TECHNICAL ASPECTS AND BENEFITS OF THE USE OF RU IN CANDU REACTORS

H. C. Suk, J. H. Park, B. J. Min and K. S. Sim
Korea Atomic Energy Research Institute
P.O. Box 105, Yusong, Taejon, Korea(R.O.K.), 305-600

W. W. Inch
Atomic Energy of Canada Limited
Chalk River Laboratories
Chalk River, Ontario, Canada K0J 1J0

T. G. Rice
British Nuclear Fuel plc
Springfields, Salwick, Preston
Lancashire, U.K., PR4OXJ

ABSTRACT

The use of recovered uranium (RU) in CANDUs is an excellent example of the environmental 3R's (Reduce, Reuse, Recycle) as applied to global nuclear energy use. RU fuel offers a very attractive alternative to the use of natural uranium (NU) and slightly enriched uranium (SEU) in CANDU reactors because fuel economy is expected to improve even more through the use of RU. RU, with a about 0.9 % ^{235}U enrichment, results in an average discharge burnup of about twice that of NU in a CANDU reactor, thereby increasing resource utilization and reducing fuel requirements. Spent fuel volumes and fuelling costs are reduced. Therefore, the use of RU in CANDU reactors potentially offers economic, environmental and public acceptance benefits on both the front-end and back-end. These benefits all fit well with the PWR-CANDU fuel cycle synergy. RU also offers greater flexibility in reactor and bundle designs and a power uprating capability. RU fuel can be packaged in the CANFLEX fuel bundle, since the full benefits of the use of RU in CANDU reactors are achieved through the provision of enhanced margins in the bundle design.

RU, like NU and SEU, is a nuclear fuel commodity available from several sources. The cumulative quantity of RU projected to arise by the year 2000 from the reprocessing of spent oxide fuel in Europe and Japan is approaching 25,000 te. This quantity would provide sufficient fuel for 500 CANDU-6 reactor years of operation. Security of supply is, therefore, not an issue, and in addition, SEU of equivalent enrichment can be always be substituted for RU. It is anticipated that using RU in CANDU reactors will provide improvements in fuel cycle economics.

The suitability of RU as a reactor fuel for CANDU has been studied in KAERI and AECL : CANDU fuel fabricated from RU meets CANDU specifications; utilizing RU does not introduce serious radiological difficulties, and no special precautions or technologies are required for handling of RU fuel bundles; hence new fuel receipt and management at reactor is particularly simple. Under current legislation and practice, it is also recognized that there are no obstacles to international or domestic transport of commercial quantities of RUO_2 powder.

1. INTRODUCTION

KAERI (Korea Atomic Energy Research Institute) has a comprehensive product development program of CANDU advanced fuels such as CANFLEX (CANDU Flexible fuelling) and DUPIC (Direct Use of spent PWR Fuel in CANDU) to introduce those fuels into CANDU reactors in Korea. KAERI has a clear vision of how the product will evolve over 10 years from 1997 to 2006[1]. These CANDU advanced fuel R & D programs are conducted currently under the Korea Nuclear Energy R & D Project of the Korea Ministry of Science and Technology as a national mid- and long-term program. CANFLEX fuel has been developed jointly by KAERI and AECL (Atomic Energy of Canada Limited) since 1991. As one of the CANFLEX fuel development programs in KAERI, RU (Recovered Uranium from spent fuel) fuel development for CANDUs is an international collaboration between KAERI, AECL and BNFL(British Nuclear Fuels plc).

CANDU nuclear reactors offer many advantages to their operators, one of which is on-power refuelling. Currently, CANDU-6 reactors use 37-element NU (natural uranium) fuel combined with on-power refuelling to achieve good fuel economy. In 1990, KAERI evaluated economics and technical aspects of CANFLEX-0.9 % and 1.2 % SEU (Slightly Enriched Uranium) fuel bundles in a CANDU-6 reactor [2]. In this evaluation, use of the CANFLEX-SEU fuel bundles are resulted in significant annual fuel cost savings compared with the 37-element NU fuel bundle. However, RU offers a very attractive alternative to the use of NU and SEU (Slightly Enriched Uranium) in CANDU reactors: fuel economy is expected to improve even more through the use of RU, and a unique country such as Korea having both PWRs and CANDUs can exploit the natural synergism between the two reactor types to minimize overall waste production and maximize energy derived from the fuel by burning the spent fuel from its PWRs in CANDU reactors. This synergism can be exploited through several different fuel cycles [3].

This paper describes the technical aspects and benefits of the use of RU in CANDU reactors, including the availability of RU in the world and also reports some of the typical physical and chemical properties of RU powder and pellets.

2. AVAILABILITY AND PROCESSING OF RU

In conventional reprocessing, uranium and plutonium are separated from the fission products and other actinides in the spent fuel. The RU from conventional reprocessing still contains valuable ^{235}U (typically around 0.9 %). The cumulative quantity of RU projected to arise by the year 2000 from the reprocessing of spent fuel in Europe and Japan is approaching 25,000 te [4]. Theoretically, this quantity would provide sufficient fuel for 500 CANDU-6 reactor years of operation, because the initial core load of uranium for a CANDU-6 reactor is 85 te and annual refuelling requirement for a RU fuel burnup of 13 MWd/kgU is around 50 te per annum. Therefore, the use of RU in Korean CANDU reactors is not dependent on reprocessing Korean spent PWR fuel because RU, like NU and SEU, is a nuclear fuel commodity available from several sources.

Current reprocessing technology has been optimized to produce an RU product suitable for interim storage pending potential re-enrichment and recycle into LWR reactors. RU produced in the reprocessing facilities is in the form of either U_3O_8 or UO_3, both produced from UNL(Uranyl Nitrate Liquor). BNFL uses thermal denitration to convert UNL to UO_3. COGEMA uses the ADU route to convert UNL to U_3O_8. Further processing would be required to convert this to sinterable UO_2 powder. Several processes exist to convert the RU from its form used in storage, to ceramic grade sinterable powder. For example, the UO_3 from BNFL's THORP reprocessing plant could be further processed to UF_6 and the existing Integrated Dry Route (IDR) facilities used to convert the UF_6 to ceramic grade UO_2. Alternatively, BNFL has a prototype facility in operation which converts the UNL directly to a ceramic grade UO_3 and then subsequently to UO_2 by the Modified Direct Route (MDR) process.

3. PHYSICAL PROPERTIES OF RU

RU is composed of ^{232}U, ^{234}U, ^{235}U, ^{236}U and ^{238}U isotopes and some of their daughter products. Traces of transuranic elements such as Pu, ^{237}Np, ^{241}Am and fission products such as ^{90}Sr and ^{106}Ru remain. The level of RU ^{235}U enrichment depends also on both the type of reactor and the adopted core management strategy. For example, a spent fuel of 33,000 MWd/MTU burnup in a 900 MWe PWR with fresh fuel of 3.25 %wt ^{235}U contains 0.92 %wt ^{235}U following 290 full power equivalent days in a 1/3 core refuelling scheme. A spent fuel of 42,000 MWd/MTU burnup in a 900 MWe PWR with fresh fuel of 3.70 %wt ^{235}U contains 0.94 %wt ^{235}U for 275 full power equivalent days following a 1/4 core refuelling. The typical composition of RU is given in Table 1. According the following illustrations, the main determinant in CANDU reactor physics with RU is the ^{235}U level.

^{232}U in RU : ^{232}U assay is closely connected to the initial ^{235}U assay. Most of the above comments relate to the general composition of the fuel. The ^{232}U influence upon reactivity in the CANDU-6 core is negligible, since both its assay and cross-section are very low. ^{232}U is α emitter. ^{232}U generates α, and β emitting daughter products with associated γ emission. ^{208}Tl, ^{212}Pb and ^{212}Bi, in minute quantities, are among the most active as very hard γ emitters. They reach their maximum activity in ten years and half of it in two years. This compels RU processors to take proper protection against radiation hazards. Since ^{232}U daughter products develop very fast, their presence and related radioactivity cannot be avoided during the initial stages of RU recycling.

^{234}U in RU : There is ^{234}U of around 0.021 % wt in RU from the PWR 900 MWe spent fuel of 33,000 MWd/TU burnup. U^{234} is closely tied to burnup and initial ^{234}U assay. ^{234}U assay is quite stable after spent fuel is unloaded from the reactor. ^{234}U is a neutron absorber. The main consequence is that it reduces the fuel efficiency. However, the ^{234}U influence upon reactivity in the CANDU-6 core is negligible as shown in Fig. 1. ^{234}U is α emitter. Its daughter products include α, β and γ emitters. ^{234}U contribute to dust contamination problems during fuel manufacture. Precautions that are to be taken will be dealt with further on.

^{236}U in RU : ^{236}U levels usually between 0.2 %wt and 0.7 % wt in RU. ^{236}U is closely tied to burnup and initial ^{235}U assay. ^{236}U originates from the neutron capture in ^{235}U in the original PWR fuel, which has a strong resonance at 5.5 eV. Like ^{234}U, ^{236}U assay is stable during the cooling period. ^{236}U has no radioactivity. ^{236}U is a neutron absorber. It reduces the fuel efficiency. However, the ^{236}U influence upon reactivity in the CANDU-6 core is negligible, as shown in Fig. 1.

Transuranic elements in RU : Despite the use of very high efficiency reprocessing flowsheets, minute traces of transuranic elements remain in RU. Their quantity is negligible, but they contribute to total radioactivity of RU. They are long life α emitters. Table 2 illustrates the influence of transuranic elements in RU radioactivity. Transuranic elements represent actually 0.38 % of RU total alpha activity while ^{232}U daughter products represent 3.8 % of RU's total γ activity. For comparison, natural uranium total alpha activity is 24,730 Bq/g.

Fission products in RU : There are also minute traces of fission products remaining in RU, such as beta emitting ^{99}Tc and the short half-life, gamma emitting ^{106}Ru isotope. Their activity decreases with time. Technetium does not cause any inconvenience, because its quantity is extremely low: the average ^{99}Tc quantity in RU is in the range of 10 to 200 ppb.

4. TECHNICAL FEASIBILITY OF USE OF RU IN CANDU

4.1 Carrier for RU in CANDU

RU fuel can be utilized in the CANFLEX 43-element fuel bundle [5] - a CANDU advanced fuel design with optimal carrier for RU fuel. The full benefits of use of RU in CANDU reactors are achieved through the provision of enhanced margins in the bundle design. The CANFLEX design (see Fig. 2) has the same bundle diameter and length as a CANDU-6, 37-element NU fuel bundle, but thirty five 11.5 mm diameter elements in its two outer rings, and eight 13.5 mm diameter elements in the center rings. The increased number of elements and the use of two element sizes reduce the peak element rating by up to 20 % compared with a 37-element (13.1 mm element diameter) bundle operating at the same bundle power output. The lower fuel rating in the CANFLEX bundle facilitates the adoption of extended burnups in CANDU reactors that are necessary for the economic use of various attractive fuel cycles. Also, the lower fuel rating reduces the consequences of most design-basis accidents. The CANFLEX design also uses critical heat flux (CHF) enhancing appendages, which enable a high power to be realized before CHF occurs, leading to a net gain in the critical channel power typically of 6 to 8 % over the existing 37-element fuel. These two features provide larger operating margins and thus great operating flexibility in existing CANDUs, and will allow higher burnups.

As a last verification test of the CANFLEX design, a two-channel 24 fuel bundle demonstration irradiation in the Pt. Lepreau commercial power reactor in Canada has been performed after completing all the preparatory work and approval [6]. In September 1998, eight CANFLEX-NU bundles were loaded into a low-power channel Q20, and eight CANFLEX-NU bundles were loaded into a high power channel, S08, using the standard 8-bundle shift[7]. In August 1999, the channel S08 was refuelled with eight CANFLEX-NU bundles, at which time 4 CANFLEX-NU bundles were discharged into the fuel bay and were shown to be successfully irradiated in the reactor.

4.2 Fuel Management of CANFLEX-RU in CANDU-6

AECL and KAERI[8] have performed fuel management calculation for the use of CANFLEX-0.9 % SEU fuel in a CANDU-6 reactor, and for CANFLEX-RU with about the same equivalent enrichment, using two-bundle-shift and four-bundle-shift bi-direction fuelling. The results confirm that a CANFLEX-0.9. % SEU fuel bundles loaded with a two- or four-bundle-shift refuelling scheme would meet CANDU fuel performance criteria, and also that practical refuelling schemes may be used to achieve acceptable fuel performance within currently-proven CANDU technology. The optimal fuelling scheme with CANFLEX-RU in CANDU-6 reactors could be the four-bundle refuelling scheme, since CANFLEX-RU is almost identical with CANFLEX-0,9% SEU on reactor physics issues.

Recently, the primary time-average characteristics of a CANFLEX-RU fuelled CANDU-6 reactor with a four-bundle refuelling scheme have been assessed, as shown in Tables 3 and 4 [9]. In these tables, the isotopic composition of the RU dioxide pellets is assumed to be ^{232}U of 0.575 ppb, ^{234}U of 0.016 % wt, ^{235}U of 0.90 % wt, ^{236}U of 0.34 % wt, and ^{238}U of 98.74 %wt. Twenty one graded adjusters (stainless steel absorber) are provided in CANDU-6 for xenon override capability, needed to restart the reactor after a short shutdown. A 30 minute xenon override capability was specified as the CANDU-6 design target, for the worth of the adjusters is 15 mk. For the xenon transient after a CANDU-6 reactor shutdown for a CANFLEX-RU equilibrium core, the xenon buildup 30 minutes after shutdown is 11.09 mk.

These results illustrate that RU can be easily accommodated in existing CANDU reactors from the reactor physics perspective.

4.3 Thermalhydraulics of CANFLEX-RU in CANDU-6

A thermalhydraulic design characteristics of CANFLEX-0.9 % RU fuel bundles in a CANDU-6 reactor have been studied [10] by investigating comparisons of channel-axial heat-flux distribution (AFD) and bundle-radial heat-flux distribution (RFD) of CANFLEX-NU and –RU bundles in a CANDU-6 reactor, and then by evaluating the critical channel power (CCP) with the fuels. Fig.3 shows a channel-axial heat-flux distribution of CANDU-6 with 37-elmement NU fuel, CANFLEX–RU fuel. The CANFLEX-RU distribution profile is flat and slightly concave in the channel center region, because of the four-bundle shift refuelling scheme, compared to the AFD of those NU fuel bundles fuelled by the eight-bundle shift fuelling scheme. The movement of the peak toward the upstream end of the channel in the CANFLEX-RU profile has two opposite effects on CCP: one is that the channel flow is decreased due to the increase in the boiling length as the peak moves to the upstream, and the other is that the decrease of the local heat-flux around the location of CHF onset increases the dryout power, where the effects of the local heat flux decrease are dominant on CCP. Therefore, the AFD of CANFLEX-RU bundles in CANDU-6 reactors is expected to increase the CCP, compared with that of CANFLEX-NU or 37-element NU bundles. As for the bundle-radial heat-flux distribution (RFD) parameters (see Fig. 4) in the study, the RFD sensitivities on CHF and then on CCP have been investigated, and it has been found that the CCP for CANFLEX-0.9% RU decreased by –0.5 % to –0.1 %, compared with that of CANFLEX-NU fuel bundle. Therefore, the thermal performance of the CANFLEX-RU fuel bundle will maintain the thermalhydraulic merits of the CANFLEX-NU fuel bundle, such as the enhancement of thermal margin, compared with the existing 37-element NU fuel.

4.4 Fuel Performance of CANFLEX-RU in CANDU-6

As stated above, CANFLEX fuel design was approved for use with NU fuel for two channel fuel demonstration irradiation at Pt. Lepreau Generation Station. AECL [11] recently calculated fuel power boosts expected in CANFLEX-0.9 % RU fuel in CANDU-6 reactors, using WIMS-AECL code [12] for the lattice-cell calculations and RFSP code[13] for the core calculations. The results indicated that the peak linear element ratings with the CANFLEX-0.9% RU bundle were below 45 kW/m through the simulation, so there would be very little fission gas accumulation in the element plenum volume during operation. Power boosts during refuelling were low: 40 kW/m at a very low element burnup of 2 MWd/kgU, decreasing to about 5 kW/m at 12 MWd/kgU. The combination of low peak element ratings, and a low and declining power boost envelope provide good confidence in fuel performance at these extended burnup.

KAERI established the power envelops on the basis of the CANFLEX-RU four-bundle shift refuelling simulation results provided by J. Donnelly of AECL in order to evaluate CANFLEX-0.9 % RU fuel element performances. Using ELESTRES code [14], the RU fuel element performances under the power envelopes were predicted as shown in Table 5. This prediction indicates that the CANFLEX-RU fuel with extended burnup will show good in-reactor performance as existing CANDU fuels do, because the fuel temperature and element internal gas pressure are far below the design criteria. The total hoop strains of the sheath are within reasonable range in terms of sheath plastic strain. The sheath strain and fission gas release predicted at EOL with STP condition are compatible with those found from 20 years experience with CANDU fuel[15].

4.5 Safety Aspects of CANFLEX-RU in CANDU-6

At KAERI, a preliminary fuel channel analysis for a 35 % reactor inlet head (RIH) break in a CANDU-6 reactor with the CANFLEX-RU fuel bundles has been performed [16], because the 35 % RIH break is a limiting accident for fuel channel integrity. According to this analysis, the maximum fuel and sheath temperatures for the CANFLEX-RU bundles' channel were lower by 338 ^{o}C and 122 ^{o}C, respectively, than those for the 37-element NU fuel bundle, because of the lower maximum linear power in the CANFLEX-RU bundle in spite of the 0.4 FPS (full power second) higher power pulse of the CANFLEX-RU bundle case. Fuel integrity margin to fuel breakup for the CANFLEX-RU bundle is about 50 J/g higher than that for the standard 37-element NU fuel bundle. The pressure tube (PT)–calandria tube (CT) contact for the CANFLEX-RU bundle occurred 2 seconds later than for the standard 37-element NU fuel bundle. The PT-CT contact temperature for the CANFLEX-RU bundle was 2 ^{o}C lower than that for the standard 37-element NU fuel bundle. These findings provide the CANFLEX-RU bundle with a negligibly enhanced safety margin for the fuel channel integrity in the CANDU-6 reactor, compared with the standard 37-element NU fuel bundle.

4.6 Occupational Health and Manufacturing Aspects of CANDU RU Fuel

Three main aspects differentiate RU fuel manufacture from NU or SEU fuel manufacture: higher specific activity of the material, criticality considerations and the increase in specific gamma activity related to the ingrowth of U^{232} decay daughter products. The radiological inventory of RU is dependent upon the fuel history prior to reprocessing, the aging stages and the various decontamination factors of processes involved. It should be noted that there is no re-enrichment of ^{236}U and ^{232}U isotopes because the CANDU route does not require re-enrichment of the ^{235}U. Thus the radiological implications of handling RU for CANDU use are greatly reduced compared with those where re-enrichment of the RU is required, e.g., for LWRs.

Although it only occurs at ppb levels in RU, ^{232}U dominates the gamma dose from RU fuel. ^{232}U itself has a 70 year half-life. It has a long decay chain, first via ^{228}Th (2 year half-life) and ending in short-lived ^{208}Tl, which emits a very high energy gamma. The decay chain is determined by ^{228}Th, with all the daughter nuclides in secular equilibrium with it. Therefore, it builds up over 10 years at a rate dictated by the 2 year half-life of ^{228}Th decay. The key to minimizing ^{232}U daughter product dose is therefore to process RU quickly before significant decay of the ^{228}Th.

^{234}U dominates the internal dose uptake. ^{234}U undergoes α-decay and is therefore important when inhaled or ingested. NU ore also contains ^{234}U(~0.0055 %wt), so ^{234}U is also a major contributor to internal dose from non-irradiated uranium fuel, but the levels of ^{234}U (~0.02 % wt) are higher in RU fuel, thereby increasing its importance.

In BNFL , calculation of the external beta, gamma and neutron dose rates have been made and compared with dose rates from NU. The dominant beta source is $^{234}Pa(m)$, which is present in all types of UO_2 since it is a product of the ^{238}U decay chain and is therefore seen at a similar level. The gamma dose rates are driven by $^{234}Pa(m)$ as well as by ^{208}Tl mentioned above. The neutron source strength has been shown to be low in all cases and below 1 μSv/h contact.

An initial assessment of the health physics aspects of manufacturing and handling RU as a fuel for CANDU reactors was done in the joint program between BNFL, KAERI and AECL, and previously, in a joint program between AECL and COGEMA[4]. To supply samples for evaluation, BNFL produced 200 kg of UO_2 from UNL produced in its THORP reprocessing plant. The conversion took place one year after reprocessing. As shown in Table 6, the characteristics of the RUO_2 powder met CANDU specifications, both in terms of chemical impurity contents and physical characteristics. The powder was granulated and pressed into green pellets, which were sintered under the normal conditions for CANDU fuel. The finished pellets met all the physical and chemical specifications for CANDU fuel and were subsequently used to manufacture a CANFLEX-RU bundle.

The manufacture of the CANFLEX-RU bundle provided an opportunity to perform practical dose measurement at various stages throughout the manufacturing process. The bundle was displayed at AECL's Sheridan Park Engineering Laboratories (SPEL) during the 5th International Conference on CANDU Fuel, September 21-25, 1997, in Toronto, Canada; delegates were able to see and handle both CANFLEX-RU and 37-element NU bundles. Activity measurements made on the finished CANFLEX-RU bundle were 1.3 times higher than a natural uranium bundle, when measured at a 30 cm distance. Although both theoretical and actual reading values were higher than for NU, as expected, the increase was only modest. Consequently, because the total fuel quantity required can be reduced by around 50 % using RU, the operator dose when handling RU bundles will be comparable with, or less than, that presently seen for natural uranium fuel. By aiming to reduce the time from reprocessing to conversion, fuel fabrication, and insertion into the reactor, the dose uptake will be reduced further. Based on these data, preliminary assessments of ZPI's Port Hope facility indicate that satisfactory control of gamma dose can be achieved [17]. Appropriate planning of fuel supplies and reactor refuelling operations should also ensure that appropriate health physics standards are also achieved at the station.

During sintering the release of ^{137}Cs and other volatile fission products from RU was below detectable levels. Also, AECL[4] earlier concluded than no significant fields in a commercial fuel manufacturing plant would build up due to release of ^{137}Cs during sintering, even after decades of production.

4.7 Transport of RU

All aspects of the transport of RU powder, for example, within the United Kingdom (UK), to Korea and within Korea have been examined jointly by BNFL and KAERI in relation to the UK and Korean national regulations and international regulations as set out in IAEA Safety Standard Document – Regulations for the Safe Transport of Radioactive Material, 1996 Edition No. ST-1. This comprises material transport of RUO_3 from the reprocessing plant to the conversion plant (Sellafield to Springfields), conversion from RUO_3 to ceramic grade RUO_2, the shipping of the RUO_2 to Korea, and the movement of the RUO_2 within Korea(Seoul to Taejon). Also considered is the transport of slightly enriched uranium (SEU) derived from natural uranium as an available substitute for RU fuel. In the Spring of 1998, a transport of BNFL RUO_2 and $SEUO_2$ powders from BNFL in the UK to KAERI in Korea was successfully carried out as part of the KAERI/BNFL development program collaboration on the RU fuel for CANDU reactors. This experience demonstrated that there are no difficulties involved in the transport of RU as either non-fissile material (<1.0 % ^{235}U) or fissile material (≥ 1.0 % ^{235}U) as defined in the above IAEA document. At the time of the transport, BNFL reviewed international and UK transport regulations and transport between the UK and Korea, and KAERI clarified the following points: the constraints that could be imposed by Korean Transport Regulations, the coverage for nuclear liability with Korean territorial waters and territory, the security arrangements for transport within Korea, and any additional constrains on handling or transporting the transport packages or containers within Korea. Under current legislation and practice, it is recognized that there are no obstacles to the transport of commercial quantities of RUO_2 powder from the UK to Korea.

5. BENEFITS OF USE OF CANFLEX-RU IN CANDU

Increased fuel-burnup and uranium-utilization without enrichment : The use of RU in CANDU reactors significantly increases burnup compared with that obtained with NU, thereby increasing resource utilization. Uranium utilization (the amount of energy derived from the mined uranium, including that derived in the original PWR fuel) is improved by about 40 %. Because of the neutron efficiency of CANDU reactors and the neutronic characteristics of RU, the RU with 0.9 % wt ^{235}U can be burned as-is in CANDU reactors (see Table 3), without re-enrichment, to obtain about twice the burnup of NU fuel, Also, approximately twice the energy would be extracted using CANDU reactors, compared to re-enrichment of RU for recycle in a PWR. The ^{235}U would be burned down to low levels (i.e., 0.2 to 0.3 %) in CANDU reactors compared to PWRs (0.8% to 1 %), so there is no incentive for further recycle of this material. The CANDU spent fuel would be disposed of, after a period of dry storage, in a deep geological repository.

Large reductions in fuel requirement and fuel cost: : The annual throughput of RU in CANFLEX bundles into CANDU-6 reactor core is 45 U tons a year (see Table 3), which is reduced by about 45 %, compared to that of the NU in the 37-element bundles. This lower volume of fuel throughput will lead to significant savings in fuel costs if recovered UO_2 prices are competitive with natural UO_2, and if the fabrication costs of the CANFLEX-RU fuel bundles are competitive with 37-element NU fuel bundles.

Larger reductions in spent fuel arising and disposal cost : The burnup in CANDU reactors with RU is about 13 MWd/kgU (depending on the specific isotopic composition, and details of the CANDU design). Table 3 illustrates that the annual spent fuel rate of the RU fuel in CANDU-6 reactors is 45 U tons a year. This quantity is about 45 % smaller than that of the NU in the 37-element bundles, which has a positive effect on economic, environmental, and public acceptance aspects of the fuel cycle.

Spent CANDU RU fuel will require some extended pool storage to allow the decay heat to reach the level of spent NU fuel before being transferred to interim dry storage in existing storage containers. AECL has recently conducted a preliminary cost assessment of the impact of SEU on spent CANDU disposal cost[18]. 0.9 % SEU enrichments equivalent to that of RU could result in a decrease in disposal costs of about 20 % compared to natural uranium fuel. The cost saving depend on the size of the repository, cooling times, and disposal method (in-room emplacement vs. boreholes). If the disposal costs of the 37-element NU fuel and CANFLEX-RU fuel are 46.0 US$/kgU and 37.0 US$/kgU, the annual disposal cost of the CANFLEX-RU fuel could be reduced by about 55 %, compared to that of the 37-element NU fuel. In the cost evaluation, the indirect costs such as interest costs, waste treatment cost, etc. were not included. Significant reduction of spent fuel disposal costs are possible with RU. Therefore, the use of RU in CANDU reactors would appear to be an extremely attractive way of dealing with a waste product while at the same time extracting additional energy.

Very attractive price and no security issue of supply of RU : RU is currently a liability to many PWR owners, who have no plans to recycle it in their PWRs, because of the complications in fuel fabrication with re-enriched RU, and a marginal, if any, economic benefit in PWR-recycle. In addition, these utilities pay for the storage of the RU. It is therefore 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.

Greater flexibility in reactor and bundle design and a power uprating capability : The extra fissile content of RU compared to NU offers greater flexibility in reactor and bundle design [19]. In new reactor designs, or in existing reactors where there is sufficient heat removal capacity, RU offers a power uprating capability instead of gaining increased burnup benefits, by flattening the channel radial power distribution across the reactor core, as described in Section 4.3. This option involves trading-off the extra burnup potential of RU (greater neutron leakage from the core) against more power output. In a new reactor design, using power flattening to obtain more power from a given-sized core has advantages in lowering capital costs relative to simply adding more channels to the reactor.

6. CONCLUSIONS

KAERI and AECL have performed the feasibility calculations of fuel management, thermalhydraulics, fuel element performance and safety for the use of CANFLEX-0.9 % RU in a CANDU-6 reactor. The CANFLEX-0.9% RU provides the required performance, and the resulting axial and radial power profiles are found to be well within current fuel performance envelopes. The CANFLEX design provides greater performance advantages with RU because of the 20 % reduction in peak element linear power, and more than 5 % CCP increase compared to CANDU 37-element fuel.

The direct use of RU in CANDU reactors avoids many of the problems associated with re-enrichment and reuse in LWRs. There is no enhancement of the radioactivity burden of ^{232}U and ^{234}U, or of the increased neutron absorption penalty of ^{234}U and ^{236}U encountered through enrichment. The softer spectrum in CANDU compared to a PWR results in the neutron absorption effect of a given concentration of ^{236}U being an order of magnitude lower than in a LWR. Since the ^{235}U is burned to tails levels in CANDU, there is no need for subsequent recycle to maximize the energy content of the fuel.

Analysis has shown that for a CANDU-6 reactor, average discharge burnups almost double when RU fuel is used: burnup goes from 7400 MWd/MTU with NU fuel to about 13000 MWd/MTU with RU fuel. Therefore, the use of RU fuel in CANDU reactors potentially offers economic, environmental and public acceptance benefits. Use of RU significantly increases burnup, thereby increasing resource utilization and reducing fuel requirements. Spent-fuel volumes and overall fuel cycle costs are both reduced.

If desired, instead of gaining increased burnup benefits, the RU fuel may be used to increase the power available from some CANDU reactors by flattening the radial power profile. A combination of increased radial flattening and increased burnup is also an option.

RU, like NU and SEU, is a nuclear fuel commodity available from several sources, because the cumulative quantity of RU projected to arise by the year 2000 from the reprocessing of spent oxide fuel in Europe and Japan is approaching 25,000 te. This quantity would provide sufficient fuel for 500 CANDU-6 reactor years of operation. Therefore, the use of RU in Korean CANDU reactors is not dependent on reprocessing Korean spent PWR. Security of supply is not an issue, as SEU of equivalent enrichment can be substituted.

Three main aspects differentiate RU fuel manufacture from NU fuel manufacture: higher specific activity of the material, criticality considerations and the increase in specific gamma activity related to the ingrowth of U^{232} decay products. According to the RU fuel manufacturing experiences in KAERI and AECL, the suitability of RU as a reactor fuel for CANDU has been shown : CANDU fuel fabricated from RU meets CANDU specifications; RU does not pose serious radiological difficulties, and no special technologies are required for handling and processing RU; and fuel handling at reactor is particularly simple. Under current legislation and practice, it is recognized that there are no obstacles to the transport of commercial quantities of RUO_2 powder, for example, from the UK to Korea.

In conclusion, the use of RU in CANDU has beneficial environmental impact on overall fuel cycle. This is an excellent example of the environmental 3R's (Reduce, Reuse, Recycle) as applied to global nuclear energy use.

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Table 1. Typical Composition of RU, Based on BNFL Process Flowsheets

Nuclide/Element	Range	Nuclide/Element	Range
U-232	0.15 to 1.0 ppb	Np	<3 x 10^{-6} □g/gU
U-234	0.014 to 0.018	Pu	<3 x 10^{-6} □g/gU
U-235	0.85 to 0.95	Am	<1x 10^{-8} □g/gU
U-236	0.28 to 0.40	Cm	<1x 10^{-9} □g/gU
		Tc-99	<3x 10^{-5} □g/gU
		Ru-106	<5 x 10^{-10} □g/gU

Table 2. Radioactivity of Transuranic Elements in RU

RU origin	Reactor : PWR 900 MWe ; Initial ^{235}U assay : 3.25 % wt.; Burnup : 33,000 MWd/TU; Cooling time before reprocessing : 3 years; Storage duration after reprocessing : 3 years.
Total alpha activity of transuranic elements	276 Bq/g
Total alpha activity of uranium isotopes	70,552 Bq/g
Total alpha activity of ^{232}U daughter products	2,832 Bq/g
Total alpha activity of RU	**73,660 Bq/g**
Remarks : 1) U-isotopes of non-enriched RU : ^{234}U:0.021%wt ; ^{235}U:0.92 %wt ; ^{236}U:0.42 %wt ; ^{238}U:98.64%wt **2) U-isotopes of the re-enriched RU enrichment level of 3.25 %wt equivalent SEU :** ^{234}U:0.088%wt ; ^{235}U:3.52 %wt ; ^{236}U:1/14 %wt ; ^{238}U:95.25%wt	

Table 3. Results of RFSP Time Average Calculation of 37-Element and CANFLEX Bundles in CANDU 6

Fuel Type / Characteristics	*37-Element NU (0.711%wt ^{235}U)*	*CANFLEX-RU (0.9%wt ^{235}U)*	*CANFLEX-SEU (0.9%wt ^{235}U) [8]*
Total reactor power (MW)	2061.4	2061.4	2061.4
Fuelling scheme	8-bundle shift	4-bundle shift	4-bundle shift
Capacity factor (fraction)	0.8	0.8	0.8
Uranium weight per bundle (kg)	19.1	18.5	18.5
Max. channel power (kW)	6,583	6,570	6,821
Max. bundle power (kW)	791.5	774.7	798
Average exit burnup (MWd/MTU)	7,404.2	13,338.3	13,496.6
Average resistance time of fuel (days)	391.0	682.3	690.4
Annual throughput of U into CANDU-6 core (ton/yr)	81.3	45.1	44.6
Annual fuel bundles	4256.3	2439.3	2410.7
Annual throughput of NU feed(ton/yr)	81.3	-	61.1
Annual throughput of RU feed(ton/yr)	-	45.1	-

Table 4. The Reactivity Worths of CANDU-6 Control Devices with 37-Element NU, CANFLEX-RU, CANFLEX-RU-S Fuel Bundles

Reactor Controllers / Bundle type	Adjuster Rods (mk)	Zone Controllers (mk)	MCA* (mk)
37-Element NU*(0.711%wt ^{235}U)*	16.6	6.5	-11.3
CANFLEX-RU*(0.9%wt ^{235}U)*	14.7	7.3	-8.5

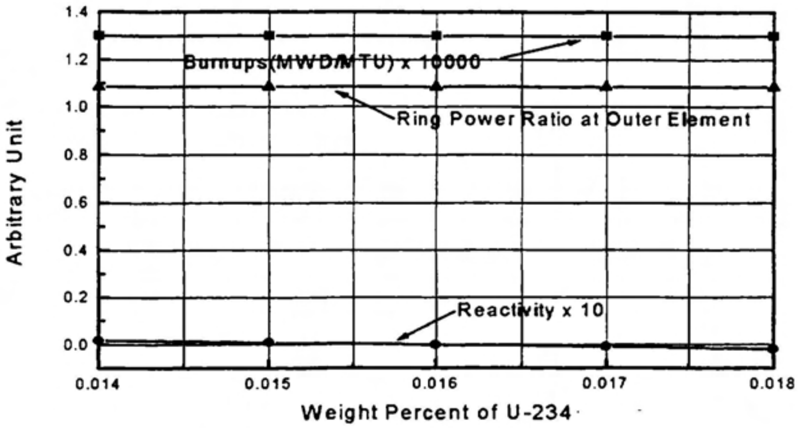
* MCA = Mechanical Control Absorbers

Table 5. ELESTRES Prediction of CANFLEX-0.9% RU Fuel Element Performance in CANDU-6

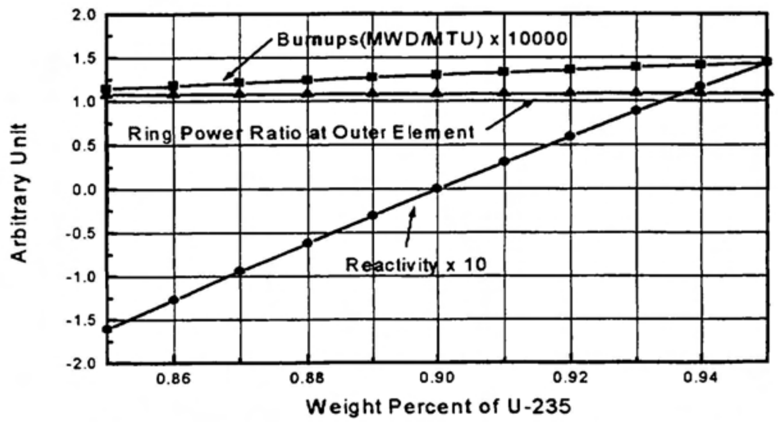
Parameter	Design Basis or Requirement	ELESTRES Prediction (Maximum Value)
Element internal gas pressure	It shall not exceed system pressure.	5.9 Mpa (inner element) 7.5 Mpa (outer element)
Fuel temperature	It shall be kept below the melting temperature of UO_2.	1,576 °C (inner element) 1,616 °C (outer element)
Sheath temperature	It shall be kept below the oxidation acceleration temperature.	342 °C (inner element) 350 °C (outer element)
Total hoop strain of Sheath (elastic+ plastic+thermal)		0.59 % at mid-plane, 1.0 % at ridge (inner element) 0.53 % at mid-plane, 0.94 % at ridge (outer element)
Plastic hoop strain of sheath		0.36 % at mid-plane, 0.75 % at ridge (inner element) 0.30 % at mid-plane, 0.69 % at ridge (outer element)
Sheath ridge height		0.03 mm (inner element) 0.02 mm (outer element)
Sheath strain after Discharge at STP	0.09 % average and 0.5 % peak for outer elements from 20 years experience [15]	-0.08 % at mid-plane, 0.21 % at ridge (inner element) +0.08 % at mid-plane, 0.32 % at ridge (outer element)
FGR after discharge at STP	2.7 % average and 8 % peak for outer elements from 20 years experience[15]	3.12 % (inner element) 3.34 % (outer element)

Table 6. KAERI Characterization Test Results of BNFL Power and KAERI Pellets of RUO_2

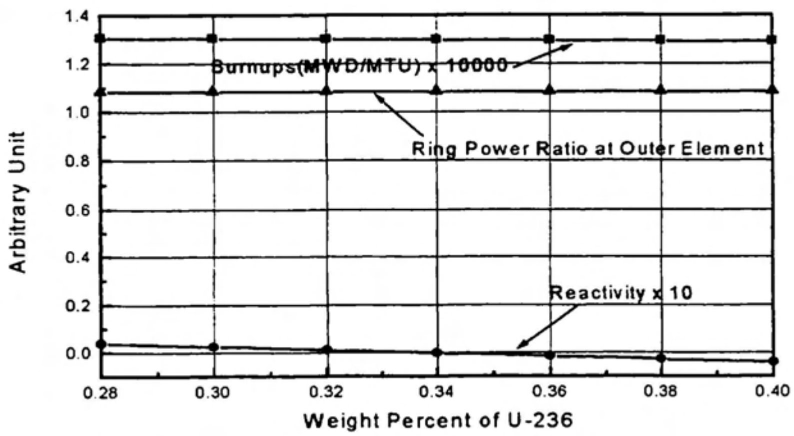
Characteristic Parameters		RUO_2	Remarks: NUO_2
Conversion route		MDR	ADU
Powder	Pour density, g/cm³	1.18	1.14
	O/U ratio	2.07	2.09
	Particle size, μm	1.7	2.2
	Content of ^{232}U, ^{234}U, ^{236}U, %wt	0.34	-
	Content of ^{235}U, %wt.	0.97	0.72
Pellet	Grain size, , μm	7.8	9.1
	Sintered density, g/cm³	10.58	10.62
Radiation	At Surface of 1.3 kg RUO_2 powder can, μSv/h	35.2	22.8
	At 1 m distance the can, μSv/h	0.34	0.22



(a) Sensitivity of ^{234}U on Lattice Characteristics



(b) Sensitivity of ^{235}U on Lattice Characteristics



(c) Sensitivity of ^{236}U on Lattice Characteristics

Fig. 1. Sensitivity of ^{234}U, ^{235}U and ^{236}U Isotopes in RU on Lattice Characteristics

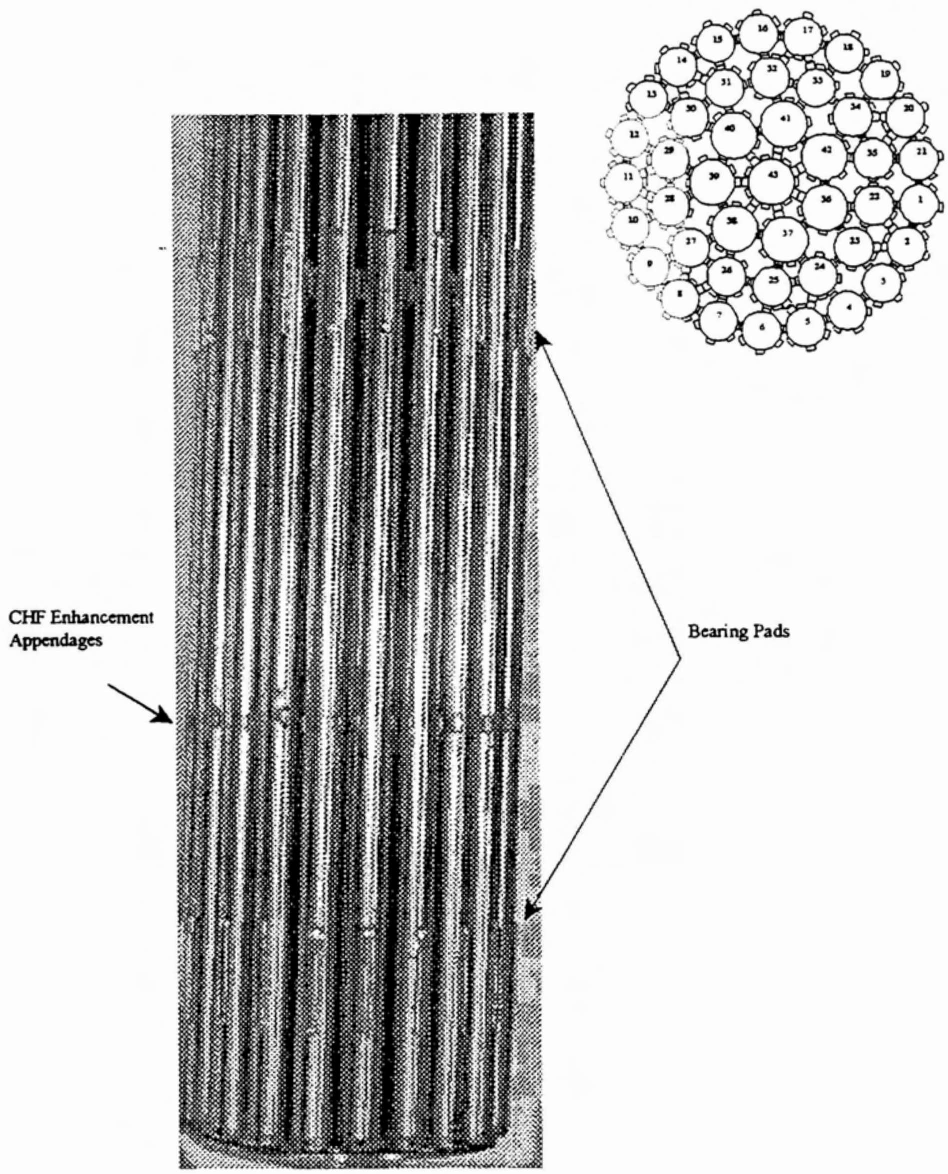


Fig. 2. CANFLEX 43-Element Bundle

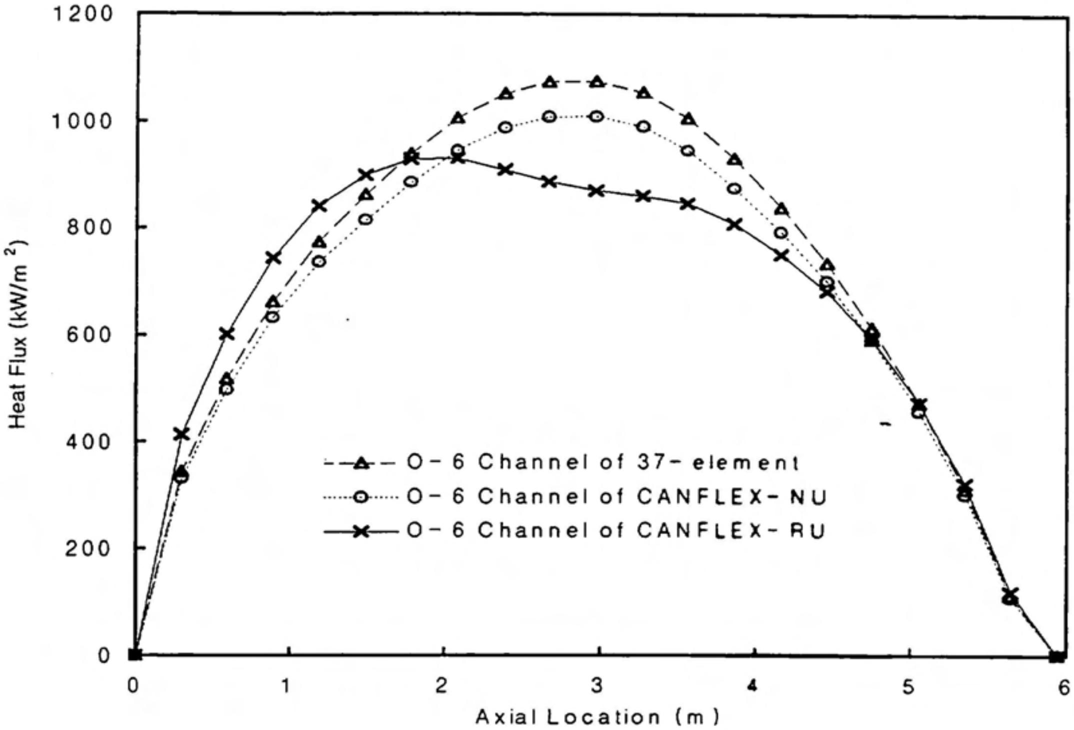


Fig. 3. Local Heat Fulx Distribution of O-6 Channel in CANDU-6

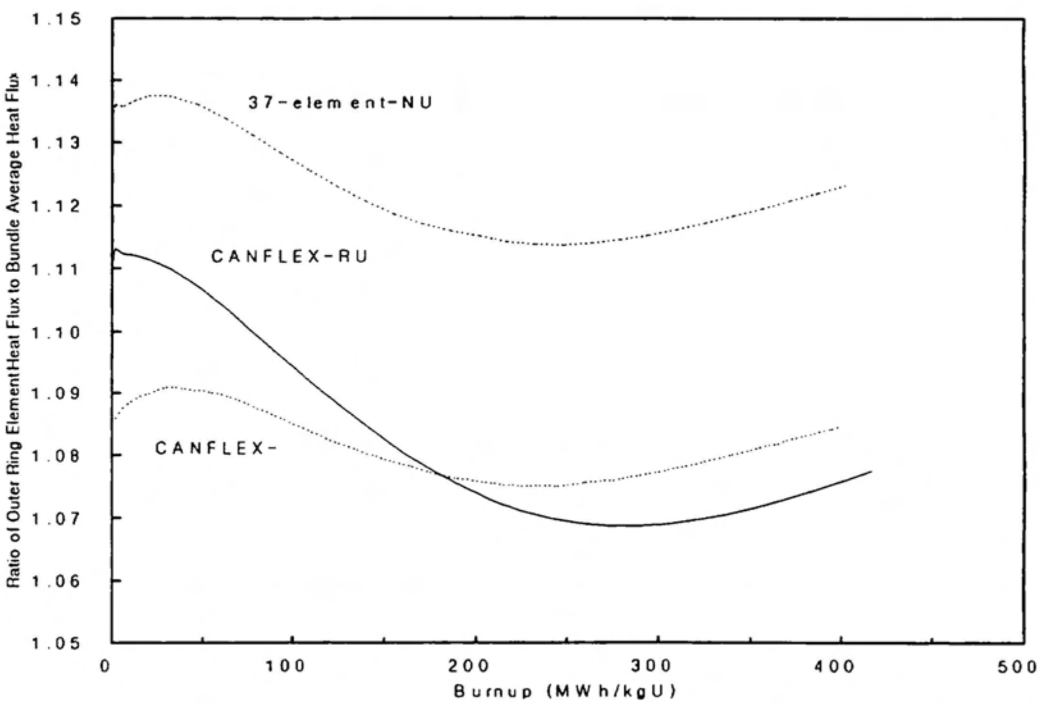


Fig. 4. The Beahavior of BRFF(Bundle Radial Form Factor) with respect to Bundle Burnup