RU FUEL DEVELOPMENT PROGRAM FOR AN ADVANCED FUEL CYCLE IN KOREA

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ABSTRACT

Korea is a unique country, having both PWR and CANDU reactors. Korea can therefore exploit the natural synergism between the two reactor types to minimize overall waste production, and maximize energy derived from the fuel, by ultimately burning the spent fuel from its PWR reactors in CANDU reactors. As one of the possible fuel cycles, Recovered Uranium (RU) fuel offers a very attractive alternative to the use of Natural Uranium (NU) and slightly enriched uranium (SEU) in CANDU reactors. Potential benefits can be derived from a number of stages in the fuel cycle: no enrichment required, therefore no enrichment tails, direct conversion to $U0_2$, lower sensitivity to ^{234}U and ^{236}U absorption in the CANDU reactor, and expected lower cost relative to NU and SEU. These benefits all fit well with the PWR-CANDU fuel cycle synergy. RU arising from the conventional reprocessing of European and Japanese oxide spent fuel by 2000 is projected to be approaching 25,000 te. The use of RU fuel in a CANDU 6 reactor should result in no serious radiological difficulties and no requirements for special precautions and should not require any new technologies for the fuel fabrication and handling. The use of the CANDU Flexible Fueling (CANFLEX) bundle as the carrier for RU will be fully compatible with the reactor design, current safety and operational requirements, and there will be improved fuel performance compared with the CANDU 37-element NU fuel bundle. Compared with the 37-element NU bundle, the RU fuel has significantly improved fuel cycle economics derived from increased burnups, a large reduction in both fuel requirements and spent fuel, arisings, and the potential lower cost for RU material. There is the potential for annual fuel cost savings in the range of one-third to two-thirds, with enhanced operating margins using RU in the CANFLEX bundle design. These benefits provide the rationale for justifying R & D efforts on the use of RU fuel for advanced fuel cycles in CANDU reactors in Korea. The RU fuel development is an international collaboration between KAERI, AECL and BNFL. It is expected that the work will be completed before 2005, and there should be no impediment to the use of RU fuel in the CANDU 6 reactors on the Wolsong site in Korea, if RU is available and competitive in price with NU and SEU..

1. INTRODUCTION

Korea, as a country lacking in natural resources, has made the development of nuclear energy a national priority to provide energy for economic growth, satisfy increased energy consumption in the future and to ensure self-reliance of energy supply. The Korean nuclear program will retain its importance for at least the next 30 years, and will be as vital then, as it is today. In Korea, twelve nuclear power plants, (10 PWRs and two CANDUs) are currently in operation, and six plants (four PWRs and two CANDUs) are under construction. The existing power plants represent about 28% (10,316 Mwe) of the domestic installed generating capacity, and produced about 36% (205,494 GWh) of the 1996 gross electrical energy generation. In 2002, a total nuclear power generation capacity of 15,742 MWe will be installed in Korea, where 18% of the capacity will be contributed by the four Wolsong CANDUs. Korea is therefore a unique country, having both PWR and CANDU reactors, and can exploit the natural synergism between these two reactor types to minimize overall waste production, and maximize energy derived from the fuel. The synergism can be exploited through several different fuel cycles [1]. 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 plutonium could be recycled as (Mixed Oxide) MOX fuel, in either PWRs or in CANDU reactors. If the political and non-proliferation considerations in the Korean peninsula were to lead to the decision to reprocess the Korean spent PWR fuel, then the resultant Recovered Uranium (RU) , which constitutes the vast majority of the spent fuel, and which still contains valuable ^{235}U (typically about 0.9%), could be recycled as-is in CANDU reactors, without re-enrichment. The fuel burnup in CANDU would be about double that of natural uranium fuel, and about twice the energy would be extracted, compared with re-enrichment and recycling in a PWR. However, the use of RU in Korean CANDU reactors is not dependent on reprocessing Korean spent PWR fuel; RU is a nuclear fuel commodity available from several sources, as is natural uranium, and enriched uranium. Hence, RU as a fuel cycle option in Korea is particularly attractive for use in CANDU reactors, with the advantage of having potentially lower fueling costs than both NU and SEU.

KAERI (Korea Atomic Energy Research Institute) has a comprehensive product development program on CANFLEX- RU fuel. This is seen as an economical alternative to natural uranium as a fuel for use either in existing or future CANDU reactors. The aim is to introduce CANFLEX into CANDU reactors in Korea and have a clear vision of how the product will evolve over the next 10 years. The RU fuel development program is currently conducted under the Korean Nuclear Energy R & D Project from 1997 to 2006[2]. The key targets of the program are enhanced safety and economics, the reduction of spent fuel volumes, and using the inherent characteristics and advantages of CANDU technology. The specific activities of the program take into account domestic and international environmental concerns regarding non-proliferation in the Korean Peninsula[2], as well as the recommendations of the Management Committee of Korea's Nuclear Energy R & D Project. These involve showing an overall evaluation and identification of the potential benefits, risks, and costs associated with the use of RU fuel in a CANDU 6 by 1999. This will provide a rationale to justify the R & D efforts on the project for the application of advanced fuel cycles in CANDU reactors in Korea. The justification includes security of supply issues for RU and the overall possibility of satisfying the licensing issues in the Korea Safety Review Guideline (KSRG)[3]. These external influences and justifications have been, and will continued to be applied to all fuel and fuel cycle R & D in Korea. The RU fuel R & D program has been enhanced through international collaboration between KAERI, Atomic Energy of Canada Limited (AECL) and British Nuclear Fuels Plc (BNFL), since the end of 1996. The prime objective of this joint program is the small-scale demonstration irradiation of 20 to 100 bundles in a CANDU power reactor, followed by the post irradiation examination of selected irradiated bundles. This is a necessary prerequisite for a full-scale conversion to RU. The program includes all necessary analysis and supporting out-of-reactor tests.

The intent of this paper is to evaluate the advantages and feasibility of CANFLEX-RU in order to provide a rationale for justifying the R & D efforts contributed to it for an advanced fuel cycle in Korea.

2. CANFLEX AS THE REFERENCE CARRIER OF RU IN CANDU

CANFLEX[4] is a 43-element CANDU fuel bundle, which acts as the optimal carrier for RU fuel. It is being developed jointly by KAERI and AECL. The full benefits of RU use are achieved through the provision of enhanced operating margins in the bundle design. The CANFLEX bundle has the same bundle diameter and length as a CANDU 6, 37-element natural uranium (NU) bundle; but 35 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, reduces the peak linear element rating by up to 20%, compared with a 37-element (13.1 mm element diameter) bundle operating at the same bundle power outputs. The lower fuel rating in the CANFLEX bundle facilitates the extended burnups in CANDU reactors that are necessary for the economic use of various attractive fuel cycles. The CANFLEX bundle design also uses critical heat flux-enhancing (CHF) appendages, which increase the minimum CHF ratio, and dryout margin of the bundle. These two features will provide larger operating margins in existing CANDUs, and will allow higher burnups. The CANFLEX bundle development program is nearing completion [5], and the next step is a small-scale demonstration irradiation of 24 CANFLEX-NU bundles in the Canadian Point Lepreau CANDU 6 reactor.

3. AVAILABILITY AND PROCESSING OF RU

RU is one of the products of conventional chemical reprocessing of spent oxide fuel. The cumulative quantity of RU projected to arise from the reprocessing of European and Japanese spent fuel by 2000 is approaching 25,000 te [6]. This RU, which is owned by the utilities or reprocessors, is an alternative fuel source to new natural uranium for use in LWR and CANDU reactors. Each country and utility will determine its strategy for RU based upon local factors. Theoretically this 25,000 te would provide sufficient fuel for 500 CANDU-6 reactor years' operation, since the initial core load of uranium for a CANDU-6 reactor is about 85 Te , and the annual refueling requirements for an RU fuel burnup of 13 MW.d/kgU are around 50 Te /a.

Current reprocessing technology has been optimized to produce an RU product suitable for interim storage pending potential re-enrichment and recycle into LWR reactors. BNFL uses thermal denitration to convert Uranyl Nitrate Liquor (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 (subsequently to UO_2) by the Modified Direct Route (MDR) process. This route offers significant savings in the longer term if sufficient CANDU RU demand develops.

4. FABRICATION AND HANDLING OF CANDU RU FUEL

The dose fields associated with RU are higher than NU. The isotopic composition and activity of un-enriched recovered $U0_2$ powders depend inter alia on the reactor type, initial enrichment and discharge burnup of the PWR fuel, the time between spent PWR fuel discharge and reprocessing, the route chosen to convert the UNL to UO_2, and the delay until fuel fabrication. RU contains typically ~1 ppb ^{232}U which decays with a half-life of 69.8 years. The daughters in the ^{232}U decay chain are removed during reprocessing but grow during storage. Conversion processes via UF_6 also remove daughter products. The first daughter in the chain is ^{228}Th with a half-life of 1.9 years. Since all the other daughters in the chain have much shorter half lives, including the radiologically important ^{208}Tl and ^{212}Bi, they are all in secular equilibrium with ^{228}Th. Therefore, the ^{228}Th build-up governs the build-up rate of gamma activity and indicates the gamma activity with time relative to the quasi-equilibrium level attained after about 10 years. RU also contains ^{234}U that contributes to a higher specific alpha activity compared to NU. However, the level is about the same as in conventional enriched PWR fuel, since the source of the increased ^{234}U is the initial enrichment of NU. RU also contains trace fission product gamma and beta emitters, and transuranic alpha emitters.

An initial assessment of the health physics aspects of manufacturing and handling RU as a reactor fuel for CANDU was done in the joint program between BNFL, KAERI and AECL, and previously in a joint program between AECL and COGEMA [6]. BNFL has converted reprocessed spent PWR fuel into 200 kg of $U0_2$. The characteristics of the recovered $U0_2$ 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.

The conversion took place one year after reprocessing. Activity level measurements made on the finished CANFLEX-RU bundle were 1.3 times higher than a natural uranium bundle, when measured at 30 cm distance. Consequently, because the total fuel quantity required can be reduced by around 50% using RU, the overall dose uptake to the workforce during the fabrication and handling of RU bundles will be comparable with, or less than, that presently seen for natural uranium fuel. By reducing the time from spent PWR fuel discharge to reprocessing, and from there to conversion, fuel fabrication, and insertion into the reactor, the dose uptake will be reduced even further.

During sintering, the release of ^{137}Cs and other volatile fission products from RU was below detectable levels. Also, AECL[6] earlier concluded that no significant fields in a commercial fuel fabrication plant would build up due to release of ^{137}Cs during sintering, even after decades of production.

A CANFLEX-RU bundle was displayed at AECL's Sheridan Park Engineering Laboratories (SPEL) during the 5th International Conference on CANDU Fuel, 1997 September 21-25, in Toronto, Canada, where delegates were able to see and handle both RU and natural uranium CANFLEX bundles.

5. CANFLEX RU - CANDU REACTOR PHYSICS, SAFETY AND FUEL PERFORMANCE

The extra isotopes in RU have a minimal effect on the reactor physics characteristics in CANDU. Spent PWR fuel contains typically 0.4 % ^{236}U with a range from 0.2% to 0.7%, originating from the neutron capture in ^{235}U in the original PWR fuel, that has a strong resonance at 5.5 eV. Because of the softer neutron spectrum in a CANDU reactor, the absorption worth of ^{236}U is an order of magnitude lower in a CANDU than in a PWR. Also, the ^{235}U is burned down to low levels (i.e. 0.2 to 0.3%) in a CANDU reactor because of the good neutron economy provided by the heavy water moderator and coolant, compared with PWRs (0.8% to 1.0%)[6]. Therefore, the main determinant in CANDU reactor physics with RU is the ^{235}U level.

AECL[7] and KAERI[8] have performed reactor physics simulations to evaluate the feasibility of CANFLEX-RU fuel being used in a CANDU 6 reactor by taking the isotopic composition of typical RU UO_2 produced by the MDR route. AECL 500 Full Power Days (FPD) core-follow simulations were made for CANFLEX-RU with 0.96 w/o ^{235}U, using a bi-directional two-bundle-shift refueling scheme, while the KAERI 600 FPD core-follow simulations were made for CANFLEXRU with 0.88 w/o ^{235}U, using with a bi-directional four-bundle-shift refueling scheme. Standard computer codes and methods were used for the simulations and analysis. WIMS-AECL[9] with ENDF/B-V nuclear data library was used to construct fuel tables for use with a core code, RFSP[10], which modeled the reactor core. To facilitate the decisions that must be made during refueling, an automated method was used to do most of the editing and calculations required to perform the steps described in References 7 and 8. The results of the CANFLEX-RU core-follow simulations show that the RU fuel would be a satisfactory fuel in an equilibrium CANDU-6, as summarized in the following table.

	AECL 500 FPD Simulations (2-bundle-shift refuelling)[9]	KAERI 600 FPD Simulations (4-bundle-shift refuelling)[10]	License Limit
RU enrichment	0.96 w/o ^{235}U	0.88 w/o ^{235}U	
Max. channel power	7.021 MW	7.086 MW	7.3 MW
Max. bundle power	857 kW	883 kW	935 kW
Average fueling rate	bundles/FPD (3.9 channels/FPD)	bundles/FPD (2.35 channels/FPD)	
Average discharge burnup	334.6 MWh/kgU	297.4 MWh/kgU	

An assessment was made of the probability of stress-corrosion cracking (SCC) through power boosting using the results of the AECL refuelling simulation. The CANFLEX-RU elements do not come close to approaching the SCC element-power threshold, and none of the linear-element powers were above 44 kW/m.

Following the KAERI preliminary results, a CANDU fuel element performance analysis code, ELESTRES [11], predicted that the internal pressure of the outer CANFLEX-RU elements in normal power operation was below 2.5 MPa, which is lower than that of the outer elements of the 37-element NU fuel bundle by a factor of about two. The maximum fuel stack length of the outer and inner CANFLEX-RU elements increased by 0.46% through thermal expansion, which is equivalent to a reduction of less than a 0.2 mm in the axial gap between the fuel stack and the end cap. In addition, a preliminary safety assessment of a CANDU-6 has shown that, for all the shorter half-life isotopes, the gap (or "free") inventory with CANFLEX-RU fuel is 5 - 10 times smaller than that for 37-element NU fuel, and the total inventory with RU-fuel is very similar to that for 37-element NU fuel. For longer half-life isotopes such as ^{137}Cs, the gap inventory with CANFLEX-RU is very similar to that with 37-element NU fuel, but the total inventory with CANFLEX RU fuel is about two times higher than that for 37-element NU fuel, because of the higher burnup.

6. FUEL CYCLE COSTS FOR RU

Generally, RU is owned by the utility that contracts for reprocessing of spent oxide fuel. Most countries and/or utilities which adopt a reprocessing strategy do so for strategic energy self-reliance and/or for waste management reasons. The uranium and plutonium recovered from reprocessing are often held as "low, or zero cost" stocks by the utilities. Hence, there is the possibility that RU will be competitively available on the open market. The potential annual saving to a CANDU utility by the utilization of RU is significant, but strongly dependent on the price paid for the RU powder and fuel fabrication.

The costs of the front-end of the fuel cycle (excluding back-end storage and disposal costs) in US dollars were assessed for RU in CANDU and re-enriched RU in a PWR by Boczar et al.[6], for a range of RU-cost assumptions. This parametric survey indicated that, with RU at no cost, CANDU fueling costs with RU are >70% lower than for re-enriched RU in PWR. With RU at no cost, the CANDU fueling costs are reduced relative to NU fueling by 45% with NU at 25 $/kgU, and by 67% with NU at 80 $/kgU. With RU at NU costs, the fueling cost savings in CANDU with RU are 28% for NU at 25 $/kgU, and 34% for NU at 80 $/kgU. With RU at NU cost, the fueling costs are 10 - 15% lower than for 1.2% SEU, which is the economic optimum SEU enrichment.

KAERI also assessed relative annual savings of CANFLEX-RU to the 37-element NU fuel bundles in

CANDU-6 by taking the relative costs of recycled UO_2 to natural UO_2 and by assuming that the fabrication cost of the RU fuel bundle is about 16% higher than that of the 37-element bundle. With recycled UO_2 priced at 25% of the natural UO_2 price, the annual fueling costs will represent a 64% saving relative to that of NU in 37-element bundles. Similarly with recycled UO_2 priced at 124% of the natural UO_2 cost, the annual fueling cost of the RU fuel bundles would show a saving of 31% relative to that of the 37-element bundles. Break-even between RU and NU UO_2 is represented with recycled UO_2 priced at 210% of the natural UO_2 price.

Ongoing work will reduce the major uncertainties in the fueling costs for RU, namely the cost of conversion of UNL to ceramic-grade UO_2, and the cost of CANFLEX-RU fuel fabrication. Finally, another paper in this conference [12] quantifies significant cost savings in the back-end of the fuel cycle with SEU (or RU).

7. CONCLUSIONS

Korea is a unique country having both PWR and CANDU reactors. It can therefore exploit the natural synergism between the two reactor types to minimize overall waste production, and maximize energy derived from the fuel, by ultimately recycling the spent fuel from its PWR reactors in CANDU reactors. As one of the possible fuel cycles, RU fuel is a very attractive alternative to the use of NU and SEU in CANDU reactors, offering among other benefits, the advantage of having potentially lower fueling costs. The RU fuel development program, an international collaboration between AECL, KAERI and BNFL, is a part of KAERI's comprehensive development program of CANDU advanced fuel and includes a clear vision of how the product will evolve over the next 10 years. The key targets of the program are safety and economic enhancements, and reduction of spent fuel volume, using the inherent characteristics and advantages of CANDU technology.

RU is one of the products from conventional reprocessing of spent oxide fuel and typically will have an overall nominal ^{235}U content of 0.9%. The composition of un-enriched RU depends on the reactor type, initial enrichment and discharge burnup of the PWR fuel, the time between spent PWR fuel discharge and reprocessing, the route chosen to convert the UNL to UO_2, and the delay until fuel fabrication. It is only slightly more radioactive than NU. The RU can be used directly in CANDU reactors. A number of options exist for the conversion of the UNL to ceramic-grade UO_2, including direct conversion using MDR and ADU processes, or fluorination to UF_6, followed by the IDR route. The RU available to utilities and reprocessors in Europe and Japan by 2000 is cumulatively expected to be approaching 25,000 te. This quantity of RU, if used solely for recycle in CANDU reactors, would provide sufficient fuel for some 500 CANDU-6 reactor-years' of operation, since the initial core load of uranium for a CANDU 6 reactor is about 85 Te, and the annual refueling requirements for an RU with burnup of 13 MWd/kgU are ~ 50 Te/a. Security of supply is not an issue, since SEU could be substituted for RU. 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 precautions or technologies are required for handing RU; and fuel management is particularly simple.

Taking the CANFLEX 43-element CANDU fuel bundle as the optimal carrier for RU fuel, some preliminary evaluations of CANDU reactor physics, safety and fuel performance of CANFLEX-RU have indicated that the fuel would not cause channel or regional overpowers, or significant risk of fuel element failure in spite of its higher burnup and slight enrichment relative to natural uranium. However, future detailed analyses of RU fuel are required to provide a detailed rationale for the justification of the R & D efforts on it for the advanced fuel cycle of CANDU reactors in Korea. The justification includes licensing issues in the KSRG.

With RU available free-issue, the annual fueling costs could be reduced by ~ 30 - 60%, compared to NU fuel. With RU at NU cost, the fueling costs are 10 - 15% lower than for 1.2% SEU, which is the economic optimum SEU enrichment. These cost savings are strongly dependent on the conversion cost of UNL to ceramic grade $U0_2$, and the cost of CANFLEX-RU fuel fabrication. Fuel management with RU is considerably simpler than that for 1.2% SEU, and good fuel performance is assured as a result of the lower ratings with CANFLEX. In the

current collaborative program between KAERI, AECL and BNFL, RU fuel development and proof testing should be completed by 2005, and there should be no impediment to the use of RU fuel in the CANDU-6 reactors at the Wolsong site in Korea, if RU is competitively available.

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