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ATOMIC ENERGY
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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

ECONOMIC POTENTIAL OF ADVANCED FUEL CYCLES IN CANDU

Potentiel économique des cycles avancés de combustible pour les réacteurs CANDU

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Chalk River, Ontario

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A Summary of this invited paper was presented
to the International ENS/ANS Conference
"New Directions in Nuclear Energy with Emphasis on Fuel Cycles",
Brussels, Belgium, April 26-30, 1982.

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Résumé

Les cycles avancés de combustible destinés aux réacteurs CANDU offrent la possibilité d'accroître considérablement le rendement énergétique obtenu par l'uranium naturel au moyen du cycle courant de combustible à passe unique. Ce rapport examine les aspects économiques des cycles avancés à passe unique ou faisant appel au recyclage. Les données obtenues montrent que ces cycles limiteront l'impact des prix majorés de l'uranium et offriront la possibilité d'une période de coûts de production stables en dollars constants qui n'excéderont que d'environ 20% les coûts actuels.

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ABSTRACT

Advanced fuel cycles in CANDU offer the potential of a many-fold increase in energy yield over that which can be obtained from uranium resources using the current once-through natural uranium cycle. This paper examines the associated economics of alternative once-through and recycle fuelling. Results indicate that these cycles will limit the impact of higher uranium prices and offer the potential of a period of stable constant-dollar generating costs that are only approximately 20% higher than current levels.

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ECONOMIC POTENTIAL OF ADVANCED FUEL CYCLES IN CANDU

1. INTRODUCTION

Atomic Energy of Canada Limited (AECL) in partnership with Canadian industry and power utilities has developed the CANDU reactor as a safe, reliable and economic means of transforming nuclear fuel into useable power. From the point of view of the fuel cycle, the keywords are neutron economy, simplicity and low costs. The reactor, fuel and fuel management scheme were designed to ensure that all parasitic (i.e. non-fuel) neutron absorptions were kept to a minimum. This has resulted in the capability of fuelling the reactor using uranium at the natural enrichment level and obtaining thermal energy outputs in the range 7000-7500 MW·d/Mg natural uranium, the highest of all commercially available reactors. The short, multi-element fuel bundle is simple and inexpensive to fabricate since it requires only a small number of different types of components to be assembled in a repetitive fashion. Fuel defect rates are very low and on-power fuelling allows discharge without disruption of reactor operation. Finally, the characteristics of the spent fuel are such that it can be stored indefinitely in safe, low-cost facilities at the reactor site. These characteristics combine to produce a reliable and simple fuel cycle with low fuelling costs that are about half those for light-water reactors.

AECL is now conducting a program to develop advanced fuel cycles for CANDU to meet the challenge of a more resource-constrained future. Although currently in surplus, as the future pace of world nuclear development quickens, supplies of natural uranium are expected to be increasingly inadequate to meet demand and could be a constraining factor during the next century. Consequently, one object of the program is to develop more fuel-efficient cycles that enhance the energy yield from existing natural resources. Fuel cycles utilizing uranium, plutonium and thorium are being developed. The impact on resource utilization is discussed in a companion paper at this conference (Reference 1) that describes the large reductions in uranium requirements that can be achieved by the introduction of these fuel cycles in a growing nuclear system. Results are similar to those obtained when this topic was studied by Working Group 1 of the International Nuclear Fuel Cycle Evaluation (Reference 2). Other papers (References 3,4) describe progress in certain aspects of fuel development and thorium reprocessing.

This paper addresses the topic of the economic potential of CANDU advanced fuel cycles. Improved uranium utilization is only one of the required characteristics of advanced fuel cycles and must be combined with the potential for low fuel cycle costs, particularly in circumstances where there are significant increases in the price of natural uranium. From a research and development viewpoint, the economic potential is investigated with the twin objectives of identifying those conditions under which these cycles become more economic than the existing natural uranium once-through cycle, and also assisting in defining topics for further increased R&D. Another paper at this conference (Reference 5) also addresses resource and economic aspects but from a Canadian power utility viewpoint.

2. ONCE-THROUGH CYCLES

Once-through cycles in CANDU are not confined to the use of only natural uranium. Four other fuels have been identified and these are listed in Table 1 together with the corresponding fuel average discharge burn-up. The impact on total unit energy cost (TUEC) of using these cycles is plotted on Figure 1 as a function of yellowcake cost, with the costs of all other fuel cycle and reactor components assumed constant. (Other major cost components and financial parameters are given in Table 4.)

The impact of tripling the cost of yellowcake, from the current level of approximately $100/kg contained uranium to $300/kg U, is to increase TUEC by approximately 25% with natural uranium fuelling. The other cycles show lower rates of increase as discussed below.

1.2% Enriched Uranium

The effect of using low-enriched uranium (LEU) as a substitute for natural uranium is to increase the reactivity-limited burnup life of the fuel. Although a greater amount of natural uranium is required to produce unit mass of the fuel, the increase in energy yield more than compensates for small increments in enrichment and the energy yield per unit mass of natural feed is increased. A broad maximum is obtained over the enrichment range 0.9-1.4% and a value of 1.2% was chosen to illustrate the impact (Reference 6). Under equilibrium fuelling, the LEU cycle uses only 0.7 kg of natural feed to obtain the same energy as 1 kg in the natural uranium cycle. Consequently, the fuelling cost is more insensitive to increases in yellowcake price as illustrated on Figure 1. However, any reduction in TUEC is dependent upon the cost of enrichment services. The LEU cycle saves 0.3 kg natural feed, as discussed above, but also requires 0.25 kg-SWU (separative work unit) of enrichment that is not required by the natural cycle. At current price levels (Table 4) LEU fuelling offers no significant advantage. However, the cycle becomes increasingly more attractive if natural uranium prices rise relative to other fuel cycle components.

Two cases are plotted on Figure 1 for 1.2% enriched uranium fuelling. The upper plot represents costs for startup with an initial core of enriched uranium, and the lower plot represents startup with an initial core of natural uranium. Even at high uranium price, the cost of an initial core of natural uranium is only approximately 40% of the cost of an enriched initial core, which translates into a 2% saving in TUEC. Fuel management schemes to handle the initial transition from a natural uranium core to the equilibrium LEU fuelling situation are being investigated by AECL and others (Reference 7), and they appear to be feasible, albeit at the expense of some increased complexity. The ability to start CANDU reactor operation with either natural or low-enriched uranium cores is of significance in that it offers the potential of combining the lowest initial inventory charges with the low refuelling charges of advanced cycles.

Two-Fuel Thorium Cycle

In this cycle, a fraction of the reactor core is fuelled with thorium oxide fuel bundles while the remainder is fuelled with low-enriched uranium (1.8% is used in the example quoted). Excess neutrons from the uranium are absorbed by the thorium to produce U-233 which gradually builds to an equilibrium level, approximately 1.5% by weight of the thorium. Studies (Reference 8) indicate that the uranium utilization and fuelling costs are similar to those for 1.2% LEU. Consequently, the plot on Figure 1 for 1.2% enriched uranium can be taken as indicative of the economic potential for this cycle. Further development work is required, however, particularly on fuel management schemes and to gain experience of irradiating thorium bundles to high burn-up, before the feasibility of this cycle can be fully evaluated.

Besides the potential for improved uranium utilization and economics, there are further reasons for interest in the cycle, because of its possible use in introducing the more efficient thorium recycle options described later. The spent uranium fuels contain very low fissile uranium values (0.25% enrichment) and fissile plutonium concentrations in the range 0.25-0.35%. However, the fissile uranium concentration in the spent thorium fuel (mainly U-233) is approximately 1.5%. Consequently, the extraction cost, per unit mass of useable fissile material, would be significantly lower than that for the uranium fuel as well as producing the most desirable fissile material. Use of this cycle over a period of time would produce a 'mine' of high-grade fissile U-233 for initial use, to be followed by use of the lower concentration plutonium in the spent uranium fuel, as required. A second aspect is that development of the necessary fuel cycle industries would proceed in a sequential pattern with the establishment of the thorium extraction and fuel fabrication industry for the once-through cycle followed by the recycle industry, when needed.

Uranium Recovered from Spent LWR Fuel

Several nations are currently planning for large-scale reprocessing of light-water reactor (LWR) spent fuel, for a variety of reasons. The recovered uranium is a potentially valuable resource that could be used for further energy production. Recycle of this material in LWRs may not be the most advantageous use, however, for several reasons. The uranium cannot be used directly but must be re-enriched - either directly or by blending (Reference 9) - and special care must be taken to avoid contamination of facilities. The uranium also contains the isotope, U-236, which acts as a neutron poison and considerably reduces the value of the uranium in LWRs (Reference 10). Recycling of the uranium will result in further build-up of the U-236 and, unless segregated, contamination of the other uranium in the cycle.

An alternative is to burn this uranium directly in CANDU. The U-236 is mainly a resonance absorber and hence its action as a neutron poison is diminished in the softer neutron spectrum of the CANDU. The uranium does not need further enrichment before reuse and can produce a further 11,000 MW·d/Mg U of energy (Table 1). In the CANDU spent fuel, the uranium is burnt to below tails enrichment and so there is no incentive for further recycle and the U-236 is isolated from the system. However, the spent fuel also contains fissile plutonium values for eventual recovery, when economic.

The potential economic impact of using this material is dependent upon the price at which it can be obtained. One method of approach is to devise a value by analogy with "clean" uranium in a once-through cycle and compare costs for fresh bundles, it being assumed that "back-end" fuel cycle costs are similar. Under these conditions, the value of the recovered uranium is dependent upon yellowcake and enrichment costs and any fabrication penalty arising from use of the recycled material. Data shown in Table 2 indicate that uranium is always worth less than yellowcake in a pressurized-water reactor (PWR), but has a greater value in CANDU.

The impact of using this recovered uranium in CANDU is shown on Figure 1. It has been assumed that it can be purchased at its PWR value (taken from Table 2). There appears to be an incentive (3% in TUEC) to implement this cycle under current economic conditions and this incentive grows with increasing uranium price.

U Plus Pu Recovered from Spent LWR Fuel

This is a variation of the previous cycle in which both recovered plutonium and uranium are used in CANDU. Again, unlike the LWR, no adjustment need be made to the plutonium/uranium ratio and the mixture can be used directly as a fuel to yield approximately 25,000 MW·d/ Mg(U+Pu). In the CANDU spent fuel, the U-235 content is burnt down to below 0.1% concentration, but again, there are significant fissile plutonium values (0.35%) for recovery, when economic.

The value for recovered plutonium can be derived using an approach similar to that for the recovery of uranium, and values are given in Table 2 as a function of yellowcake price. There are two aspects to be noted. First, the fabrication penalty for CANDU fuel has been assessed at half that for LWR fuel (Reference 11). This is in line with estimated fabrication costs for CANDU mixed-oxide fuel (e.g. Reference 12) and also in line with cost experience with the current uranium fuel (Reference 13). The simplicity of the CANDU fuel design lends itself more readily to the remote, automatic fabrication processes that current experience indicates will be necessary for large-scale commercial production (References 14,15). Secondly, the plutonium has a slightly higher value in PWR than in CANDU, although in neutron yield it is worth less. This arises because it displaces much larger amounts of enrichment work units when used in PWR fuel.

The impact on CANDU TUEC when purchasing plutonium at its PWR value is very similar to that obtained by using the recovered uranium on its own, and the appropriate plot on Figure 1 can be taken as indicative.

These four fuel cycles all show considerable potential for further improving the uranium utilization in CANDU and significantly reducing the impact of rising uranium prices on TUEC. The possibility of an LWR-CANDU symbiosis is of particular near-term interest. The material recovered from LWR spent fuel can be used directly in CANDU without the need for enrichment adjustment and with the potential of enhanced energy production and reduced TUEC.

3. THORIUM-U-233 RECYCLE

The use of Th/U-233 recycle in CANDU gives the potential for the greatest reduction in natural uranium requirements (References 1,16). Characteristics of the fuel cycle considered in this paper are given in Table 3 for equilibrium fuelling conditions. Most of the fissile material is obtained by recycling (mainly U-233) and only a small make-up is required from external sources. Thorium is non-fissile and the cycle is initiated by fuelling the reactor with a mixture of thorium and either U-235 or plutonium, assuming that an external source of U-233 will not be generally available. Successive generations of fuel contain an increasing amount of recycled U-233 until an equilibrium is established.

The relative TUEC for thorium recycle and natural uranium once-through cycles is plotted on Figures 2 and 3 as a function of natural uranium price. On Figure 2, thorium recycle has been initiated using 20% enriched uranium (the "denatured" thorium cycle), and on Figure 3, the cycle has been initiated using plutonium. Major economic parameters used in deriving these figures are given in Table 4. Additional data (e.g. reactor capital costs) have been taken from Reference 16 and escalated to 1982 conditions.

For the plutonium-initiated cycle (Figure 3), the plutonium value-in-PWR has been taken from Table 2 (i.e. $29 per fissile gram rising to $60/g as yellowcake price changes from $100 to $300/kg U).

A HIGH and LOW set of active fabrication and reprocessing costs have been used. This range is based upon internal and other estimates (e.g. References 17,18) and reflects two sorts of uncertainties. The first is the technical uncertainty that arises from lack of direct experience of building and operating large-scale facilities. Little commercial experience is available world-wide but the situation should be clearer by the end of the decade when several major facilities will be in operation. The second uncertainty arises from the institutional setting in which recycle facilities will be operated. Such aspects will vary from nation to nation, and the extremes of high debt, low equity and low debt, high risk equity can influence the specific service cost by a factor of up to 3. The range selected reflects these uncertainties and appears reasonable in the light of current information and other factors discussed later.

The data show that thorium recycle is not economically competitive at current price levels. The saving in uranium is not sufficient to off-set increased costs associated with reprocessing and fabrication. TUEC is very sensitive to the LOW-HIGH differential in recycling costs (the differential is equivalent to approximately 15% in TUEC), which in turn strongly influences the uranium break-even price, i.e. the uranium price at which the TUEC for recycling and once-through cycles is the same. The results also highlight the significance of utilizing the lowest enrichment, lowest cost initial core inventory to reduce TUEC. The cost of an LEU initial core is only 30-40% of that of an equivalent thorium core and reduces TUEC by 5-7%.

Thorium recycle initiated by plutonium results in TUEC that are 5-8% lower than U-235-initiated cycles, if the plutonium can be purchased at the equivalent-PWR price given in Table 2. Compared to its use in the once-through cycle, discussed earlier, this cycle will be more economically attractive when uranium prices reach the $200-300/kg range.

4. OTHER CYCLES

Plutonium can be used in at least three ways:

(i) in a once-through cycle (discussed in Section 2),

(ii) to initiate Th/U-233-recycle (discussed in Section 3),

(iii) recycled with uranium (either natural or depleted).

This latter method has also been studied for CANDU, and significant improvements in uranium utilization can be achieved, i.e. a factor greater than two over the natural uranium once-through cycle. Compared to thorium recycle, the neutronic characteristics are such that the required enrichment levels in the reactor are lower, but the net fissile requirements from external sources are higher (Reference 20). The opposing effects of these changes on fuel cycle costs balance, and the resultant TUEC and trends with increasing uranium price are similar to those described previously for thorium recycle.

5. FUEL CYCLE COSTS

The range of costs associated with "back-end" fuel cycle activities (i.e., namely, reprocessing, waste management and recycle fuel fabrication) which have been used for this study, appear reasonable in the light of published estimates. However, the range [$(CAN)450-950] appears low when compared with current information on commercially available services. Current contracts for reprocessing with COGEMA and BNFL are quoted as cost-plus (Reference 19) and indicate a cost of $(US)500+ for reprocessing and waste glassification alone. Belgonucleaire have quoted a price range of \$(US)420-720/kg for fabrication of mixed oxide LWR fuel (Reference 2). Consequently, a range of \$(CAN)1350-1700 may be more appropriate for current conditions.

However, there are several reasons for anticipating that costs for fuel recycle will fall to the levels used in this paper. First, considerable engineering experience will be gained over the next decade from the design, construction and operation of the currently planned facilities in the UK, France, FRG and Japan. This, combined with the necessary increase in scale to meet demand, should ensure that specific costs for second-generation plants are significantly lower. It is expected that such experience can be transferred to other nations under appropriate co-operative agreements. Secondly, growth of the demand for fuel recycle will lead to the colocation and integration of reprocessing and fabrication facilities, leading to a reduction in costs through sharing of a common site and services and the ability to optimize the overall system (e.g. the in-process inventories and overall time required should be reduced). Thirdly, the CANDU-specific characteristics of the fuel will result in lower costs. As discussed earlier, compared to other systems, the fuel design lends itself more readily to the remote, automatic fabrication processes that will be required, and investigations for reprocessing (e.g. Reference 17) indicate similar savings. Finally, R&D on modified approaches to reprocessing may well be fruitful in further reductions in cost. An example is coprocessing, in which the separation and purification of several individual product streams is eliminated. The necessity for remote, automatic fabrication also raises the possibility of less stringent standards for material decontamination from fission products with attendant cost savings. These approaches, when combined with the concept of colocated, integrated facilities, should allow an overall optimization of the combined reprocessing-fabrication process to achieve minimum costs.

A further consideration arises when the decision whether to commit to recycling is being debated within a national nuclear power program. The customer-utilities will play a large role in the process, including considerations of partial ownership and financing of the industry. In such a case, the capital structure of the industry (including decisions on debt/equity ratio) will be directly influenced by the customer with strong impact on the cost of services provided. As shown on Figures 2 and 3, this will have a major feedback influence on when, and at what uranium price, recycling becomes economically competitive with once-through fuelling.

6. THE LONG TERM

In the long term, it is anticipated that the need for nuclear power will continue to grow and the combination of fuel recycling and diminishing natural uranium supplies will be inadequate to meet the demand for fissile material. Several nations are developing the Liquid Metal Fast Breeder Reactor (LMFBR) as one potential solution to this problem. AECL is investigating other approaches.

Self-Sufficient Equilibrium Thorium Cycles

When equilibrium fuelling conditions have been reached, the annual external fissile requirements for CANDU-PHWs operating on the thorium cycle can be minimized by adopting a low average discharge fuel burn-up. For the current CANDU reactor design, the minimum in equilibrium external fissile requirements occurs at a burn-up in the region of 10-15 MW·d/kg HE. At this burn-up the requirements are finite but relatively small.

By paying careful attention to neutron and material economy, it is potentially possible to design and operate CANDU-PHWs, of essentially the current concept, on thorium cycles with an average discharge fuel burn-up equal to or greater than 10 MW·d/kg HE and with zero external fissile requirements for equilibrium fuelling. Such thorium cycles are referred to as self-sufficient equilibrium thorium (SSET) cycles (References 21,22).

SSET cycles would probably not compete economically with the higher burn-up thorium cycle case. In order for SSET cycles to compete, reprocessing and active fabrication costs must be relatively low and/or uranium prices very high. Nevertheless, the feasibility of SSET cycles in

CANDU-PHWs is important from a strategic point of view. These cycles will secure the existing installed nuclear capacity against uranium shortages and provide an upper limit to nuclear energy costs. Consequently, SSET cycles guarantee the long-term viability of the CANDU-PHW concept, regardless of future developments with respect to uranium resources.

For this reason, AECL has selected SSET cycles as one target in planning research and development programs on advanced fuel cycles with the specific aim of demonstrating their feasibility. The choice of this target has the additional advantage of imposing a strict discipline on the program. This should prove to be beneficial to most advanced fuel cycles in CANDU-PHWs, even if SSET cycles are never introduced.

The Accelerator Breeder

AECL is investigating the potential of accelerator breeding as a means of augmenting fissile material supplies (Reference 23). In an accelerator breeder facility, a high-energy (1 GeV) current of protons is directed at a heavy-element target and the resulting neutrons are used to produce fissile material through capture in fertile materials (either U-238 or Th-232). Although self-sufficient in energy, the facility is not a net producer of power and is designed and operated solely as a fissile material production facility. One major advantage of this approach is that it does not require an initial inventory of fissile material to start operation. Unlike LMFBR, it does not have a dual role, and can be optimized to produce fissile material at the lowest possible cost. However, while the performance of major components of the accelerator has been demonstrated separately in research accelerator applications and in development laboratories, the performance has not been demonstrated under realistic accelerator breeder conditions. AECL has recently initiated a new research centre near Montreal, Quebec, to pursue development of this technology.

In addition to the two approaches described above, another possibility is that of CANDU-LMFBR symbiosis. Although LMFBR technology offers great potential because of its ability to create more fissile material than is consumed in power production, there are two disadvantages for large-scale implementation compared with thermal reactors. The LMFBR requires a much larger inventory of fissile material for the early period of reactor operation and this, combined with higher reactor costs, results in significantly higher initial capital investment (Reference 24). However, CANDU and LMFBR technology could combine in a fruitful symbiotic relationship. The lifetime plutonium production of a 1 GWe CANDU is sufficient to launch more than 2 GWe of LMFBR. The excess fissile material produced by the LMFBR is, in turn, sufficient to support more CANDUs operating on recycle fuelling. Such an arrangement benefits from the lower capital costs of the thermal system and allows a faster build-up of generating capacity than an LMFBR-only system, because of the lower initial fissile requirements of CANDU.

7. SUMMARY

The technology and necessary industrial infrastructure for the CANDU reactor and large-scale heavy water production are now well established. The performance of CANDU nuclear generating stations has exceeded that of any other type of nuclear station in the world. Fuelling costs are low due to the simple fuel design and good uranium utilization in the natural uranium once-through cycle. Based on these characteristics, CANDU can make a significant contribution to meeting future energy requirements in a reliable and economical fashion.

A broad range of potential fuel cycle options have been identified to protect against uranium shortages and higher prices. Significant improvements in uranium usage can be obtained by use of alternative once-through cycles utilizing either low-enriched uranium or material recovered from spent LWR fuel. The impact of a tripling of uranium prices from current levels can be reduced to less than a 20% increase in total unit energy costs.

Resistance to further increase in uranium cost and TUEC is provided by recycle fuelling. These cycles could become competitive at uranium prices as low as $150/kg U but this depends critically on the cost of "back-end" fuel cycle services. A major challenge will be the need to develop low-cost techniques for remote, automatic fuel fabrication. However, this also allows the flexibility to explore cheaper methods of reprocessing and to optimize the overall integrated system for minimum costs. Industrial evolution and continued R&D in this area, combined with the favourable CANDU-specific characteristics of the fuel, gives the potential for back-end costs significantly lower than those quoted for currently available sources. The utility-customer can also play a large role in determining the level of costs by directly influencing the financial groundrules for the industry.

For the longer-term, AECL is investigating the potential of self-sufficient equilibrium thorium cycles and the accelerator breeder as alternatives to CANDU-LMFBR symbiosis.

The economics of CANDU advanced fuel cycles will limit the impact of higher uranium prices and offer the potential of a period of stable generating costs at a level that is only about 20% higher than current levels (in constant-dollar terms). If this is combined with the potential for significant reductions in CANDU capital costs offered by variants of the basic design (e.g. the CANDU-OCR, discussed in a companion paper at this conference, Reference 25), then the long-term prospect is for generating costs near to current levels. It is not anticipated that uranium supplies will prove a constraint to world-wide growth of nuclear power until well into the next century. The near-term availability of low-enriched once-through cycles will guard against anticipated increases in uranium price, and there is adequate time to perform the development and demonstration of CANDU-optimized recycle technology before deployment is required. Consequently, the overall prospect is for continued commercial viability of CANDU as a long-term energy technology.

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TABLE 1

CANDU ONCE-THROUGH CYCLES

Material	Average Discharge Burn-up
Natural Uranium	7.0 - 7.5
1.2% Enriched Uranium	21.0
Two-fuel Cycle:	
1.8% Enriched Uranium Plus Thorium	~22 (LEU) ~59 (Th)
Material Recovered from LWR Spent Fuel:	
Uranium Only	11.0
Uranium Plus Plutonium	25.0

TABLE 2

VALUE OF MATERIAL RECOVERED FROM SPENT LWR FUEL

Recovered Uranium Composition: 0.84% U-235, 0.48% U-236, 98.68% U-238
Recovered Plutonium: 0.0063 kg Fissile Pu/kg U

Value In	PWR		CANDU	
Fabrication Penalty				
- U only ($/kg)	40		20	
- U+Pu ($/kg)	300		150	
Yellowcake Cost ($/kg U)	100	300	100	300
Uranium Value ($/kg U)	81	283	119	353
Fissile Plutonium Value ($/g fissile)	29	60	21	58

TABLE 3

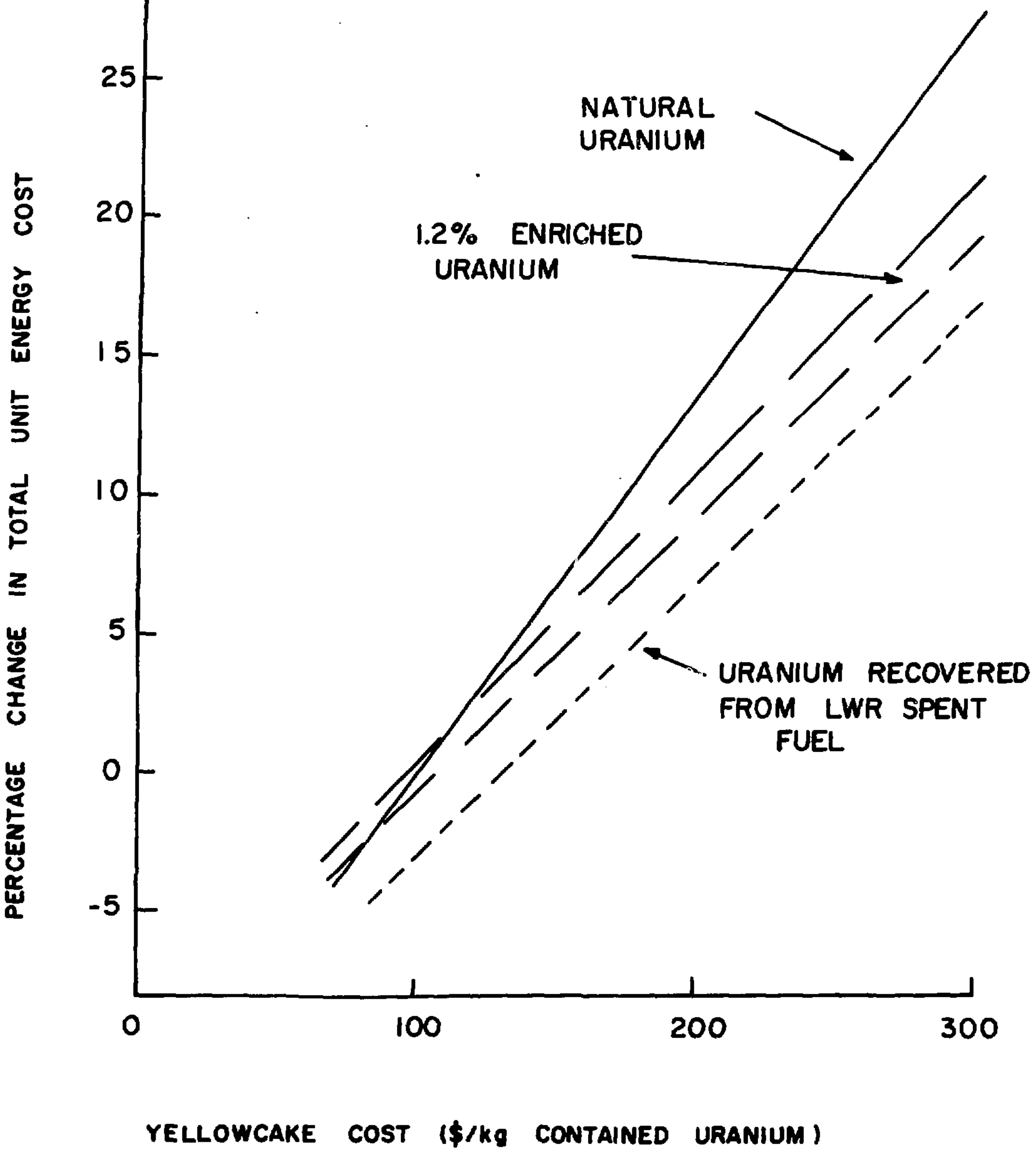
CANDU Th/U-233 RECYCLE, EQUILIBRIUM FUELLING

Average Fuel Discharge Burn-up	30 MW·d/kg HE
Make-up Enrichment	0.5-0.6 wt.% (U-235 or Pu)
Recycled Enrichment	1.7-1.9 wt.% (mainly U-233)
Total Fresh Fuel Enrichment	2.2-2.5 wt.%

TABLE 4

MAJOR FUEL CYCLE COSTS AND PARAMETERS
(1982 Canadian Dollars)

Yellowcake Cost	Variable
Thorium Cost	\$30/kg Th
Natural Uranium Fabrication	\$55/kg U
LEU Fabrication	\$75/kg U
EU-Th Fabrication	\$95/kg U
Separative Work Cost	\$150/kg U
Enrichment Plant Tails	0.2%
Pu/Th or U-233/Th Fabrication	\$250-500/kg HE
Thorium Reprocessing and Waste Disposal	\$200-450/kg HE
Reactor-out to Reactor-in Recycle Time	2 a
Plant Capacity Factor	80%
Plant Life	30 a
Discount Rate/Interest Rate	4%
Constant Dollar Costing	



CANDU TOTAL UNIT ENERGY COST, ONCE-THROUGH CYCLES

CONSTANT DOLLAR COSTING
DISCOUNT RATE = 4%

FIGURE 1

CANDU, THORIUM-U233 RECYCLE INITIATED BY ENRICHED URANIUM

TOTAL UNIT ENERGY COSTS RELATIVE TO NATURAL URANIUM, ONCE-THROUGH CYCLE

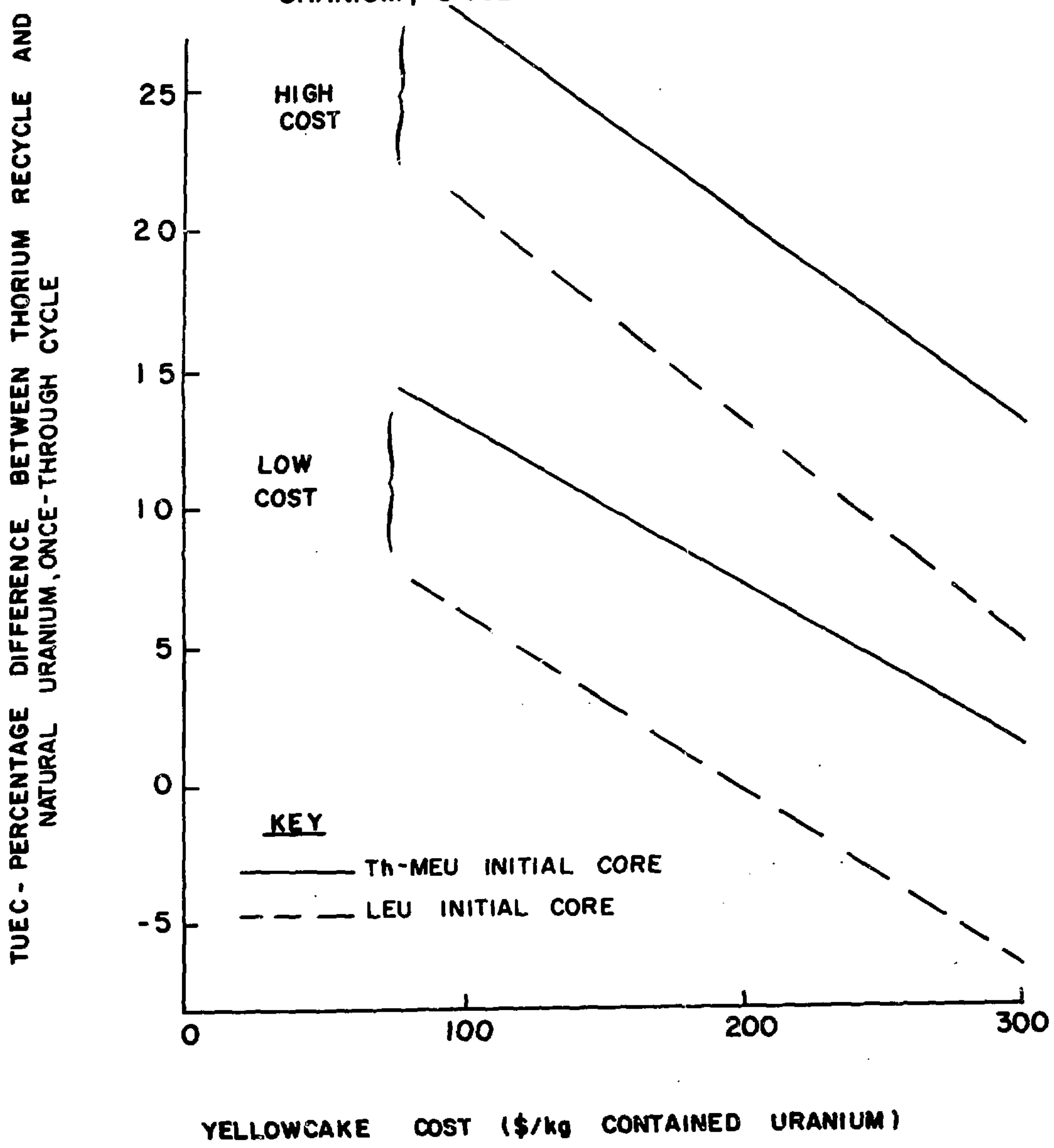
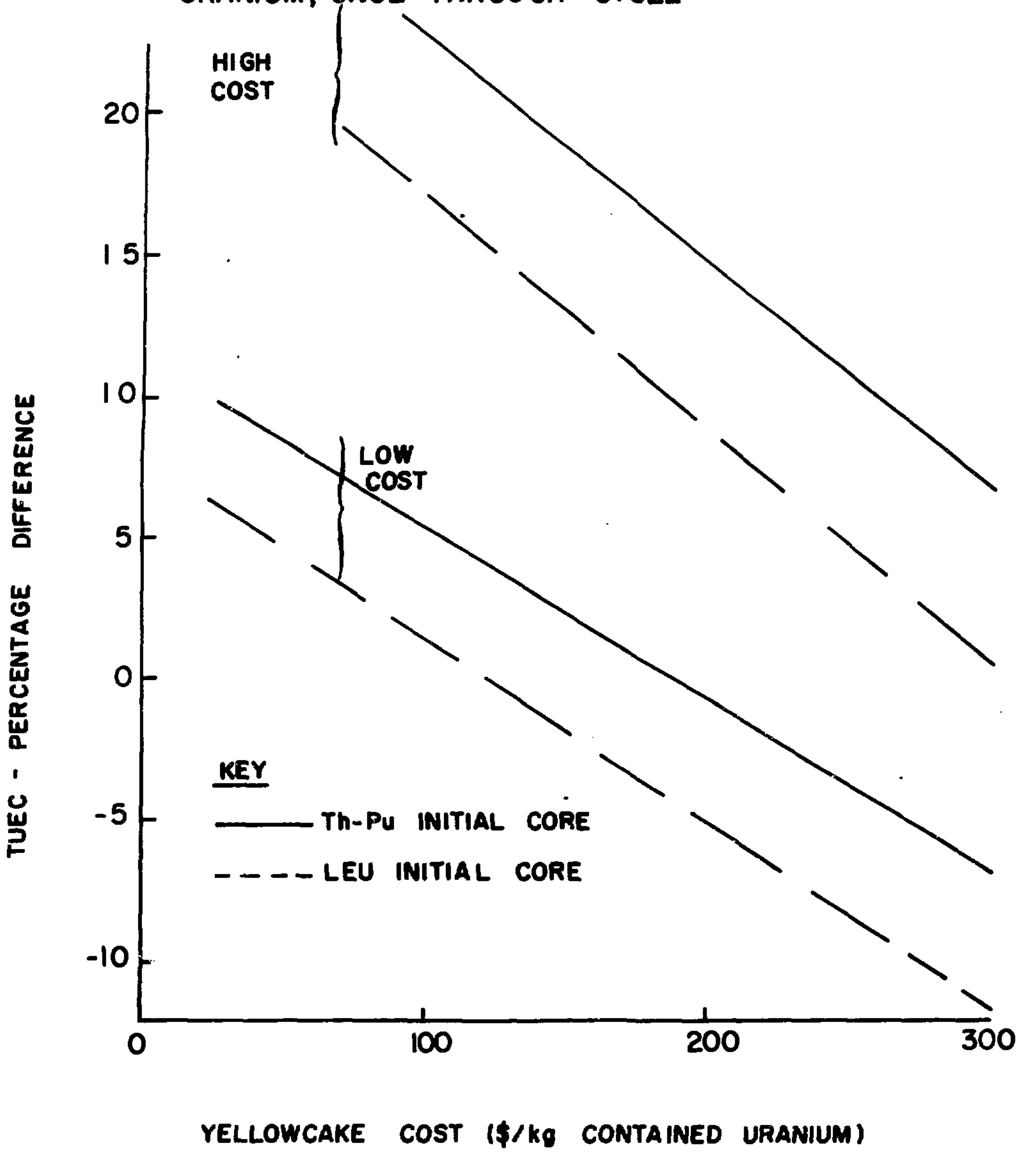


FIGURE 2



CANDU, THORIUM-U233 RECYCLE INITIATED BY PLUTONIUM

TOTAL UNIT ENERGY COST RELATIVE TO NATURAL URANIUM, ONCE-THROUGH CYCLE

FIGURE 3