AECL-6414

ATOMIC ENERGY
OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

SOME THORIUM FUEL CYCLE STRATEGIES

Quelques stratégies relatives au cycle de combustible au thorium

M.F. DURET and H. HATTON

Chalk River Nuclear Laboratories
Laboratoires nucléaires de Chalk River

Chalk River, Ontario

February 1979 février

ATOMIC ENERGY OF CANADA LIMITED

SOME THORIUM FUEL CYCLE STRATEGIES

by

M.F. Duret & H. Hatton

Chalk River Nuclear Laboratories
Chalk River, Ontario K0J 1J0
February 1979

AECL-6414

Quelques stratégies relatives au cycle de combustible au thorium

par

M.F. Duret et H. Hatton

Résumé

On traite dans ce rapport du problème de l'introduction au Canada d'un cycle de combustible nucléaire avancé à base de thorium. On souligne l'importance de certaines considérations comme le calendrier de la mise en oeuvre de ce nouveau cycle. De mauvais choix dans les variables pourraient donner lieu à des fluctuations commerciales indésirables dans certaines industries engagées dans la production d'énergie nucléaire.

L'Energie Atomique du Canada, Limitée
Laboratoires nucléaires de Chalk River
Chalk River, Ontario K0J 1J0

Février 1979

AECL-6414

ATOMIC ENERGY OF CANADA LIMITED

SOME THORIUM FUEL CYCLE STRATEGIES

by

M.F. Duret & H. Hatton

ABSTRACT

The report deals with the problem of introducing an advanced nuclear fuel cycle based on thorium in Canada. It is pointed out that timing and introduction rate are important considerations, certain choices of these variables leading to undesirable business fluctuations in some of the industries involved in the production of nuclear energy.

Chalk River Nuclear Laboratories
Chalk River, Ontario K0J 1J0
February 1979

AECL-6414

TABLE OF CONTENTS

SOME THORIUM FUEL CYCLE STRATEGIES

M.F. Duret & H. Hatton

SUMMARY AND CONCLUSIONS

The report AECL-6202 mapped out a range of possibilities for the future of nuclear energy in Canada. In that study the approach was to investigate the consequences of increasing both the nuclear contribution and the contribution of advanced fuel cycles as rapidly as appeared to be possible. Using Scenario 3 from AECL-6202 (which has an average annual growth rate of 2.7% in total energy) as a base, it is shown here that the high penetration rates used in that study would give rise to undesirable fluctuations in production for the three main nuclear industries:

(1) mining
(2) reactor construction
(3) fuel reprocessing.

In this study the penetration rate of the nuclear component of electricity generation is chosen as 11% (instead of 20% in AECL-6202) to approximate the reactor construction rate envisaged for Canada during the next decade. A high burnup thorium cycle is introduced in the year 2000 with a penetration rate arbitrarily chosen at 9% (25% in AECL-6202) to limit cumulative uranium commitments in 2050 to one million tonnes.

These ground rules lead to a forecast that the installed Canadian nuclear generating capacity in the year 2000 would be 40 GW(e).

The major benefit of using these lower penetration rates (compared with AECL-6202) is that the projected increases in the three main industries are all smooth during the period up to 2050; the violent fluctuations are either removed or postponed for many years.

The penalty paid for the slower introduction of nuclear energy is that it reduces the contribution that nuclear energy would make towards the total energy production in the short term and it increases the total amount of uranium eventually required.

The effect of delaying the introduction of an advanced thorium fuel cycle has also been investigated. The longer the delay, the greater the fluctuation in the annual uranium requirements and the more rapidly one is required to provide reprocessing facilities.

The present study shows that, given the timely availability of *about one million tonnes of uranium over the next century*, the nuclear contribution to scenario 3 could be supplied without crises by CANDU reactors with a suitable mix of natural uranium and thorium fuel cycles, providing the introduction of fuel processing is not too long delayed.

The stability of the fuel cycle industries is an important criterion in planning the introduction of advanced fuel cycles in Canada. Many other fuel cycle strategies could help smooth the fluctuations described. Options such as

(a) stockpiling uranium or plutonium
(b) exporting uranium
(c) importing fissile material
(d) *using other interim fuel cycles involving enriched* uranium or U^{235} topping

remain to be investigated.

ATOMIC ENERGY OF CANADA LIMITED

SOME THORIUM FUEL CYCLE STRATEGIES

M.F. Duret & H. Hatton

INTRODUCTION

Over the first part of this century energy consumption in Canada has increased at an average rate of about 3.8% per year. A much higher growth rate (∿5%) was sustained from 1960 to 1973. However, this high rate has now been interrupted and this period is apparently similar to other short-lived periods of high growth which have occurred in the past. In view of the recent dramatic increase in the price of oil and consequent emphasis on energy conservation it is perhaps unwise to assume a return to this high rate or, possibly, even a continuation of the longer term historic trend in energy consumption. For this reason a number of lower growth rates have been used to illustrate some general features associated with introducing advanced nuclear fuel cycles in Canada(1). During that study it became apparent that rapid introduction of advanced fuel cycles could lead to very large variations in the fuel reprocessing rates required.

In any industry, but particularly where risk capital is involved, smooth and predictable evolution is desirable; rapid fluctuations present a problem in generating capital and training people. This applies not only to the processing industry but for many of the other industries involved in nuclear power. For this reason attention here is focused on the three major industries associated with the development of nuclear power in Canada

(1) the uranium mining industry
(2) the reactor construction industry
(3) the fuel reprocessing industry

in order to assess factors which could affect the smooth development of these industries.

---

(1) M.F. Duret - Introducing Advanced Nuclear Fuel Cycles in Canada
AECL-6202, 1978 May

Energy Growth Scenarios

The main characteristics of the five energy growth scenarios considered in AECL-6202 are summarized in Table I below. Results in this report refer to Scenario 3.

TABLE I

Energy Growth Scenarios

Scenario Number	Average Annual Growth rate 1970-2050 % per year	Remarks
1	0.7	end-use consumption remains at 1970 levels.
2	1.7	per capita consumption as in 1970 + population growth
3	2.7	increasing per capita consumption at less than historic rate
4	2.2	Scenario 3 + conservation in excess of that inherent in lower growth rates
5	3.7	< long term historic rate

These scenarios were not intended to be projections; they merely span a range of growth rates, all below the historical average of 3.8% to give some perspective to the implications involved.

Nuclear power is expected to make an increasing contribution to Canadian energy requirements. The magnitude of this contribution will depend partly on the magnitude of Canadian uranium resources and the rate at which they can be made available for domestic consumption. Advanced nuclear fuel cycles may be necessary to guarantee adequate fuel supplies in the future.

Nuclear Fuel Cycles

Most advanced fuel cycles will require fuel reprocessing. Because of the present world concern about nuclear weapons proliferation a large number of different reactor types and fuel cycles are being re-examined for possible future use. These reactors and fuel cycles fall into 3 main categories - converters operating on the uranium cycle, converters operating on the thorium cycle with plutonium or uranium topping and fast breeders operating on the plutonium-uranium cycle. Only 2 of these cycles are considered in this report, the CANDU converter operating on the natural uranium cycle or the thorium cycle with plutonium topping. Some comparisons with a fast breeder fuel cycle are made. The pertinent fuel cycle characteristics are given in Table II below.

TABLE II

Reactor Fuel Cycle Characteristics

1 GW(e) at 80% Capacity Factor

Time Delay 1.5 years

Reactor	CANDU-PHW †		Fast Breeder
Fuel Cycle	Natural Uranium	Thorium with Pu topping	Plutonium-Uranium doubling time ∿ 24 years
Burnup MW·d/kgHe*	7.5	37.2	37.4
Equilibrium net feed rates			
Fissile Pu Mg/a	0	0.1345	0
Natural U Mg/a	133.4	0	0
Equilibrium Net Production rates			
Fissile Pu-Mg/a	.360	0	.152
Inventories			
Fissile Pu Mg	0	4.07	4.05
Natural U Mg	173	0	0

* Burnup is given in Megawatt days per kilogram of heavy element.

† The CANDU reactor with pressurized heavy water coolant.

Methodology

The method used to assess the penetration of a new technology into an existing market is based on the work of Fisher and Pry(2). The model is simple and easily understood. It is based on three simple assumptions:

(1) Many technological advances can be considered as competitive substitutions of one method of satisfying a need for another.

(2) If the substitution has progressed as far as a few percent of the total consumption, it will proceed to completion.

(3) The percentage rate of fractional substitution of new for old is proportional to the remaining amount of old left to be replaced.

The model has been successfully applied to the substitution of synthetics for natural rubber, margarine for butter, detergents for natural soaps, plastic for leather and many others. Mathematically it is described by the equation

$$\frac{1}{f}\frac{df}{dt} = \alpha(1-f)$$

where f is the fraction of the market captured at time "t".
α = rate at which the remaining market is penetrated.

Initially when the fraction f is small the fraction grows exponentially. The initial rate may be considered as dependent on normal commercial limitations to the introduction of a new technology, such as transfer of capital and effort from one technology to another.

As the fraction f increases, the term (1-f) becomes increasingly more important and ensures that the fraction f does not exceed 1. At this point the new product is supplying the entire market, which may be constant or increasing with time.

---

(2) J.C. Fisher and R.H. Pry
A Simple Substitution Model of Technological Change. Industrial Applications of Technological Forecasting, John Wiley, 1971

This model has been used with the minor modifications of assumption 2 described below to predict successively the increasing share of energy provided in the form of electricity, the increasing share of electricity produced by nuclear power and the increasing share of nuclear power which could be provided by advanced fuel cycles. Electricity cannot provide all our energy requirements; for example transportation is a large user of energy which could not be provided entirely in the form of electricity. The fraction of primary resources devoted to electricity production must then tend asymptotically to some fraction less than 1.0. It has been assumed to be 0.6 in this assessment. In a similar way nuclear power is assumed to capture, at most, 60% of the electricity generation. It has also been assumed that eventually all nuclear power could be provided by the advanced fuel cycles.

The penetration of electricity into the energy market is already well advanced and history provides a fairly good estimate of the penetration parameter α. It is about 3% per year. Nuclear technology, however, is new and only a few data are available to suggest plausible penetration parameters for nuclear power and advanced fuel cycles. The selection of these parameters is discussed in more detail later.

URANIUM RESOURCES

Plutonium generated in CANDU-PHW reactors can be used to initiate the thorium cycle in CANDU-PHW reactors or, alternatively, can be used to provide the initial core inventory required in fast breeders. If natural uranium proves to be plentiful (and hence cheap) there will be no requirement for these advanced fuel cycles. However, the price of uranium will probably be determined by world demand (and supply) so that one cannot examine uranium demand and supply for a particular region in isolation. Because of this uncertainty it is only prudent to examine the implications of using plutonium as well as uranium as the fissile material support for a nuclear power program. This problem has been investigated in some detail in AECL-6202 and a concise way of displaying the results is shown in Figures 1 & 2, where cumulative uranium commitments (including only operating reactors with an assumed 30 year life) are plotted as a function of cumulative plutonium used for topping and inventories for a variety of penetration rates for the advanced fuel cycle system which is introduced in the year 2000. The figures shown correspond to growth scenario 3 in AECL-6202. The nuclear penetration rate is 11% which was chosen to approximate the reactor construction rate foreseen for Canada over the next decade. The different symbols in the figure correspond to 12 different penetration rates varying uniformly from 2% per annum to 24% per annum. With low penetration rates very little plutonium is used and the fissile material for power system operation and expansion comes almost entirely from natural uranium. As the penetration rate is increased more plutonium is used and less uranium. Isochronous lines (at intervals of 5 years starting from 2015) are plotted on the figures.

For the regions of interest these lines are straight lines of constant slope corresponding to some equivalence between plutonium and uranium for a particular advanced fuel cycle.

Several points in these summary figures are worth noting:

(1) The isochronous lines become farther apart as the system grows, corresponding to the greater requirements for fissile material.

(2) There is a law of diminishing returns as the penetration rates are increased, significant reduction in uranium being obtained by increasing the penetration from 2% to about 12%. Increasing the penetration rate beyond 12% decreases uranium requirements still further but at a much reduced rate.

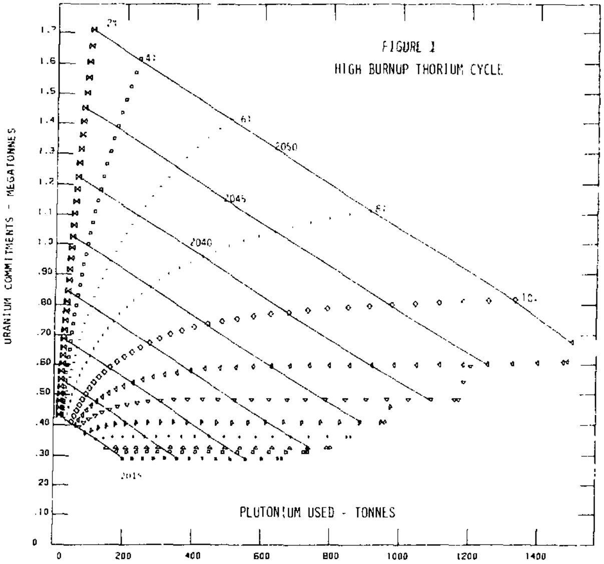


FIGURE 1
HIGH BURNUP THORIUM CYCLE

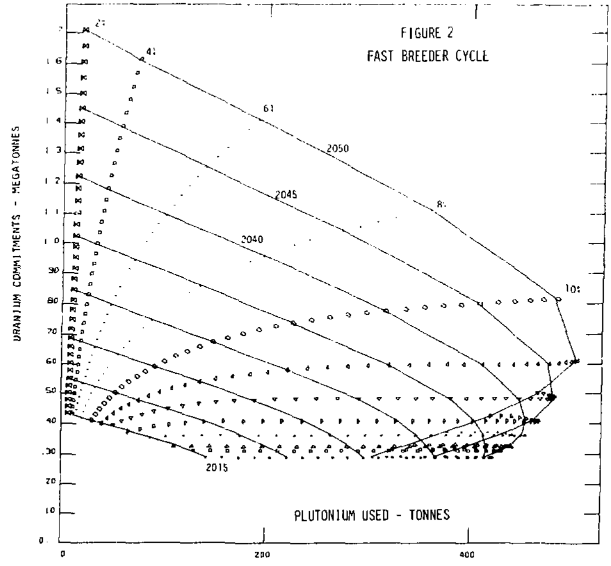


FIGURE 2
FAST BREEDER CYCLE

(3) Penetration rates corresponding to very rapid introduction of the advanced fuel cycles lead to horizontal "trajectories" corresponding to a system relying entirely on plutonium for its fissile material requirements. Not only does this imply very rapid fuel reprocessing rates but also means that a uranium mining industry is not required. Both implications are extreme and moderate penetration rates of about 10-12% appear more probable. This would call for a more realistic introduction of fuel reprocessing technology, some continued growth in the uranium mining industry and in addition is likely to prove adequate to sustain the growth implicit in the scenario shown. Cumulative commitments of about 10^6 Mg of uranium by 2050 do not seem unrealistic.

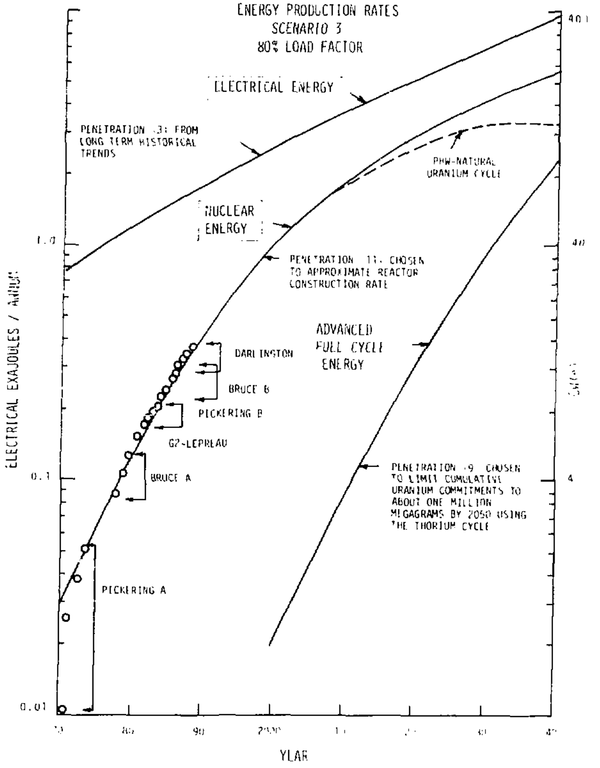
(4) Significantly less plutonium is required to introduce the fast breeder, with a corresponding reduction in processing requirements early in the next century. On the other hand, the LMFBR has not yet attained the commercial status of the water reactors and thus represents a significant business risk at the present time.

INDUSTRIAL RESOURCES

A number of different industries are required to provide nuclear power. A mining industry must provide uranium; the construction, manufacturing industries and heavy water production facilities are required to provide the reactors and fabricated fuel and, if advanced fuel cycles are required, a fuel processing industry must provide fissile material from irradiated fuel. Finally, radioactive wastes must be dealt with. If nuclear power is to be a viable source of energy in the future each of these industries must operate on a normal commercial basis, generating enough cash flow for exploration and mine development in the mining industry, research, development and normal business expansion in the construction and manufacturing industries. Ideally, expansion should be smooth since cyclical industries tend to be risky, and their products expensive. In a highly technological industry such as the nuclear industry there is the additional problem of maintaining the highly skilled work force required. General considerations such as these have a bearing on how rapidly a new technology can grow.

FIGURE 3

ENERGY PRODUCTION RATES
SCENARIO 3
80% LOAD FACTOR



Consider first the reactor construction program. The present schedule of reactor construction in Canada does not represent the highest possible rate which could be realized by Canadian industry(3). However, it represents a possible schedule and thus can be used to estimate a plausible penetration parameter for the introduction of nuclear power in Canada. The value of α determined in this way is about 11%. If, in addition, we wish to limit our domestic uranium commitments by 2050 to about one

---

(3) Leonard and Partners Ltd.
Economic Impact of Nuclear Energy Industry in Canada C.N.A.
August 1978.

million tonnes, Figure 1 indicates that a penetration parameter for the advanced thorium cycle of about 9% is appropriate. Using these two values leads to the curves of installed power shown in Figure 3 for scenario 3. Installed power in the year 2000 is about 40 GW(e); about 40 GW(e) of advanced fuel cycle reactors are in operation some thirty years later, if they are introduced in the year 2000.

The nuclear growth curve fits the proposed reactor construction schedule fairly well and in this sense these curves represents a projection of present trends in nuclear power. If one believes that the design and construction of processing plants are no more difficult than designing and building reactors then there is every likelihood that the schedule for introducing advanced fuel cycles could also be met, at least from the technical point of view.

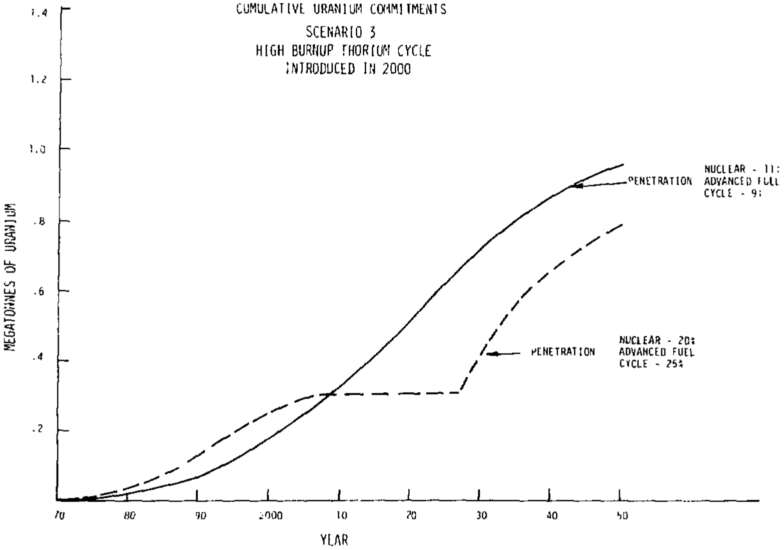


FIGURE 4
CUMULATIVE URANIUM COMMITMENTS
SCENARIO 3
HIGH BURNUP THORIUM CYCLE
INTRODUCED IN 2000

What does this projection imply from the point of view of the mining industry? Figure 4 shows cumulative uranium commitments increasing modestly while the industry is small. When commitments reach about half a million tonnes growth begins to decelerate, the total commitment reaching approximately a million tonnes by 2050. Shown for comparison are results from AECL-6202 where the penetration parameter for total nuclear growth was 20% and for advanced fuel cycle growth 25%. A more rapid introduction of nuclear power and advanced fuel cycles requires a more rapid growth initially, then a rest period until about 2030 while plutonium stocks are being used up. The reduction in commitments in 2050 obtained by introducing fuel cycles rapidly amounts to about 170,000 tonnes.

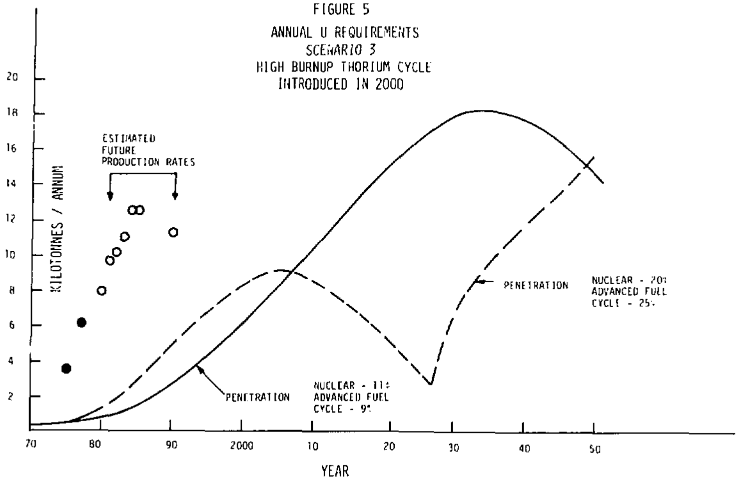


FIGURE 5

ANNUAL U REQUIREMENTS
SCENARIO 3
HIGH BURNUP THORIUM CYCLE
INTRODUCED IN 2000

Maximum annual uranium production reaches about 18,000 tonnes by 2035 and then begins to fall off as shown in Figure 5. Clearly the smoother picture resulting from the lower penetration rates is to be preferred from the point of view of exploration and mine development but whether uranium in the required amounts and timing will actually be discovered is still a matter for conjecture.

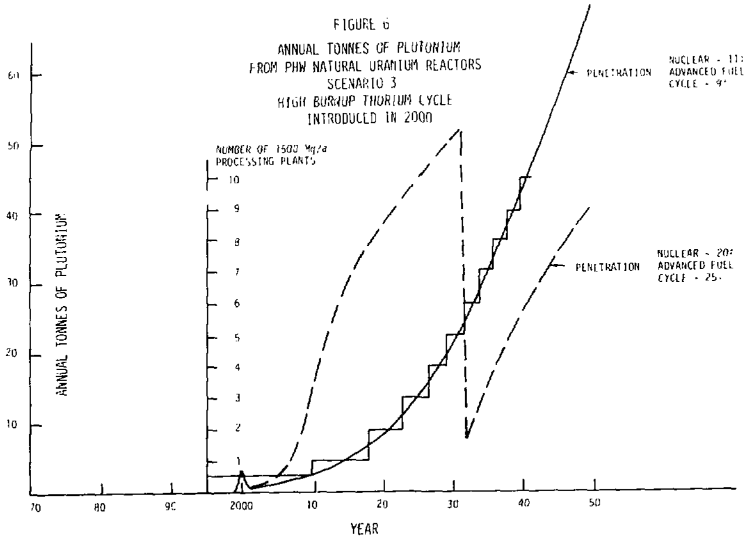


FIGURE 6

ANNUAL TONNES OF PLUTONIUM
FROM PHW NATURAL URANIUM REACTORS
SCENARIO 3
HIGH BURNUP THORIUM CYCLE
INTRODUCED IN 2000

If advanced fuel cycles are to be introduced as postulated in the year 2000, fissile material must be available from the year 2000 onwards. To provide this as plutonium from irradiated natural uranium fuel, processing plants must be built. The required growth of this part of the processing industry is shown in Figure 6. Shown also are results for the higher penetration parameters used in AECL-6202. The sharp drop in 2031 for this case arises because all available irradiated PHW fuel has been processed at this point. From this point on new converters must be installed to provide new fuel for processing. If one were to switch to U^{235} as a means of topping in the thorium cycle from this point onwards, no more plutonium would be required. However, in addition to the processing plants required between 2000 and 2030, development of enrichment facilities would also be required in this period. Clearly the slower, more orderly growth associated with lower penetration rates is more acceptable, if sufficient uranium could be found. The requirements shown in Figure 6 would represent a large part of the total Canadian processing industry, because of the low plutonium content in CANDU-PHW fuel. However, the recycle fuel in the thorium fuelled reactors must also be processed and Figure 7 compares the two components for the high burnup thorium cycle.

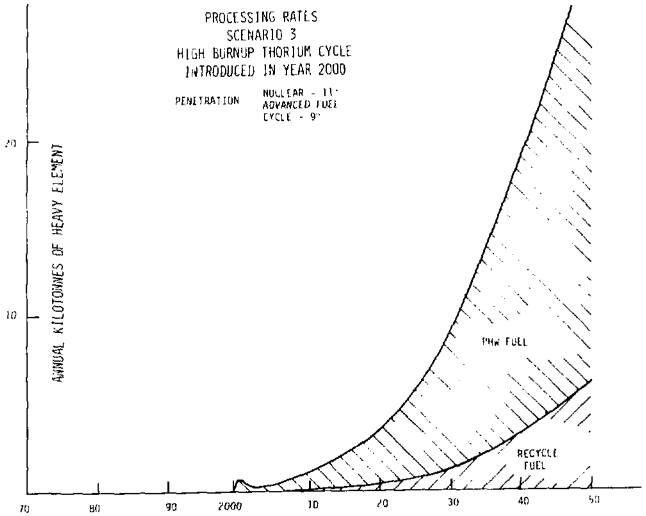
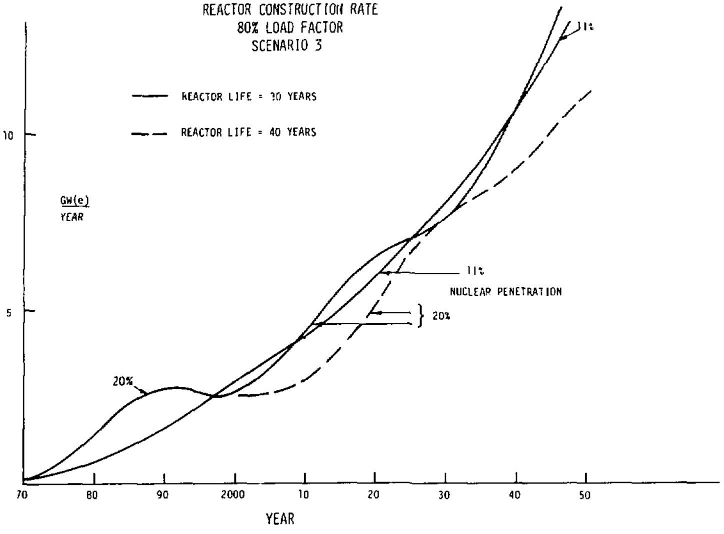


FIGURE 7
PROCESSING RATES
SCENARIO 3
HIGH BURNUP THORIUM CYCLE
INTRODUCED IN YEAR 2000

The choice of penetration parameters also has an effect on the reactor construction industry. The reactor construction rate is plotted in Figure 8 for nuclear penetration parameters of 20% and 11%. The more rapid introduction of nuclear power would result in a short period of no growth from 1990 to about 2000. This is due to a feature of the penetration model where higher penetration parameters lead to earlier market saturation effects. Since we have assumed a 30 year reactor life, replacement business starts to come into effect in the year 2000 and tends to propagate in time the initial oscillation generated by the high growth rate. The only way to eliminate this oscillation without reducing the penetration parameter is to increase the growth rate for electricity, or find other markets for reactors such as off-shore markets or markets using the reactor as a heat source. If reactor life proves to be 40 years instead of 30 years, the initial period of no growth is extended by about 10 years, and the construction rate is reduced, as shown in Figure 8. The longer reactor life also has the effect of increasing uranium commitments by about 30%.

FIGURE 8
REACTOR CONSTRUCTION RATE
80% LOAD FACTOR
SCENARIO 3



In general, introducing nuclear power and advanced fuel cycles significantly more rapidly than shown in Figure 3 will tend to introduce undesirable fluctuations in the commercial aspects of mining, reactor construction, and fuel reprocessing. On the other hand, the slower approach reduces the contribution nuclear power makes to our energy requirements in the short term as shown in Figure 9. It also requires about 20% more uranium by 2050 but postpones the date at which the plutonium supply is used up by decades.

DELAYED INTRODUCTION OF ADVANCED FUEL CYCLES

The results presented above are all based on introducing the advanced fuel cycles in the year 2000. If the introduction of the advanced fuel cycle is delayed, more power must be supplied from the natural uranium cycle and more uranium will be required. This is illustrated in Figure 10 which shows cumulative commitments in 2050 as a function of the year in which the advanced fuel cycle is introduced.

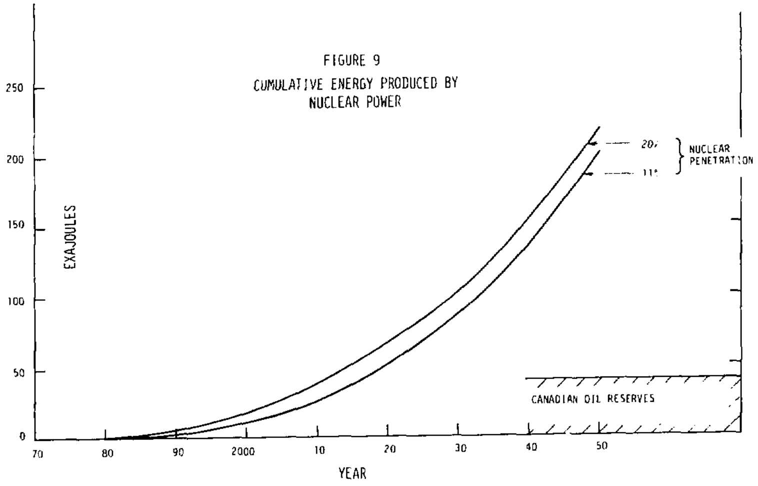
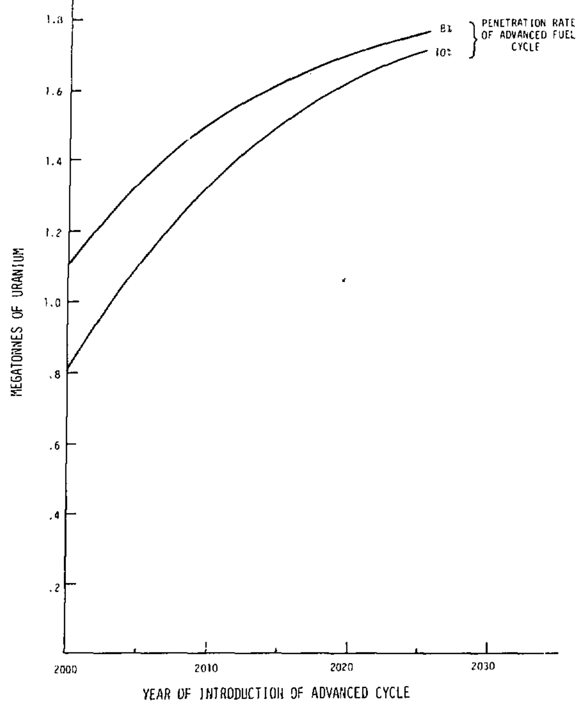


FIGURE 9
CUMULATIVE ENERGY PRODUCED BY NUCLEAR POWER

The later the date of introduction the smaller the impact of the advanced cycle on commitments in the year 2050, which approach the limit of 1.8 million tonnes required using only the natural uranium cycle. Some reduction in commitments can be obtained by increasing the penetration rate of the advanced fuel cycle to compensate for the later date of introduction. If the penetration rate is selected to maintain a constant cumulative commitment of about one million tonnes of uranium in 2050, uranium must be mined more rapidly (to fuel the greater fraction of converters in the nuclear system) and the processing rates required will rise much more rapidly as the delay becomes larger. The magnitudes of these effects are shown in Figures 11 and 12.

FIGURE 10
CUMULATIVE COMMITMENTS IN 2050



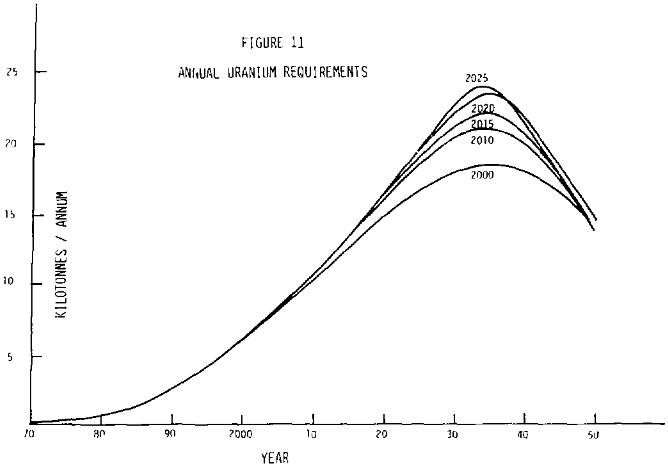


FIGURE 11

ANNUAL URANIUM REQUIREMENTS

A delay of 25 years increases the peak mining rate (which occurs about 2035) by about 30%. The implications of such a delay in fuel reprocessing are probably much more serious. About 30 tonnes of plutonium are required annually by about 2035 whatever the introduction date of advanced fuel cycles. The later this date, the less time is available to put this capacity (about seven 1500 t/a plants) in place.

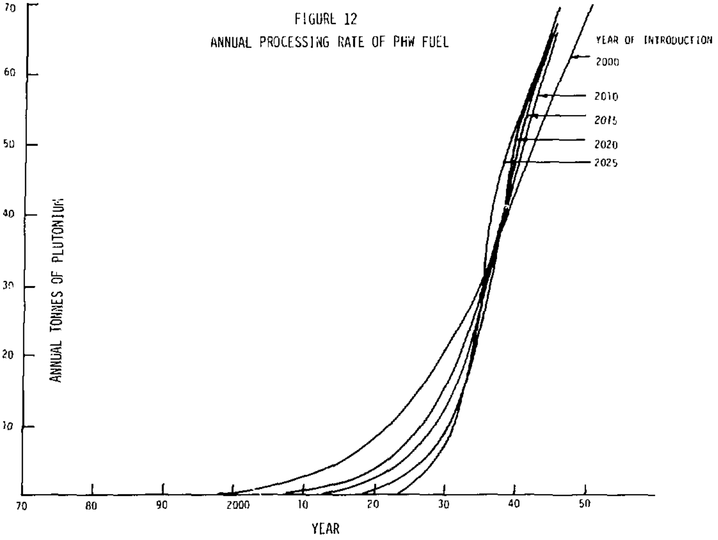


FIGURE 12

ANNUAL PROCESSING RATE OF PHW FUEL

DISCUSSION

The results presented in this report are based on several important assumptions. The selection of scenario 3 as an example implies an average annual growth rate in total energy demand of about 2.7% which is significantly lower than both historical and present demand in Canada. Historically, the fraction of primary energy sources allocated to electricity production has increased. A continuation of this trend has been assumed by selecting a penetration parameter for electricity which represents this historical development. While we recognize the long term growth rates are not predictable, we believe that these assumptions are conservative and may underestimate requirements for uranium and reactors using advanced fuel cycles.

ISSN 0067 - 0367

To identify individual documents in the series we have assigned an AECL- number to each.

Please refer to the AECL- number when requesting additional copies of this document

from

Scientific Document Distribution Office
Atomic Energy of Canada Limited
Chalk River, Ontario, Canada
KOJ 1JO

Price $3.00 per copy

ISSN 0067 - 0367

Pour identifier les rapports individuels faisant partie de cette série nous avons assigné un numéro AECL- à chacun.

Veuillez faire mention du numéro AECL- si vous demandez d'autres exemplaires de ce rapport

au

Service de Distribution des Documents Officiels
L'Energie Atomique du Canada Limitée
Chalk River, Ontario, Canada
KOJ 1JO

Prix $3.00 par exemplaire

264-79