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AECL-11629

CANDU Advanced Fuel Cycles: Key to Energy Sustainability

Cycle du combustible avancé CANDU : la solution au développement durable des ressources énergétiques

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To be presented at the 10th Pacific Basin Nuclear Conference
in Kobe, Japan 1996 October 20-25

June 1996 juin

VOL 28 № 19

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by

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Chalk River Laboratories
Chalk River, Ontario KOJ 1J0
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CYCLE DU COMBUSTIBLE AVANCÉ CANDU : LA SOLUTION AU DÉVELOPPEMENT DURABLE DES RESSOURCES ÉNERGÉTIQUES

par

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RÉSUMÉ

En raison du développement économique rapide de la région du bassin du Pacifique, la durabilité constitue une condition préalable essentielle au développement des ressources énergétiques. De nombreux pays de cette région ont fait face à une augmentation importante de la demande en électricité et cette demande ne cesse d'augmenter. Les investissements dans une technologie nucléaire quelle qu'elle soit sont substantiels. Les pays qui font ces investissements veulent s'assurer que la technologie peut faire l'objet d'un développement durable et qu'elle pourra continuer à évoluer en fonction de l'environnement. Trois aspects clés permettant d'assurer le développement durable de l'énergie sont :

- la durabilité technologique;
- la durabilité économique;
- la durabilité environnementale (notamment l'utilisation des ressources).

La souplesse du cycle du combustible du réacteur CANDU^MD ouvre la voie à un développement durable de l'énergie à court et à long terme.

Laboratoires de Chalk River
Chalk River (Ontario)
1996 Juin

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ABSTRACT

In the fast-growing economies of the Pacific Basin region, sustainability is an important requisite for new energy development. Many countries in this region have seen, and continue to see, very large increases in energy and electricity demand. The investment in any nuclear technology is large. Countries making that investment want to ensure that the technology can be sustained and that it can evolve in an ever-changing environment. Three key aspects in ensuring a sustainable energy future are

- technological sustainability,
- economic sustainability, and
- environmental sustainability (including resource utilization).

The fuel-cycle flexibility of the CANDU® reactor provides a ready path to sustainable energy development in both the short and the long term.

Chalk River Laboratories
Chalk River, Ontario
1996 June

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CANDU technology offers a single reactor type that can evolve to meet energy requirements into the foreseeable future. This obviates the need to invest in several nuclear reactor types. Nonetheless, if a country does decide to invest in different reactor technologies, CANDU technology provides a natural synergism with other reactors — light-water reactors (LWRs) and fast breeder reactors (FBRs) — to optimize the overall system (in terms of economic, waste-minimization, and resource considerations).

The fuel-cycle flexibility of the CANDU reactor provides a ready path to sustainable energy development in both the short and the long term [1, 2]. Three key features lead to the CANDU reactor's unsurpassed degree of fuel-cycle flexibility: high neutron economy, on-power refuelling, and a simple fuel-bundle design.

High neutron economy. The requirement to be able to use natural-uranium fuel has resulted in the CANDU reactor being the most neutron-efficient commercial reactor. This was achieved through the use of heavy water for both coolant and moderator, the use of low-neutron-absorbing structural materials in the fuel and core, and on-line refuelling. High neutron economy provides a flexibility in fuel use that is not available in other reactors and, in particular, the ability to utilize low-grade (e.g., low fissile content) nuclear fuels.

For example, recovered uranium (RU, from conventional reprocessing of used LWR fuel) can be used as-is in CANDU reactors, thereby providing a simpler, more economical, and more resource-efficient recycle option than re-enriching for recycle in a PWR. Recycle in CANDU reactors would reduce the ^{235}U level from ~0.9% down to around tails level (0.2%), after which the fuel would be disposed of. It is anticipated that RU will be commercially available from either BNFL or COGEMA, who are amassing sizable quantities on behalf of their reprocessing clients. The recycle of RU from used PWR fuel into CANDU fuel is an illustration of the CANDU/PWR synergism on a global scale [3].

CANDU reactors, by nature of their high neutron economy, offer another opportunity for fuel-cycle flexibility: the Direct Use of Spent PWR Fuel In CANDU (DUPIC); this will be discussed in a later section.

On-power refuelling is a second feature of CANDU reactors that contributes to their technological sustainability by facilitating the use of different fuel types. As well as contributing to high neutron economy, on-power refuelling provides a great deal of flexibility in accommodating new fuels. The fuel-management scheme can be chosen to shape the power distribution in the core: both axially, along each channel, and radially from channel to channel across the core. Axially, the number, type, and location of bundles added at each visit of the fuelling machine to a channel can be varied, as well as the fuelling frequency. The fuel-management scheme can be chosen to optimize the axial power distribution in terms of thermalhydraulic margin, peak element and bundle powers, refuelling "ripple" (or local power increase upon refuelling), and fuel performance. The choice of a fuel-management scheme depends on the enrichment and on the placement of reactivity devices in the core. With relatively small enrichment levels (~ 0.9%, either with RU or with slightly enriched uranium, SEU), a simple 2- or 4-bundle shift, bi-directional fuelling scheme can be used throughout the core. With higher enrichment, say 1.2% SEU, a slightly more complex "axial shuffling" or "checkerboard" fuelling scheme provides suitable power distributions in the region of the adjuster rods [4-6].

Fuel management can be used to shape the radial (or channel) power distribution through the core. Again, this flexibility helps to ensure long-term viability of the CANDU product. With enrichment, the extra burnup potential can be traded off for increased power in the outer channels: by "flattening" the channel power distribution, more power can be derived from a given sized core. In this fashion, with SEU, the 480-channel Darlington-sized CANDU 9 reactor can be uprated from a nominal 935 MW(e) to 1100 MW(e) [7].

Two more examples will illustrate how fuel-management flexibility provides long-term fuel-cycle viability. The thorium fuel cycle provides long-term assurance of fuel supply. Since thorium does not have a fissile isotope, a source of neutrons must be provided to convert fertile ^{232}Th to fissile ^{233}U. Fuel-management flexibility in CANDU reactors enables a variety of once-through thorium fuel cycles to be considered, in which thorium is loaded into selected channels, which are surrounded by "driver" fuel containing SEU, DUPIC, or even natural-uranium fuel. The dwell times of the thorium-fuelled channels and of the driver fuel channels can be optimized. Extra reactivity can even be recovered by removing the thorium bundles from the channel, letting the ^{233}Pa decay to ^{233}U, then reinserting the thorium bundles back into the core [8, 9].

In the longer term, actinide burning in CANDU reactors is feasible because of the on-power refuelling; very high destruction rates of either military plutonium, or actinide waste, can be achieved by shuffling the fuel into high-flux positions. The fuel in such an application would consist of a mixture of actinides and plutonium, with an inert matrix carrier [10, 11].

Finally, fuel-management flexibility provides many options in the transition from one fuel type to another.

The **simple bundle design** facilitates an evolutionary approach to fuel development. This evolution has, in fact, been ongoing, from the original 7-element-NPD bundle, to the 19-element bundle in the Douglas Point reactor, to the 28-element fuel bundle still used in Pickering, to the 37-element bundle in the Bruce, Darlington, and CANDU 6 reactors. This trend to greater bundle sub-division has allowed more power to be extracted from the fuel and fuel channel, without increasing linear element ratings. This development continues with the CANFLEX bundle, a 43-element bundle with 2 pin sizes. This bundle has ~20% lower linear element ratings than the 37-element bundle at the same bundle power, and it employs critical heat flux (CHF) enhancement technology to increase critical channel power by 6 to 8%. The lower ratings in CANFLEX bundles will reduce fuel temperatures and fission-gas release, which are beneficial for achieving extended burnup. AECL and the Korean Atomic Energy Research Institute (KAERI) are in the final stages of a program leading to the demonstration of CANFLEX bundles in a commercial power reactor [12].

One example will illustrate how the simplicity in fuel design provides fuel-cycle flexibility. There is global interest in dispositioning military-derived plutonium, recovered from warheads. One option actively being studied is the use of that plutonium as mixed-oxide (MOX) fuel in CANDU reactors, thereby using military plutonium to generate electricity, and converting the plutonium to the spent fuel standard [13]. A full core of MOX fuel could be used in operating CANDU reactors with no changes to the reactor hardware, and within the natural-uranium operating and safety envelopes. The fuel bundle for such an application would be either a 37-element bundle (at current natural-uranium burnups) or a CANFLEX bundle (at about double the natural-uranium burnup). Depleted uranium would be the matrix material throughout the bundle; plutonium would be confined to the outer two rings of the bundle, and to load as much plutonium into the bundle as possible, a burnable poison (dysprosium) would be mixed with the depleted uranium in the central element and next ring of the bundle. The relative enrichment of the plutonium in the outer two rings would be chosen to minimize the overall peak element rating. Void reactivity in such a bundle is negative. Hence the ability to optimize the bundle design enables a variety of fuels to be accommodated in operating reactors without changes to the reactor hardware.

Technological sustainability is assured by ongoing advances in CANDU fuel design to meet the needs of future fuels and fuel cycles. Features that can be employed in future fuel designs, either singly or in combination, include the following: optimization of the internal element design for high-burnup applications; the use of graphite disks between pellets to lower fuel temperatures; advanced welding techniques; improved CANLUB coatings for high-burnup applications; further bundle sub-division (such as a 61-element bundle) for very high-burnup applications; tailoring the reactivity coefficients; and further enhancements in the thermalhydraulic margins.

2. Economic Sustainability

Political and economic factors, as well as strategic decisions, all influence the availability and cost of energy resources, including nuclear fuel. The CANDU reactor's ability to use a variety of fuels helps a utility adapt to these factors, ensuring long-term economic sustainability.

The simple fuel design and efficient use of uranium result in CANDU fuelling costs being half those of PWR fuel [14]. Fuelling costs can be further reduced by using SEU. The economic optimal enrichment is ~1.2%, although most of the benefits are achieved at enrichments of about 0.9% [15]. It is expected that RU will be even more economical. The ability to use either natural or enriched fuels permits optimization of the fuel cycle with respect to both front-end (uranium and enrichment) and back-end (disposal, or used-fuel processing for recycling) cost parameters. It also allows flexibility in the overall plant optimization of future CANDU reactors. Pressure-tube thickness, heavy-water inventory, values of reactivity coefficients — these are but a few of the design parameters that can be optimized using enrichment to improve either economics or performance [16]. As mentioned, enrichment also provides a cost-effective means of reactor power uprating, by increasing the power of the outer channels. This will be particularly attractive for new reactor designs, but could also be done during a major plant refurbishment (such as replacing pressure tubes to extend plant life).

Economic sustainability is particularly important in terms of the back-end of the fuel cycle — used-fuel storage and disposal. As operating reactors age and pool storage at reactors fills, the ability to provide additional used-fuel storage capacity is becoming increasingly important. AECL has developed two dry-storage technologies: concrete silos, housing baskets of used CANDU fuel, and passive air-cooled monolithic storage structures (MACSTOR for used CANDU and PWR fuel). Dry storage of used CANDU fuel is now widespread. These dry-storage systems provide economic, simple, and easy-to-implement used-fuel storage for decades [17].

AECL has intensely studied the technical, environmental, and economic aspects of used fuel disposal for over 15 years. A detailed Environmental Impact Statement (EIS) for geological disposal is currently undergoing public review, including a comprehensive technical review, through the Federal Environmental Assessment and Review Process [18]. The nuclear fuel waste would be isolated from humans and the environment by a multiplicity of engineered and natural barriers: the waste form itself (oxide pellets), the container, the buffer, backfills and other vault seals, and the plutonic rock in which the disposal vault would be located. The EIS includes quantitative estimates of the radiological risk for one potential design of a vault for a period of 10 000 years. For this case, the mean dose rate to a hypothetical group of people assumed to live at a time and place and in such a way that its risk from the disposal facility is likely to be the greatest is more than 100 million times less than the dose rate from natural background radiation. This is consistent with the international consensus that geological disposal can be implemented safely.

The technical viability and soundness of the disposal concept is an important requisite for long-term economic predictability and stability in the back-end costs. The EIS includes estimates of the cost for a geological disposal facility based on emplacement of containers in boreholes. The total cost, including siting, construction, operation, decommissioning and closure, for a disposal facility that would contain 10 million natural-uranium used-fuel bundles (which corresponds to the quantity of natural-uranium fuel that would be produced in Canada by the year 2070 at the current nuclear capacity) is about $70/kg heavy element (in 1991 undiscounted Can$) [18]. The disposal vault would occupy an underground area of only 4 km^2. Costs for a smaller facility would be somewhat greater, ~$90/kg. Used-fuel disposal costs are currently being recovered by the nuclear electric utilities in Canada in the rates being charged to electricity consumers.

The use of enrichment to achieve higher burnup in CANDU fuel would further reduce disposal costs. The impact of SEU on disposal costs involves a tradeoff between the quantity of used fuel (which decreases with increasing enrichment), and the heat-load of the fuel (which increases with burnup), which determines the spacing between the containers in the vault. The cost of a disposal facility includes several fixed-cost components that are relatively independent of fuel type, size of facility, or quantity of waste (such as site selection, R&D, engineering design, decommissioning and closure), and variable costs that are dependent on fuel quantity, fuel burnup and fuel cooling time. For CANDU SEU fuel, significant cost reductions can be obtained by employing an extended cooling period before disposing. For SEU enrichments of interest, extending the storage period from 10 years to 50 years would be expected to lead to a reduction in operating costs for disposal of up to 30% (for the design considered) and a reduction in total disposal costs of up to 20% compared with disposal of natural-uranium fuel (P. Baumgartner, AECL, WL, private communication, 1996). For natural-uranium fuel the benefit of an extended period of cooling is less, but is still significant, about 5% on overall costs. Hence the basis for CANDU fuel cycle costs, both front- and back-end, is well established. The use of enrichment, and other advanced fuels and fuel cycles, will ensure economic sustainability in both the short and long term.

3. Environmental Sustainability

The environmental benefits of nuclear power are not generally recognized by the public. Greenhouse gases and other pollutants are not released during the nuclear process, and radioactive emissions are a small fraction of the naturally occurring background radiation. The best kept secret of the nuclear industry is that its waste, and in particular used fuel, can be isolated from man and the environment in a straightforward, cost-effective fashion, through geological disposal. The quantities and volumes of waste produced through nuclear electricity production are extremely small.

The 3Rs of environmentalism are *Reduce, Recycle, and Reuse.* CANDU technology can play an indispensable role in achieving these objectives, both nationally and globally. High neutron economy makes CANDU reactors the most resource-efficient of the commercially available reactors. This reduces the uranium mining requirements, by extending uranium resources and reducing the environmental impact of the front-end of the cycle. For those countries lacking in indigenous uranium resources, high uranium utilization also reduces the amount of foreign uranium that has to be imported, which may assist in meeting national strategic objectives of security of energy supply, and may contribute to global security. CANDU reactors, fuelled with natural uranium, are extremely resource-efficient, extracting ~50% more thermal energy from mined uranium than a PWR, but this resource efficiency is even higher with SEU. Most of this benefit can be derived at an enrichment of ~0.9%, although the optimum, from both the economic and resource perspective is ~1.2%. The SEU option not only improves resource efficiency, but reduces the quantity of used fuel — by a factor of 3 for 1.2% SEU, compared with natural uranium.

High neutron economy in CANDU reactors results in a natural synergism with PWR reactors. Used PWR fuel can be considered a mine of fissile material, containing nominally 0.9% ^{235}U and 0.6% fissile plutonium. Up to double the thermal energy can be extracted from that material by recycling in a CANDU reactor, rather than in a PWR [1]. A variety of recycling options is available to match strategic, economic, environmental and political considerations. With conventional reprocessing of used PWR fuel, the direct recycling of the recovered uranium into CANDU fuel avoids the difficulties and expenses associated with re-enrichment. Because the ^{235}U is burned to tails levels in CANDU reactors, the fuel would then be directly disposed of. The recycling of the plutonium from reprocessing as MOX fuel in operating CANDU reactors is an alternative to plutonium recycle in a PWR. The CANDU MOX designs have been conceived to achieve high burnup (>40 MW•d/kg HE), based on further subdivision of the bundle (e.g., 61-element design) to lower the linear element ratings. Void reactivity would be reduced in these fuel designs, to accommodate the faster neutronic response of MOX fuel.

However, the full potential of the CANDU/PWR synergism can only be realized with new recycling processes. The unique capability of CANDU reactors to utilize low-grade (e.g., low fissile content) nuclear fuels means that it is not *necessary* to separate the plutonium from the uranium and fission products in used PWR fuel, to recover the energy potential of the plutonium. In fact, not only is the addition of fissile material not required, but the removal of fission products is not required for recycling used PWR fuel in CANDU reactors. This opens the way to advanced reprocessing or recycling options, in which plutonium is not separated; these options are potentially simpler, cheaper, and more easily safeguarded than conventional reprocessing.

In the TANDEM fuel cycle, uranium and plutonium would be co-precipitated using aqueous chemistry. A variant of this would be to remove only the high neutron-absorbing fission products from the used PWR fuel, thereby increasing the proliferation resistance, simplifying the process, and reducing processing costs. "DUPIC" refers to the recycle of fissile material from PWR to CANDU using only dry processes. It therefore has the potential to be a simpler and cheaper fuel recycle option, having a high degree of safeguardability since fissile material is not separated, and the reconstituted fuel has a high radiation field. The use of only dry processes also ensures that the system cannot be tampered with to selectively remove plutonium. The range of DUPIC options is wide. A cooperative program between AECL, KAERI and the US Department of State will demonstrate the technical feasibility of the chosen option, termed "OREOX", which involves a thermal/mechanical conversion of the PWR pellets into a sinterable powder using a series of oxidation / reduction cycles [19, 20].

The CANDU/PWR synergistic fuel cycles contribute to environmental sustainability, not only by extending uranium resources but also by reducing the quantity of used fuel that will ultimately require disposal. For example, in an equilibrium system of CANDU and PWR reactors, in which the used fuel from the PWR reactors supplies the fresh fuel requirements of CANDU reactors, the used-fuel arisings would be reduced by a factor of 3 to 4, as compared with direct disposal [1].

All these recycling options extend global fissile resources by extracting more energy from the original mined uranium. In the longer term, more significant improvements in uranium utilization can be realized by using either ^{235}U or fissile plutonium to convert ^{232}Th into fissile ^{233}U, which is an even more valuable fuel material. A wide range of thorium cycles is conceivable, that would significantly extend the energy available from uranium [21]. The once-through thorium cycles would extend uranium resources by burning in situ the ^{233}U produced in natural thoria fuel, without relying on reprocessing to recover and recycle the ^{233}U. The full potential of the thorium fuel cycle in CANDU reactors would require some form of fuel processing to recover the ^{233}U from the used fuel. The challenge will be to achieve this in an economical process that is highly proliferation-resistant.

Ultimately, the thorium cycle can provide fissile resources for centuries. One possibility is the self-sufficient-equilibrium thorium cycle in CANDU reactors. In this "near-breeder" cycle, once equilibrium has been reached, as much fissile ^{233}U remains in the used fuel as is required in the fresh fuel; hence no fissile make-up is required from one cycle to another. This fuel cycle would require further improvements in neutron economy, such as removal of the adjuster rods and use of enriched zirconium from which most of the high cross-section ^{91}Zr has been removed.

Alternatively, a CANDU/FBR synergism can be envisioned, in which MOX fuel in the FBR would provide the plutonium required for the thorium cycle in CANDU reactors. A single FBR reactor could provide the plutonium requirements for a fleet of lower cost, high conversion CANDU reactors running on the Pu/Th cycle [22, 23].

Thorium cycles also offer a resource-efficient alternative for dispositioning weapons-derived nuclear material — either highly enriched uranium, or plutonium. In the Pu/Th cycle, a high fraction of plutonium would be consumed (>90% of the fissile plutonium, or >75% of the total plutonium), while valuable ^{233}U would be produced. The used fuel would be stored until the ^{233}U could be recovered in manner that was both economical, and highly safeguardable.

4. Sustainable PHWR Fuel Cycle Strategies For Today And Tomorrow

These considerations lead to a natural CANDU fuel-cycle evolution. One of the most important considerations for a country embarking on a first nuclear program is the ability to "localize" the technology. In the fuel cycle, natural-uranium CANDU fuel presents an easily attainable first step. The simple bundle design, ease of fabrication, and abundance of cheap natural uranium from a variety of suppliers facilitate the localization of technology for CANDU fuel fabrication.

The first step from natural-uranium fuel will be slight enrichment, either SEU or RU. This may be either in a new reactor optimized for the use of enrichment or in an existing reactor. The CANFLEX bundle will be the optimal vehicle for introducing enrichment in CANDU fuel, but CANFLEX bundles may be introduced with natural uranium first, to provide greater thermalhydraulic margins in aging reactors.

The use in the Bruce A reactors in Ontario of MOX fuel derived from military plutonium from the United States and the Commonwealth of Independent States (the former Soviet Union) is a real possibility that is currently being assessed. The dispositioning of military plutonium as MOX fuel in CANDU reactors is perhaps the most compelling illustration of sustainability in the broadest context — extending world energy resources while contributing to global peace and disarmament.

In a country that has both PWR and CANDU reactors, the natural synergism between these reactors will eventually lead to the recycling of used PWR fuel into CANDU fuel. The timing of this will depend on many factors — the importance of strategic energy considerations such as independence and diversity of fuel supplies, both nuclear and non-nuclear; the cost and availability, both domestic and abroad, of fuel processing options such as conventional reprocessing, DUPIC, or other advanced fuel processing technologies; the costs of the various components of the fuel cycle, and in particular uranium, reprocessing, and disposal. This synergism will improve uranium utilization and reduce spent fuel volumes.

Long-term assurance of nuclear fuel supplies will be provided by the use of thorium fuel in CANDU reactors, possibly in conjunction with FBRs. Various once-through thorium cycles provide an economical way of introducing thorium without the need for reprocessing.

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Cat. No. /No de cat.: CC2-11629E
ISBN 0-660-16637-2
ISSN 0067-0367

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