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CANDU Fuel Cycle Options in Korea

Options de cycles du combustible CANDU en Corée

P.G. Boczar, P.J. Fehrenbach, D.A. Meneley

Presented at the KAIF/KNS Annual Conference
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ATOMIC ENERGY OF CANADA LIMITED

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* AECL, Sheridan Park, 2251 Speakman Drive, Mississauga, Ontario, Canada, L5K 1B2

Chalk River Laboratories
Chalk River, Ontario K0J 1J0
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OPTIONS DE CYCLES DU COMBUSTIBLE CANDU EN CORÉE

P.G. Boczar[1], P.J. Fehrenbach[2] et D.A. Meneley[3]

[1] Directeur, Combustible et Cycle du combustible, EACL

[2] Directeur général, Mise au point de la technologie CANDU, EACL

[3] Ingénieur en chef, EACL

RÉSUMÉ

Le fait que des pays qui mettent sur pied un programme CANDU^{MD}, optent pour un cycle du combustible à l'uranium naturel peut s'expliquer de plusieurs façons. La conception simple du combustible, la facilité avec laquelle on peut le fabriquer et les réserves importantes d'uranium naturel font que l'on peut implanter localement la technologie, ce qui évite ainsi d'avoir à s'en remettre à la technologie étrangère. Néanmoins, il peut arriver que les avantages offerts par l'utilisation d'autres cycles du combustible soient plus nombreux que ceux de l'uranium naturel. L'excellente économie neutronique, le renouvellement du combustible pendant la marche du réacteur et la conception simple de la grappe de combustible assurent une souplesse inégalée pour les réacteurs CANDU.

La première étape, probablement la plus simple, dans l'évolution des cycles du combustible CANDU consiste à utiliser de l'uranium légèrement enrichi (SEU), notamment l'uranium récupéré à la suite du retraitement du combustible irradié LWR. À quantité égale d'énergie produite, un enrichissement relativement faible (jusqu'à 1,2 %) se traduira par une diminution de deux à trois fois de la quantité de combustible irradié produite, une diminution des coûts du cycle du combustible et une souplesse accrue dans la conception des nouveaux réacteurs. La grappe de combustible CANFLEX (*CANDU FLEXible*) serait le modèle optimal de porteur pour le combustible.

Un pays qui possède des réacteurs CANDU et PWR est en mesure d'exploiter la synergie naturelle entre ces deux filières afin de réduire au minimum la production de déchets et d'optimiser la quantité d'énergie produite avec le combustible. Cette synergie peut être exploitée par le biais de plusieurs cycles du combustible.

On pourrait utiliser du combustible CANDU MOX à hauts taux de combustion pour permettre l'utilisation du plutonium issu du retraitement classique ou des options de retraitement plus sophistiquées (telles le co-retraitement). Le programme DUPIC (utilisation directe du combustible du réacteur à eau sous pression dans le réacteur CANDU) constitue une option de recyclage qui présente des avantages du point de vue de la non-prolifération par rapport au retraitement classique, car on utilise uniquement des procédés à sec pour la transformation en combustible CANDU du combustible PWR irradié, sans séparation du plutonium. On a pu réaliser des progrès importants dans la démonstration de la faisabilité technique du concept DUPIC dans le cadre du programme réunissant KAERI, EACL et le *Department of State* des É.-U.

À long terme, les réacteurs CANDU permettront de profiter d'une synergie encore plus grande sur le plan des cycles du combustible avec les réacteurs PWR ou FBR (*Fast Breeder Reactor* - surgénérateur rapide). L'objectif d'un programme national de cycles du combustible étant de réduire au minimum les déchets (actinides) ou la destruction des produits de fission à longue période, des études ont démontré la supériorité des réacteurs CANDU dans la réalisation de cet objectif. La sécurité à long terme des approvisionnements en énergie est assurée par le cycle au thorium ou par un système CANDU / FBR, où le FBR serait exploité comme « usine de fabrication de combustible », fournissant la matière fissile pour alimenter plusieurs réacteurs CANDU économiques et performants.

En résumé, la conception simple du combustible du réacteur CANDU, la grande économie neutronique et le rechargement en marche offrent toute la souplesse nécessaire pour satisfaire aux exigences changeantes quant aux cycles du combustible, à long terme et dans un avenir indéterminé.

CANDU^{MD} est une marque déposée d'Énergie atomique du Canada limitée (EACL).

Laboratoires de Chalk River
Chalk River (Ontario) K0J 1J0
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CANDU FUEL CYCLE OPTIONS IN KOREA

by

P.G. Boczar[1], P.J. Fehrenbach[2] and D.A. Meneley[3]

[1] Director, Fuel and Fuel Cycle Division, AECL

[2] General Manager, CANDU Technology Development, AECL

[3] Chief Engineer, AECL

ABSTRACT

There are many reasons for countries embarking on a CANDU® program to start with the natural uranium fuel cycle. Simplicity of fuel design, ease of fabrication, and ready availability of natural uranium all help to localize the technology and to reduce reliance on foreign technology. Nonetheless, at some point, the incentives for using natural uranium fuel may be outweighed by the advantages of alternate fuel cycles. The excellent neutron economy, on-line refuelling, and simple fuel-bundle design provide an unsurpassed degree of fuel-cycle flexibility in CANDU reactors.

The easiest first step in CANDU fuel-cycle evolution may be the use of slightly enriched uranium (SEU), including recovered uranium from reprocessed LWR spent fuel. Relatively low enrichment (up to 1.2%) will result in a two- to three-fold reduction in the quantity of spent fuel per unit energy production, reductions in fuel-cycle costs, and greater flexibility in the design of new reactors. The CANFLEX (CANDU FLEXible) fuel bundle would be the optimal fuel carrier.

A country that has both CANDU and PWR reactors can exploit the natural synergism between these two reactor types to minimize overall waste production, and maximize energy derived from the fuel. This synergism can be exploited through several different fuel cycles.

A high burnup CANDU MOX fuel design could be used to utilize plutonium from conventional reprocessing or more advanced reprocessing options (such as co-processing). DUPIC (Direct Use of Spent PWR Fuel In CANDU) represents a recycle option that has a higher degree of proliferation resistance than does conventional reprocessing, since it uses only dry processes for converting spent PWR fuel into CANDU fuel, without separating the plutonium. Good progress is being made in the current KAERI, AECL, and U.S. Department of State program in demonstrating the technical feasibility of DUPIC.

In the longer term, CANDU reactors offer even more dramatic synergistic fuel cycles with PWR or FBR reactors. If the objective of a national fuel-cycle program is the minimization of actinide waste or destruction of long-lived fission products, then studies have shown the superiority of CANDU reactors in meeting this objective. Long-term energy security can be assured either through the thorium cycle or through a CANDU / FBR system, in which the FBR would be operated as a "fuel factory," providing the fissile material to power a number of lower-cost, high-efficiency CANDU reactors.

In summary, the CANDU reactor's simple fuel design, high neutron economy, and on-line fuelling provide flexibility to respond to changing fuel-cycle requirements in the short term and in the indefinite future.

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Chalk River Laboratories
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CANDU FUEL CYCLE OPTIONS IN KOREA

P.G. Boczar, P.J. Fehrenbach and D.A. Meneley

1. INTRODUCTION

Nuclear fuel-cycle considerations are not static in time. They depend on many factors, both global and domestic, a few of which are short-and long-term availability, cost, security, and diversity of energy resources; the state of industrial development; and government policy on energy and industrial development. Given the historical difficulty in predicting the availability and cost of energy resources, whether nuclear or fossil, a superior nuclear energy strategy must include fuel-cycle flexibility.

The simple and robust fuel-bundle design, on-line refuelling, and high neutron economy necessitated by the use of natural uranium fuel, provide the CANDU reactor with an unsurpassed degree of fuel-cycle flexibility. This enables a variety of fuels to be burned, including natural and enriched uranium, mixed plutonium/uranium oxide fuel (MOX), thoria fuels, and even actinide waste. The same reactor can act as a near-breeder of nuclear material (in the self-sufficient equilibrium thorium cycle) or as a burner of surplus military fuels. This capability enables a country to adapt to a changing and, sometimes, unpredictable environment, through evolution of the fuel cycle used.

Korea is unique among nations in having both CANDU and PWR reactors. This two-reactor policy provides Korea with the opportunity of exploiting the natural synergism that exists between these two reactor types, by burning in CANDU reactors the spent fuel from its PWR reactors. This would enable Korea to optimize its overall nuclear fuel cycle with respect to the energy it derives from the initial mined uranium, and the overall quantity of spent fuel produced.

2. NATURAL URANIUM

One of the initial factors supporting the introduction of CANDU in Korea was its ability to burn natural uranium fuel. The wide availability of natural uranium compared favorably with the more limited availability and foreign supply dependence aspects of enriched fuel for the PWR. The use of natural uranium has increased the security of fuel supply and has enhanced Korean energy independence, by reducing reliance on foreign technology and foreign enrichment. Korea already owns important reserves of uranium ore in Canada that are available for long-term fuelling needs in Korea's CANDU reactors. In addition, the simplicity of the fuel design has enabled Korea to quickly adopt this technology. For several years, Korea has fabricated its own CANDU fuel at significantly less cost than PWR fuel. The Korea Nuclear Fuel Company (KNFC) is now building a new, larger CANDU fuel-fabrication plant. Because of the lower fabrication cost and the efficient use of the fissile component in CANDU reactors, natural uranium fuel cycle costs are about half those of PWR.(1)

CANDU fuel technology is a good example of the "middle-entry strategy," which has enabled Korea to quickly join the ranks of technologically advanced nations. This strategy refers to the acquisition, localization, and further improvement of technology originally developed in other advanced countries. Korea, in partnership with Canada, is now improving CANDU fuel technology through development of the advanced CANFLEX bundle, described in another paper in this conference.(2)

3. SLIGHTLY ENRICHED URANIUM (SEU)

The natural uranium CANDU fuel cycle has served Korea well, and it continues to do so. However, as already mentioned, fuel cycle considerations are not static in time. Korea is now technically far more advanced than when it first embarked on its ambitious nuclear program. At some point in Korea's industrial development, the incentives for using natural uranium fuel in CANDU reactors may be outweighed by the advantages of adopting a different fuel cycle.

It is anticipated that CANDU fuel-cycle development will evolve in a stepwise manner. The first logical step from natural uranium may be the use of slightly enriched uranium (SEU).(3) Enrichment is now competitively available from several suppliers, and the Korean nuclear industry has experience in fabricating and handling enriched fuel. The use of SEU in CANDU reactors may now be attractive in Korea.

SEU would reduce the quantity of spent fuel produced in CANDU reactors, and this may be positively viewed by the public. A U-235 content of between 0.9% and 1.2% would increase the burnup by a factor of 2 to 3, and hence reduce the quantity of spent fuel produced by the same factor. SEU would further improve the uranium utilization (the energy derived from the mined uranium). A reduction of about 25% in uranium requirements (per unit energy) is achieved for enrichments between 0.9% and 1.2%. Uranium utilization is an important consideration in Korea, a country that has few indigenous uranium resources and that has a keen strategic interest in energy self-reliance. Enrichments between 0.9% and 1.2% also reduce CANDU fuel-cycle costs by 20-30% compared with natural uranium fuel.

SEU offers greater flexibility in reactor design.(4) In new reactors or in existing reactors where there is a sufficient heat-removal capacity, SEU can be used to uprate reactor power without exceeding existing limits on bundle or channel power, by flattening the channel power distribution across the reactor core.(5) In a new reactor design, the use of power flattening to obtain more power from a given-sized core has an advantage in capital costs over simply adding more channels to the reactor. In the SEU-fuelled CANDU 9 reactor, enrichment of around 0.9% can flatten the channel power distribution in the core, obtaining 1100 MW(e) from a 480-channel, Darlington-size core, nominally rated at 935 MW(e). Alternatively, the power flattening from SEU could be used to lower the peak bundle and element ratings, without increasing reactor power. If CANFLEX bundles were used as the carrier for SEU in this application, the peak linear element ratings could be reduced to less than 40 kW/m, thus significantly reducing fuel temperature, fission-gas release, and fuel-failure probability.

SEU could also be used to reduce the capital cost of new plants by increasing the pressure-tube thickness to upgrade the primary heat transport system (PHTS) conditions, thereby achieving higher thermodynamic efficiency or by reducing the moderator inventory by decreasing the moderator and reflector volumes. The use of enrichment in CANDU fuel also offers greater flexibility in fuel-bundle design. One example is the Low Void Reactivity Fuel (LVRF) bundle, in which the use of enrichment and neutron absorber materials allows any value of void reactivity and discharge burnup to be designed.(6)

The CANDU reactor's on-power refuelling offers flexibility in fuel management that facilitates the use of SEU and other advanced fuel cycles. This flexibility extends from the equilibrium core where, for example, different fuel management strategies could be used to accommodate different levels of enrichment, to the transition from one fuel type (such as natural uranium) to another (such as SEU). Fuel-management strategies have been identified for both the equilibrium core, and for the transition from natural uranium to SEU. (7-10)

Recent analysis using AECL's latest cost models for geological disposal indicate that there would be about a 20% reduction in the total disposal cost for CANDU SEU fuel having an enrichment between 0.9% and 1.2%, compared with natural uranium.[1] The higher heat generation rate with SEU is offset by the lower quantity of spent fuel, for a given amount of electricity produced. To a first order, the disposal cost of CANDU natural uranium fuel is about the same as for PWR fuel, for equal electricity generation.(11,12)

4. CANFLEX

AECL and KAERI are developing an advanced fuel bundle as the optimum carrier of enriched fuels in CANDU reactors. This new bundle, called CANFLEX, provides greater subdivision of the fuel than other CANDU bundles, having 43 elements with two pin sizes. When operated at current bundle powers, peak linear element ratings are reduced by 15-20%, depending on burnup. The lower ratings will facilitate the achievement of extended burnup in CANDU reactors by reducing fuel temperatures and, hence, fission-gas release within the fuel element. Critical heat flux and critical channel power will be increased, due to optimized heat removal characteristics of the bundle. This will increase operating margins in operating reactors.

5. CANDU/PWR SYNERGISM

Energy self-sufficiency is an important consideration in the two-reactor strategy in Korea that makes the fuel cycle synergy between the CANDU and PWR reactor units in Korea particularly attractive. Spent PWR fuel is a valuable source of fissile material (U-235 and plutonium). Maximum energy can be derived from this material by burning it in CANDU reactors. This synergism can be exploited by the use of several fuel-cycle alternatives. (13-15)

6. RECOVERED URANIUM (16)

In conventional reprocessing, which is currently available from several sources, uranium and plutonium are separated from the fission products and other actinides in the spent fuel. The recovered uranium (RU) from conventional reprocessing still contains valuable U-235 (typically around 0.9%, compared with 0.7% in natural uranium fuel). This can be burned as-is in CANDU reactors, without re-enrichment, to obtain about double the burnup of natural uranium fuel. About twice the energy would be extracted, compared with re-enrichment of RU for recycle in a PWR. The U-235 would be burned down to low levels (i.e., 0.2 to 0.3%) in CANDU reactors compared with PWRs (0.8% to 1.0%); thus there would be no economic incentive for further recycle of this material. The spent fuel would then be ultimately disposed of, after a period of dry storage, in a deep geological repository.

Recovered uranium offers similar benefits as SEU. This fuel-cycle option is available for use in CANDU reactors now, and it could be introduced very quickly in Korea. Recovered uranium is currently a liability to some PWR owners who have no plans to recycle it in their PWRs, because of the complications in fuel fabrication with re-enriched RU, and marginal, if any, economic benefit in PWR recycle. In addition, these utilities pay for the storage of the RU. It is therefore

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[1] Peter Baumgartner, AECL Whiteshell Laboratories, private communication, 1996

anticipated that RU can be obtained at a very attractive price. Security of supply is not an issue, as SEU of equivalent enrichment can be substituted.

7. MIXED OXIDE $(PU,U)O_2$ FUEL (MOX)

The other major product from conventional reprocessing is plutonium. Plutonium is currently mixed with depleted uranium to form MOX fuel, which is recycled in 1/3-core PWRs in Europe. The CANDU / PWR two-reactor system in Korea opens the possibility of recycling the MOX fuel from reprocessed PWR fuel back into CANDU reactors. This would have potential benefits compared with recycling in a PWR. A full MOX core could be used in existing CANDU reactors. Although MOX fuel fabrication will be much more expensive than natural uranium, the simplicity of the CANDU fuel bundle and its short length, will result in cheaper MOX fuel fabrication costs compared with PWR MOX. A high burnup CANDU MOX fuel therefore has the potential of lower fuel cycle costs than PWR MOX. Up to 50% more energy could be extracted from the plutonium as MOX fuel in CANDU reactors, compared with recycle in a PWR. This has important advantages in improving natural uranium utilization, reducing enrichment requirements, and in reducing the amount of spent fuel for ultimate disposal.

There is now considerable world experience in the fabrication and irradiation of MOX fuel. Because AECL commenced irradiation testing of MOX fuel more than 25 years ago, it has significant experience in both fabricating and irradiating this fuel type.(17) Irradiation testing in the NRU reactor loops and post-irradiation examination (PIE) are still being conducted as part of AECL's advanced fuel-cycle program. AECL's Recycle Fuel Fabrication Facility at the Chalk River Laboratories has recently been recommissioned for the fabrication of MOX fuel. There is currently significant interest in the use of MOX fuel in CANDU reactors as a means of dispositioning plutonium from dismantled weapons.(18) Since high-burnup CANDU MOX designs would incorporate generic CANDU high-burnup fuel technology developed in the past, this fuel cycle could be available for commercial use in CANDU reactors within the next 5 to 10 years.

8. TANDEM FUEL CYCLE

In the TANDEM fuel cycle, the uranium and plutonium from PWR spent fuel are co-precipitated without separation. Only the fission products, and higher actinide isotopes, are removed. AECL and KAERI jointly investigated this fuel cycle in the mid-1980s. This fuel cycle is unique in that it takes advantage of the fact that the fissile component in PWR spent fuel (about 1.5%) can be used directly in CANDU reactors, without readjustment of the enrichment. Fuel burnup in this cycle would be at least 25 MWd/kg HE. Although this process is potentially cheaper than, and has a higher degree of proliferation resistance compared with, conventional reprocessing, it does not offer the very high degree of proliferation resistance afforded by the DUPIC cycle. Nonetheless, future interest in this process could arise from the possibility of reducing the cost of conventional reprocessing, reducing the cost of fuel fabrication, and increasing the degree of proliferation resistance, by leaving some of the fission products in the recycled material. Processing costs could be reduced by reducing the number of purification steps; fabrication costs could be reduced through a simpler fuel-fabrication route (such as VIPAC), and proliferation resistance would be enhanced by the high radioactivity of the fresh fuel.

9. DUPIC

The DUPIC process involves converting the spent PWR fuel into CANDU fuel without any wet chemical processing.(19) Only dry processes are used, in which there is no selective element removal. This, along with the high radiation fields associated with the fuel, offers a very high level of proliferation resistance. KAERI and AECL have examined several possible DUPIC cycles. These include converting the spent PWR rods into CANDU fuel bundles with or without double cladding; vibratory packing of milled PWR pellets into fresh sheaths (VIPAC); and thermal/mechanical processing of the spent PWR pellets to form sinterable CANDU pellets. All options were judged to be technically feasible, and the last option, called "OREOX," or oxidation / reduction of spent PWR pellets, was chosen for further study.

The OREOX process involves the following steps: (20)

- decladding the spent PWR fuel;
- subjecting the exposed fuel to thermal cycles of oxidation and reduction, to produce a fine powder;
- milling, or any subsequent powder conditioning, to improve the sinterability of the powder;
- fabricating CANDU-quality fuel pellets from that powder;
- loading the pellets into sheaths;
- assembling the CANDU bundles;
- disposing of irradiated PWR assembly hardware; and
- trapping and disposing of volatile fission products released during the decladding, OREOX and sintering processes.

The current technical feasibility study by KAERI, AECL and the U.S. Department of State involves fabricating, then irradiating, a small number of fuel elements and bundles. The intent is to confirm the technical feasibility of the process, to optimize the process, and to obtain technical information that would enable an economic comparison to be made with alternate technologies. Good progress continues to be made. Reactor physics studies show that the addition of a small amount of UO_2 (depleted or enriched) to the OREOX product powder will achieve the necessary neutronic homogeneity of fuel derived from different PWR batches. Detailed fuel management simulations confirm that the power/burnup envelope is within the current limits. CANFLEX reduces the peak linear element ratings. Fabrication trials have been conducted using simulated PWR spent fuel (i.e., unirradiated UO_2 in which fission product surrogates have been added), as well as small quantities of PWR spent fuel. Fuel pellets that meet the density specifications for CANDU fuel have now been fabricated using the OREOX process on a small quantity of PWR spent fuel. Equipment has been purchased in preparation for the in-cell fabrication of DUPIC elements from PWR spent fuel in AECL's hot cells at the Whiteshell Laboratory and in KAERI's Irradiated Material Examination Facility (IMEF). These elements will then be irradiated in the HANARO and NRU research reactors.

In an equilibrium system in which the PWR/CANDU ratio of electrical generation was such that the spent PWR fuel from Korea's PWRs would provide the fuelling needs of Korea's CANDU reactors (about 2.4 to 1), the DUPIC cycle would improve the uranium utilization by about 25% compared with an open system, in which the CANDU reactors were fuelled with natural uranium and the PWR reactors were fuelled with enriched uranium. More significantly, the quantity of spent fuel would be reduced by a factor of 3 compared with an open system of

CANDU and PWR reactors and would be 30% lower compared with an all-PWR system. The fissile content of the spent fuel from DUPIC would be low enough that further recycling would not be warranted, and the fuel would then be directly disposed of.

10. FUTURE FUEL CYCLE APPLICATIONS

In the longer term, CANDU reactor's high neutron economy, on-power refuelling, and simple fuel design offer even more dramatic opportunities to develop advanced fuel cycles in Korea. For example, an important long-term advantage of CANDU reactors is the fact that they can utilize the extensive thorium reserves available in Korea, essentially without design modification, whenever such a strategy becomes beneficial. AECL has expended considerable effort over the past decades in developing thorium cycles. That effort continues today, with reactor physics assessments of various once-through thorium cycles, fuel fabrication development, and irradiation testing of thoria fuel in the NRU research reactor. A variety of thorium cycles exists, all utilizing in one way or another the U-233 that is produced.

Another two-reactor policy that could be established in the longer term to secure fuel supplies is the CANDU/FBR system. In this system, a small number of efficient breeder reactors could provide the fissile material that would fuel a number of lower-cost CANDU reactors that are already installed.

Finally, CANDU reactors can be extremely efficient eliminators of nuclear waste. If the objective of a national fuel cycle program is the minimization of actinide waste, studies have shown the potential for CANDU reactors in achieving high rates of actinide destruction in an inert-matrix fuel. There is also the possibility of destroying long-lived fission products, such as I-129 and Tc-99. AECL is performing the reactor physics assessments of such systems, as well as investigating suitable inert-matrix materials. (21,22)

11. SUMMARY

Table 1 summarizes the natural uranium utilization (natural uranium requirements for a given electrical generation), equivalent natural uranium burnup, and fuel disposal rates for various systems of PWR and CANDU reactors. The Appendix lists the fuel-cycle assumptions, and the formulae for uranium utilization. It is evident from this table that up to twice as much energy could be extracted from recycled fissile material from PWR spent fuel by utilizing it in CANDU reactors rather than recycling in a PWR. An equilibrium system of CANDU/PWR reactors in which the fresh fuel needs of CANDU reactors were met by the fissile material in the PWR spent fuel would result in a reduction in natural uranium requirements of up to 40% and a reduction in the discharge rate of spent fuel by 30%, compared with an all-PWR system. The optimal ratio of PWR/CANDU electrical generation to exploit the synergism between the two reactor types ranges from 1.4:1 (for the TANDEM fuel cycle) to 3:1 (for recycling of recovered uranium in CANDU).

Korea's two-reactor PWR/CANDU strategy provides flexibility in optimizing the overall Korean fuel cycle requirements, and in the future benefit can be derived from the synergism between the two reactor types. In the short term, CANDU fuel-cycle flexibility may be manifested first through the use of SEU, either in a new reactor or in an existing reactor. Recovered uranium is particularly attractive for use in CANDU reactors. In the medium term, MOX fuel or DUPIC fuel would allow full exploitation of the PWR/CANDU synergism.

The CANDU reactor's simple fuel design, high neutron economy, and on-line fuelling provide Korea with the flexibility to respond to changing fuel cycle requirements in the short term, and in the indefinite future.

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Table 1

Equilibrium Natural Uranium Requirements, Equivalent Natural Uranium Burnup, and Fuel Disposal Requirements for CANDU and PWR Systems

Fuel Cycle Option	Natural U Requirements Mg NU/GW(e) a	Natural U Burnup MWd(th)/kg NU	Fuel Disposal Requirements Mg HE/GW(e)a (HE = heavy element)
PWR with Enriched U	218	5.1	33
PWR with re-enriched RU recycled	182 (-16%)	6.1 (19%)	28
PWR with Pu recycled	185 (-15%)	6.0 (18%)	28
PWR with re-enriched RU recycled, and Pu recycled	160 (-27%)	7.0 (37%)	24
CANDU reactor with Natural U	157 (-28%)	7.5 (48%)	157
CANDU reactor with 0.9% SEU	119 (-45%)	9.9 (95%)	84
CANDU reactor with 1.2% SEU	116 (-47%)	10.2 (101%)	56
PWR/CANDU (2.8/1)*, with RU recycled in a CANDU reactor	161 (-26%)	7.0 (38%)	25
PWR/CANDU (2.9/1)*, with RU recycled in a CANDU reactor, and Pu recycled in a PWR	143 (-34%)	7.9 (55%)	22
PWR/CANDU (1.4/1)*, with RU+Pu recycled in a CANDU reactor (TANDEM)	129 (-41%)	8.8 (73%)	20
PWR/CANDU (2.4/1)*, with DUPIC fuel in a CANDU reactor	154 (-29%)	7.4 (45%)	24

NOTES:

(1) Numbers in parenthesis are % change from reference PWR.

(2) System uranium requirements and fuel disposal requirements for recycling options refer to an equilibrium system, in which the fresh fuel requirements of the "receiving" reactor (either CANDU or PWR) are exactly met by the spent fuel discharge rate of the "supplying" PWRs.

(3) * Ratio of PWR/CANDU electrical generation in equilibrium

APPENDIX: Fuel-Cycle Data and Formulae

CANDU Reactor:

Net thermal efficiency	0.31 (η_1)
Burnup with NU, MWd/kg HE	7.5 (B_1)
Burnup with RU from PWR spent fuel (0.9% U-235), MWd/kg HE	13 ($B_{1,ru}$)
Burnup with 0.9% / 1.2% SEU, MWd/kg HE	14 / 21 ($B_{1,SEU}$)
NU feed for 0.9% / 1.2% SEU, kg U/kg HE*	1.41 / 2.06 (F)
Burnup with RU and PU from PWR spent fuel (TANDEM), MWd/kg HE	25 ($B_{1,tandem}$)
Burnup with DUPIC fuel	15 ($B_{1,DUPIC}$)

PWR reference:

Net thermal efficiency	0.33 (η_2)
Burnup, MWd/kg HE	33 (B_2)
U-235 content in fresh fuel, (%U-235 in U)	3.25
U-235 content in enrichment plant tails, (%U-235 in U)	0.25
NU feed, kg U/kg HE*	6.51 (F)
U-235 content in spent UO_2 fuel, (%U-235 in U)	0.92
U-236 content in spent UO_2 fuel, (%U-235 in U)	0.41

PWR with re-enriched RU:

Burnup, MWd/kg HE	33 (B_2)
U-235 content in re-enriched RU, %	3.62
U-236 content in re-enriched RU, %	1.23
U-235 content in enrichment plant tails, %	0.25
RU feed, kg RU/kg HE**	5.03 (NR_{ru})
(also equal to the number of PWRs required to provide re-enriched RU for 1 PWR)	

PWR with recycled MOX:

Number of PWRs required to provide Pu for 1 MOX PWR (33 MWd/kg) (23)	5.65 (NR_{pu})

Formulae: ***Equilibrium Natural Uranium Utilization (Mg U / GW(e)a)***

PWR or CANDU reactor with enriched U: $365 * F / [\eta * B]$, with the appropriate values of F, η and B
System, PWR with re-enriched RU: $365 * NR_{ru} * F / [\eta_2 * B_2 * (NR_{ru}+1)]$
System, PWR with plutonium recycle: $365 * NR_{pu} * F / [\eta_2 * B_2 * (NR_{pu}+1)]$
System, PWR with re-enriched RU & Pu recycle: $365 * NR_{pu} * F / [\eta_2 * B_2 * (NR_{pu}+1+NR_{pu}/NR_{ru})]$
CANDU reactor with natural uranium: $365 / [\eta_1 * B_1]$
System, PWR/CANDU, with RU recycled in a CANDU reactor: $365 * F / [0.956 * \eta_1 * B_{1,ru} + \eta_2 * B_2]$
(the factor 0.956 is the fraction of uranium in the PWR spent fuel)
System, PWR/CANDU, with RU recycled in a CANDU reactor
and Pu recycled in PWR: $365 * NR_{pu} * F / [0.956 * \eta_1 * NR_{pu} * B_{1,ru} + \eta_2 * B_2 * (NR_{pu}+1)]$
System, PWR/CANDU (TANDEM): $365 * F / [0.966 * \eta_1 * B_{1,tandem} + \eta_2 * B_2]$
(the factor 0.966 is the fraction of uranium and plutonium in the PWR spent fuel)
System, PWR/CANDU (DUPIC): $365 * F / [0.985 * \eta_1 * B_{1,DUPIC} + \eta_2 * B_2]$

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* F = (E-0.25) / (.711-0.25), where E is the U-235 % (3.25% for PWR, 0.9% or 1.2% for CANDU)

** U-236 concentration in spent PWR fuel is assumed to be 0.41%, and in the enriched RU product is 1.23%. An additional 0.3% U-235 enrichment is needed for every 1% U-236 in the final product: $NR_{ru} = ([3.25 + 1.23*0.3] - 0.25) / (0.92-.25) = 5.03$

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