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Plutonium Dispositioning in CANDU

Élimination du plutonium dans les réacteurs CANDU

P.G. Boczar, J.R. Hopkins, H. Feinroth, J.C. Luxat

Presented at the IAEA Technical Meeting
Recycling of Plutonium and Uranium in Water Reactor Fuels
Windermere, U.K., 1995 July 3-7

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ATOMIC ENERGY OF CANADA LIMITED

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ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

ÉLIMINATION DU PLUTONIUM DANS LES RÉACTEURS CANDU

par

P.G. Boczar, J.R. Hopkins, H. Feinroth, J.C. Luxat

RÉSUMÉ

Dernièrement, le Department of Energy (DOE) des États-Unis a chargé Énergie atomique du Canada limitée (EACL) d'évaluer les paramètres saillants à caractère technique et stratégique et du point de vue échéancier et coûts relatifs à l'utilisation des réacteurs CANDU^{md}* pour l'incinération du plutonium à usage militaire sous la forme de combustible oxyde mixte (MOX). Un groupe d'étude, composé du personnel clé choisi parmi les concepteurs et chercheurs (EACL), les exploitants (Ontario Hydro) et les fournisseurs de combustible de la filière CANDU, a analysé tous les facteurs importants que comporte une telle application, avec pour objectif de trouver un moyen de brûler le combustible MOX dans les réacteurs CANDU, dans les plus brefs délais.

Une des centrales à tranches multiples d'Ontario Hydro, la centrale nucléaire Bruce A (quatre tranches de 769 MW(e)) a été retenue comme référence pour l'étude. L'évaluation a permis de démontrer qu'aucune modification importante du réacteur ou des circuits de procédé n'était nécessaire pour exploiter le réacteur, le coeur chargé de MOX. Les modifications apportées à la centrale seraient limitées à la manutention du combustible et à celles nécessaires pour satisfaire aux prescriptions plus rigoureuses au point de vue de la sécurité et des garanties nucléaires. Aucune limite relative à la sûreté n'a été signalée.

Une tâche importante de l'étude consistait à définir les paramètres optimums de conception du combustible MOX pour atteindre les taux d'élimination cibles, soit deux tonnes de plutonium par année dans le cas de référence et quatre tonnes par année dans un autre cas, sans pour autant modifier la conception fondamentale des paramètres d'exploitation et de sûreté de la filière et sans nécessiter un approvisionnement excessif en combustible. Le type de combustible MOX de référence employait la grappe CANDU standard à 37 éléments. Ce combustible serait exploité à la même combustion massique et la même puissance nominale que le combustible d'uranium naturel standard de la filière CANDU, et ses paramètres nucléaires permettraient d'exploiter le réacteur sans dépassement des limites d'autorisation actuellement en vigueur. La grappe de combustible CANFLEX à 43 éléments a été retenue pour l'autre cas. Cette grappe de combustible, qui est actuellement en voie d'être qualifiée pour l'utilisation commerciale, a deux dimensions d'éléments et est exploitée à une puissance linéique nominale inférieure, ce qui permet des concentrations de plutonium et des combustions massiques supérieures. L'utilisation de ce modèle réduirait la quantité des grappes de combustible MOX requise presque de moitié, ce qui représenterait un avantage économique important.

Deux des réacteurs de Bruce A seraient utilisés pour le cas de référence d'incinération de deux tonnes de plutonium par année, et quatre autres pour le cas d'incinération de quatre tonnes par année.

*CANDU signifie CANada Deutérium Uranium (marque de commerce déposée)

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Abstract

Recently, the U.S. Department of Energy (DOE) sponsored Atomic Energy of Canada Limited (AECL) to evaluate salient technical, strategic, schedule, and cost-related parameters of using CANDU[*] reactors for dispositioning of weapons-grade plutonium in the form of Mixed OXide (MOX) fuel. A study team, consisting of key staff from the CANDU reactor designers and researchers (AECL), operators (Ontario Hydro) and fuel suppliers, analyzed all significant factors involved in such application, with the objective of identifying an arrangement that would permit the burning of MOX in CANDU at the earliest date.

One of Ontario Hydro's multi-unit stations, Bruce A nuclear generating station (4x769 MW(e)), was chosen as the reference for the study. The assessment showed that no significant modifications of reactor or process systems are necessary to operate with a full MOX core. Plant modifications would be limited to fuel handling and modifications necessary to accommodate enhanced security and safeguards requirements. No safety limitations were identified.

An important task of the study was to define the optimum design parameters of MOX fuel to achieve the target disposition rates -- two tonnes of plutonium per year in the reference case, and four tonnes per year for an alternative case -- without altering the design base of operating and safety parameters of the reactor system, and without requiring excessive fuel supply. The reference MOX fuel design employed the standard 37-element CANDU geometry bundle. This fuel would operate within the same burnup and power rating envelope as standard CANDU natural-uranium fuel, and its nuclear parameters would allow the reactor to operate within its existing licensing envelope. The 43-element CANFLEX fuel bundle was chosen for the alternative case. This fuel bundle, which is currently being qualified for commercial use, has two sizes of elements, and operates at a lower linear power rating, thus permitting higher plutonium concentrations and higher burnups. Use of this design would reduce the quantity of MOX fuel bundles required by almost half, a significant economic advantage.

Two Bruce A reactors would be used for the reference case of dispositioning of two tonnes of plutonium per year, and four for the alternative case of dispositioning of four tonnes per year.

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[*] CANDU: CANada Deuterium Uranium; registered trademark

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1. Introduction: Overview of Plutonium Dispositioning in CANDU

The U.S. Government is currently considering about a dozen options for dispositioning of weapons plutonium. The U.S. National Academy of Sciences, in its 1994 January report, "Management and Disposition of Excess Weapons Plutonium", urged the U.S. and Russian Governments to act expeditiously to demilitarize excess fissile material from dismantled nuclear weapons, calling the continued availability of such materials, even when placed in safe storage, a "clear and present danger".

As part of this assessment, the U.S. DOE sponsored AECL to lead a study on dispositioning weapons-grade plutonium using CANDU technology. To perform this study, AECL Technologies Inc., the U.S. corporation of AECL, assembled a team to analyze significant technical, strategic, schedule, and economic aspects of plutonium dispositioning in CANDU. The team consisted of AECL's reactor design and research staff, Ontario Hydro (which owns and operates twenty CANDU reactors), the U.S. DOE Hanford site contractor (which manages an existing facility that could be converted to fabricate CANDU MOX fuel), Zircatec Precision Industries (a Canadian CANDU fuel supplier that fabricates about half of the natural uranium fuel bundles used in Canada), MOX fuel fabrication experts from Babcock and Wilcox, and technical experts from Gamma Engineering Corporation. In addition, input was provided by the IAEA, the Atomic Energy Control Board (the Canadian nuclear regulator), and DOE's Los Alamos and Lawrence Livermore National Labs.

The focus of the study was on utilizing the ex-weapons plutonium as MOX fuel in CANDU. The U.S. DOE specified a plutonium disposition rate of two tonnes per year in the reference case, and four tonnes per year in an alternative study case. These options would render the plutonium inaccessible to diversion through the characteristics of spent MOX fuel (such as high radiation fields), and at the same time generate electricity. A longer-term option considered was plutonium annihilation in CANDU, mixing the plutonium in a non-fertile matrix material (hence, destroying the ex-weapons plutonium without producing new plutonium).

The study concluded that the main objective, a plutonium disposition rate of two tonnes per year, could be achieved by burning the plutonium as MOX fuel in two Bruce A reactors. The Bruce reactor site contains eight reactors, four Bruce A reactors, and four Bruce B reactors, each about 769 MW(e). The Bruce generating station, located on Lake Huron, about 300 km northeast of Detroit, is particularly suited for this mission, because of its base load operating mode, its proximity to the U.S. border, and its existing safeguards and security infrastructure. The Bruce A units have further neutronic advantages for accommodating plutonium, which will be discussed later in the paper.

A primary objective in the reference case was a MOX fuel design that would allow the reactor to operate within its current licensing envelope. The standard 37-element bundle design was chosen for the reference case, with depleted uranium as the matrix material. The outer two rings of elements contained plutonium, while the central seven elements in the bundle contained a burnable neutron absorber (dysprosium). The neutron absorber allowed a greater amount of plutonium to be loaded into the bundle than would otherwise have been possible, by suppressing the extra reactivity, and resulted in the coolant void reactivity coefficient being negative. The alternative case, of dispositioning four tonnes of plutonium per year, clearly could be achieved by burning the MOX reference fuel in four Bruce A reactors rather than two. However, the economics favour using the same size of fuel-fabrication facility as in the reference case, and not increasing significantly the MOX fuel-fabrication rate. This was achieved by using the higher-burnup 43-element CANFLEX design [1] for the alternative case, and increasing the plutonium content of the bundle, and hence the fuel burnup.

The study concluded that the reference MOX fuel design could be used without any changes to the reactor core. The main engineering change required to the plant would be to enhance the physical security for the MOX fuel; specifically, a new, secure building would be required for the storage of the fresh MOX fuel, and the route to the new fuel loading room would require hardening.

The philosophy in MOX fuel fabrication was to manufacture the MOX fuel close to the source of the plutonium, and to transport finished MOX bundles to the Bruce site. The study found a significant economic advantage and shorter implementation schedule by using an existing facility and infrastructure, rather than constructing a new facility. The simplicity of the CANDU fuel-bundle design facilitates MOX fuel fabrication. The fuel-fabrication requirements in both the reference and advanced MOX fuel cases could be met by modifying the existing Fuel and Materials Examination Facility (FMEF) at the U.S. DOE Hanford reservation (with a CANDU MOX fuel fabrication capacity of about 170 metric tonnes of heavy metal per year). A lead time of about four years would be required for conversion, licensing, and testing of the facility. A subsequent study determined that the existing, unused Barnwell Nuclear Fuel Plant, which is located adjacent to DOE's Savannah River facility, would also be suitable.

One month's supply of fuel in the reference case will be about 754 bundles, for two Bruce A reactors. It is proposed that seven CANDU MOX bundles (each with its own packaging/shielding material) would be packaged in a standard, stainless-steel, 55-gallon (US) drum. The drums would be loaded into a DOE Safe Secure Transport (SST) vehicle, which has the ability to carry 48 drums on pallets. Three such SSTs would be loaded and travel in a convoy to the Bruce site. Hence, one month's fuel supply (for two Bruce A reactors) can be moved in one convoy. The fabrication, transport, and utilization at the Bruce site of the CANDU MOX fuel would comply with all national and international safeguards and security regulations. The study assumed that the spent MOX fuel would be stored at the Bruce site in wet and/or dry interim storage, and would then be transported to permanent disposal at either a U.S. or a Canadian geological repository.

The focus of the remainder of this paper is on the fuel design and performance, and the reactor physics results of the study.

2. MOX Fuel Design

The high neutron economy of the CANDU reactor and fuel design, required for using natural-uranium fuel, facilitates the use of other fuels [2]. While this paper focuses on the use of military plutonium as MOX fuel in CANDU, the CANDU reactor is an ideal machine for deriving the maximum energy potential from spent PWR fuel [3, 4, 5].

The simple CANDU fuel bundle design not only simplifies MOX fuel fabrication, but provides a large degree of flexibility in terms of the fuel composition across the bundle. Some considerations in optimizing the reference MOX fuel design for plutonium dispositioning were as follows:

- Maximize the amount of plutonium in the bundle (to minimize the number of bundles required), without needing to hold down additional excess reactivity in the core. A neutron absorber was added to the bundle, to accommodate a larger amount of plutonium, and to obviate the need to add additional dissolved poison in the moderator. The use of depleted uranium as the matrix material also necessitated a higher plutonium content in the bundle.

- Achieve acceptable reactivity coefficients. The addition of a burnable poison to the central elements made the coolant void reactivity negative. This offsets the effects of both a smaller delayed neutron fraction and neutron lifetime with MOX fuel. Accident consequences are similar or are more benign than with natural-uranium fuel.

- Minimize the peak linear element ratings over the fuel burnup. Enrichment grading was chosen for the outer two rings of fuel containing plutonium, to reduce ratings. The choice of enrichments also was near-optimal, from the thermalhydraulics consideration of critical heat flux.

- Maintain the existing fuel power/burnup envelopes for the reference case. Average discharge burnup in the reference MOX fuel case was only slightly higher than natural uranium, and peak element burnup was about the same as for natural uranium. Also, the fuel-management strategy (regular bi-directional two-bundle shift) helped reduce peak bundle powers, and the refuelling ripple.

- Minimize the implementation time. The reference MOX fuel design has a high degree of "provenness", employing the standard 37-element bundle and a power/burnup envelope within that of natural uranium. Hence, the time required to verify the fuel design and performance for MOX fuel, and to licence the reactor, will be minimized.

The reference fuel design has depleted uranium throughout (0.2% U-235), with 5% dysprosium in the central 7 elements (the central element, and the next ring of 6 elements); 2.0% plutonium in the third ring of 12 elements, and 1.2% plutonium in the outer ring of 18 elements. The bundle average burnup of the reference MOX fuel is 9700 MWd/te heavy element (HE), compared to 8300 MWd/te HE for natural uranium fuel in Bruce A. Peak element burnup is about the same as for natural uranium (about 16 000 MWd/te HE). The fresh reference MOX fuel design contains 232 g plutonium per bundle, of which 94% is fissile.

The advanced MOX fuel design utilizes the 43-element CANFLEX geometry, which features two element diameters, arranged in rings of 1, 7, 14 and 21 elements. The central 8 elements are larger than the outer 35 elements. The greater subdivision in the bundle, along with two element sizes, reduces the peak element rating by about 20%, compared to the 37-element bundle operating at the same bundle power. This lower element rating facilitates the achievement of extended burnup in CANDU, by lowering the fuel temperature and fission-gas release. The core-average burnup of the advanced MOX design was chosen to be 17 100 MWd/te HE, which results in a peak burnup of under 30 000 MWd/te HE. These are burnups for which we have some experience. The advanced MOX bundle contains 374 g plutonium in the fresh fuel. As in the reference bundle, the plutonium is confined to the outer two rings of fuel: 3.5% plutonium in ring 3, and 2.1% in ring 4, mixed with depleted uranium. The central 8 elements contain 6% dysprosium mixed with depleted uranium. There is some minor optimization of the internal element design (pellet size and shape, and clearances).

In both the reference and advanced MOX fuel designs, coolant void reactivity is negative, about -4.7 mk and -1.7 mk, respectively, compared to about +11 mk for natural uranium. This number refers to the change in reactivity that would accompany a hypothetical, instantaneous voiding of all the coolant in the reactor core.

Each Bruce A reactor would consume about one tonne of plutonium per year, in both the reference and alternative cases. In the reference 37-element MOX fuel design, the plutonium content in the spent fuel is 154 g, while in the advanced MOX fuel the plutonium content in the spent fuel is 254 g. In both cases, the initial plutonium content is reduced by about one third in the spent fuel. (Keep in mind that the objective of this strategy is not to *destroy* the plutonium, but to convert it to a form that has a high degree of diversion resistance through the characteristics of spent fuel, while producing electricity.)

3. CANDU Reactor Physics With MOX Fuel

The use of MOX fuel is facilitated in the Bruce A reactor through two features of the core design. First, Bruce A has no adjuster rods. Adjuster rods are used in some CANDU reactors, primarily to provide a certain xenon override capability following a reactor shutdown. The adjuster rods also flatten the flux in the center of the core. With enriched fuel, a suitable axial power profile can be obtained through use of a simple axial fuel-management scheme, so the adjuster rods are not needed for shaping the axial power distribution. Second, the Bruce A station plans to change the fuelling direction to that of the coolant flow. This will increase the margin to dryout with the MOX fuel.

The on-power refuelling of CANDU not only enables the reactor to be operated with only a small amount of excess reactivity in the core, but also provides a great deal of flexibility in fuel management, because of the ability to shape the power distributions through the core, both axially and radially. With both the reference and advanced MOX fuel designs, a very simple, bi-directional (adjacent channels are refuelled in the opposite direction), two-bundle shift fuelling scheme in the direction of coolant flow results in an excellent axial power distribution. The power peaks around axial bundle position 4, and decreases along the length of the channel. Hence, the bundles at the downstream end of the channel have the lowest power, which increases the margin to dryout. This fuelling scheme causes only relatively fresh fuel to experience a power boost as a result of refuelling. This simple fuel-management strategy results in good axial flattening of the axial power distribution, with the peak bundle power being about 20% lower than with natural-uranium fuel.

Radially, the distribution of burnup through the core was chosen to give a similar channel power distribution to natural uranium.

The core design with MOX fuel was based on the lattice code WIMS-AECL [6], with the two-dimensional finite-difference reactor code RFSP [7]. A 100-day time-dependent refuelling simulation was performed for the reference MOX core, in which the refuelling of individual channels was modelled. The maximum element, bundle and channel powers, power/burnup envelopes, power-boost envelopes, and refuelling ripples were all below the corresponding values experienced for Bruce A with natural uranium fuel. Table 1 compares the characteristics of the natural uranium, reference MOX, and advanced MOX cores. The burnup with the advanced MOX fuel design of course extends past that normally experienced in Bruce A. However, the power/burnup envelope for the advanced MOX fuel is within that for experimental fuel irradiations in the NRU research reactor at AECL's Chalk River Laboratories.

The reactivity worths of the reactivity devices (liquid zone controllers, mechanical control absorbers, and shutoff rods) are lower with MOX fuel than with natural uranium. However, the worths are adequate for reactivity control and shutdown. The reactor control system was modelled for MOX fuel, and no hardware changes are required (a modest change to the primary control feedback gain may be required.)

4. CANDU MOX Fuel Performance

Figure 1 shows a typical snapshot of peak linear element ratings and corresponding element burnup for the reference MOX fuel, for an arbitrary point in time from the refuelling simulation. Each point in the plot corresponds to the peak element rating and corresponding element burnup for a bundle in the core. Superimposed on the snapshot is the natural-uranium high-power envelope, for Bruce A. The power envelope for the reference MOX fuel is considerably lower than for natural uranium, and is well below known failure thresholds.

Further confirmation of fuel performance was provided by modelling the fuel behaviour for the high-power envelope, for both the reference and advanced MOX fuel designs, and for natural uranium. The ELESTRES [8] code was used for this modelling, with a focus on fission-gas release, internal pressure, and ridge strains. In ELESTRES, a single element is modelled by accounting for the radial and axial variations in stresses and displacements. Predictions of total fission gas released to the "free inventory", maximum internal gas pressure, and sheath strains for both the reference and advanced MOX fuel designs were well below the values corresponding to the natural-uranium high-power envelope. This is due to the lower peak element ratings for the MOX fuel designs, which reduce fission-gas release, and the optimized internal design of the MOX fuel elements, which reduces internal pressure and sheath strains.

The thermalhydraulic performance of the MOX fuel was assessed using the ASSERT [9] subchannel code, and the NUCIRC [10,11] steady-state-system thermalhydraulics code. ASSERT provided critical heat flux (CHF) data for the MOX bundles, while NUCIRC provided the critical channel power (CCP), the channel power at which CHF first occurs on any fuel element in the reactor. The ASSERT calculations (at constant flow) indicated that the steep radial power profile through the MOX bundles reduced CHF, while the axial power profile, skewed towards the inlet end, increased CHF. The net result for the reference MOX fuel was a slight increase in both the CHF, as well as in the pressure drop along the channel. To calculate the effect on CCP, the effect of the increase in both CHF and pressure drop on the dryout power at constant header-to-header pressure drop was determined using NUCIRC. The same dryout power was predicted for the reference MOX and natural-uranium cases, within the uncertainty of the calculation. For the CANFLEX bundle with MOX fuel, ASSERT predicted slightly lower CHF and pressure drop (because of the larger flow area in the CANFLEX bundle compared to the 37-element bundle). NUCIRC predicted a slightly greater (2%) CCP for the CANFLEX MOX fuel compared to the 37-element natural-uranium reference case. It is noted that this calculation did not include the CHF-enhancement features of the CANFLEX bundle, which are expected to increase CCP by 6-8% for natural uranium. Thus, it is expected that the advanced MOX bundle will have a CCP several percent higher than the existing 37-element natural-uranium bundle.

5. Safety and Licensing with MOX Fuel

Table 1 includes a comparison of the neutron kinetic parameters of MOX and natural-uranium fuel. With both a smaller delayed neutron fraction and prompt neutron lifetime, the response of MOX fuel to a reactivity change is faster than with natural-uranium fuel. This faster response is compensated by the negative coolant void reactivity designed in the MOX fuel bundle.

A systematic investigation of all the design-basis accidents was made for the MOX fuel, with emphasis on those accidents that rely on a neutronic trip. For some design-basis accidents, typically loss-of-coolant-accidents (LOCA) and loss-of-flow events, neutronic trips would not occur, due to the negative coolant void reactivity in the MOX core. However, it was found that existing process trip parameters will provide effective protection for these events.

In the particular case of a large-break LOCA, with natural-uranium fuel the reactor trips quickly (in less than 0.5 s) with one of the two, independent shutdown systems. With MOX fuel, both shutdown systems will trip the reactor on either heat-transport-system low pressure or low flow. The total energy deposited in the fuel five seconds after LOCA initiation will be lower for the MOX fuel than for natural-uranium fuel, indicating that fuel heatup will be reduced and that existing safety design objectives would be met.

The response to other design-basis accidents was either similar or better than for natural-uranium fuel.

6. Transition to MOX Fuel

The on-power refuelling of CANDU would enable the reference MOX fuel to be introduced to the natural-uranium core during the normal course of refuelling. The similarity of burnups between natural uranium and the reference MOX fuel, and the two-bundle shift fuelling scheme with the MOX fuel, would reduce the reactivity perturbations during refuelling. Natural uranium would be replaced by MOX, two bundles at a time. The fuelling rate is 15.5 MOX fuel bundles per full-power day (FPD), and there are 6240 fuel bundles in the core. Hence, it would take at least 400 FPDs to displace all the natural-uranium fuel bundles with MOX. (The fact that channels are refuelled at different rates means that it will take longer to convert to a full MOX core; it is expected to take at least 600 FPDs to reach the equilibrium MOX core condition.) The absence of adjuster rods in Bruce A would also be an advantage during the transition. The same procedure could be used to replace the reference MOX fuel with the CANFLEX MOX fuel bundles at a later stage, if desired. This approach would enable the earliest start to the transition, and would derive the maximum energy from the MOX fuel.

Another strategy for the transition would be to start up after a major scheduled outage with a full MOX core.

The transition from natural uranium to MOX fuel has not been modelled during this study, and would be optimized as part of the implementation program. On-power refuelling again provides flexibility in shaping the axial power profile during the transition, should that be required.

7. Plutonium Annihilation In CANDU

A longer-term option for the near complete destruction or annihilation of the plutonium is to burn the plutonium in an inert matrix (rather than in a fertile uranium matrix) in CANDU [12-14]. The absence of uranium-238 eliminates the source of further creation of plutonium and over 40% of the neutron absorption in the lattice, resulting in a remarkable improvement in neutron economy. The absence of the neutron absorption reduces the fissile requirement of the plutonium annihilator relative to the natural-uranium-fuelled core. A lower fissile inventory requires a correspondingly higher operating neutron flux level, to produce the rated power, and makes CANDU superior to other reactor types (including fast breeder reactors) in the annihilation process. This superiority is evident from the high (>80%) annihilation rate that is achievable per pass through the reactor. By using the on-power fuelling machines to "shuffle" the fuel through one or two additional passes, essentially all of the plutonium may be annihilated. While this option would require substantially more development than the MOX option, it resolves the question of ultimate disposal without requiring highly advanced technology or reprocessing.

AECL is currently investigating the suitability of various candidate inert matrix materials, with emphasis on SiC.

8. Status of Technology

There is now significant favourable world-wide experience with the fabrication and irradiation performance of MOX fuel. AECL has over 25 years of experience with MOX fuel. Irradiation testing in the NRU research reactor and post irradiation examinations are still being conducted as part of AECL's advanced fuel-cycle program. Rehabilitation of the Recycle Fuel Fabrication Laboratory (RFFL), a series of glove boxes for the remote fabrication of alpha-active fuel, is currently underway at Chalk River Laboratories. A companion paper in this conference summarizes AECL's experience and current programs with MOX fuel [15].

The CANFLEX (CANDU Flexible Fuelling) program, upon which the advanced MOX fuel design is based, is nearing completion [1]. This program was started by AECL in 1986, and since 1991, the Korean Atomic Energy Research Institute (KAERI) has been a partner in the program. The program is aimed at demonstrating the CANFLEX bundle to the point that would enable a power reactor demonstration in the next couple of years. The major milestones over the next year are:

- fabrication of 50 natural-uranium CANFLEX bundles for flow, endurance and handling tests, and for reactor physics measurements,
- ZED-2 reactor physics measurements with 35 CANFLEX bundles with natural-uranium fuel,
- completion of licensing-rigour CHF tests in Freon, to demonstrate the improvement in CCP over the 37-element bundle,
- completion of fuel-handling tests and fuelling-machine-compatibility tests,
- initiation of flow and endurance tests, and
- continuation of NRU irradiation of CANFLEX bundles to burnups beyond natural uranium.

Hence, the timing of the CANFLEX program is consistent with its availability for plutonium dispositioning.

Another advanced fuel program underway in AECL that would provide support to the plutonium dispositioning program is low void reactivity fuel (LVRF) [16]. This fuel design is similar to the MOX fuel designs used in the plutonium dispositioning study, but employs enriched uranium rather than MOX fuel in the outer two rings of elements. By varying the level of burnable poison in the center of the bundle, and the enrichment in the outer two rings, the level of void reactivity and fuel discharge burnup can be tailored to meet customer requirements. The concept was conceived for those jurisdictions in which reduced or negative void reactivity is required. A short-term demonstration program is currently underway to establish the technical feasibility of the LVRF design, in both the 37-element and CANFLEX geometries. The program includes NRU prototype irradiations, reactor physics testing in the ZED-2 reactor, and measurements of CHF in Freon. Prototype elements containing dysprosium have already been irradiated and examined, and the expected good fuel performance has so far been confirmed. This program provides a solid technology base for the MOX fuel designs for plutonium dispositioning.

9. Deployment Strategies

The CANFLEX design would require fabrication of roughly half the number of MOX fuel bundles to achieve a certain plutonium disposition rate, compared to the 37-element design. Hence, with a given size MOX fuel fabrication plant, CANFLEX could be used to either double the amount of plutonium that could be dispositioned in a given time, or to halve the time required to dispose of a given amount of plutonium.

One of the attractive features of the CANDU plutonium dispositioning option is the symmetry of a CANDU reactor in Canada burning military plutonium from both the U.S. and from Russia. Conversion of the Russian military plutonium to CANDU MOX fuel could take place in Russia, and would involve considerable Russian nuclear technology, resources and labour. Shipment of CANDU MOX fuel containing only about 2% plutonium to Canada would be better, from a safeguards and security viewpoint, than would shipment of relatively pure plutonium. Alternatively, a CANDU reactor in Russia or Eastern Europe could burn the MOX fuel fabricated in Russia from weapons plutonium. This option would provide energy value from the plutonium, an important objective of Russian policy.

Fabrication of CANDU MOX fuel from military plutonium is the subject of a similar joint study being planned by the Russian and Canadian Governments.

Finally, the plutonium annihilation option in CANDU offers the possibility of a longer-term solution to the ultimate destruction of plutonium, in parallel with an immediate short-term solution to dispositioning of military plutonium.

10. Summary

This study performed for the U.S. DOE has identified practical and safe options for the dispositioning of military plutonium in existing CANDU reactors. By careful fuel design, the fuel and nuclear characteristics will be within existing envelopes for fuel performance, safety and licensing. Utilization of existing fuel fabrication and transportation facilities and methods has resulted in a low-cost, low-risk method for long-term plutonium dispositioning. The integrated system can be ready to begin plutonium consumption in four years. No changes are required to the existing reactor system, other than for provision of safe and secure storage of new fuel. An annihilation option that uses the unique features of the CANDU system to achieve high levels of destruction of plutonium offers an attractive option for ultimate disposition without requiring reprocessing of spent fuel or advanced technology.

REFERENCES

[1] LANE, A.D. et al., "Recent Achievements in the Joint AECL/KAERI Program to Develop the CANFLEX Fuel Bundle", presented at the 10th Korea Atomic Industry Forum/Korea Nuclear Society Conference, Seoul, Korea, 1995 April 6-7.

[2] TORGERSON, D.F., BOCZAR, P.G., DASTUR, A.R., "CANDU Fuel Cycle Flexibility", presented at the 9th Pacific Basin Nuclear Conference, Sydney, Australia, 1994 May 1-6.

[3] BOCZAR, P.G., KUPCA, S., FEHRENBACH, P.J., DASTUR, A.R., "Plutonium Burning in CANDU", presented at the NATO Advanced Research Workshop on "Mixed Oxide Fuel (MOX) Exploitation and Destruction in Power Reactors", Obninsk, Russia, 1994 October 16-19.

[4] BOCZAR, P.G., DASTUR, A.R., "CANDU/PWR Synergism", Proc. IAEA Technical Committee Meeting on Advances in Heavy Water Reactors, Toronto, Canada, 1993 June 7-10.

[5] BOCZAR, P.G. et al., "Recovered Uranium in CANDU: A Strategic Opportunity", Proc. International Nuclear Congress and Exhibition (INC 93), Toronto, Canada, 1993 October 3-6.

[6] DONNELLY, J.V., "WIMS-CRNL: A User's Manual for the Chalk River Version of WIMS", Atomic Energy of Canada Limited Report, AECL-8955, 1986 January.

[7] AKHTAR, P., "Heavy Water Reactors (CANDU) Fuel Management", IAEA Training Course on Technology of Water Cooled Power Reactors, lecture CA1.7.8, IAEA, 1984 October - November.

[8] TAYAL, M., "Modelling CANDU Fuel Under Normal Operating Conditions: ELESTRES Code Description", Atomic Energy of Canada Limited Report, AECL-9331, 1987.

[9] CARVER, M.B., KITELEY, J.C., BANAS, A.O., TAHIR, A., ROWE, D.S., "Multidimensional Simulation of the Distribution of Flow and Phases in Horizontal Bundles", Proc. ANS Topical Meeting on Thermalhydraulics and Nuclear Reactors, Seoul, Korea, 1988.

[10] SOULARD, M.R., HAU, K.F., "Recent Model Developments in NUCIRC and Application to CANDU 6 Heat Transport System Performance Evaluations", Proc. 1991 Canadian Nuclear Society Nuclear Simulation Symposium, Saint John, New Brunswick, August, 1991.

[11] SOULARD, M.R., DAM, R. et al., "NUCIRC Simulations of Asymmetries in CANDU 6 Heat Transport System Operating Conditions", Proc. International Nuclear Congress and Exhibition (INC 93), Toronto, Canada, 1993 October 3-6.

[12] DASTUR, A.R., GRAY, A.S., GAGNON, N., BUSS, D.B., "The Role of CANDU in Reducing the Radiotoxicity of Spent Fuel", Proc. Global '93 - Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options, ANS Topical Meeting, Seattle, Washington, USA, 1993 September 12-17.

[13] DASTUR, A.R., GAGNON, N., "The Role of CANDU in Actinide Annihilation", published in CNS Bulletin, 15, Autumn, 1994.

[14] DASTUR, A.R., MENELEY, D.A., VERRALL, R.A., LUCUTA, P.G., ANDREWS, H.R., "Annihilation of Plutonium in CANDU Reactors", presented at IAEA Technical Committee Meeting on Options for Plutonium Dispositioning, Obninsk, Russia, 1994 November 7-11.

[15] DIMAYUGA, F.C., "AECL's Experience in MOX Fuel Fabrication and Irradiation", these proceedings.

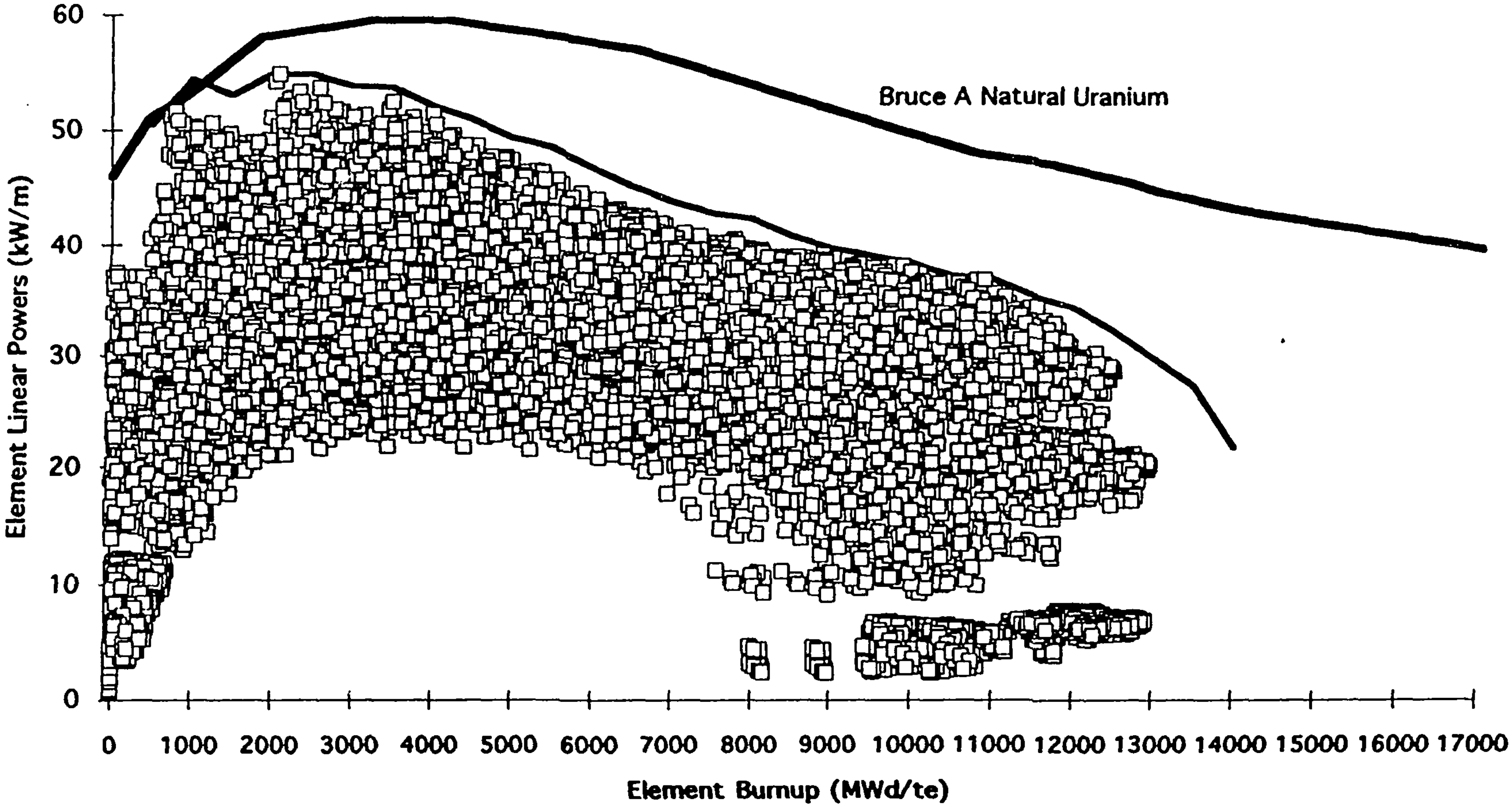
[16] BOCZAR, P.G. et al., "A Low Void Reactivity Fuel CANDU Fuel Bundle", Proc. 3rd Int. Conf. on CANDU Fuel, Chalk River, Canada, 1992 October 4-8.

Table 1: Comparison of Core Characteristics with Natural Uranium and MOX Fuel

	Natural Uranium	MOX, 37-element Reference	MOX, CANFLEX
Average burnup (MWd/te HE)	8300	9700	17 100
Maximum burnup (MWd/te HE)	15 000	15 500	28 000
Bundles / full power day / reactor	18	15.5	9
Bundles per channel refuelled	2, 4 or 8	2	2
Maximum channel power (kW)	7200	7000	7000
Maximum bundle power (kW)	960	780	800
Full core void reactivity (mk)	+11	-4.7	-1.7
Fuel temperature coefficient (micro-k/degree C)	-6.0	-3.0	-2.0
Total delayed neutron fraction	0.00582	0.00383	0.00369
Prompt neutron lifetime (s)	0.0009	0.0005	0.00046

Figure 1

Snapshot of Intermediate- and Outer-Element Powers and Burnups for Reference MOX Fuel in Bruce A



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