TECHNICAL SUPPLEMENT

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CANDU ADVANCED PLUTONIUM BURNER THE CANADIAN RESPONSE TO THE ALWR

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Abstract – *A CANDU based concept that utilizes energy produced by subcritical multiplication in a fertile region designed for accelerated plutonium production is presented. Its feasibility is based on incorporating the channels with fertile material into the primary heat transport circuit. Calculations with multigroup transport codes predict very high fuel utilization due to the production and burnup of fissile plutonium in the fertile region.*

INTRODUCTION

The neutron economy of CANDU and consequently its ability to burn natural uranium has been one of its desirable attributes. The low U235 content of CANDU fuel is one of the reasons why the contribution of plutonium to energy production is high, making the CANDU fuel cycle extremely efficient in terms of fuel utilization. Unfortunately, during the past two decades, this advantage has been diminished due to the availability of cheap uranium. Consequently, the significance of fuel utilization to the cost of producing nuclear energy has been reduced. As an example, it is now predicted that the fuelling cost of the next CANDU, if built in Canada, may comprise only 5 percent of the Total Unit Energy Cost (TUEC).

Furthermore, the prospects of advances in enrichment technology, such as Atomic Vapour Laser Isotope Separation (AVLIS) means that the CANDU advantage of better fuel utilization will be reduced further. The effect of enrichment efficiency on the CANDU advantage is shown in Table 1.

TABLE 1

CANDU Advantage in Fuel Utilization

Isotopic Percent U235 Extracted From Natural Uranium	CANDU Advantage in Percent Utilization Over LWR
0.398	48
0.520	17
0.620	0

What Table 1 indicates is that if AVLIS makes it feasible to extract 0.62 of the 0.72 isotopic percent U235 contained in natural uranium, the CANDU advantage will disappear.

In addition, it is now predicted that the next generation of LWRs (ABWR & APWR) will utilize fuel cycles that increase the energy contributed by plutonium. Such fuel cycles will compete effectively with the present CANDU fuel cycle.

THE CANDU ADVANCED PLUTONIUM BURNER

The prospect of a reduced CANDU advantage in fuel utilization over the LWR in the longer term is the major incentive for this study. We demonstrate that the present CANDU design concept has potential for increased conversion and resource utilization compared with other reactor concepts, so there is potentially a CANDU conversion which offers an excellent response to the ALWR.

The principle behind the conversion can be understood by looking at Table 2 where the energy dependence of the U238 and Pu239 absorption cross sections is given. A significant amount of Pu239 is produced by neutrons in the 4 to 75 eV energy range, whereas it is destroyed mostly by neutrons in the 0 to 0.625 eV energy range. Hence, plutonium production should be carried out in a spectrum that is rich in 4 to 75 eV neutrons and plutonium burnup should be carried out in a spectrum that is rich in 0 to 0.625 eV neutrons. Such spectra can be created in a CANDU lattice by adjustment of the moderator volume. Furthermore, due to the fuel handling capability available (a necessity for on-power fuelling) in CANDU the fertile material can be held in close proximity to the fissile material which allows (as will be shown below) the creation of a large interfacial area between the fertile and fissile material.

Based on the above considerations, we have investigated the neutronic implications of a reactor concept that has two insurmountable advantages over other converter concepts in that it (a) circumvents fuel reprocessing and (b) produces marketable energy during the conversion.

We cannot over-emphasize the fact that this study was carried out to illustrate a principle and that the results should not be considered as constituting a new reactor design. It is quite obvious that there are engineering problems to be addressed (especially in the area of fuel handling) and the feasibility of this concept will primarily depend on the success with which these are solved. Furthermore, the configurations that we are presenting are by no means optimum from operating and capital cost viewpoints.

GENERAL LATTICE CONFIGURATION AND FUELLING SCHEME

The reactor lattice is divided into two zones (Figure 1); a hard spectrum zone (HSZ) that is relatively rich in 4 to 75 eV neutrons and a soft spectrum zone (SSZ) that produces the normal complement of 0 to 0.625 eV neutrons as in the standard CANDU lattice. The HSZ consists of a group of fuel channels with reduced moderator volume. This hardens the spectrum and increases the plutonium production rate. Fuel is first irradiated in the HSZ and after the plutonium concentration has increased, it is irradiated in the SSZ. The SSZ has sufficient moderator to produce a spectrum which is soft enough to burn the accumulated plutonium.

Due to the lack of moderator, the HSZ is a subcritical region. The SSZ therefore has to be reactive enough to make the multiplication factor for the superlattice of HSZ & SSZ high enough to support neutron leakage from the reactor and parasitic neutron absorption in reactivity devices. This is a key issue that determines the neutronic feasibility of this concept and to test it will ultimately require an extensive set of measurements in zero energy and other integral facilities.

At this stage, some indication of the feasibility was obtained by simulation.

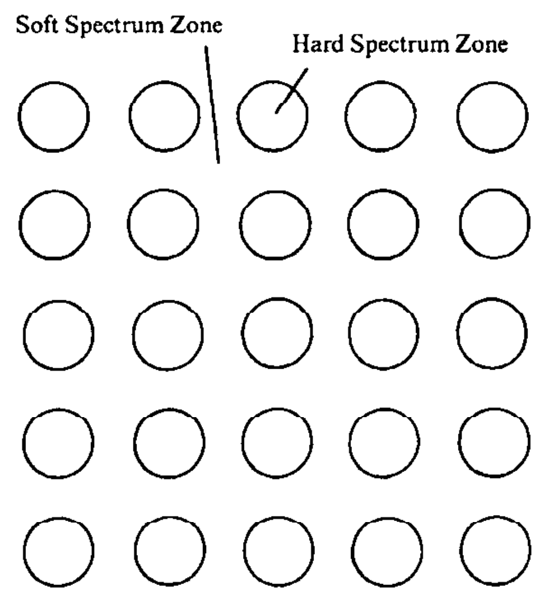

FIGURE 1 Schematic Representation of Hard and Soft Spectrum Zones as Part of the CANDU APB Core

TABLE 2

Energy Dependence of U238 & Pu239 Cross Sections

Energy (eV)	Microscopic Cross Section (barns)	
	U238	Pu239
10^7 to 8.2×10^5	20	7
8.2×10^5 to 1.11×10^5	20	10
1.11×10^5 to 9.11×10^3	20	15
9.11×10^3 to 9.07×10^2	20	15
9.07×10^2 to 1.49×10^2	20	28
1.49×10^2 to 7.5×10^1	100	40
7.5×10^1 to 4.8×10^1	500	100
4.8×10^1 to 2.77×10^1	4000	60
2.77×10^1 to 1.6×10^1	4000	100
1.6×10^1 to 9.9×10^0	8	300
9.9×10^0 to 4.0×10^0	3500	900
4.0×10^0 to 3.3×10^0	9	22
3.3×10^0 to 2.6×10^0	9	23
2.6×10^0 to 2.1×10^0	9.5	27
2.1×10^0 to 1.1×10^0	9.5	35
1.1×10^0 to 1.02×10^0	9.5	50
1.0×10^0 to 6.25×10^{-1}	9.5	95
6.25×10^{-1} to 3.0×10^{-1}	9.5	600
3.0×10^{-1} to 1.4×10^{-1}	9.5	1750
1.4×10^{-1} to 5.0×10^{-2}	10	800
5.0×10^{-2} to 2.5×10^{-2}	10	950
2.5×10^{-2} to 0	12	5000

SIMULATION METHODOLOGY

Simulation of the hard spectrum in the HSZ required multigroup lattice calculations. Proper representation of the HSZ & SSZ configuration required a two-dimensional model. Furthermore, since the spectrum in the HSZ is generated by subcritical multiplication of neutrons migrating from the SSZ, it was necessary to represent correctly the magnitude and shape of the interfacial area between the HSZ and SSZ.

The WIMS-CRNL[1] code with the Pij option was used with the WINFRITH (1985) 69 group neutron cross section data. The transport equations were solved in 22 energy groups. The latter were chosen with special consideration of the U235 and Pu239 resonance energies.

The Pij option in WIMS allows representation of each fuel pin at its proper location in the HSZ and the SSZ. The important requirement, of regenerating the correct neutron spectrum by subcritical multiplication of neutrons entering from the SSZ, is satisfied with this representation. This then gives the proper plutonium production and burnup rates in the HSZ and in the SSZ.

SPECIFIC LATTICE CONFIGURATION AND FUELLING SCHEME

To demonstrate the principle of this reactor concept, we present results for a specific HSZ and SSZ configuration. The HSZ consists of a 4 × 4 array of 16 fuel channels in contact with each other (Figure 2). A single calandria tube is used to separate the fuel channels from the moderator. The SSZ consists of four channels (each with its own calandria tube) that surround the HSZ and are separated from it by 25 cm of heavy water moderator.

Natural UO_2 fuel (the 37 element bundle was chosen for this study) is introduced into the outermost channels of the HSZ (designated as 1 in Figure 2). After an irradiation of 150 full power days (FPD), it is shifted to the channels designated as 2 and then following another 150 FPD into 3. The final irradiation step in the HSZ of 150 FPD is carried out in channels 4. Following irradiation in the HSZ, the fuel is irradiated in the SSZ for 150 FPD.

Due to the absence of moderator, the HSZ is a subcritical region and neutrons are produced in the HSZ by subcritical multiplication of neutrons born in the SSZ. Consequently, a large fraction of the neutron population in the HSZ has the energy spectrum of the SSZ. This limits the number of hard spectrum neutrons in the HSZ and therefore limits the rate of plutonium production in the HSZ. Even then, the plutonium production is high enough to provide a fuel exit burnup of 22,500 MWd / teU (compared with 6000 MWd/teU with the normal CANDU lattice). This extremely high burnup is a result of utilizing the energy produced by subcritical multiplication in the fertile region (the HSZ) by incorporating

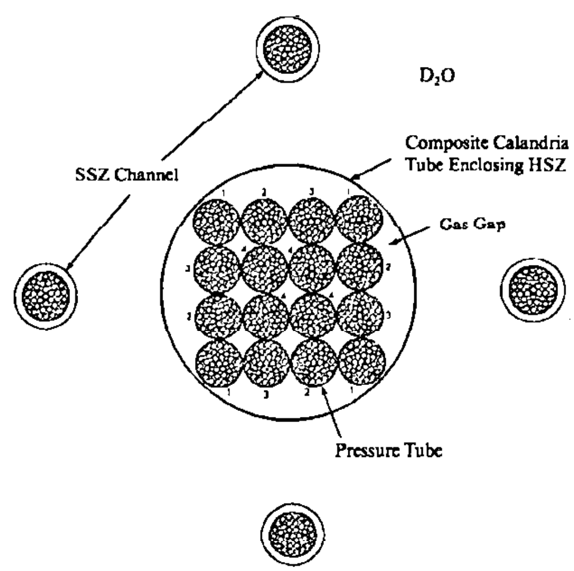

FIGURE 2 Supercell Showing Hard and Soft Spectrum Zones

the latter into the PHT system, a concept that is feasible in CANDU due to the versatility of its fuel handling system. If the HSZ could be made critical by the use of enriched fuel, the plutonium production and the exit burnup could be increased several times these values. More will be said about this when discussing the use of Recovered Uranium fuel.

Since the HSZ is subcritical, the neutron flux level in the HSZ is between 2 and 3 times lower than in the SSZ. The power density (rate of fuel burnup) and the rate of fission product formation is significantly lower than in the SSZ. As fission products accumulate, the fuel is progressively placed in the inner channels of the HSZ, i.e., into regions of lower neutron flux. As a result, neutron absorption by fission products is only a fraction of the neutron absorption in the normal CANDU lattice at comparable fuel burnup. In contrast, the fissile plutonium concentration increases with fuel movement into the inner channels (Table 3). On exit from the HSZ, the fuel contains 0.5 atom percent fissile plutonium compared with 0.2 atom percent from the normal CANDU lattice. At equilibrium burnup, the nuclide compositions at two consecutive irradiation periods of 750 FPD are shown in Table 2. The closeness of the two sets of values indicates that a dynamic equilibrium in the refuelling process has been reached. The multiplication factor of the superlattice once equilibrium is reached is in excess of 1.05.

The fuel burnup on exit from the HSZ is 13,000 MWd/teU. This indicates that the amount of energy produced in the HSZ by Pu239 fission and by fast fission of U238 is about four times that in the normal CANDU lattice.

When transferred into the SSZ, the fission product absorption increases by 30 percent due to the higher neutron flux level in the SSZ. However, the increase in the Pu239 absorption is greater because of the response of the Pu239 cross section to the softer spectrum. This limits the fractional absorption (or reactivity load) of the fission products in the SSZ to 0.049 (or 49 mk). The total fission product load in the superlattice (HSZ + SSZ) is 77 mk. The relatively low absorption rate in the fission products eliminates the need for fuel reprocessing (separation of plutonium from fission products) in contrast to a conventional fuel cycle that uses recycled plutonium.

TABLE 3

Nuclide Concentrations in the HSZ and SSZ Using Natural Fuel

($\times 10^{24}$ nuclides/cc)

Equilibrium Exit Burnup = 22,500 MWD/teU

STAGE A:

ZONE		U^{235}	Pu^{239}	Pu^{240}	Pu^{241}
	Outer*	1.0009×10^{-4}	5.3646×10^{-5}	9.1967×10^{-6}	1.2527×10^{-6}
	Middle	7.0501×10^{-5}	7.6022×10^{-5}	2.1422×10^{-5}	3.9311×10^{-6}
HSZ	Inner	5.2490×10^{-5}	9.0012×10^{-5}	3.2596×10^{-5}	6.7097×10^{-6}
	Centre	4.0684×10^{-5}	9.8805×10^{-5}	4.2968×10^{-5}	9.4359×10^{-6}
SSZ		9.9836×10^{-6}	5.8456×10^{-5}	6.0593×10^{-5}	1.3010×10^{-5}

STAGE B:

ZONE		U^{235}	Pu^{239}	Pu^{240}	Pu^{241}
	Outer*	1.0011×10^{-4}	5.3635×10^{-5}	9.1915×10^{-6}	1.2515×10^{-6}
	Middle	7.0513×10^{-5}	7.6027×10^{-5}	2.1417×10^{-5}	3.9286×10^{-6}
HSZ	Inner	5.2981×10^{-5}	9.0042×10^{-5}	3.2605×10^{-5}	6.7071×10^{-6}
	Centre	4.0508×10^{-5}	9.8917×10^{-5}	4.3125×10^{-5}	9.4688×10^{-6}
SSZ		9.9291×10^{-6}	5.8483×10^{-5}	6.0767×10^{-5}	1.3052×10^{-5}

(* outer, middle, inner and centre refers to channels 1, 2, 3 & 4 in Figure 2)

ALTERNATIVE FUELS

As stated earlier, the HSZ is a subcritical region and produces neutrons by the subcritical multiplication of neutrons that migrate from the SSZ. This process continues until the fissile content of the SSZ fuel is reduced to a level such that the absorption in the HSZ cannot be supported. Any increase in the initial fissile content of the fuel leads to a remarkable increase in the fuel exit burnup. This occurs due to a combination of reasons:

- the subcritical multiplication in the HSZ is higher and the residence time of the fuel in the HSZ is increased. This increases the energy production in the HSZ and also the plutonium accumulation
- the higher plutonium content of the fuel discharged from the HSZ increases the residence time of the fuel in the SSZ as the fuel can now support a higher accumulation of fission products.

Calculations with Recovered Uranium (a product of reprocessing spent LWR fuel) with an initial U235 content of 1.0 wt percent (compared with 0.72 wt percent for natural uranium) indicates an exit burnup of 52,500 MWd/teU. Since recovered uranium is not reusable in the LWR without enrichment, the CANDU APB is an attractive concept for countries that plan to recycle plutonium in an LWR and consequently have large quantities of recovered uranium at their disposal.

At equilibrium burnup, the nuclide compositions at two consecutive irradiation periods of 1750 FPD are shown in Table 4. In this case over 5.7 times the energy from U235 is produced by fissile plutonium and U238 fast fission.

The higher initial fissile content of the Recovered Uranium increases the subcritical multiplication in the HSZ leading to a higher power density.

CONCLUDING REMARKS

There are indications that fuel utilization in CANDU can be improved substantially by adopting a concept that allows a spectral shift during the fuel life to increase the energy contributed by fissile plutonium. These indications are based on analytical work and confirmation of this concept would require extensive experimentation.

The results presented here are to illustrate the principle of the CANDU APB. Major engineering design

TABLE 4

Nuclide Concentrations in the HSZ and SSZ using Recovered Uranium

($\times 10^{24}$ nuclides/cc)

Equilibrium Burnup = 52,500 MWD/teU

STAGE A:

ZONE		U^{235}	Pu^{239}	Pu^{240}	Pu^{241}
HSZ	Outer*	8.6828×10^{-5}	7.8632×10^{-5}	2.5955×10^{-5}	4.9668×10^{-6}
	Middle	4.5100×10^{-5}	1.0110×10^{-4}	5.0111×10^{-5}	1.0942×10^{-5}
	Inner	2.6997×10^{-5}	1.1655×10^{-4}	6.8436×10^{-5}	1.5806×10^{-5}
	Centre	1.6958×10^{-5}	1.2523×10^{-4}	8.3749×10^{-5}	1.9882×10^{-5}
SSZ		1.1617×10^{-6}	5.4464×10^{-5}	7.4067×10^{-5}	1.6629×10^{-5}

STAGE B:

ZONE		U^{235}	Pu^{239}	Pu^{240}	Pu^{241}
HSZ	Outer	8.6825×10^{-5}	7.8615×10^{-5}	2.5953×10^{-5}	4.9639×10^{-6}
	Middle	4.5109×10^{-5}	1.0108×10^{-4}	5.0103×10^{-5}	1.0931×10^{-5}
	Inner	2.6932×10^{-5}	1.1649×10^{-4}	6.8503×10^{-5}	1.5820×10^{-5}
	Centre	1.6825×10^{-5}	1.2522×10^{-4}	8.3946×10^{-5}	1.9923×10^{-5}
SSZ		1.1533×10^{-6}	5.4461×10^{-6}	7.4147×10^{-5}	1.6649×10^{-5}

(* outer, middle, inner and centre refer to channels 1, 2, 3 & 4 in Figure 2) problems need to be addressed before the feasibility of the concept is confirmed.

There is some potential in the use of the CANDU APB concept as a response to the high utilization fuel cycles being predicted for the ALWRs.

REFERENCE

[1] J.V. Donnelly, "The CRNL Version of the Lattice Code WIMS", AECL 8955, January 1988.