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THORIUM FUEL CYCLES IN CANDU REACTORS: A REVIEW

L'auteur compare les caractéristiques des divers cycles de combustible avancés pouvant être employés dans les réacteurs CANDU.

by

MICHAEL S. MILGRAM

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

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Cycles de combustible au thorium pour les réacteurs CANDU: compte rendu

par

Michael S. Milgram
Département de mathématiques appliquées
L'Energie Atomique du Canada, Limitée
Chalk River, Ontario, KOJ 1JO

Résumé

L'auteur compare les caractéristiques des divers cycles de combustible avancés pouvant être employés dans les réacteurs CANDU.

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Michael S. Milgram
Applied Mathematics Branch
Atomic Energy of Canada Limited
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ABSTRACT

The characteristics of various advanced fuel cycles possible in CANDU reactors are compared.

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M.S. Milgram
Applied Mathematics Branch
Atomic Energy of Canada Limited
Chalk River, Ontario K0J 1J0

Introduction

From the earliest days of nuclear power development it has been recognized that world reserves of cheap or easily mined ore bodies containing the fissile isotope U235 are limited, and so the amount of energy available through the medium of nuclear reactors is finite. Just what that finite limit is, is a matter of opinion, ranging from shortages[1] in the year 2020, to essentially unlimited quantities[2] extractable from dilute sources such as seawater or non-mineralized rocks. Basically, the computation of reserves is a matter of economics, since the availability of any material is essentially unlimited if the price is high enough, so the cost of competing sources of energy must be predicted in any evaluation of fissile reserves.

In contrast to other energy sources however, nuclear reactors have the unique feature that the spent fuel contains valuable fissile material which can be recycled, through "reprocessing" in which the fissile material is extracted from the waste, and "fabrication" in which new fuel is constructed.

If recycling of spent fuel were to be implemented, the energy available from nuclear power would be increased by a factor of about 50, since nuclear power would effectively be decoupled from dependence on reserves of U235. The difficult question concerning this implementation becomes one of the competitive economies of fuel recycling compared to the cost and availability of reserves, and the availability of energy from other competing sources such as fusion[3], spallation[4], solar power and conservation[5]. Since the development of new types of fuel cycle is a long term proposition (20-30 years), and the economic climate many years hence is a matter of conjecture, prudence dictates that development work on the new cycle continue over a period of years in order to highlight areas of potential difficulty and prove at least the economic feasibility of the components of the cycle. Thus the technology for implementing such cycles will be available when, and if, the need arises. As a consequence, Atomic Energy of Canada Limited (AECL) has been evaluating and investigating the characteristics of various cycles in order to isolate weaknesses and strengths of each. Some of these are described in the next section.

The Contenders

Attracted by the flexibility[6] of the CANDU-PHW* design, analysts of advanced fuel cycles (AFC) cling to the philosophy of utilizing a new kind of fuel in a known and well-developed reactor. This eliminates tangential paths such as the development of liquid metal (sodium) cooled fast breeder reactors[5]

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*A glossary of acronyms is presented on p. 15

(LMFBR), or closely packed pressure vessel reactors with heavy water coolant[7,8], for which development costs would be very large. This philosophy also eliminates many other possibilities, because the neutron energy spectrum of a CANDU-PHW is invariably well thermalized, and of the four practical fissile isotopes, U233 has the highest value of the multiplication factor η in such a spectrum (Table 1). Since the parameter η-1 is a measure of the number of excess neutrons available for breeding after providing for neutrons to sustain the nuclear chain reaction, the most promising investigations focus on thorium fuel cycles.

Table 1: η for Four Fissile Isotopes

	2200 m/s	LMFBR Neutron Spectrum
U233	2.28	2.31
U235	2.07	1.93
Pu239	2.11	2.49
Pu241	2.15	2.72

Thorium is a fairly common metal[9] that is often found in conjunction with uranium in orebodies. It has the property that after the principle isotope Th232 captures a neutron, it transmutes into the fissile isotope U233 by radiative capture and sequential β^- decay. U233 has the desirable property outlined earlier; unfortunately it is unstable with a half-life of 1.6x10^5 years and so does not occur naturally. This is the greatest disadvantage of thorium fuel cycles - they rely on a material which must be created before it can be used.

In order to overcome this difficulty a number of fuel cycles have been devised to bridge the transition from a natural uranium fuelled CANDU-PHW to a reactor fuelled with mixed thorium-U233 oxide. They fall into two categories, illustrated schematically in Fig. 1.

The first category consists of transition reactors fuelled with plutonium (Pu) created in natural uranium fuel. The plutonium is mixed with thorium which is irradiated to eventually form U233. This U233 can be extracted and mixed with thorium and varying amounts of plutonium (or highly enriched uranium[*]) topping to adjust the burnup of the fuel according to the dictates of local economics. A possible sequence is shown in Figs. 1a and 1b. An important physical principle governs the irradiation of Pu-U233/Thorium mixtures. Irrespective of the burnup (provided only that it exceeds 10000 MW.d/Mg[†]), U233 eventually builds up to an equilibrium level of $\sim$1.5% enrichment in the thorium. Thus if the initial fuel contains slightly less than 1.5% U233, the reactor will

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[*] The most suitable candidate is 93% enriched uranium. Because of the risk of proliferation and diversion, in practice the maximum enrichment likely to be available in the foreseeable future is 20% - this is known as a denatured fuel cycle. (See also article by J.A.L. Robertson, Preventing Nuclear Weapons Proliferation, The Energy Newsletter, Vol. 3, No. 3, October 1982.)

[†] Megawatt day per megagram.

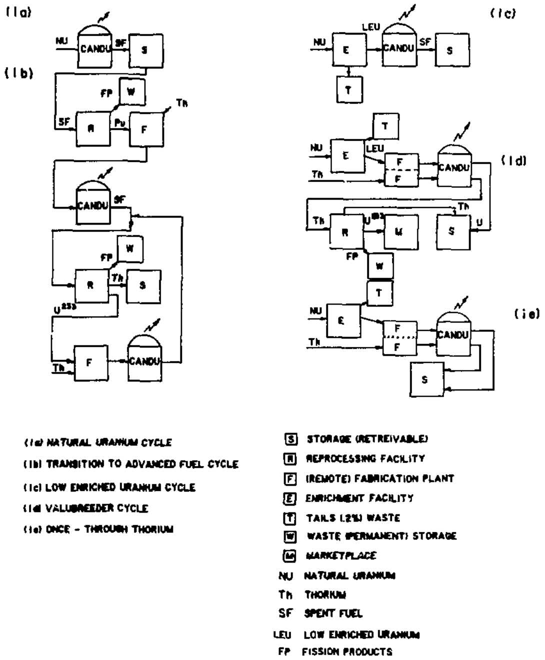

Fig. 1: Possible configurations of reactors in Advanced Fuel Cycles.

breed more U233, but the burnup will be low. If the initial fuel contains more than 1.5% U233, some U233 will be consumed, but the burnup will be high. Since U233 is a scarce material, in practice this would never be done. The initial U233 enrichment would be kept at about 1.5%, and varying amounts of plutonium (or highly enriched uranium) added. Thus U233 is always conserved, and plutonium stocks are depleted.

The second category of fuel cycles seeks to eliminate the intermediate step of employing plutonium fuelled reactors, by introducing distinct and separate fuels, and utilizing the known technology of enrichment. The first reactor in such a sequence consists of a CANDU-PHW operating on a low enriched uranium (LEU) cycle[10]. In this concept, the proportion of U235 is increased from its natural concentration of .71% to between .9% and 1.2% of the uranium. With this enrichment it is possible to extract about 25% more energy from a given amount of uranium mined compared to the natural uranium fuel cycle, at about the same cost[11], and delay the need for thorium cycles.

An interesting variant on this approach is the tandem fuel cycle[12,13], where the fresh fuel for the reactor in Fig. 1c consists of spent fuel from a Light Water Reactor (LWR) initially fuelled with ∿3% enriched uranium. This cycle relies on the fact that spent LWR fuel still has a content of ∿1.4-1.6% in fissile materials so that if such spent fuel were to be reprocessed and refabricated, it would be sufficiently reactive to be subsequently burnt in a CANDU-PHW. Overall, about 10,000 MW.d of energy could be extracted from one Mg of natural uranium in a tandem cycle, about a 30% increase over a once-through natural uranium CANDU.

Another possibility in the second category of fuel cycles are the Valubreeder[14] cycles (Fig. 1d) and the once-through thorium cycles[15] (OTT) (Fig. 1e). In the Valubreeder, enriched uranium is irradiated separately and at a faster feed rate than is the thorium. This allows the thorium to breed U233 and burn this material in situ, thereby gaining an immediate advantage in extractable energy as well as creating a supply of U233. (However, this does create some as yet unsolved engineering problems related to the fuel management of such reactors). Since the effect of this cycle is to transmute enriched U235 into the more valuable U233, the economics are predicated on receiving an economic credit for U233, which implies the existence of a marketplace and a reprocessing industry.

The OTT cycle[15] is a relative of the Valubreeder, but recognizes that reprocessing is an industry that is as yet commercially undeveloped. The economics of the OTT cycle are arranged so as to justify the creation of a U233 stockpile at a competitive cost to natural uranium and LEU cycles, without taking credit for U233 created, in analogy to the (once-through) natural uranium cycle (Fig. 1a) in which a plutonium stockpile is being created, with no credit received for the spent, plutonium bearing, fuel. In either of these once-through cycles, a "mine" of plutonium and/or U233 is being created for the future if it is ever needed, with no obligation that it be used unless needed.

A final possibility among the advanced fuel cycles are the Pu-U cycles where plutonium is recycled with natural uranium instead of thorium in Fig. 1b; all references to U233 and Th in this future would be replaced by references to plutonium and uranium.

As described previously, it is possible to view the first generation natural uranium or the OTT cycles as progenitors of a mine of fissile material for the future. In the case of Pu-U cycles, it is possible to recycle the plutonium with very little addition of extra plutonium; these are the (nearly) self-sufficient (Pu/U(s)) cycles depicted in Fig. 2. In such cycles, the ratio

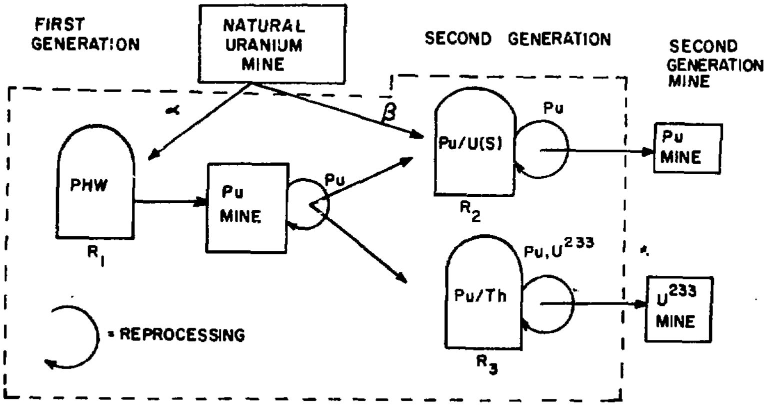

Fig. 2: Natural uranium is burned in a PHW to produce a plutonium mine. The plutonium is eventually exploited in Pu/U reactors, with excess plutonium diverted to Pu/Th reactors.

of any fixed quantity of uranium that can be committed to a second generation of reactors is a variable measured by the ratio α/β in the figure. This ratio is a measure of the conscious decision by society to allocate a fixed resource to the present (if $\alpha=1$, and $\beta=0$) or to the future (if $\beta>\alpha$). There will be a certain value of β which cannot be exceeded (e.g. $\beta=1$ is physically impossible since there would be no pre-existing stockpile of Pu). Any excess Pu in such a system may be used to fuel Pu/Th reactors, in a manner illustrated in Fig. 1b.

In contrast, a U233/Pu mine created by a OTT cycle depicted in Fig. 3

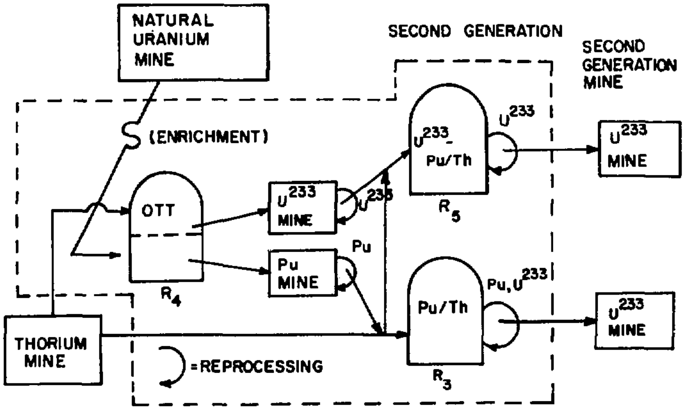

Fig. 3: *Use of a once-through thorium reactor to create a mine of U233 and* Plutonium. The products are eventually irradiated in U233-Pu/Th reactors; excess Pu is used in a Pu/Th reactor.

permits the full exploitation of a fixed resource in the first generation, without prior allocation. The mine of fissile material would then be used to fuel a U233-Pu/Th reactor in the second generation if needed, with any excess plutonium being diverted to Pu/Th reactors. A similar comment applies to the plutonium created by a once-through LEU or natural uranium first generation reactor, if the plutonium were used in a Pu/Th reactor.

The Characteristics

We are now in a position to examine the burnup characteristics of some of the cycles described in the previous section. The most important of these relate to the tradeoff between achievable fuel burnup and fissile material topping of thorium fuel in the form of plutonium or U235. The amount of topping can furthermore be related to the amount of uranium mined to obtain this topping. In Fig. 4 such a comparison is presented for U233-Pu/Th and U233-U235/Th systems. The characteristics cited earlier are immediately obvious - high burnup (and lower costs) requires (relatively) higher consumption of fissile material. At the extreme left are the self-sufficient equilibrium thorium (SSET) cycles[17] which require no consumption of uranium ore, but have low burnup and high reprocessing requirements. At the high burnup end of the scale, uranium requirements are at most only 30% of those of a natural uranium fuel cycle. The figure also indicates a fairly sensitive dependence on the magnitude of losses during reprocessing and fabrication.

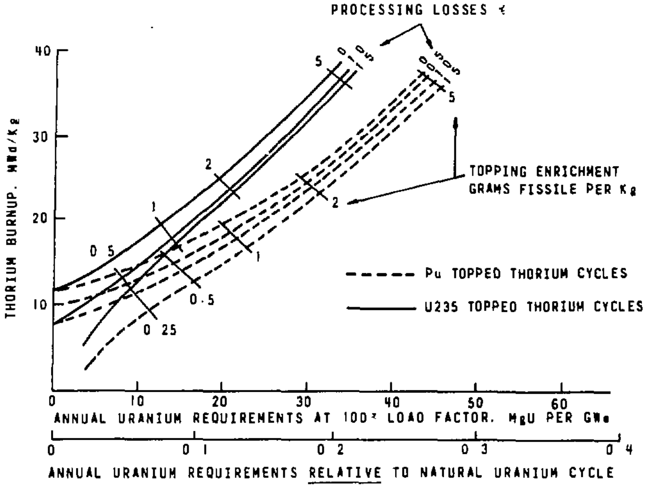

Fig. 4: Comparison of the annual uranium requirements for thorium cycles initiated and enriched with fissile Pu from spent natural uranium fuel, or 93% enriched uranium fuel.

A similar calculation can be performed for the LEU and OTT cycles. Fig. 5 shows the uranium consumption of the LEU cycle as a function of the

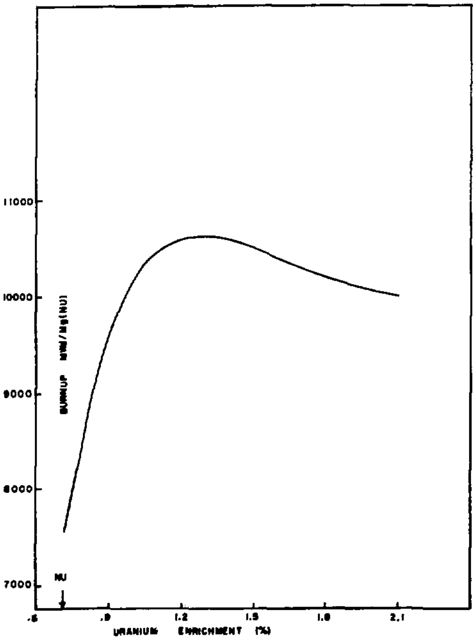

Figure 5: Attainable burnup of LEU (and OTT) cycles as a function of the enrichment of the fuel.

Fig. 5: Attainable burnup of LEU (and OTT) cycles as a function of the enrichment of the fuel.

enrichment of the uranium used, indicating a $\sim$25% decrease in uranium consumption. The OTT cycles are chosen to be competitive with LEU cycles over this range of enrichments, so the resource requirements of OTT cycles would approximate the curve of Fig. 5.

From these figures, we can trace a natural evolutionary progression of reactor fuel cycles in the future. At present we have the once-through natural uranium (NU) fuel cycle consuming $\sim$160 g NU/ekW-a[*]. A transition to an LEU, tandem or OTT cycle would reduce the consumption to about 120 g NU/ekW-a, without requiring a sally into the technology of commercial reprocessing. With natural uranium or LEU a mine of plutonium is created; with OTT a mine of U233 and plutonium is formed. At some point in the future these mines would be tapped using either (a) a high burnup Pu/Th reactor reducing the uranium consumption to $\sim$30 gm NU/ekW-a, or (b) a U233-Pu/Th reactor of varying burnup and topping. In the far future, the self-sufficient U233/Th cycles promise complete independence from natural uranium stocks, if the growth of the power system were to cease.

One other factor that could conceivably affect the ranking of such cycles, is the concentration of fissile material in the spent fuel. Spent uranium fuel is a very poor "ore" to mine for its plutonium content, because its fissile content is low[10], varying between 2.7 and 3.5 g/kg, depending on the source of the spent fuel. In contrast, the U233 content of spent thorium fuel is about 15 g/kg, so it is a much richer lode of fissile material. Consequently, throughput in a plant devoted to thorium reprocessing would be about 20% of the throughput of a plant whose intent it is to extract plutonium. In the early years of a reprocessing industry, this factor could tip the scales in favour of OTT cycles.

In order to substantiate the above evolutionary scenario it is important that the costs of such cycles be investigated. In addition, in a nonstatic system of reactors with a variety of fuels, it is necessary to study the impact of the new reactor fuelling schemes on the system, rather than in isolation. These two aspects are discussed in the following two sections.

The Costs

The incremental costs of an LEU fuel cycle can be mainly attributed to the cost of enrichment, as measured by the cost of a separative work unit[†] (SWU). The benefit is higher production of energy from a given amount of uranium. In Fig. 6, the breakeven costs of a natural uranium versus LEU cycle are shown at different periods of time, indicating that at the present, LEU is marginally more attractive than is the natural uranium cycle.

The OTT cycles may be subdivided into three categories:

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[*] electric kilowatt year.

[†] (SWU) is a measure of the effort required to enrich uranium from a certain feed enrichment - usually natural - to a final enrichment, with a waste stream (tails) of given enrichment (usually 0.2%).

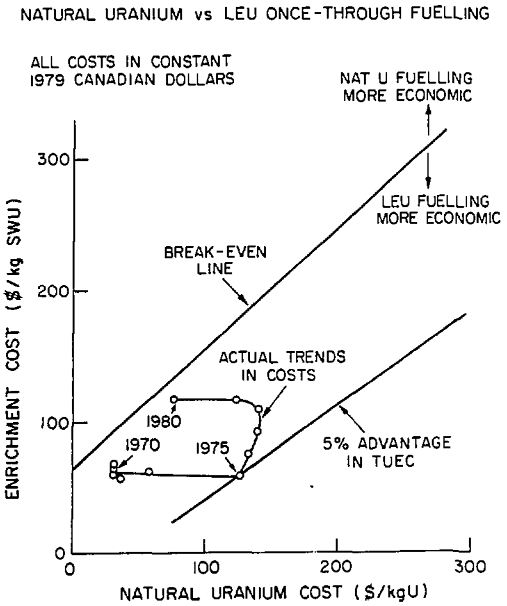

Fig. 6: Breakeven costs for natural uranium and LEU once-through fuel cycles.

- "throwaway" having costs and resource utilization better than LEU,
- "stowaway" having costs and resource utilization equal to LEU,
- "layaway" having costs and resource utilization inferior to LEU.

The enrichment of the feed fuel in an OTT cycle is variable, and again the tradeoff is between the cost of a SWU and the cost of uranium compared to the benefit of better resource utilization. Fig. 7 depicts the costs of natural uranium, LEU and OTT cycles at different uranium enrichments for several combinations of costs of uranium and SWU's at two interest rates. Here we see that at the present (lower left) all three candidates are fairly competitive. As the cost of uranium increases (upper half) the LEU cycles have a distinct advantage, particularly if the cost of a SWU remain low (upper left). If both the cost of uranium and that of a SWU increases (upper right), we discover that it is cheaper to retain the natural uranium or LEU cycles and deplete the resource than it is to implement a OTT cycle and create a U233 stockpile. However if the OTT cycle had been implemented at an earlier time when both uranium and SWU costs were lower (lower left) the incremental cost of creating a stockpile would have been negligible. This is an example of the "over the hump" paradox about which more will be said later.

The cost of fuelling a reactor as it shifts from Pu-Th to U233-Th fuelling can also be estimated. In Fig. 8, the total unit energy cost (TUEC) is plotted as the percentage change compared to the cost of a natural uranium cycle, again as a function of the price of uranium. Two scenarios (high and low) were chosen[13] to represent estimates of the cost of refabrication and reprocessing. In an attempt to reduce inventory costs of the initial core, a second curve shows the TUEC under the assumption that the initial core is LEU with the

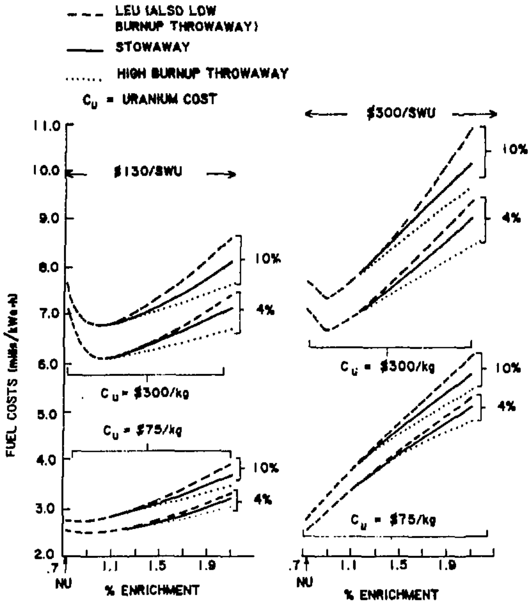

Fig. 7: Comparison of fuel costs of natural uranium, LEU and OTT fuel cycles as a function of fuel enrichment, assuming different prices for uranium, SWU's and interest rates.

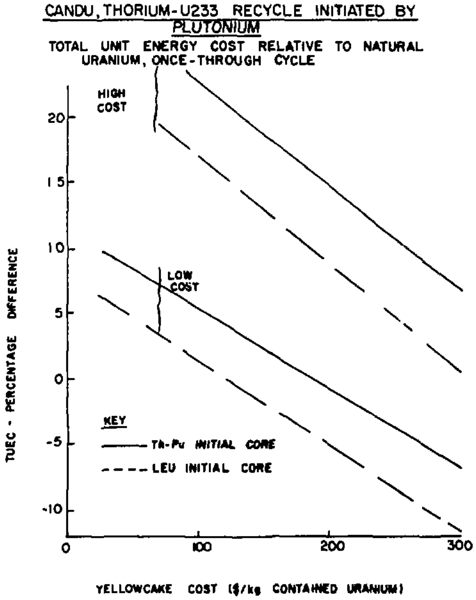

Fig. 8: Comparison of total unit energy cost (TUEC) of Pu-U233/Th and U235-U233/Th with natural uranium fuel cycles using two scenarios for the cost of reprocessing and fabrication.

plutonium eventually being recycled back into Pu-Th fuel, and then U233-Th fuel, a melange of figures 1b and 1c. The figure indicates a breakeven cost for U233-Th recycle cores if the price of uranium rises to between $200-400/kg assuming the initial core consists of Pu-Th fuel. A lower uranium breakeven price occurs with an initial core made up of LEU.

Finally we may consider in isolation cycles in which Pu-Th fuelling converts to U233-Th fuelling, and ask whether the economics favour the high, intermediate or low burnup cycles of Fig. 4. In Fig. 9 the breakeven costs of the three cycles are illustrated for a variety of assumed costs of uranium, and reprocessing. In all cases the higher burnup cycles become more competitive with natural uranium prior to the intermediate ones. The self-sufficient cycles are least competitive because of their great reliance on reprocessing, and as the figure shows, the price of uranium would have to rise significantly before self-sufficient cycles became competitive with natural uranium cycles. No calculations on the comparative economics of U233-Th reactors started with OTT are available.

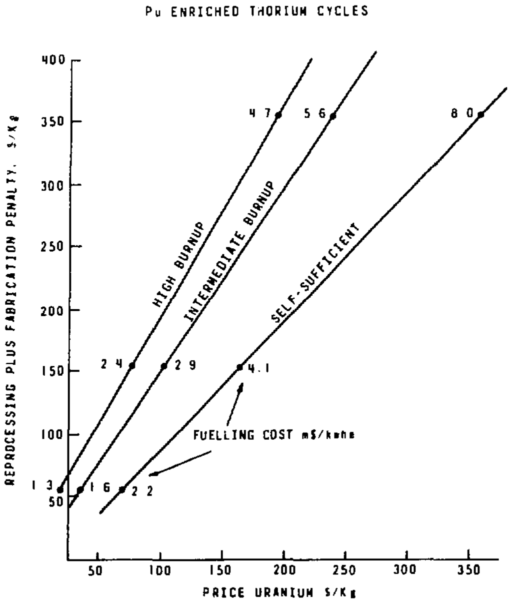

Fig. 9: Breakeven curves for three Pu/Th fuel cycles having different burnups. The vertical scale is the incremental cost of reprocessing and thorium fuel fabrication. Each line is a breakeven boundary - above and to the left of each line, natural uranium is cheaper.

This assessment of costs supports the evolutionary development of fuel cycles hypothesized in The Characteristics. The most likely cycles to be first realized are the least costly.

The Carrot

As we have seen, thorium fuel cycles with reprocessing are not economic unless or until the price of uranium rises by a factor of two to three. In contrast LEU and OTT cycles are marginally competitive at the present. Are there any compelling arguments arguments to offer for considering recycle thorium fuel cycles as an immediate option?

In Fig. 10 the cumulative uranium commitment for Canada is shown[18], for the years 2015 to 2050, for a variety of penetration rates[†] of the high burnup Pu-Th fuel cycle first introduced in the year 2000. This figure demonstrates that there is little incentive to increase Pu-Th penetration rates to greater than 10-12%, at which point cumulative uranium commitments will be between .6 and .8 Tg[††]. If the Pu-Th fuel cycle is not implemented, the required uranium

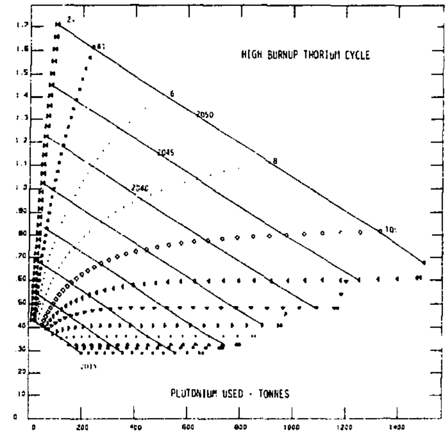

Fig. 10: Canada's uranium commitments for different penetration rates of a high burnup Pu-Th fuel cycle, at different years shown.

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[*] "Commitment" refers to the guaranteed 20 year supply of uranium required for any reactor committed for construction.

[†] "Penetration rate" is a constant describing the rate at which a new technology (Pu-Th fuel cycles) penetrates the remaining market within a Fisher-Pry model[19] of economic substitution. The "remaining market" refers to the nuclear portion of an electrical system. The nuclear penetration rate itself (into the electrical system) is assumed to be 11%, which approximates reactors committed to the year 1990. This also corresponds to a 3.7% growth rate of the electrical system which is below the historical norm.

[††] Teragram ≡ 10^9 kg.

commitment can be read by projecting each of the solid lines onto the left hand axis. For example, in the year 2020, Canada's uranium commitments would be respectively 0.6 Tg if the nuclear portion were entirely fuelled by natural uranium, and 0.5 Tg if high-burnup Pu-Th reactors with a penetration rate of 12% were deployed. In the succeeding 30 years, the cumulative uranium commitment would rise by a factor of three if all reactors were natural uranium, but by only 20% if the Pu-Th route were followed. To place these figures in perspective, note that Canada's uranium reserves in all categories are thought[16] to total ∿.9 Tg at a price of less than $156/kgU, and that Canada's (1980) established light and heavy oil reserves are thought to contain the energy equivalent of about 0.08 Tg of uranium[18,22].

The impact of using LEU or OTT cycles without exploiting the mine of fissile material can also be estimated from the figure. This scenario would result in a less than 25% decrease in uranium commitments on the left hand axis, because of the better resource utilization of both these cycles.

A novel attempt has been made[20] to quantify the competing importance of nuclear power cost, cost of alternate energy sources, achievable burnup, inventory costs and resource utilization, by measuring the significance of future impact through the use of a variable discount rate. Fig. 11 presents a comparison of a figure of merit for candidate fuel cycles at three different discount rates. This figure of merit weights all the above factors and represents the present worth of the cumulative saving realized by using a nuclear rather than a non-nuclear source of energy. When the discount rate is low - great weight attached to future benefits - the high burnup U235/Th cycles (HEU/Th) have the

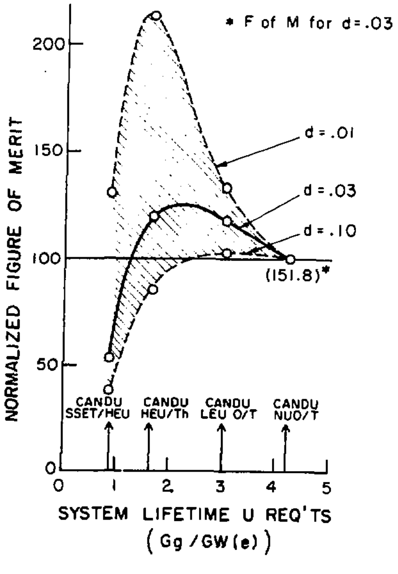

Fig. 11: Figure of merit (F of M) at three discount rates for four possible fuel cycles, *normalized to a natural uranium once-through* (NUO/T) CANDU reactor. The higher the F of M, the better the cycle.

best figure of merit. No similar calculations are available for Pu-U233 fuel cycles, but considerable work is available[20] on the sensitivity of the figure of merit to variations in the above quantities.

Many other strategies for implementing advanced fuel cycles have been proposed, and studied[16,21-24], and the overriding conclusion is that unless some sort of fuel cycle with reprocessing is implemented, a nuclear and electrical growth scenario is untenable. This would have profound effects on the prospects for economic stability and growth for the economy as a whole, because of the close correlation[25] between GNP and use of electricity. Furthermore, the penetration rate of advanced cycles is limited because of difficulties in matching the growth of ancillary industries such as reprocessing and fabrication with the need for the products of these industries in a growing economy. As might be expected, and as can be surmised from Fig. 10, any delay[18] in introducing the Pu-Th reactor has little effect in the first few years of the twenty-first century, but greatly exacerbates the problems of uranium reserve diminution and demands on satellite industries thereafter.

The Cane

In the last section we investigated the incentives for advanced fuel cycles and saw that they dealt mainly with a decreased demand for uranium, and an increase in Canada's available energy reserve by about an order of magnitude. Iconoclasts would point out that all is not so rosy.

In the first place, when Th232 or U233 is irradiated a fast neutron reaction occurs which results in the production of the radio-active isotope U232. In Canadian thorium ore, trace amounts of Th230 (Ionium), the daughter product of the natural decay of U238, are always found in thorium. This enhances the production of U232. This uranium isotope is a precursor of a family of α and β-active isotopes which includes the penetrating 2.6 MeV γ-ray associated with Tl208. Consequently, recycle fuel containing U233 cannot be fabricated except by remote operations (robots) in well-shielded caverns[26]. The cost of reprocessing and fabricating U233-Th fuel will be high and considerable research to establish its viability is required.

On the other hand, the competition to establish viable advanced fuel cycles is intense worldwide, because of the widespread acknowledgement that they will be needed sometime in the future[27]. Canada's lead in development of nuclear power could easily be broken by overseas advances in recycle fuel technology if they made CANDU uncompetitive as a result. Furthermore, potential overseas customers for CANDU reactors, for which the uranium supply/demand curve may differ greatly from Fig. 10, want assurance of a supply of uranium or recycle fuel into the foreseeable future, before committing themselves to purchase a CANDU reactor. Thus CANDU's position as a supplier of energy both domestically and abroad, must contain elements of doubt unless the viability of advanced fuel cycles is established. This factor must be acknowledged as part of the impetus to establish the feasibility of thorium cycles.

The Conundrum

In the previous sections we have described the multiple options possible with advanced fuel cycles, and examined their characteristics and costs. The promise of such cycles is a reduced dependence on fixed energy reserves of U235, the driving forces are competition and uncertainty. This uncertainty gives rise to an interesting paradox that characterizes all fuel cycle development today, and has been alluded to earlier. The "over the hump" paradox arises because society tends to procrastinate. The paradox, as applied to the implementation of advanced fuel cycles, observes that second generation reactors burn stockpiles of fissile material previously created, at a time when pressure to build such stockpiles would not have existed. By the time an advanced cycle is implemented, a large portion of the original resource will have been depleted, and options will be limited. In general, pressure to substitute a new cycle grows when about half the existing resource is spent.

Two examples of this paradox appear in the figures of the text. In Fig. 7 we saw that at the present there is no pressure to implement an OTT or LEU cycle, because natural uranium cycles are adequate and competitive. In the future, the cost of implementing such cycles will be higher than if they were implemented now, but there is no pressure to do so now. Future deferment will make matters worse. In Fig. 10 we saw that implementation of a Pu-Th fuel cycle would have a negligible effect on resource commitments for 20 years after it was first brought into service, at which time uranium commitments would appear to be plentiful. Yet many years later, the early deployment of such cycles would have a profound effect on availability of fissile uranium. In the case of Pu/U(s) cycles depicted in Fig. 2, a similar situation can be shown to exist[28]. Only if plutonium recycle begins at a very early stage of nuclear reactor development ($\beta/\alpha \sim 5$) can the advantages of this cycle be realized. In our society, today, there is no pressure for a "crash" deployment of plutonium recycle CANDU's and a commitment of 83% of all uranium reserves to such reactors. But without such a commitment, this option will be foreclosed. The entire analysis of advanced fuel cycles hinges on such questions as - what discount rate is realistic, when will reserves begin to deplete, how much uranium is economically exploitable, which route allows maximum flexibility, and a host of others. Our actions today, even our inactions will profoundly affect the future.

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Glossary of Acronyms

AECL	Atomic Energy of Canada Ltd.
AFC	Advanced Fuel Cycles
CANDU	Canadian-Deuterium-Uranium
F of M	Figure of Merit
HEU	High Enriched Uranium
LEU	Low Enriched Uranium
LMFBR	Liquid Metal Fast Breeder Reactors
LWR	Light Water Reactor
NU	Natural Uranium
NUO/T	Natural Uranium Once-Through
OTT	Once-through Thorium Cycles
PWR	Pressurized Water Reactor
SSET	Self-sufficient Equilibrium Thorium
SWU	Separative Work Unit
TUEC	Total Unit Energy Cost

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