for highly enriched UF_6. This corresponds to the price of about 70% enriched uranium on the July 1961 price scale. The corresponding price on the July 1962 price scale is about $8400. Also, the contents of Pu-239, 241 in the recovered plutonium are about 60% or less for the cases considered. Unless there is a reduction in the shipping and the reprocessing costs, fuel reprocessing for the CANDU reactor does not seem worthwhile.

When fuel richer than natural uranium is under consideration, its production by blending natural UO_2 with UO_2 containing 3.2% U-235 is economically justified in all cases considered. The technical feasibility of blending remains to be demonstrated.

The magnitude of the savings from blending varies with enrichment and burnup from 0.04 to 0.24 mills/kwhr.

At each enrichment, the reactor was optimized by varying the peak-to-average power density ratio. For a peak power density limited reactor, a low power density ratio permits the use of a smaller reactor core and thus reduces capital costs; however, it also increases the neutron leakage which leads to smaller burnup and therefore higher fuel cycle costs. For the cost assumptions used, a decrease of the reactor volume from the reference design volume V_o to 0.8 V_o leads to a decrease of about 0.16 mill/kwhr. The savings from optimization are thus rather limited.

In the cases for batch irradiation or discontinuous out-in movement of fuel, a 2% difference in the fueling load factor (which increases with increasing burnup) leads to a difference of about 0.11 mill/kwhr in the overall power costs.

In general, the effect of the three cost reductions is of course to reduce the fuel cycle costs, and hence the overall power costs computed in NYO-9715. Both in mills/kwhr and in percent, the reductions are greatest for natural uranium, and are correspondingly smaller at higher enrichments. However, the use of slightly enriched uranium still results in some savings over natural uranium for all three methods of fuel management, and the optimum enrichments are not affected greatly by the cost reductions.

A. Continuous Bidirectional Fuel Movement

Results are given in Table 1. The natural uranium case is for the CANDU Reference Design as described in Report No. AECL-949, December, 1959. The slightly enriched cases are for reactors optimized for minimum peak-to-average power density ratio by variation of radial burnup. The use of slightly enriched uranium (at 1 a/o U-235) leads to slightly lower fuel cycle cost, and appreciably lower overall power cost than natural uranium (0.10 and 0.25 mill/kwhr less respectively with blending but without reprocessing). The reason for the lower fuel cycle cost is because the increase in burnup from the use of slightly enriched uranium results in a lower fabrication cost (in mill/kwhr) which more than offsets the increase in uranium cost and interest charges. The further reduction in overall power cost is due to the use of a smaller reactor becuase of flatter power distribution. This is discussed in more detail in Section 4.5 of NYO-9715.

B. Batch Irradiation

Results are given in Table 2. At each enrichment, the reactor is optimized by variation of the ratio of the magnitude of the initial uniform poison in the outer zone to that in the central zone, as illustrated in Tables 6.16 and 6.17 in NYO-9715. Slight changes in ratio do not affect the burnup very much, while the peak-to-average power density ratio changes appreciably. Table 2 shows that the overall power cost versus enrichment curve has a rather broad minimum in the region between 1.3 to 1.75 a/o U-235. The use of natural uranium results in a large increase in cost because of the very short burnup attainable.

C. Discontinuous Out-in Fuel Movement

Results are given in Table 3. As in the batch case, the optimization at each enrichment is again done by varying the inner to outer zone poison ratio. The cost at each enrichment lies in between that of the bidirectional fuel movement and batch irradiation. A rather broad minimum in overall power cost occurs at about 1.3 a/o U-235 enrichment.

4. Sample Cost Calculation

Cost calculations for the optimum 1.0 a/o U-235 reactor with bidirectional fueling with blending and reprocessing are given below. Meaning of symbols and values of the constants (except the three cost reductions stated in this report) are given in NYO-9715, Section 4.4, Table 4.2, and Appendix C - where a sample calculation is also given. Fuel cycle data are given in Table 4:

$$G = \frac{1000}{24\ \bar{B}\ \gamma} = \frac{1000}{24 \times 15810 \times 0.2795} = 0.00943\ \frac{\text{mill}/\text{kwhr}}{\$/\text{kg}}$$

1.0 a/o U-235 = 0.9875 w/o U-235

1. Cost of natural UO_2

$$W_1 = \frac{x_{opt} - x}{x_{opt} - 0.007115} = \frac{0.032 - 0.009875}{0.032 - 0.007115} = 0.889$$

$$\bar{C}_1 = f_1 W_1 C_1 G = 1.015 \times 0.889 \times 13.55G = 0.115 \text{ mill/kwhr}$$

2. UF_6 from AEC

$$W_2 = 1 - W_1 = 0.111$$

$$\bar{C}_2 = f_2 W_2 C_2 G = 1.018 \times 0.111 \times 276.40\ G = 0.294 \text{ mill/kwhr}$$

3. UF_6 to UO_2 conversion

$$\bar{C}_3 = f_3 W_3 C_3 G = 1.018 \times 0.111 \times 12.50G = 0.013 \text{ mill/kwhr}$$

4. Fabrication

$$\bar{C}_4 = f_4 W_4 C_4 G = 1.015 \times 1 \times 42.78G = 0.409 \text{ mill/kwhr}$$

5. Shipping

$$\bar{C}_5 = f_5 W_5 C_5 G = 1 \times 1 \times 15.45G = 0.146 \text{ mill/kwhr}$$

6. Solvent extraction

$$C_6 = \frac{D_6(t + WFL/R)}{WFL} = \frac{17100\ (8 + 38.21)}{38210} = \$20.68/\text{kg}$$

$$\bar{C}_6 = f_6 W_6 C_6 G = 0.99 \times 1 \times 20.68G = 0.193 \text{ mill/kwhr}$$

7. and 8. For all the cases considered, the concentration of U-235 in the spent fuel is too low to be economically worthwhile for conversion to UF_6, thus these two terms are taken to be zero.

9. Conversion of $Pu(NO_3)_4$ to Pu

$$\bar{C}_9 = f_9 W_9 C_9 G = 0.98 \times \frac{43.0}{10000} \times 1500G = 0.075 \text{ mill/kwhr}$$

10. Sale of Pu to USAEC

$$\bar{C}_{10} = f_{10} W_{10} C_{10} G = -0.98 \times \frac{43.0}{10000} \times 9500G = -0.473 \text{ mill/kwhr}$$

$$\text{Net reprocessing cost} = \bar{C}_5 + \bar{C}_6 + \bar{C}_9 + \bar{C}_{10} = -0.059 \text{ mill/kwhr}$$

11. Non-reactor UF_6 lease

$$\bar{C}_{11} = \bar{C}_2 \cdot \text{TUPR} \cdot F_U = 0.294 \times 0.6 \times 0.045 = 0.008 \text{ mill/kwhr}$$

12. Non-reactor working capital

$$\bar{C}_{12} = (\bar{C}_1 + \bar{C}_3 + \bar{C}_4)\text{TWPR} \cdot F_W = 0.537 \times 0.5 \times 0.045 = 0.012 \text{ mill/kwhr}$$

13. Reactor time UF_6 lease

$$\bar{C}_{13} = \bar{C}_2 \cdot \frac{TR \cdot F_U}{2 \cdot L_o} = 0.294 \times \frac{1.874 \times 0.045}{2 \times 0.8} = 0.015 \text{ mill/kwhr}$$

$$\text{where } TR = \frac{\text{Reactor Charge (Tonnes)} \times \text{Burnup (MWD/T)}}{\text{Thermal Power (MW)} \times 365 \text{ D/Year}}$$

$$= \frac{38.21 \times 0.81 \times 15810}{715.5 \times 365} = 1.874 \text{ years}$$

$(0.81 = V/V_o)$

14. Reactor time working capital

$$\bar{C}_{14}=(\bar{C}_1+\bar{C}_3+\bar{C}_4)\ \frac{TR\cdot F_W}{2L_o} = 0.537 \times \frac{1.874 \times 0.045}{2 \times 0.8} = 0.028 \text{ mill/kwhr}$$

$$\text{Total fuel cycle cost} = \sum_{i=I}^{14} C_i = 0.835 \text{ mill/kwhr}$$

15. Reactor capital costs

$$\bar{C}_{15} = \frac{C_{15}\cdot FCAPR}{8.766L} = \frac{(156 + 68 \times 0.81)}{8.766 \times 0.8 \times 1} \times 0.0813 = 2.447 \text{ mills/kwhr}$$

16. Non-reactor capital costs

$$\bar{C}_{16} = \frac{C_{16}\cdot FCAPNR}{8.766L} = \frac{183 \times 0.0731}{8.766 \times 0.8 \times 1} = 1.908 \text{ mills/kwhr}$$

17. Reactor operating costs

$$\bar{C}_{17} = \frac{C_{17}}{8.766L} = \frac{4.37}{8.766 \times 0.8 \times 1} = 0.623 \text{ mill/kwhr}$$

18. Non-reactor operating costs

$$\bar{C}_{18} = \frac{C_{18}}{8.766L} = \frac{2.78}{8.766 \times 0.8 \times 1} = 0.396 \text{ mill/kwhr}$$

$$\text{Overall power cost} = \sum_{i=1}^{18} \bar{C}_i = 6.209 \text{ mills/kwhr}$$

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Table 1. Continuous Bidirectional Fueling

Fuel prepared by blending	Yes		No	
Fuel reprocessed	Yes	No	Yes	No
Fuel enrichment	Fuel cycle costs, mills/kwhr			
Natural U	-	-	(1.03)*	0.99
1.0 a/o U-235	0.83	0.89	0.99	1.05
1.3	0.86	0.92	0.93	0.99
1.5	0.93	0.96	0.97	1.00
	Overall power costs, mills/kwhr			
Natural U	-	-	(6.56)	6.52
1.0 a/o U-235	6.21	6.27	6.37	6.43
1.3	6.30	6.36	6.38	6.44
1.5	6.45	6.48	6.50	6.53

*Numbers in parentheses are for cases where reprocessing is not economically justified.

Table 2. Batch Irradiation

Fuel prepared by blending	Yes		No	
Fuel reprocessed	Yes	No	Yes	No
Fuel enrichment	Fuel cycle costs, mills/kwhr			
Natural U	-	-	(2.99)	2.33
1.3 a/o U-235	(1.80)	1.75	(1.94)	1.89
1.5	(1.76)	1.74	(1.85)	1.83
1.75	1.74	1.75	1.79	1.80
	Overall power costs, mills/kwhr			
Natural U	-	-	(8.69)	8.03
1.3 a/o U-235	(7.23)	7.18	(7.38)	7.33
1.5	(7.20)	7.18	(7.29)	7.27
1.75	7.18	7.18	7.23	7.23

Table 3. Discontinuous Out-in Fueling

Fuel prepared by blending	Yes		No	
Fuel reprocessed	Yes	No	Yes	No
Fuel enrichment	Fuel cycle costs, mills/kwhr			
1.0 a/o U-235	(1.45)	1.39	(1.69)	1.63
1.3	1.33	1.34	1.44	1.45
1.5	1.35	1.37	1.42	1.44
1.75	1.38	1.42	1.42	1.46
	Overall power costs, mills/kwhr			
1.0 a/o U-235	(6.93)	6.87	(7.17)	7.11
1.3	6.78	6.79	6.89	6.90
1.5	6.84	6.86	6.91	6.93
1.75	6.90	6.94	6.94	6.98

Table 4. Fuel Cycle Data Needed For Cost Calculations
(Taken from NYO-9715)

Total reactor power = 715.5 MW

Net thermal efficiency = 0.2795

Initial amount of uranium in reactor = $38.21 \frac{V}{V_o}$ Tonnes U

V_o = CANDU Reference Design reactor volume

Batch size for reprocessing = 38210 kg of irradiated uranium

Bidirectional fueling	Enrichment (a/o)			
	Nat.	1.0	1.3	1.5
Core volume	V_o	$0.81V_o$	$0.9V_o$	V_o
Average burnup (MWD/T)	9080	15810	21920	25400
Pu yield (kg Pu/10000kg initial U)	43.0	53.8	56.6	52.6

Batch irradiation	Enrichment (a/o)			
	Nat.	1.3	1.5	1.75
Core volume	$1.02V_o$	$0.82V_o$	$0.84V_o$	$0.84V_o$
Average burnup (MWD/T)	3800	11030	13200	15820
Pu yield (kg Pu/10000kg initial U)	24.4	41.0	43.9	46.5
Fueling load factor	0.972	0.990	0.992	0.993

Discontinuous out-in fueling	Enrichment (a/o)			
	1.0	1.3	1.5	75
Core volume	$0.8V_o$	$0.8V_o$	0.87V	$.93V_o$
Average burnup (MWD/T)	10020	14470	16970	9890
Pu yield (kg Pu/10000kg initial U)	41.1	47.1	49.6	51.9
Fueling load factor	0.979	0.985	0.988	0.990