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ATOMIC ENERGY
OF CANADA LIMITED

ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

ADVANCED FUEL CYCLES IN CANDU REACTORS: RECONFIRMING THE NEED

CYCLES DE COMBUSTIBLE AVANCÉS DES RÉACTEURS CANDU: NOUVELLE CONFIRMATION DE LEUR NÉCESSITÉ

R.E. GREEN and P.G. BOCZAR

Presented at the 5th Korea Atomic Industrial Forum/Korea Nuclear Society (KAIF/KNS)
Joint Annual Conference Seoul, Korea, 1990 April 17-19

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

Chalk River, Ontario K0J 1J0
April 1990 avril

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RÉSUMÉ

Dans cette communication, on réexamine la nécessité de faire appel à des cycles de combustible nucléaires avancés en général, et à des cycles de combustible avancés CANDU en particulier. Les arguments traditionnels reposant sur la question des ressources et justifiant les cycles de combustible nucléaire qui économisent davantage l'uranium sont actuellement réfutés par les prix de l'uranium qui sont à leur plus bas. Toutefois, les ressources en uranium classiques ne peuvent satisfairent la demande d'uranium prévue que pour environ 50 ans, ou moins s'il y a une reprise importante de l'énergie nucléaire au cours de cette période comme solution partielle aux problèmes touchant l'environnement à l'échelle du globe. Bien que les ressources mondiales en uranium soient très vastes, l'incertitude de l'offre et du prix de l'uranium est la raison principale liée aux ressources qui motive les recherches sur les cycles de combustible avancés.

Signalons qu'il y a d'autres raisons importantes de poursuivre les recherches sur les cycles de combustible avancés. L'emploi des cycles de combustible avancés permettrait de suivre la règle des 3 R du mouvement écologiste -- réduire, recycler, réutiliser -- dans la production électronucléaire. L'adoption de cycles de combustible économisant l'uranium réduirait la quantité d'uranium extraite du sol et, partant, l'impact de l'exploitation minière sur l'environnement. Cela réduirait également les inquiétudes écologiques concernant la partie terminale du cycle de combustible. La combustion massique plus élevée du combustible réduit le volume de combustible irradié devant être stocké. La transmutation des actinides et des produits de fission à longue période en produits de fission à courte période réduirait les risques radiologiques des déchets. Calculé en années, ce risque passerait de milliers d'années à des centaines d'années. Le recyclage de l'uranium ou du plutonium, ou des deux, du combustible irradié permet de récupérer et de réutiliser des matières fissiles précieuses, ne laissant ainsi que les véritables déchets à stocker. Les cycles de combustible avancés offrent également des avantages économiques, en permettant de fixer un plafond des coûts du cycle de combustible, qui représentent typiquement 20 à 30 % du prix de revient de l'énergie. Les cycles de combustible avancés favoriseraient également l'atteinte des objectifs stratégiques nationaux d'une autonomie et d'une diversification énergétiques plus poussés.

Ces arguments sont encore plus forts dans le cas du CANDU. L'utilisation d'uranium légèrement enrichi dans le CANDU permettrait une réduction d'environ 30 % des coûts du cycle de combustible et de la consommation d'uranium. Le volume du combustible irradié pourrait être réduit par au moins un facteur 3. L'utilisation d'uranium légèrement enrichi dans le CANDU offrirait une plus grande souplesse de conception du réacteur, en permettant de sacrifier l'économie neutronique en contrepartie d'autres objectifs répondant aux exigences du client. La grappe de combustible avancée CANFLEX, actuellement en cours de mise au point, constituera la forme optimisée des combustibles enrichis CANDU.

L'économie neutronique remarquable du CANDU rend possible une synergie unique avec les réacteurs à eau ordinaire. Dans le cycle de combustible TAMDEM, l'uranium et le plutonium récupérés du combustible irradié des réacteurs à eau ordinaire seraient brûles dans le CANDU et produiraient environ le double de l'énergie que l'on pourrait obtenir dans les réacteurs à eau ordinaire d'un combustible recyclé.

En dernier lieu, les cycles de combustible au thorium dans le CANDU offrent la sécurité énergétique à long terme, sous forme d'un cycle de combustible presque surrégénérateur.

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ABSTRACT

This paper re-examines the rationale for advanced nuclear fuel cycles in general, and for CANDU advanced fuel cycles in particular. The traditional resource-related arguments for more uranium-conserving nuclear fuel cycles are currently clouded by record-low prices for uranium. However, the total known conventional uranium resources can support projected uranium requirements for only another 50 years or so, less if a major revival of the nuclear option occurs as part of the solution to the world's environmental problems. While the *extent* of the uranium resource in the earth's crust and oceans is very large, *uncertainty* in the *availability* and *price* of uranium is the prime resource-related motivation for advanced fuel cycles.

There are other important reasons for pursuing advanced fuel cycles. The three R's of the environmental movement-- *reduce, recycle, reuse* - can be achieved in nuclear energy production through the employment of advanced fuel cycles. The adoption of more uranium-conserving fuel cycles would reduce the amount of uranium which needs to be mined, and the environmental impact of that mining. Environmental concerns over the back end of the fuel cycle can be mitigated as well. Higher fuel burnup reduces the volume of spent fuel which needs to be disposed of. The transmutation of actinides and long-lived fission products into short-lived fission products would reduce the radiological hazard of the waste from thousands to hundreds of years. Recycling of uranium and/or plutonium in spent fuel *reuses* valuable fissile material, leaving only the true waste to be disposed of. Advanced fuel cycles have an economical benefit as well, enabling a ceiling to be put on fuel cycle costs, which are typically 20-30% of the total energy cost. National goals of greater energy self-reliance or diversity are strategic considerations which also favour advanced fuel cycles.

These arguments are even more compelling for CANDU. The use of slightly enriched uranium (SEU) in CANDU would result in about a 30% reduction in both fuel cycle costs and uranium requirements. The volume of spent fuel could be reduced by at least a factor of three. The use of SEU in CANDU would allow greater flexibility in reactor design, allowing a trade-off of neutron economy with other goals to match customer requirements. The advanced *CANFLEX* fuel bundle is being developed as the optimum carrier of enriched fuels in CANDU.

CANDU's excellent neutron economy makes possible a unique synergism with light-water reactors (LWRs). In the TANDEM fuel cycle, the uranium and plutonium recovered from spent LWR fuel would be burned in CANDU, yielding about double the energy obtainable from recycle in LWRs.

Finally, thorium fuel cycles in CANDU offer long-term energy security, in the form of a near-breeding fuel cycle.

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1. INTRODUCTION

As we enter a new decade and move towards the end of the twentieth century, there is a growing awareness of and concern for the world's environment. This has focussed mankind's attention on how energy is produced, transported, and used, particularly in the industrialized countries. Nuclear energy is no longer alone in undergoing intense public scrutiny. The greenhouse effect, exacerbated by the burning of fossil fuels, has been called "the central environmental problem of our times" by Professor Kenneth Hare, chairman of the 1988 Toronto Conference on the Environment [1]. Hydroelectric generating projects are also being opposed on environmental grounds, as seen in the public opposition to the construction of a major hydroelectric project on the Yangtse River in China, and the extension of the James Bay complex in Canada.

Many in the nuclear industry are cautiously optimistic that nuclear energy will become part of the solution to the environmental problem; some call for a dramatic increase in the role played by nuclear power in supplying our energy needs. Given these circumstances, it is opportune to re-examine the rationale for advanced nuclear fuel cycles, and to re-establish their importance in meeting ever-increasing energy needs in an environmentally conscious world.

This paper is in two parts: the first part deals with some of the issues which are central to the nuclear fuel cycle, irrespective of reactor type, such as the demand for, and the extent, availability and cost of uranium resources; environmental aspects; economic factors; and finally, political and strategic considerations. The second part of the paper examines the benefits of using advanced fuel cycles in CANDU* reactors.

2. FUEL-CYCLE CONSIDERATIONS

2.1 Uranium Demand and Availability

2.1.1 Uranium Demand. Projections of nuclear capacity and uranium requirements to the year 2030 were recently updated by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) "Ad Hoc Working Group on Reactor Strategies and their Uranium Requirements" [2], for use in the next edition of the Red Book. These projections continue the trend of revising downward earlier estimates of the growth of nuclear power. Nuclear capacity is projected to increase in WOCA countries (World Outside Centrally planned economics Areas), from 338 GWe in the year 2000, to between 604 GWe and 861 GWe in 2030. Annual uranium requirements for the reference reactor strategy are projected to increase from about 55 000 tonnes in the year 2000 to between 73 000 and 109 000 tonnes by 2030. Cumulative uranium requirements by 2030 are projected to be between 2.4 million and 3.1 million tonnes.

The high-growth scenario assumes a revival of the nuclear option by the turn of the century, but not a major swing to nuclear power. Long-term projections are obviously very uncertain, but concern over the environmental impact of burning fossil fuels and further hydroelectric developments could lead to a major increase in the role of nuclear power. The greenhouse effect is potentially the most critical issue [3], if the dire predictions of the consequences of increasing levels of CO_2 in our atmosphere are shown to be correct, and if there is a worldwide political will to curb the burning of fossil fuels. However, modelling the global climate is difficult, and the global warming phenomenon may be exaggerated [4], so optimism about a major rejuvenation of nuclear power must be tempered. Nuclear power will not assume a larger role unless it is more generally accepted by the public. Another major accident at a nuclear plant could do irreparable damage to the future of the industry. Finally, the coming decades will see greater emphasis on energy conservation and energy efficiency as a means of reducing the need for more electrical generating capacity.

2.1.2 Uranium Resources. The traditional rationale for advanced nuclear fuel cycles is based on resource considerations. For example, the Chairman of AEA Technology, in arguing the need for fast breeder reactors, recently said that the power reactors in operation or under construction today will have consumed all of the world's proven resources of uranium in 30 years [5]. A headline in the Montreal Gazette last year warned "World uranium

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* CANDU: CANada Deuterium Uranium. Registered Trademark.

shortage is expected in early '90s as reactors go onstream" [6]. These predictions of impending shortages of uranium are in sharp contrast to the current record low price of uranium. What then is the uranium situation, and are advanced fuel cycles warranted from the perspective of the availability of uranium resources?

The OECD/NEA "Red Book" gives estimates of uranium reserves in each of several categories, defined according to the estimated price of recovery of the uranium, and the degree of confidence in the quantities reported [7]. These estimates are given only for WOCA countries and deal primarily with "conventional" resources recoverable at costs less than $130/kg U (1987 $US; all costs are quoted in US $).

For the category of conventional uranium resources having the highest assurance of existence, the Reasonably Assured Resources (RAR), there are 2.2 million tonnes of uranium recoverable under $130/kg U. Using the latest NEA/OECD estimates of uranium consumption, one finds that indeed this uranium will be exhausted in about 30-40 years, depending on the rate of growth of nuclear power.

There is less assurance, though still good confidence, in the existence of the next category of conventional uranium resources, the Estimated Additional Resources (EAR-1). At prices under $130/kg U, there are an additional 1.3 million tonnes of uranium, bringing the total known conventional resources recoverable under $130/kg to about 3.5 million tonnes, in the WOCA countries. While this would supply projected power reactor needs for an additional 10 or 20 years beyond that supported by the RAR resources, the total known conventional resources will be exhausted by about the middle of the next century.

The Red Book also reports estimates of undiscovered conventional resources of about 13 million tonnes recoverable at $130 /kg or less. Even this amount would not support world energy needs over the long term, particularly if nuclear energy is to contribute an increasing fraction of those needs.

The average concentration of uranium in the earth's crust is about 1 ppm. The conventional resources described above have an ore grade typically between 1000 and 100 000 ppm uranium. The total world uranium resources were examined by Deffeyes and MacGregor in 1980 [8]. They postulate a 300-fold increase in the amount of recoverable uranium for every tenfold decrease in the ore grade, recoverable, of course, at increased cost. This suggests the existence of a vast uranium resource of lower grade, and higher price. The amount of uranium in lower-grade deposits (10 to 1000 ppm) such as in fossil sediments, sandstones, volcanic deposits, black shales, marine shales and phosphates could amount to some 500 billion tonnes!

Small amounts of low-grade uranium are currently being extracted as a by-product of the mining of copper and other metals, and of phosphate production. Morocco reports over 6 million tonnes of uranium in phosphate deposits having a grade of about 110 ppm [9], and until 1986 had plans for commercial extraction of a few hundred tonnes of uranium annually from a phosphate chemical plant [10]. That project was put on hold because of low uranium prices. Even when the extraction of uranium as a by-product of other mineral production becomes economically viable (Israel has developed a uranium-from-phosphate process, at a recovery cost of about $65/kg U [11]), the uranium production rate will be relatively low, and will not significantly affect the uranium supply/demand situation.

Other unconventional sources of uranium are low-grade surface deposits, although these generally have not been explored [12]. They are potentially low-cost sources of uranium, since the ore can be simply scooped off the ground. In the U.S. these deposits range in size from a few hundred pounds of uranium up to 1 million pounds, with a maximum grade of about 1%. Environmental opposition has prevented the exploitation of these deposits in the U.S. and Canada.

There are some 4 billion tonnes of uranium dissolved in sea-water, in extremely low concentrations (less than 0.001 ppm). Until recently, considerable research was directed at developing a means for extracting this uranium. A Japanese pilot plant extracted a total of 15 kg of U_3O_8 over a two-year period [13]. Significant technical advances are necessary before this becomes a realistic source of uranium. Production costs for extracting uranium from sea-water are very uncertain, but are at least a factor of ten greater than for conventional uranium resources [14,15].

While the uranium resources in the earth's crust and in the sea are vast, amounting to hundreds of billions of tonnes, there are several important factors that affect their availability:

- the amount of uranium recoverable,
- the rate at which it can be recovered,
- the cost of recovery, and
- the impact on the environment.

2.1.3 Uranium Production. Only a small fraction of the world's uranium resources have yet been exploited. Since 1985, uranium production has been below power reactor requirements. The shortfall has been met by drawing down the stockpile of uranium, previously built up to higher-than-required levels. This stockpile, equivalent to 3-4 years of reactor requirements, is having the same effect on the price of uranium as a low-cost uranium mine. Consequently, uranium prices have been driven down to a record low level. These low uranium prices have already resulted in the closure of some higher cost mines, and other mine closures are planned [16].

The Red Book concludes that new production centres will be needed by the middle of this decade to meet the uranium demand. Higher-cost production centres (having recovery costs up to $130/kg U) will be needed to meet the demand in the year 2000. As the uranium recovery costs for the new production centres will be as much as five times the current spot-market price of uranium, increases in uranium prices will result.

In the longer term, new discoveries and new mines will be needed to meet the demand. Uranium exploration expenditures declined steadily over the past decade, and will have to increase if new uranium resources are to be found. Long lead-times are required to bring in a new mine, typically more than 10 years from first investment in exploration until production commences. Environmental reviews could extend even further the time required to bring a new mine to the production stage.

Hence, while there is plenty of uranium in the ground and in the sea, without the timely development of new mines or production centres, shortages of uranium could occur. Uranium prices will rise as high-grade deposits are depleted, and low-grade ores are recovered.

It is clear from the foregoing that the *extent* of the world's uranium resources is not a driving force for the development of more uranium-conserving fuel cycles, since that resource appears to be very large. Rather, *uncertainty* in the *availability* and *price* of uranium is the prime resource-related motivation for advanced fuel cycles. Such fuel cycles will provide *assurance* of the *availability* of fissile material, and place a ceiling on the price of nuclear fuel.

2.2 Environmental Considerations

In assessing fuel-cycle strategies, the environmental impact of both the front end and the back end of the fuel cycle are important considerations.

2.2.1 Front end. Environmental concern has prevented the exploration for, and development of, uranium resources in the past, and will probably do so in the future. In Canada, for example, environmental opposition to the proposed development of the Blizzard Property in British Columbia in 1980 led to a seven-year moratorium on uranium mining in that province, even though a royal commission determined that the site could be mined with acceptable environmental impact [17]. While the radiological hazard of mine tailings is small, there is public concern over the management of these large-volume wastes. As low-grade ores are mined, more ore will have to be processed to extract the uranium, with increasing environmental impact.

Hence, in assessing the uranium resource situation, one must also consider the environmental impact of extracting the uranium. Advanced fuel cycles can reduce the environmental impact of the front end of nuclear energy production by reducing the amount of uranium that needs to be mined.

2.2.2 Back end. Public opinion polls consistently show that the disposal of spent fuel and reactor safety are the nuclear issues of major public concern. Currently, there is not an urgent *technical* need for disposing of spent fuel, since the relatively small volumes of fuel are being safely stored at the reactor sites. In fact, the relatively small volume of high-level waste produced and the ease with which it can be isolated from the environment would appear to be the best-kept secrets of the nuclear industry: *we* have long known that nuclear power is the option of choice for *environmental* considerations. While spent fuel disposal is not a major *technical* issue, it is, however, a major *societal* concern.

One attraction of advanced fuel cycles is their potential for reducing concerns over the back end of the fuel cycle, by applying the three R's of the environmental movement: *reduce, recycle, reuse.* Through the use of advanced fuel cycles, the nuclear industry can achieve a reduction in the *volume* of spent fuel, and also the *radiotoxicity* of the waste.

Some might argue that the public's concerns over nuclear waste management are fundamental, and that a two- or five-fold reduction in the *volume* of spent fuel would not significantly alter this concern. This argument may be valid under the present circumstances, but as spent fuel volumes increase, and the need for high-level waste disposal increases, a reduction in the production rate of spent fuel may become an important environmental asset. The nuclear industry can take the initiative and anticipate the public's needs by reducing the volumes of spent fuel which will need eventual disposal.

Of course, the residual U-235 and plutonium in the spent fuel are not wastes, but are valuable fuel resources which can be *recycled* and *reused.* However, the environmental ramifications of fuel reprocessing are complex. While removal of most of the plutonium and uranium from the spent fuel does result in a small reduction in the long-term radiological risk, near-complete removal of all the actinides is necessary for a significant reduction in this risk [18]. Reprocessing reduces the volume of high-level waste by about a factor of five, but increases the volumes of low-level waste, as well as short-lived and long-lived intermediate level waste [19].

Another consideration in fuel reprocessing is the risk resulting from release of the actinides and fission products from the ceramic fuel, which is very effective in immobilizing most of the radioactive species. The health effects of routine emissions from reprocessing plants, and the health of reprocessing-plant workers, are certainly of concern to the public [20], and care must be taken to limit personnel exposures.

Ultimately, an "actinide burner" would seem to offer the best long-term solution to deal with spent fuel concerns: burning the actinides and long-lived fission products could reduce the lifetime of the radiological hazard of the remaining waste from tens of thousands of years to a few hundred years [21].

2.3 Economics

One of the traditional advantages of nuclear-generated electricity over fossil fuels has been that while nuclear plants are capital-intensive, they are largely insulated from future increases in the cost of fuel [22]. Thus, in Ontario the real price of electricity has increased by only about 10% over the last 40 years, due in part to the extensive use of nuclear power [23]. One of the allures of advanced fuel cycles is that they enable a ceiling to be put on future fuel-cycle costs, and in some instances (for example, the use of slightly enriched uranium (SEU) in CANDU) they would provide a reduction in current fuel-cycle costs.

A recent study by the OECD/NEA compares nuclear and coal electricity-generation costs, and breaks down the levelised discounted costs into investment, operation and maintenance, and fuel [24]. For the majority of the countries considered, typically 20-30% of the nuclear-generated electricity costs are due to the fuel cycle. If uranium accounts for 45% of the fuel-cycle cost [25], then uranium accounts for about 10% of the total electrical generating cost. For operating stations, fuel-cycle costs are one of the few areas where cost reductions are possible. The ability of advanced fuel cycles to increase the energy extracted from the mined uranium can lower the total fuel-cycle cost.

2.4 Strategic and Political Considerations

While the extent of uranium resources is important, who owns these resources can be equally important, in terms of both availability and price. National goals of energy self-sufficiency or greater self-reliance are important for many countries, particularly those lacking indigenous energy resources. Energy diversity is another important strategic consideration. Since advanced nuclear fuel cycles offer less reliance on, and potential independence from, external fuel resources, they are of strategic interest to many countries.

Political considerations can result in higher-priced resources being exploited locally, even though lower-priced resources are available elsewhere. In some countries, strategic goals have led to the reprocessing of LWR fuel, and plutonium recycle. In other countries, non-proliferation policies have prevented the development of fuel cycles dependent on reprocessing. Hence, strategic and political considerations can either advance or hinder the development of advanced fuel cycles.

2.5 Design Flexibility

Advanced fuel cycles (more specifically, fissile enrichment) can provide greater flexibility in the design of reactors capable of operating with natural uranium. The requirement of being able to use natural uranium places extreme importance on neutron economy. The use of enrichment in CANDU (SEU in particular) would allow a trade-off of this neutron economy for other objectives. This is discussed in more detail in Section 3.1.

2.6 Summary

The total uranium resource in the earth's crust and in the oceans is very large. However, there is uncertainty about our ability to extract this resource in a manner which is environmentally acceptable, timely, and economical. It is this uncertainty which provides the resource-related incentive for the development of advanced fuel cycles: to assure the future availability of nuclear fuel at reasonable cost.

There are other compelling reasons to pursue advanced fuel cycles. Greater efficiency in the burning of uranium reduces the need for more uranium, and the environmental impact of uranium mining and processing. Environmental concerns over the disposal of spent fuel can be ameliorated by reducing the volumes involved, and ultimately by reducing the radiotoxicity of the waste.

Advanced fuel cycles offer a ceiling on fuel-cycle costs, an important feature if nuclear power is to continue to compete against other energy alternatives. Another benefit is strategic: the potential for greater self-reliance or even self-sufficiency in energy. Finally, advanced fuel cycles in reactors traditionally fuelled with natural uranium, such as CANDU, can provide greater design flexibility.

3. CANDU ADVANCED FUEL CYCLES

Excellent neutron economy enables CANDU to burn natural uranium fuel, and results in the best uranium utilization (in terms of energy extracted from the mined uranium) of all commercial reactors. Moreover, CANDU's neutron economy also makes it ideal for burning other fuels: SEU, uranium recovered from the reprocessing of spent LWR fuel (RU), mixed uranium/plutonium -- also obtained from spent LWR fuel -- and thorium. Advanced fuel cycles in CANDU offer other benefits as well.

The uranium utilization and fuel-cycle costs for a wide range of CANDU fuel cycles are reported in References 25 and 26. The remainder of this paper will focus on the following: two CANDU fuel cycles of near-term interest -- the use of SEU in CANDU, and CANDU/LWR synergism; the development of an advanced fuel bundle as the optimum carrier of enriched fuels in CANDU; and finally, the use of thorium in CANDU.

3.1 SEU

The current focus of the advanced fuel-cycle program of Atomic Energy of Canada Limited (AECL) is the use of SEU fuel in CANDU. The use of SEU is the economical first step towards advanced fuel cycles in CANDU, and offers several benefits [27].

Using SEU in CANDU would be *economical* now. An enrichment of 1.2% is near-optimum for a range of enrichment and uranium costs, and results in about 30% savings in fuel cycle costs relative to natural uranium fuel. This translates into yearly savings of about $5 million per year for a CANDU 6 reactor. Cost savings occur in both the front end and back end of the fuel cycle. SEU fuelling would also enable CANDU to benefit from expected cost savings that will arise from the use of new enrichment technologies.

An important *environmental* benefit of SEU is a significant reduction in the volume of spent fuel produced. An enrichment of 1.2% SEU yields a burnup of about three times that with natural uranium, hence a three-fold reduction in the volume of spent fuel.

The use of SEU in CANDU is even more *resource-conserving* than the natural-uranium cycle. The amount of uranium required to produce a unit of energy is reduced by 30% with 1.2% SEU, relative to natural-uranium fuelling. It is very likely that the introduction of advanced enrichment technologies, such as AVLIS (atomic vapour laser isotope separation), will reduce the optimum tails enrichment for LWR fuel. A residual enrichment of 0.1% in the tails would reduce the advantage in uranium utilization that a natural-uranium-fuelled CANDU currently enjoys over the LWR. The use of SEU would enable CANDU to maintain its competitive advantage in uranium utilization over the LWR [28].

Using SEU fuel would also provide *flexibility* in fuel-bundle and reactor design, by trading off some neutron economy for other benefits, to match customer requirements. Some examples are [29-31]:

- lowering the capital cost by, for example, reducing the heavy-water inventory, or flattening the fuel-channel and fuel-element power distributions;
- increasing component lifetimes, by use of different structural materials or material thicknesses;
- more efficient operating conditions, by using higher coolant pressures or temperatures;
- changes in reactivity coefficients, via changes in bundle design made possible through the use of fuel enrichment.

An important *strategic* benefit of SEU use is that it would demonstrate many of the generic, technical aspects common to all CANDU advanced fuel cycles. Some examples are: fuel performance and fuel management at extended burnup; reactor physics, fuel, and safety modelling at extended burnup; and licensing of enriched fuel in CANDU.

3.2 CANFLEX Fuel

An advanced fuel bundle is being developed as the optimum carrier of enriched fuels in CANDU [32,33]. This new bundle, called *CANFLEX* (CANDU Flexible fuelling) is more subdivided than other CANDU bundles, having 43 elements, with two pin sizes. Some of the key features of CANFLEX are:

- When operated at current bundle powers, peak linear element ratings are reduced by about 20%. This improves safety margins (in both operating and future reactors) due to lower temperatures, lower stored energy, and a smaller free inventory of fission products. The lower ratings, combined with optimized fuel-element internals, facilitate the achievement of extended burnup and power manoeuvring.

- Critical heat flux and critical channel power are improved, due to optimization of the number and location of bundle appendages, which act as turbulence promoters. This feature can be used to increase operating margins in current reactors.

- The bundle could be used in new reactors to increase peak bundle powers, without exceeding current limits on fuel-element ratings.

- The CANFLEX bundle is compatible with existing and future CANDU reactors.

The above benefits apply to both natural uranium and enriched fuels.

The CANFLEX fuel-bundle development program includes activities in the following areas:

- Reactor physics work has included lattice studies, fuel-management studies for SEU fuel [34-36], and an on-going program to validate the computer codes being used [37]. This work will likely culminate in full-core critical experiments with SEU fuel in the ZED-2 lattice facility.

- Thermalhydraulic optimization of the bundle was performed using sub-channel analysis, and is currently being verified using loop tests with freon as the coolant.

- Prototype CANFLEX bundles have been fabricated for irradiation in the NRU reactor. Independently, elements with various sheath coatings (conventional CANLUB, Siloxane, and zirconium barrier clad) are being irradiated in NRU in preparation for power ramp tests, at burnups typical of those expected for SEU fuel.

- Extensive safety analyses are being performed for both natural uranium and SEU fuel. The capabilities of fuel modelling codes are being extended to higher burnups, for both normal operation and accident conditions.

- Fuel-chemistry effects at extended burnup are being addressed through membership in the International High Burnup Chemistry Program, coordinated by Belgonucleaire, and by a program of inactive testing of the effect of simulated fission products on the conductivity of and gas diffusion in UO_2, using SIMFUEL technology [38].

Future work will involve irradiations of bundles of optimized design, and the demonstration of CANFLEX in a commercial reactor, with natural uranium or SEU.

3.3 CANDU/LWR Synergism

The neutronic differences between CANDU and LWR reactors make possible a unique synergism between the two reactor types [39]. The higher discharge burnup of LWR fuel and the harder spectrum results in a higher concentration of plutonium in the spent fuel than for CANDU fuel, even when SEU is used in the latter. While the exact difference depends on the burnups of the two reactors, there is about twice as much plutonium in spent LWR fuel. Moreover, spent LWR fuel contains a sizable quantity of U-235 (typically between 0.8% and 1%), while in CANDU the U-235 is burned down to a level below enrichment-plant tails. This means that spent LWR fuel is a cheaper source of fissile material than is spent CANDU fuel.

On the other hand, CANDU is a more efficient burner of fissile material than the LWR. Twice as much energy can be derived from the plutonium in spent LWR fuel by burning it in CANDU than by recycling it in the LWR. Similarly, about twice as much energy can be extracted from the uranium recovered from spent LWR fuel by burning it in CANDU rather than re-enriching it and burning it in the LWR.

This, then, forms the basis of the potential CANDU/LWR synergism: using spent LWR fuel as a source of fissile material for CANDU. Three distinct possibilities arise:

If a country has *conventional* reprocessing facilities, or access to them, then

(1) the plutonium from reprocessed LWR fuel can be blended with depleted uranium, uranium recovered from the reprocessed LWR fuel (RU), or natural uranium to form MOX (mixed uranium/plutonium oxide), and then burned in CANDU. This is a variant of the TANDEM cycle, employing conventional reprocessing.

(2) The RU can also be burned as-is in CANDU, without the need for re-enrichment [40]. This is sometimes referred to as the CANFURL cycle, i.e., CANDU Fuelled with Uranium Recycled from LWR.

If a country does not possess conventional reprocessing facilities, or have access to them, but wishes to employ CANDU to realize the full energy potential of its spent LWR fuel, then

(3) a chemical decontamination process could be used to separate fission products and unwanted actinides from the uranium/plutonium mixture, and then co-convert the mixture into MOX fuel. This is the so-called TANDEM fuel cycle, which will be discussed further below.

(From the reactor physics perspective, it is even possible to use spent LWR fuel directly in CANDU, but the practicality of this still needs to be demonstrated.)

An important advantage of the TANDEM fuel cycle employing the chemical decontamination process is that plutonium is never separated from the mixture: this greatly reduces the proliferation concerns associated with conventional reprocessing. Moreover, the chemical decontamination process which separates the plutonium/uranium mixture from the fission products and unwanted actinides is simpler than conventional reprocessing, and therefore is potentially cheaper in a new plant designed for that purpose, since partitioning of the uranium and plutonium is not required, nor is purification of separated uranium and plutonium.

Korea is uniquely positioned to take advantage of the TANDEM fuel cycle, having both PWR and CANDU reactors. By the year 2000, PWR reactors in Korea will be discharging about 156 tonnes of uranium per year, and 1.5 tonnes of plutonium (1.0 tonne fissile plutonium) [41]. At that time, 2246 tonnes of uranium will have accumulated in the spent PWR fuel, and 22 tonnes of plutonium (14 tonnes fissile plutonium). The uranium in the spent fuel will have a U-235 enrichment of between 0.7 and 0.8 wt %. The annual discharge rates of uranium and plutonium from spent PWR fuel in Korea in the year 2000 could support the annual equilibrium fuel requirements of 3-4 GWe of CANDU, having a burnup of about 25 MWd/kg HE (heavy element). The reduction in annual uranium requirements in such a CANDU/PWR TANDEM system in equilibrium would approach 40%, compared to an all-PWR system.

Earlier joint studies with Korea on the TANDEM fuel cycle have led to an appreciation of the benefits of this cycle. Zero-energy ZED-2 reactor physics experiments have been performed on a variety of MOX fuels [42,43], in order to validate reactor physics methods. As well, the MOX fabrication route has been demonstrated, and MOX fuel has been irradiated in AECL research reactors.

AECL's advanced fuel-cycle program also has some elements in support of the use of RU in CANDU. The main uncertainty with RU is the impact on fuel fabrication of the radiological hazard posed by the presence of U-232, U-234, U-236, and trace quantities of some fission products. To help address this question, representative samples of RU product have been obtained and characterized.

3.4 Thorium Fuel Cycles

Several thorium fuel cycles are possible in CANDU reactors [44]. Since thorium has no fissile isotope, an external source of fissile material is needed to initiate the cycle, either fissile plutonium or U-235. Of nearer-term interest is the thorium once-through cycle (OTT), in which uranium and thorium are irradiated in separate channels. The U-233 produced in the thorium is burned in situ, and can be recovered if economic conditions warrant [45]. Of longer-term, strategic interest is the self-sufficient equilibrium thorium (SSET) cycle, which can produce nearly as much fissile material (U-233) as it consumes, thereby reducing uranium requirements to near-zero in a non-expanding system

[46]. An important aspect of thorium cycles is that since they rely on an external source of fissile material to start the cycle, decisions made today on the use of fissile resources will affect the availability of future fuel-cycle options [47].

Currently, experiments with (U-233, Th)O_2 fuel are in progress in the ZED-2 lattice test facility [48].

4. SUMMARY

There are several incentives for the development of advanced nuclear fuel cycles:

- assurance of the availability of nuclear fuel at reasonable price,
- a reduction in the environmental impact of the front end and back end of the fuel cycle,
- strategic considerations, such as security of energy supply and energy diversity, and
- in CANDU reactors, the provision of greater design flexibility.

CANDU reactors are particularly well positioned to take advantage of advanced fuel cycles. CANDU's neutron-efficient design enables it to maximize the energy available from a variety of fuels. The benefits from SEU fuelling in CANDU extend far beyond resource considerations. The CANFLEX advanced fuel bundle is being developed as the optimum vehicle for introducing enriched fuels into CANDU. A unique CANDU/LWR synergism, wherein the uranium and/or plutonium recovered from spent LWR fuel is burned in CANDU, would yield about twice the energy obtainable from recycle in LWRs. Finally, the thorium cycle assures CANDU's role as a long-term efficient energy option for the world.

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