Journal of the Korean Nuclear Society
Volume 23, Number 2, June 1991

A Scheme of Better Utilization of PWR Spent Fuels

B. J. Chung and C. S. Kang
Department of Nuclear Engineering
Seoul National University
(Received July 13, 1990)

가압경수로 사용후핵연료 이용확대 방안연구

정범진 · 강창순
서울대학교
(1990. 7. 13 접수)

Abstract

The recycle of PWR spent fuels in a CANDU reactor, so called the tandem fuel cycle is investigated in this study. This scheme of utilizing PWR spent fuels will ease the shortage of spent fuel storage capacity as well as will improve the use of uranium resources. The minimum modification to the design of present CANDU reactor is seeked in the recycle. Nine different fuel types are considered in this work and are classified into two categories: refabrication and reconfiguration. For refabrication, PWR spent fuels are processed and refabricated into the present 37 rod lattice structure of fuel bundle, and for reconfiguration, meanwhile, spent fuels are simply disassembled and rods are cut to fit into the present grid configuration of fuel bundle without refabrication. For each fuel option, the neutronics calculation of lattice was conducted to evaluate the allowable burnup and power distribution. The fuel cycle cost of each option was also computed to assess the economic justification. The results show that most tandem fuel cycle options considered in this study are technically feasible as well as economically viable.

요 약

가압경수로의 사용후핵연료를 CANDU 원자로에 재순환시키는, 이른바, 탄뎀 핵연료주기가 본연구에서 다루어졌다. 이러한 방식으로 가압경수로의 사용후핵연료를 활용하는 것은 우라늄자원의 이용을 개선시킬뿐만 아니라 사용후핵연료 저장능력의 부족도 다소 해결할 수 있을 것이다. 핵연료를 재순환 시키는데 있어서는 CANDU 원자로의 수정을 최소화하는 방향으로 연구가 진행되었으며 본연구에서는 9종의 핵연료가 고려되었다. 탄뎀 핵연료는 크게 핵연료재가공과 노심재구성의 두 분야로 나뉘어지는데, 핵연료 재가공의 경우, 가압경수로의 사용후핵연료는 처리되고 현재의 37 봉형 격자구조인 핵연료 다발에 맞도록 다시 성형가공되며 노심재구성의 경우, 가압경수로 사용후핵연료는 단지 격자 구조를 해체하고 CANDU의 격자길이에 맞춰 재구성만 된다. 각 탄뎀 핵연료 옵션에 대하여, 허용연소도와 출력분포를 계산하기 위해 노심연소계산이 수행되었다. 또한 경제성에 대한 접근으로 각 핵연료 옵션에 대한 핵주기비가 계산되었다. 그 결과 본연구에서 다루어진 대부분의 탄뎀 핵연료 옵션이 경제성이 있었을 뿐만 아니라 기술적인 타당성이 있었다.

I. Introduction

For an efficient utilization of uranium resources, the recycle of PWR spent fuels in a CANDU reactor (called 'tandem fuel cycle' hereafter) is investigated in this study. Since the fissile isotopic composition of PWR spent fuels is higher than that of natural uranium which is presently used for CANDU fuels, it is feasible to recycle the spent fuels for CANDU feed. This scheme will not only ease the shortage of spent fuel storage capacity which will be exhausted by the end of 1990's, but will also suggest a better utilization program of uranium resources.

In this study, the minimum modification to the design of present CANDU reactor is seeked in recycling the PWR spent fuels to the CANDU reactor. The use of depleted uranium is also looked into. Nine different fuel types are considered in this work. As a matter of course, the fuels made of natural uranium (NAT) and slightly enriched uranium (SEU) are studied for the purpose of comparison with the other fuel options. Tandem cycle fuels are classified into two categories according to geometrical configuration of the fuel: refabrication and reconfiguration. For refabrication, where PWR spent fuels are coprocessed and refabricated into CANDU fuel rods, the 37 rod lattice structure of the fuel bundle is unchanged and identical to that used in Wolsung Unit 1. Five different cases are studied for the case of refabrication. For reconfiguration, meanwhile, spent fuels are simply disassembled and rods are cut to fit into the present grid reconfiguration of fuel bundle without refabrication. Since the diameter and length of PWR fuel rods are fundamentally different from those of CANDU rods, they should be consequently adjusted to the design structure of CANDU fuel bundle. Two types of fuel configurations are looked into for the case of recon-

Table 1. Summay of Tandem Fuel Cycle Options

	Abbreviation	Geometry	Compositions
	NAT	Standard CANDU Lattice	Natural Uranium (0.711 w/o)
	SEU		Slightly Enriched Uranium (1.2 w/o)
Refabrication	REFAB	Standard CANDU Lattice	PWR Spent Fuel
	REFCOP		Coprocessed PWR Spent Fuel
	REF1.2S		REFCOP+Nat.U (1.2 w/o)
	REF0.7D		REFCOP+Dep.U (0.711 w/o)
	REF1.2D		REFCOP+Dep.U (1.2 w/o)
Reconfiguration	RECON37	37 PWR Fuel Element Bundle	PWR Spent Fuel
	RECON61	61 PWR Fuel Element Bundle	PWR Spent Fuel

Table 2. Standard CANDU Lattice and PWR Fuel Element Data

Core	Specific Power	25.43 MWD/THM
	Bundle Length	49.53 cm
Calandria	Inner diameter	12.90 cm
	Outer diameter	13.18 cm
Pressure Tube	Inner diameter	10.34 cm
	Outer diameter	11.21 cm
CANDU Fuel Element	Number	37
	Pellet diameter	1.2154 cm
	density	10.4497 g/cc
	Gap thickness	0.0455 mm
	Clad thickness	0.0419 cm
PWR Fuel rod	Pellet diameter	0.7844 cm
	Gap thickness	0.0787 mm
	Clad thickness	0.0572 cm

figuration: 37–rod and 61–rod bundle assemblies.

For each tandem fuel option, the neutronics calculation of lattice was conducted to evaluate the allowable burnup and power distribution. The fuel cycle cost of each option was also computed to assess the economic justification. The fuel options studied in this work are summarized in Table 1.

II. Neutronics Analyses

Two types of analyses were performed to investigate the nuclear characteristics of the tandem fuel cycle. The first one is the estimation of PWR spent fuel isotopic compositions and the other one is the assessment of burnup characteristics of each fuel option. In particular, the cycle length of each fuel option should be decided based on the calculated fuel burnup.

ORIGEN2 was used to estimate the isotopic compositions in the PWR spent fuel. A typical PWR fuel with 3.2 w/o enrichment was chosen and burned in an equilibrium core to 33,000 MWD/MTU, and then cooled for one year in the spent fuel storage pool before its use for tandem fuel. Table 3 summarizes the computed isotopic compositions of the PWR spent fuel.

WIMS was used to assess the reactor lattice cell. Carlson DSN method was adopted to solve the transport equation rather than the collision probability method since the cell geometries are not considered quite complicated in this CANDU lattice calculation. 18 main transport groups and 2 edit groups were employed for computation and the diffusion method was used in leakage calculation. In this study, a CANDU fuel bundle is divided into total of 14 annuli where inner 4 annuli are subdivided into 3 regions, i.e., fuel, gap and cladding. 4 annuli out of 14 have their boundary radii of the remaining 3 annuli coincide with the geometric radii, i.e., pressure tube inside and outside walls and calandria tube inside wall. The calandria tube outer wall and cell boundary are divided into 4 and 3 regions, respectively.

WIMS calculations provide information on cycle length, discharge isotopic compositions, local power distribution and reactivity coefficients. WIMS, however, is a lattice calculation code, which requires appropriate adjustments to reflect the entire core in the calculation. The computed

Table 3. PWR Spent Fuel Compositions

Element	Mass(gram)	Element	Mass(gram)
He 3	.17500E−02	He 4	.28040E+01
Li 7	.10600E+01	B 11	.82700E+00
C 12	.88300E+02	N 14	.24800E+02
O 16	.13400E+06	F 19	.10700E+02
Na 23	.15000E+02	Al 27	.16700E+02
Si 29	.58700E+00	Cr 52	.33600E+01
Mn 55	.16400E+01	Fe 56	.16500E+02
Ni 58	.16000E+02	Cu 63	.67800E+00
Mo 95	.75642E+03	Ag109	.76318E+02
Cd112	.22530E+02	In115	.24220E+01
Pb207	.23500E+00	U234	.18200E+03
U235	.79600E+04	U236	.39600E+04
U238	.94400E+06	Np237	.44300E+03
Np239	.73600E−04	Pu239	.50400E+04
Pu240	.23100E+04	Pu241	.11700E+04
Pu242	.45300E+03	Am243	.85700E+02
Kr 83	.41000E+02	Zr 91	.59000E+03
Tc 99	.77100E+03	Ru101	.77200E+03
Ru103	.81500E−01	Rh103	.46700E+03
Pd105	.37500E+03	Pd108	.15000E+03
Cd113	.15200E+00	Sb121	.82300E+01
Sb123	.10100E+02	I127	.55400E+02
Xe131	.43100E+03	Cs133	.11300E+04
Cs134	.86000E+02	Cs135	.30000E+03
Nd143	.77800E+03	Nd145	.67200E+03
Pm147	.11500E+03	Sm147	.87700E+02
Pm148	.21200E−04	Pm148m	.28900E−02
Sm149	.26800E+01	Sm150	.25400E+03
Sm151	.12300E+02	Sm152	.12700E+03
Eu153	.10600E+03	Eu154	.35600E+02
Eu155	.12100E+02	Gd155	.18800E+01
Gd157	.10700E+00	Dy164	.42500E−01
Pseudo	.35667E+05		

local power distribution of each tandem fuel option is presented in Table 4.

Option SEU is known to be well operable with current reactivity control devices. Hence, without any modification in the reactivity control system, the other fuel options of the tandem fuel cycle are considered to be very acceptable except REFCOP. In case of REFCOP, due to its high initial excess reactivity, major modifications are expected in the reactivity control system of present CANDU

Table 4. Power Distributions in CANDU Lattice

OPTION	BURN-UP (MWD/MTU)	K-EFF	RELATIVE POWER DENSITY IN EACH RING				
			1st	2nd	3rd	4th	5th
NAT	0.0	1.06684	0.7786	0.8166	0.9158	1.1296	
	3153.2	1.00873	0.7821	0.8197	0.9142	1.1294	
	6500.0	0.95281	0.8042	0.8381	0.9201	1.1182	
SEU	0.0	1.26152	0.7130	0.7604	0.8868	1.1713	
	10273.4	1.00221	0.8213	0.8556	0.9326	1.1030	
	20532.4	0.84812	0.8437	0.8660	0.9205	1.1064	
REFAB	0.0	1.08736	0.5714	0.6372	0.8198	1.2649	
	3356.7	0.99986	0.6383	0.7022	0.8649	1.2094	
	6397.5	0.94080	0.6986	0.7573	0.8961	1.1669	
REFCOP	0.0	1.30444	0.6010	0.6638	0.8356	1.2439	
	11799.2	1.00306	0.8094	0.8495	0.9342	1.1046	
	23824.4	0.83353	0.8649	0.8829	0.9269	1.0956	
REF1.2S	0.0	1.26195	0.6584	0.7142	0.8638	1.2051	
	9663.1	0.99501	0.8066	0.8441	0.9281	1.1107	
	18882.8	0.86200	0.8400	0.8648	0.9232	1.1052	
REF0.7D	0.0	1.11987	0.7454	0.7892	0.9034	1.1488	
	3153.2	1.00106	0.7766	0.8157	0.9130	1.1319	
	6325.4	0.94179	0.7998	0.8344	0.9179	1.1211	
REF1.2D	0.0	1.26294	0.6461	0.7035	0.8581	1.2131	
	9052.8	1.00310	0.7984	0.8378	0.9262	1.1145	
	18582.6	0.86371	0.8385	0.8638	0.9232	1.1056	
RECON37	0.0	1.12335	0.7903	0.8277	0.9221	1.1210	
	3967.0	1.00804	0.8473	0.8761	0.9452	1.0863	
	8136.6	0.90607	0.8945	0.9145	0.9605	1.0607	
RECON61	0.0	1.10019	0.6843	0.7165	0.7966	0.9437	1.2280
	3560.1	1.00406	0.7494	0.7779	0.8453	0.9608	1.1727
	7139.6	0.92754	0.8084	0.8317	0.8844	0.9692	1.1309

design. Even though the options have the same fissile contents, they show different initial reactivities and reactivity rundowns due to the difference in the amounts of uranium and plutonium contained in the fuel. As plutonium has larger fission cross section than uranium, the fuel options having higher plutonium contents will have higher initial excess reactivities, meanwhile they rapidly run down.

Maximum local power peaks are seen in the early stages of fuel burnup and power densities decrease rapidly toward their centers because of the attenuation of thermal neutrons within the bundle. In case of NAT, the maximum local power peak is observed to occur early in life in the outer ring of the fuel and reaches the maximum value of 1.13, which is within the designed overpower envelope. And the local peakings of the other tandem fuel options are 2 to 11 percent higher than that of NAT.

The cycle length of each fuel option computed by WIMS differs from the actual cycle length due to a number of factors neglected in the cell calculation, such as inclusion of control rods for power shaping and other minor parasitic captures. More accurate prediction of the cycle length requires a great deal of more efforts. Thus, in this study, computed cycle lengths were adjusted by the factor obtained when the computed result of NAT is compared with the nuclear design report data.

In PWRs, the cycle length is established based upon the instantaneous core reactivity. That is, the cycle length is determined when the fuel burnup reaches such a point that the neutron production rate just equals the neutron loss rate ($k_{eff}=1$) in the absence of control poisons. For the reactors with on-power refueling such as CANDU, however, the allowable burnups are limited by the time integrated reactivity of a cell rather than by the instantaneous value of the entire core. In these reactors, a fuel bundle may be a net producer or absorber of neutrons at any particular burnup, but there are other bundles elsewhere in the reactor absorbing or producing enough neutrons to eliminate any net excess or deficit. This is equivalent that the excess neutrons produced from a cell early in the cycle are saved for later in the cycle where the fuel produces less neutrons than absorbs. The above assumption can be formulated as follows ;

$$\text{Total neutron production} = \int_0^T \nu\Sigma_f \phi \, dt \qquad (2\text{-}1)$$

$$\text{Total neutron removal} = \int_0^T [\Sigma_a + \text{Leakage}] \phi \, dt$$

$$= \int_0^T \frac{1}{k_{eff}} \nu\Sigma_f \phi \, dt \qquad (2\text{-}2)$$

Equating these integrals and assuming that $\nu\Sigma_f\phi$ is approximately constant (since power generation is constant in the calculation), we obtain

$$\frac{1}{T}\int_0^T \frac{1}{k_{eff}} dt = 1 \qquad (2\text{-}3)$$

where T is the time corresponding to the discharge exposure. For the situation where all neutron losses are not accounted for in the calculation of k_{eff}, this equation may be written

$$\Delta\rho = 1 - \frac{1}{T}\int_0^t \frac{1}{k_{eff}} dt \qquad (2\text{-}4)$$

where k_{eff} is the calculated reactivity and $\Delta\rho$ is the reactivity worth of neutron losses excluded in the calculation of k_{eff}. This formulation is convenient, in which it permits adjustments to be readily made for power shaping, different fuel management options, and the presence of control rods which are not usually accomodated in a cluster cell calculation such as that performed with WIMS.

Figure 1 illustrates the reactivity vs. burnup, which is computed by WIMS. The results show that the predicted burnup of NAT fuel is 9381.3 MWD/MHM. In this computation, however, many neutron losses are neglected. To obtain the actual cycle length, allowance must be made for the neutron losses not included in the WIMS calculation. Meanwhile nuclear design report suggests 6500 MWD/MTU for the same fuel. This means that the reactivity should be adjusted by 22.9mk as shown in Figure 1. The other options are adjusted the same way based upon this concept.

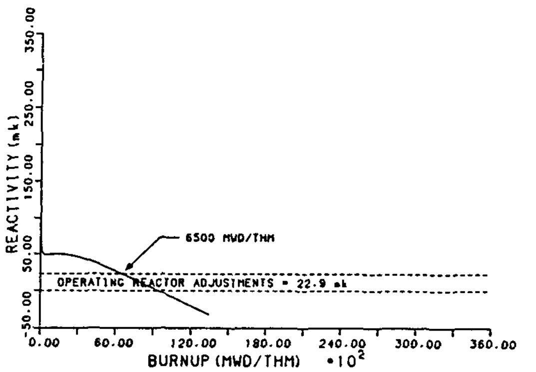

Figure 1. Reactivity Rundown Curve for Option "NAT

Ⅲ. Economic Analyses

The purpose of economic analyses is to determine the best economical option by comparing fuel cycle costs. In this study, the discounted cash flow analysis was performed for a single fuel bundle to produce the fuel cycle cost for each option. This analysis assumes an equilibrium core, which may be justified in view of ratio of equilibrium cycle length to the entire cycle length. All the fuel cycle costs are levelized to the point where the expenditure of the investor equals his revenue income, i.e. the sum of discounted cash payments for materials and services equals the sum of discounted revenues from power generations.

In this analysis, continuous discounting method was adopted, which was particularly suitable for on-power fueling. Due to the continuity in discounting, the power generation periods can also be included in discounting. If S is the sum of money at time t earning interest continuously at the rate of r, then the interest earned after time dt is given by;

$$dS = S\ r\ dt$$

or

$$S = So\ \exp(rt) \tag{3-1}$$

where So is the quantity of money at some reference in time.

Levelization requires the discounting of electricity. The discounted electricity is given by:

$$E_{dc} = \int_0^T [\eta\ P_s\ M_F\ \exp(-rt)]\ dt$$

$$= (\eta/r)\ P_s\ M_F\ [1 - \exp(-rT)] \tag{3-2}$$

$$T = \frac{B}{L_f \times P_s}$$

where

T = Time in reactor (year),
E_{dc} = Discounted Electrictity (kWh),
B = Burnup (MWD/MTU),
r = Discount rate.
η = Thermal efficiency of CANDU,
L_f = Load Factor,
P_s = Specific Power (kW/kg), and
M_F = Fuel Mass (kg).

In this case the levelized fuel cycle costs are calculated as follows:

$$e_{lfc} = 1000 \frac{FEC_i + BEC_i}{E_{dc}} \tag{3-3}$$

where

e_{lfc} = Levelized fuel cycle cost (mills/kwh),
FEC_i = Front-end cost of option i ($/kgHM), and
BEC_i = Back-end cost of option i ($/kgHM).

In the back-end cycle, the costs of AR(At-Reactor) storage, AFR(Away-From-Reactor) storage, and ultimate disposal, and in case of spent fuel recycling, reprocessing and other material credits were included. Transportation costs were also appropriately included in the calculation. The economics of tandem fuel options are very much influenced by the cost of coprocessing. If it is high, the tandem fuel cycle will be less feasible than the once-through cycle. Hence, a reasonable choice of cost data is very essential in this feasibility study. Economic evaluations of tandem fuel cycle options have been made using a set of economic data as given in Table 5. The results are summarized in Table 6.

The results shows that "REFAB" and "REFO.7D" are the most expensive options due to relatively high front-end fuel cost and low electricity generation and also "REF1.2D" fuel is cheaper than "REF1.2S" because of the low cost of depleted uranium fuel. Table 6 also shows that reconfigured option fuels ("RECON37" and "RECON61"), having low front end costs, are economically superior to the others since the spent fuel cost is treated as the credit. However this result does not include the cost of possible design modification required in the CANDU reactor to accomodate the change in the fuel bundle. Including all these fac-

Table 5. Cost Data Used in Economic Analyses

	Unit Cost ($/kg)	Fractional Loss	Delay Time (year)
Yellow cake	30.0	–	0.2000
Conversion			
(U_3O_8 to UO_2)	10.0	0.0050	0.3000
(U_3O_8 to UF_6)	6.0	0.0050	0.3000
(UF_6 to UO_2)	6.0	0.0050	0.0833
Enrichment	115.0	0.0148	0.3333
Fabrication			
(UO_2)	50.0	0.0050	0.5000
(MOX)	150.0	0.0050	0.5000
(Spent Fuel)	550.0	0.0050	0.5000
Temporary Storage	18.0	–	1.0000
Ultimate Disposal			
(CANDU)	228.2	–	–
(PWR)	350.0	–	
Coprocessing	750.0	0.0150	0.8333

Table 6. Economic Analysis Results

Fuel Option	Front-end Cost ($)	Back-end Cost ($)	Electricity Generation(kwh)	Levelized Fuel Cost(mills/kwh)
NAT	2594.148	4807.887	864966.8	8.55760
SEU	7397.292	4102.787	2546595.	4.51587
REFAB	6893.414	4592.270	812624.5	14.13406
REFCOP	15351.75	3951.724	2906792.	6.64082
REF1.2S	11491.07	4179.405	2961005.	6.63721
REF0.7D	12334.74	4817.257	842437.7	20.35996
REF1.2D	6801.358	4193.620	2326812.	4.72534
RECON31	−604.3105	2221.714	505456.3	3.19989
RECON61	−996.3029	3704.284	734927.1	3.68469

tors, hence, it is probable that the reconfigured options could actually be more expensive than the calculated results. "REFCOP" fuels are neither economic nor suitable for the current CANDU-600 reactivity control system.

IV. Conclusions and Recommendations

Based upon the results of study, the following conclusions and recommendations apply:

1. Seven cases of tandem fuel cycle were investigated in this feasibility study. The investigation, by nature, is limited to the evaluation of burnup calculation and fuel cycle cost calculation. Based upon the evaluation, one can observe that all the options except "REFAB" and "REF0.7D" are more economical than the present fuel cycle option of CANDU(NAT).

2. Without going through detailed additional studies, the reconfigured fuels ("RECON37" and "RECON61" are the cheapest of all options. They also do not require the coprocessing facility. Therefore, one can conclude that these two options are very feasible and economical. However, a lot of detailed technical works are required to accomodate these types of fuels in the present design of CANDU reactor. It is strongly recommended to carry out extensive research work in this line.
3. Coprocessing options require the spent fuel reprocessing technology as well as refabrication technology. Futher studies on safe handling of highly radioactive materials as well as processing technologies are also required. The resolution of safe-guard problems is also the pre-requisite.
4. As predicted, in the once-through cycle, the option of using the slightly enriched uranium fuel cycle is more economical than that of using the natural uranium or tandem fuel cycle.
5. However, in using the slightly enriched uranium and tandem fuels, the additional cost increase is expected due to associated unresolved technical issues, especially safety-related, which should be closely scrutinized.
6. It is a general outlook that the tandem fuel cycle options are technically feasible and economically justifiable for the CANDU reactor.

Acknowledgements

The authors like to thank Korea Science and Engineering Fund for its financial aid.

References

1. C.S. Rim and J.B. Slatter, "AECL–KAERI Joint Research Program on PWR–CANDU Tandem Fuel Cycles Phase 1 Program," Dec. 1983
2. J.R. Askew, F.J. Fayers, and P.B. Kemshell," A General Description of the Lattice Code WIMS," JBNES, Oct. 1966
3. M.J. Halsall, C.J. Taubman, "The '1981' WIMS Nuclear Data Library," AEEW–R–1442, Sep. 1983
4, H.S. Kim et. al., "Economic Modelling Study for Nuclear Fuel Cycle Analysis," KAERI/PR–504/85, Jan. 1986
5. J.Veeder and R.Didsbury, "A Catalogue of Advanced Fuel Cycles in CANDU–PHW Reactor," AECL–8641, Jun. 1985
6. L.L. Clark and A.D. Chockie, "Fuel Cycle Cost Projections," Battelle Pacific Northwest Laboratory, Dec. 1979
7. A.G. Croff, ORIGEN2 : A Versatile Computer Code for Calculating the Nuclear Compositions and Characteristics of Nuclear Materials, Nuclear Technology vol.62, Sep. 1983
8. C.J. Lim et. al., "Estimation of Discharged Amounts of U and Pu Nuclides from the PWR Spent Fuels in Korea," Journal of Korea Nuclear Society, vol.20, No.3, Sep. 1988