Thorium Fuel Cycles in CANDU

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ABSTRACT

In recent years, Atomic Energy of Canada Limited has been examining in detail the implications of using thorium-based fuels in the CANDU reactor. Various cycles initiated and enriched either with fissile plutonium or with enriched uranium, and with effective conversion ratios ranging up to 1.0, have been evaluated. We have concluded that:

1. Substantial quantities of uranium can be saved by adoption of the thorium fuel cycle, and the long-term security of fissile supply both for the domestic and overseas market can be considerably enhanced. The amount saved will depend on the details of the fuel cycle and the anticipated growth of nuclear power in Canada.

2. The fuel cycle can be introduced into the basic CANDU design without major modifications and without compromising current safety standards.

3. The economic conditions that make thorium competitive with the once-through natural uranium cycle depend on the price of uranium and on the costs both to fabricate a- and y-emitting fuels and to either enrich uranium or to extract fissile material from spent fuel. While timing is difficult to predict, we believe that competitive economic conditions will prevail toward the end of this century.

4. A twenty-year technological development program will be required to establish commercial confidence in the fuel cycle.

INTRODUCTION

For several years, as witnessed by a sampling of recent publications, Atomic Energy of Canada Limited has been studying in detail the implications of using thorium-based fuels in the CANDU reactors as a means of:

1. Providing long-term security of fissile supply by a more efficient use of uranium

2. Stabilizing fuel cycle costs against the inevitable rise in price of natural uranium.

The potential of fertile 232Th as a source of energy has long been recognized by many workers in the nuclear energy field, notably Weinberg, Kasten, and Lewis, and the writings of Lewis on this topic go back to the earliest days of the Chalk River Project. However, the priority at that time was to achieve a viable nuclear power reactor by the simplest and most expeditious route then available to Canada and one that would compete economically with coal-fired power stations. What emerged, with remarkable éclat, is the natural UO2-fueled, heavy-water-moderated and -cooled, pressure tube reactor. The successful operation and commercialization of this system has been well described by Morrison, Woodhead and Ingolfurad, and Pon, including an excellent overview by Robertson which contains many useful references for further reading.

Of the countries committed to nuclear power, Canada currently enjoys one of the highest per capita reserves of uranium, and so at first sight it may seem unnecessary for us to want to pursue an advanced fuel cycle program. Yet a close examination of the published known reserves and resources suggests that we do not have a cornucopia of "cheap" uranium, and that if we are to guarantee supplies for growing domestic requirements and at the same time maintain a sizable export market, it is essential we utilize uranium more efficiently than is presently done. In essence, we have addressed ourselves to the following four basic questions:

1. To what extent does the use of thorium reduce our dependence on uranium, and will it be adequate?

2. Can the thorium cycle be introduced into CANDU reactors without major redesign and without compromising current nuclear safety standards?

3. What are the economic conditions that make thorium competitive with the once-through natural uranium cycle, and when are these conditions likely to occur?

4. What needs to be done to arrive at a point where thorium can be committed on a commercial scale, and how long will it take to do it?

Clearly an affirmative answer to the first two questions could have a profound effect on the future Canadian nuclear power program since it might prove to be the optimum route for a country like Canada to follow. That is to say, uranium conservation could be practiced without the need to introduce a completely new reactor type.

The discussion of the thorium cycle will be confined to the Canadian scene, though other countries that either have CANDU reactors or are in the process of building or contemplating installing them will wish to do similar analyses and be guided, where appropriate, by the results of our studies. A complication that has arisen during the past year is the INFCE study, and while Canada is taking a very active role in these deliberations, it is felt, at the time of writing, that it would be premature to include results pertaining to the nonproliferation cycles since many of the questions surrounding this topic are of a quasi-technical nature and are not yet fully formulated. What we wish to present in this paper is the full potential of thorium cycles in CANDU and provide an update of previous publications.

PHYSICS OF THE THORIUM CYCLE

Abundance

Before discussing the physics of the thorium cycle it is appropriate to briefly mention the availability of this isotope. The abundance of thorium in the earth's crust is known to be approximately three times as great as...
uraniun. The major concentrated deposits are to be found in the monazite beach sands in such places as India, Australia, and Brazil. Thorium is also often found in association with uranium ore bodies, and in the uranium mining district of Elliot Lake in Ontario it is estimated that the ratio of thorium-to-uranium is at least one-to-one and, in some instances, is as high as three-to-one (Ref. 16). There has been comparatively little exploration for thorium, and therefore much less is known about the reserves and distribution of this material compared to uranium: but since the purpose of the proposed fuel cycles is to increase the amount of nuclear energy by the recycling of thorium, the question of supply is of importance only in the early years after the introduction of the cycle. Monazite thorium consists almost entirely of the isotope $^{232}$Th, whereas thorium found in conjunction with uranium can contain up to several hundred ppm of $^{234}$Th (lumutum) as a result of the decay of $^{238}$U. This is of little practical consequence in the fuel cycle proper, but can be of major significance if one is trying to produce low-activity $^{233}$U for experimental purposes. (See section on Fabrication Problems Pertinent to Thorium.)

**Basic Comparison of Thorium and Uranium in Thermal Reactors**

Whereas natural uranium consists of the fertile isotope $^{238}$U and the fissile isotope $^{235}$U in the ratio 138:1, thorium contains no thermally fissionable material and is a purely fertile isotope. Uranium can therefore be used directly either in its natural form in heavy-water-modernated reactors or in graphite-modernated, gas-cooled reactors, or can be enriched in $^{235}$U content (by an isotopic separation process) for use in the light-water-modernated and -cooled reactors. Thorium, by contrast, must be deliberately enriched either with $^{235}$U or with fissile plutonium if it is to be used as a reactor fuel. Neutron capture in $^{232}$Th leads to the formation of the fissile isotope $^{233}$U via the intermediate product $^{233}$Pa, which is analogous to the formation of fissile $^{233}$Pu via $^{233}$Np through neutron capture in $^{233}$U. In thermal reactors the $v_\text{f}$-value (neutron yield per neutron absorbed) of $^{233}$U is higher than for $^{233}$Pu or $^{235}$U, typical values being 2.28, 1.94, and 2.04, respectively, in CANDU neutron spectra. This immediately implies that $^{233}$U has more "spare" neutrons available for converting fertile into fissile material. This is an important advantage of $^{233}$U over $^{233}$Pu and $^{235}$U and, therefore, of thorium over $^{235}$U.

One of the characteristics of thorium lies in its absorption cross section which is about three times greater than that of $^{235}$U; consequently, more fissile material is required to establish an equilibrium fuel cycle than would be the case with a uranium-based fuel cycle of equivalent burnup in a reactor of the same power output. However, once established, the thorium cycle consumes less $^{233}$U (from which all fissile power is ultimately derived) than fuel cycles based on $^{233}$U. $^1$The additional fissile material required for the thorium cycle is an inventory problem, and therefore adds an extra burden to the economics of the fuel cycle. It can also enter the picture as a resource problem if the system is growing rapidly, since additional quantities of fissile material have to be found to supply the inventory for each additional unit of power. But, it must be stressed that, once supplied, the inventory is there in perpetuity and can be handed down to successive replacement power plants.

**Some Detailed Comparisons Between Thorium-and Uranium-Fueled CANDUs**

Milgram and Walker$^2$ have discussed some of the physics problems peculiar to the thorium cycles in CANDU and how they differ from those of the natural uranium-fueled CANDU. Here we will give only a resume of what the main differences are and how they affect core design, but it should be stated at once that no major feasibility problems have been encountered. The differences are ones of detail: the need to improve basic nuclear data, to improve both lattice physics and reactor core calculational methods, and to validate codes by means of cross-energy lattice measurements and depletion experiments on $^{233}$U/thorium fuels.

1. **Protactinium-233:** This nuclide is the radioactive precursor of $^{233}$U and has a 27.4-day half-life. Because of its relatively long half-life (compared to its analog $^{234}$Np in the uranium cycle, which has a half-life of only 2.4 days and is therefore relatively unimportant), it takes several months to come into equilibrium at startup or after a protracted shutdown. These changes are relatively slow and there should be no problem in designing control systems to take care of the reactivity-induced effects within the core. Furthermore, the concentration of $^{233}$Pa across the core is flux history dependent and tends to produce a certain degree of self-flattening of the power distribution. This is a beneficial effect since less external parasitic absorption need be included in the core design for flattening purposes. Of course, the calculational problems associated with this effect are more difficult, but we now have codes that will calculate the consequences of these effects in the axial and radial directions. During a prolonged shutdown period, the decay of $^{233}$Pa into $^{233}$U can add up to 100 mk (10%) reactivity to the system, so that in the design of thorium reactors it will be necessary to provide a greater total shutdown depth than is commonly employed in the natural uranium-fueled reactor.

2. **Xenon Override Requirements:** It is customary to provide xenon override capability in the natural uranium CANDU reactors by means of absorber rods which are held permanently in the core during normal operation and which can be removed when needed to counteract the poisoning-out effect of xenon resulting from a power trip or power setback. The amount of reactivity holdup in these absorber rods determines the time of the reactor operator has to make a decision whether to return to power or allow the reactor to poison out, and is commonly referred to as the decision/action time. The decision/action time is currently on the order of a half hour. Since the yield of $^{135}$Xe following a trip is less than half that of a natural uranium reactor. Consequently, for the same decision and action time the thorium reactor requires no more than half the reactivity penalty associated with the override system. This feature assists the conservation of uranium by extending the burnup of a given equilibrium fuel composition. Alternatively, one could improve design flexibility in the matter of decision/action time by slightly lowering the conversion ratio according to the dictates of local economics. Thorium absorber rods could also be used in place of the more usual poison rods and these could eventually be reprocessed to recover $^{233}$U and help increase the overall conversion ratio.

3. **Fission Product Poisoning:** Thorium burnup estimates are quite sensitive to the calculation of fission product poisoning. An error of 0.1% leads to a spread in burnup of ±0.5 MWD/kg, and since fission
The product poisoning eventually dictates the discharge burn-up, it is important that this area of measurement and code development be given special attention, and work is proceeding in this direction.

4. Basic Nuclear Data: Absorption and fission cross sections of $^{235}$U vary between evaluations given by ENDF/B-II, ENDF/B-IV, and by the CSWEG Normalization Subcommittee. Our analysis of the data and its effect on burnup indicated that it is most important to pin down as accurately as possible the fission cross section of $^{235}$U since a given uncertainty in fission cross section has about twice the reactivity effect of a similar uncertainty in the absorption cross section.

Since $^{235}$U, $^{237}$Pa, and $^{239}$U have resonances in the 1- to 10-eV range, we recognize the need for a continuing effort in the area of estimating self- and mutual-shielding effects. We have recently made significant advances in this direction by incorporating appropriate modifications into the LATREP lattice physics code.11,19

Control and Safety-Related Aspects

Our work to date on the control and safety aspects of thorium-fueled reactors indicates there are no feasibility problems, and that the safety features of the CANDU reactor will in no way be compromised as a result of fueling with thorium. While the average delayed-neutron fractions and mean neutron lifetimes are, in general, smaller for thorium systems, they are compensated by other relevant parameters in this area such as reactivity coefficients, xenon parameters, and improved thermal conductivity of thorium. The net effect is that, in general, both fast and slow control in thorium reactors are expected to be similar or better than those in natural uranium reactors of the same size.

In the previous section we spoke of the long-term effects of $^{237}$Pa and its spatial variation and this will undoubtedly have some effect on fuel management, especially after a shutdown. However, continuing fuel design improvements, such as silicon-coated sheathing20 will lead to more tolerant fuels, and this, when coupled with our steadily improving knowledge of heat transfer behavior of fuel bundles in horizontal channels, will assist considerably in the fuel management problem.

CHARACTERISTICS OF THE THORIUM CYCLE IN CANDU

Description of the Cycles

Since thorium contains no naturally occurring fissile material, the fuel cycles must be initiated by the addition of either $^{235}$U or fissile Pu. The decision as to whether one should use $^{235}$U or Pu is a complex one, and will be taken up later in the discussion. In our studies to date we have examined the addition to thorium of plutonium extracted from spent natural uranium fuel, and also the addition of highly enriched uranium (93 wt% $^{235}$U). In both cases the uranium isotopes generated in the thorium are recycled back into the thorium after the removal of fission products. This process is repeated until the uranium isotopes come into an equilibrium composition. To this mixture may be added extra quantities of either Pu or enriched U to give us the 'topping' cycles, which result in fuel burnups ranging from about 20 to 40 MWd/kg HE (heavy element) for topping additions of from 1 to 5 g of fissile isotope per kg of heavy element. Alternatively, no topping need be added, and this case we have examined the self-sufficient equilibrium thorium cycle (SSET); that is to say, once the equilibrium isotopic composition has been established, no further supply of mined uranium is required. This cycle, which would have a burnup of about 10 MWd/kg HE, is especially sensitive to the degree of neutron economy incorporated into the design of the reactor core, and

![Table 1](image)

<table>
<thead>
<tr>
<th>Fissile Topping, g/kg HE</th>
<th>U Recycling and Pu Topping</th>
<th>U Recycling and $^{235}$U Topping (93% enr U)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feed</td>
<td>Discharge</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feed</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Self-Sufficient</td>
</tr>
</tbody>
</table>

### Notes

1. Discharge concentrations are g/kg of initial HE in feed fuel.

2. Pu is discharged at the end of each irradiation and is not recycled. The quantities are small, and the $^{239}$Pu concentration too high for it to be of value.
methods for doing this have been proposed and discussed in the open literature. We thus are able to design thorium cycles having effective conversion ratios ranging from about 0.88 to 1.0 (including processing losses). It so happens that both Pu and U initiated and topped cycles result in virtually identical burnups and have very similar feed and discharge isotopic compositions (see Table I) although the utilization of mined uranium by means of enriched uranium is more efficient than by means of Pu extracted from spent fuel. The reason for this is not difficult to trace. In a uranium enrichment plant it is possible to extract ~5 g of 235U from each kilogram of natural uranium, whereas the spent fuel from the natural CANDU reactor contains only 2.7 g of fissile Pu per kg of initial uranium. Of course, the natural uranium fuel in the intervening period has produced useful energy, but the detailed calculations show that when proper allowance is made for this factor, the utilization of mined uranium is more efficient if separated 235U rather than fissile Pu is used. This fact is illustrated in Fig. 1, which contains relevant information on uranium resource utilization in relation to the type and quantity of fissile material used, fuel burnup and processing losses. It should be noted that processing losses should be kept below 1% if a burnup of ~10 MWD/kg is to be achieved with the SSET cycle. That particular graph illustrates the supply conditions for a static nuclear system (i.e., one that is not growing), but it serves to illustrate the resources utilization efficiency of the thorium cycle relative to the once-through natural uranium cycle in CANDU, and to indicate the basic superiority of 235U versus fissile Pu. However, in assessing the final route to be chosen into the thorium cycle, there are considerations in addition to those of basic physics.

In the calculations we have done thus far, we discard all Pu and do not recycle it (a) because the quantities are small compared to the 235U and 233U fissile isotopes, and (b) the Pu is of rather poor quality in the sense that it contains more than 50% 240Pu and therefore its parasitic burden outweighs its potential usefulness as a fertile source material for 239Pu. There is, however, one area where one or two recycles of Pu may be beneficial and that is in reducing the fissile inventory required to establish an equilibrium cycle. Preliminary calculations indicate that the Pu inventory may be reduced by ~10% by recycling the Pu twice; further recycles do not reduce the inventory requirement. Inventory, in the sense used here, is the one defined by Critoph in his Salzburg paper, "...the difference between actual requirements over a fairly long period of time and the requirements determined from the equilibrium net fuel rates applied
from the in-service date.' The inventories given in Table I are for zero delays in the recycle of fissile material and 100% load factor. The reader can, if he wishes, correct these inventories to allow for delays and different load factors by adding a term that is proportional to the product of the load-factor, the delay-time, and the production rate of fissile material in the reactor. When this is done it will be found that the inventories for the SSET cycles are in fact greater than those for the intermediate or high burnup cases simply because of the lower burnup of the SSET cycle, which in turn implies that a greater proportion of the total fuel cycle time is spent out of the reactor.

So far we have examined the static case, but it is also important to examine the effects of system growth rate on the annual uranium requirements. This we have done in Fig. 2 for a load factor of 0.7, an out-reactor delay of one year, processing losses <1%, and for a range of equilibrium growth rates. We have also thought it useful for comparative purposes to include on the same graph the situation for the PWR on a once-through cycle and also in combination with an FBR (see Table II), the characteristics of which are such that it could sustain an equilibrium system growth rate of 3 to 4%/yr without the need for additional Pu from converter reactors. Similar calculations have also been made for the CANDU natural uranium reactor in combination with the same FBR. The range of thorium cycles in CANDU shown in the figure broadly covers the band of possibilities. Not shown on the graph, but perhaps worth mentioning, is the characteristic of a slightly enriched, once-through CANDU (~1.2 wt% $^{235}$U) which would further reduce the uranium requirements by about 20 to 25% compared to the once-through natural CANDU. These graphs essentially rank the various reactors and fuel cycles in their ability to conserve uranium. Note that the "best" combination is the CANDU plus FBR system simply because the natural CANDU reactor is a very efficient producer of plutonium (about a factor of 1.7 greater than LWRs) and this, in combination with its basic neutron economy, makes it a very efficient springboard from which to launch advanced fuel cycles, be they thorium or fast breeder cycles. What is not considered here, but which must also be assessed by those engaged in long-term planning, are the supporting facilities, such as reprocessing and active fabrication plants, and isotopic separative capability required to put into practice any of these uranium conservation

![Graph](https://via.placeholder.com/150)

**Fig. 2.** This graph gives the annual mined uranium requirements, Mg U/a, to support 1 GW(e) of nuclear power system in a system which is expanding at the indicated growth rate. The system may consist of only one reactor type, such as the natural U CANDU, or it may consist of two reactors, say CANDU plus FBR.

**TABLE II**

Fast Breeder Reactor Characteristics Used in This Paper

*(Liquid-Metal Fast Breeder Design Study, General Electric GEAP-4418)*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Thermal Specific Power (core and blanket)</td>
<td>44.2 kW/kg</td>
</tr>
<tr>
<td>Burnup - averaged over core and blanket</td>
<td>37.4 Mwd/kg</td>
</tr>
<tr>
<td>- core</td>
<td>113 Mwd/kg</td>
</tr>
<tr>
<td>- axial blanket</td>
<td>10 Mwd/kg</td>
</tr>
<tr>
<td>- radial blanket</td>
<td>4.5 Mwd/kg</td>
</tr>
<tr>
<td>Fissile Pu Inventory</td>
<td>2.93 Mg/GW(e)</td>
</tr>
<tr>
<td>Annual Fissile Pu Supply Rate (100% load factor)</td>
<td>1.26 Mg/GW(e)</td>
</tr>
<tr>
<td>Annual Fissile Pu Production Rate (100% load factor)</td>
<td>1.47 Mg/GW(e)</td>
</tr>
<tr>
<td>Compound Doubling Time - 70% load factor</td>
<td>19.5 years</td>
</tr>
<tr>
<td>- recycle delay time 1 year</td>
<td></td>
</tr>
<tr>
<td>- 1% processing losses</td>
<td></td>
</tr>
</tbody>
</table>
Thorium Fuel Cycles in CANDU

Fabrication Problems Peculiar to Thorium

Whereas natural uranium fuel involves but small amounts of protection for the fabricators of this fuel, the recycle of \(^{238}\)U (and of thorium itself) demands remote handling in shielded facilities, typically three feet of concrete will be required, and it will be economically desirable to incorporate much automation into the process. The source of the trouble is buildup of the \(^{234}\)U isotope, which decays with a 70-yr half-life into \(^{230}\)Th, which in turn gives rise to a progeny of \(\gamma\)-active daughters, the most noxious of which is \(^{228}\)Th having a very penetrating \(\gamma\) photon of 2.6 MeV. The production of \(^{230}\)Th in the reactor is initiated by (a) an \(n,2n\) reaction on \(^{233}\)U, (b) by a direct \((n,2n)\) reaction on \(^{235}\)U, and (c) by an \((n,\gamma)\) reaction on \(^{233}\)Th (if there is any present in the thorium). The first two reactions proceed by way of fast-neutron interactions and the third by thermal-neutron captures. In the fuel cycles considered in this report, the predominant route for \(^{230}\)Th formation is by routes (a) and (b), and the presence of \(^{232}\)Th adds but little to the activity and required protection.\(^{26}\) However, if one is interested in producing low-activity \(^{230}\)U for ease of handling in an experimental program, then one should irradiate for short periods of time, in as high a thermal flux as is achievable, thorium which contains no \(^{232}\)Th. And this is of course what was done in the U.S. to produce \(^{235}\)U for the light-water breeder reactor at Shippingport.\(^{27}\)

The thorium discharged from the reactor contains a few ppm of \(^{230}\)Th and the activity could complicate the ceramic-powder preparation route unless it were allowed to decay for a period of about 20 years, which would reduce its activity by a factor of about 1000 since its half-life is 1.9 years. However, since the fabrication route for the thorium cycle has to be remote anyway, there may be a case for remote production of reactor-grade thorium without having to store the material for 20 years. The economics of this has to be assessed.

Uranium Savings to Be Derived from Thorium Cycles (Method of Scenarios)

In examining the potential for thorium cycles to reduce our dependence on uranium and to provide long-term security of economic feasible supply, it is necessary to examine the problem in the context of some plausible futures and also to relate these scenarios to current knowledge about the extent of our known uranium resources. While we cannot predict the future, we shall cover a range of reasonable scenarios and examine the uranium supply problem from the framework of these scenarios. Ultimately one has to exercise judgment based on present knowledge and a range of reasonable guesses about the future. Proof in these matters is not possible, but the same is true also of many spheres of human activity and in matters pertaining to the well being of society.

Three scenarios are postulated for the 21st century and are shown in Fig. 3.

A. Assumes the installed nuclear capacity in Canada by the year 2000 will be 60 GW. Thereafter there is no further growth in nuclear capacity.

B. Assumes 2%/yr growth in nuclear capacity up to the year 2050, and then 1%/yr growth to the end of the century.

C. Assumes 4% growth to the year 2050 and then no further growth to the end of the century.

All scenarios assume that the thorium cycles (or advanced cycles in general, such as the FBR) can be introduced in the year 2000 with 1% of the capacity then in place; namely, 800 MWe. Thereafter the new fuel cycles can penetrate the system more or less completely in a period which I have assumed to be 30 years. (A Fisher-Pry penetration model\(^{28}\) was used for this paper, but we believe this is an area that requires further analysis and elucidation with respect to the introduction of advanced fuel cycles.) The average capacity factor for the system is assumed to be 75% over the period of interest, and the life of the reactors is equal to their amortization period. They may of course last longer, but they then may only be used infrequently as sources of power if the newer systems are more economical. Note that scenario C would give each Canadian an average of about 8-kW nuclear electric in the year 2050 if the population reaches 50 million by that time. Scenario A would confer slightly more than 1-kW nuclear electric in the year 2050, or 2 kW if the population did not increase beyond the end of this century.

What this implies in terms of committed uranium is shown in Fig. 4 if the nuclear system were confined to the once-through cycle. Superimposed are the most recent estimates of Canadian uranium reserves and resources published by the Department of Energy, Mines and Resources. Table III also shows the history of these resources.

![Fig. 3](image-url)
THORIUM FUEL CYCLES IN CANDU 273

Fig. 4. The cumulative uranium commitments shown are for the natural uranium cycle in CANDU based on a forward 30-year supply requirement for each reactor committed. The dashed horizontal lines are taken from Table III for the June 1977 published estimates.

Table IV summarizes the cumulative consumption for the once-through natural uranium cycle in CANDU as a function of year for the three scenarios. The other columns in the table show the amounts of uranium that can be saved if the thorium cycle is adopted at the turn of the century. Also shown for comparison are the results of adopting an FBR having the characteristics shown in Table II.

For all scenarios, the uranium savings are large. For the growth scenarios, the breeder does a little better over the century than the thorium cycles, but the differences are small in proportion to the total resource requirements. During the penetration period of 30 years all cycles (for a given scenario) do more or less equally well, and during periods of no growth the SSET cycles are comparable to the FBR.

ECONOMICS

It is difficult at this time to be categoric about the economics of the thorium cycle since there are uncertainties in the costs of reprocessing and active fabrication. We have made preliminary estimates of what these might be, but we are still in the assessment stage and are reviewing the economics of advanced cycles as a progressive exercise which will depend on our own and others' experience. What is shown in Figs. 5 and 6 is a set of breakeven graphs for the various thorium cycles as a function of uranium price and the cost of reprocessing plus active fabrication penalty (natural uranium fabrication costs have, as it were, been factored out of the comparison). The ground rules on which the breakeven exercise is based are given in Table V. For the assumptions used, the Pu or "92U routes seem to give about the same fuel cycle costs. If the combined processing and fabrication penalty can be held to <350 to 400$/kg (1978 $, utility-financing), then the intermediate or high burnup thorium cycle begins to compete with the once-through cycle when uranium reaches a price of about 200$/Vtg U. That situation could well prevail toward the century. For the growth scenarios, the situation seems precarious.

TABLE III

<table>
<thead>
<tr>
<th>WE/IAEA Terminology</th>
<th>Reasonably Assured</th>
<th>Estimated Additional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Terminology</td>
<td>Measured plus Indicated</td>
<td>Inferred plus Prognosticated</td>
</tr>
<tr>
<td>1974</td>
<td>62,000</td>
<td>158,000</td>
</tr>
<tr>
<td>1975</td>
<td>74,000</td>
<td>173,000</td>
</tr>
<tr>
<td>1976</td>
<td>83,000</td>
<td>182,000</td>
</tr>
</tbody>
</table>

*These are the latest estimates issued by the Department of Energy, Mines & Resources, Canada. The reports on uranium reserve and resource estimates are usually published in the middle of the year and give results applicable up to the end of the previous year.

Inferred from (a) and OECD/IAEA, Uranium: Resources, Production and Demand, 1975.
**CONCLUSIONS**

It is evident that substantial quantities of uranium can be saved if we go via the thorium route. This is beneficial both to the long-term security of economic fissile supply for the domestic market and also to the overseas market since uranium saved can, in principle, be made available for export.

There appears to be no feasibility problem with regard to introducing the thorium cycle into the CANDU design. The work to date has uncovered no problem that would compromise nuclear reactor safety standards as presently practiced in Canada. Because of its activity, the fuel would have to be remotely fueled into the reactor, and freshly fabricated fuel would have to be shipped in shielded containers to the power station and stored there in a shielded room until it is charged into the reactor.

It would appear that the economic timing of the cycle and the time required to put the technology onto a commercial basis should coincide about the turn of the century, provided we move ahead now with the necessary research and development, especially in the fields of reprocessing and active fabrication.

The self-sufficient cycle demands tighter neutron economy than hitherto practiced in the natural uranium cycle. This could be accomplished in several ways, such as by increasing the D,0 purity, by reducing the Zr inventory, in the core, and by using thorium absorber rods. However, the economics and resource picture suggest that, for the immediate application of the thorium cycle, the preferred route might be an intermediate burnup cycle.

For the scenarios examined there is no clear evidence to prefer the FBR over the thorium cycle in CANDU. For a country like Canada, the optimum route might be thorium. This may strike a balance between securing our own reserves, permitting overseas sales of uranium, and avoiding the introduction of a major new reactor type.

Clearly, the unfolding picture of uranium discoveries in Canada over the next several years will have an important effect on future decisions, but based on present evidence one must conclude that new discoveries of uranium would have to be very substantial indeed to avoid or postpone the decision not to go for advanced cycles.

**APPENDIX**

**CANADIAN DEFINITIONS OF URANIUM RESERVES AND RESOURCES**

Measured (Proven) Ore comprises ore from which tonnage is computed from dimensions revealed in outcrops, trenches, workings, or drill holes, and for which grade is computed from adequate sampling. The sites for inspection, sampling, and measurement are so closely spaced on the basis of defined geological character that...
Fig. 5. Breakeven curves for three thorium cycles in CANDU having different burnups. These cycles are initiated and topped by fissile Pu extracted from natural U CANDU fuel. The vertical scale is the sum of the reprocessing costs and the penalty to fabricate active thorium fuels over and above the fabrication cost of natural uranium fuel bundles. Above and to the left of the lines the once-through natural U cycle is cheaper. The lines themselves denote the breakeven boundaries. Numbers on the lines indicate levelized fueling costs corresponding to uranium price, reprocessing plus fabrication penalty, and the particular fuel cycle.

Fig. 8. Breakeven curves for three thorium cycles in CANDU having different burnups. These cycles are initiated and topped by enriched U. The vertical scale is the sum of the reprocessing costs and penalty to fabricate active thorium fuels over and above the fabrication cost of natural uranium fuel bundles. Above and to the left of the lines the once-through natural U cycle is cheaper. The lines themselves denote the breakeven boundaries. Numbers on the lines indicate levelized fueling costs corresponding to uranium price, reprocessing plus fabrication penalty, and the particular fuel cycle.

TABLE V
Assumptions Used in Deriving Breakeven Economics

1. Uranium price, reprocessing cost, and active fabrication penalty (in excess of cost to fabricate natural U) are treated as variables.
2. Thorium cycles introduced commercially in year 2000, when total installed nuclear capacity is 60 GW(e).
3. Scenario B used for analysis.
4. Thorium cycles completely penetrate the nuclear system in a period of about 30 years. Since the system is continually growing over the period of interest, there is always a need for natural uranium reactors to produce Pu for the Pu-topped thorium reactors. In the case of Pu-topping all reactors are thorium burning in 30 years assuming availability of enrichment capacity.
5. Effective discount rate = 4% (difference between interest and inflation).
6. Comparison between cycles is based on method of levelized costing from start of introduction of cycles to end of period.
7. The results are expressed in constant 1978 $. 
8. Price of thorium is assumed to be 35$/kg based on a 20-yr recycle time. The cost of thorium is not an important parameter.
9. A one-year delay is assumed in recycling fissile material.
10. Natural uranium fuel fabrication (excluding U) is 45$/kg.
the size, shape, and mineral content are well established. It must be stated whether the tonnage and grade refer to in situ or to recoverable ore, with recovery factors shown and explained.

Indicated (Probable) Ore comprises ore for which tonnage and grade are computed partly from specific measurements, samples, or production data, and partly from projection for a reasonable distance on geological evidence. The openings or exposures available for inspection, measurement, and sampling are too widely or inappropriately spaced to outline the ore completely or to establish its grade throughout.

Inferred (Possible) Ore comprises ore for which quantitative estimates are based largely on broad knowledge of the geological character of the deposit and for which there are few, if any, samples or measurements. Estimates are based on assumed continuity or repetition for which there is geological evidence; this evidence may include comparison with deposits of similar types. Bodies that are completely concealed but for which there is some geological evidence may be included. Estimates of inferred ore should include a statement of the specific limits within which the inferred material may lie. These limits vary depending on the characteristics and knowledge of the ore bodies.

Prognosticated Resources comprise estimated tonnage of deposits that are located beyond specific limits established for inferred ore. They may include tonnages of portions of identified ore bodies or of concealed satellite ore bodies, existence of which can be geologically assumed. Parameters of the prognosticated resources are, as a rule, derived from identified deposits by extrapolation or by quantification of geological information.

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