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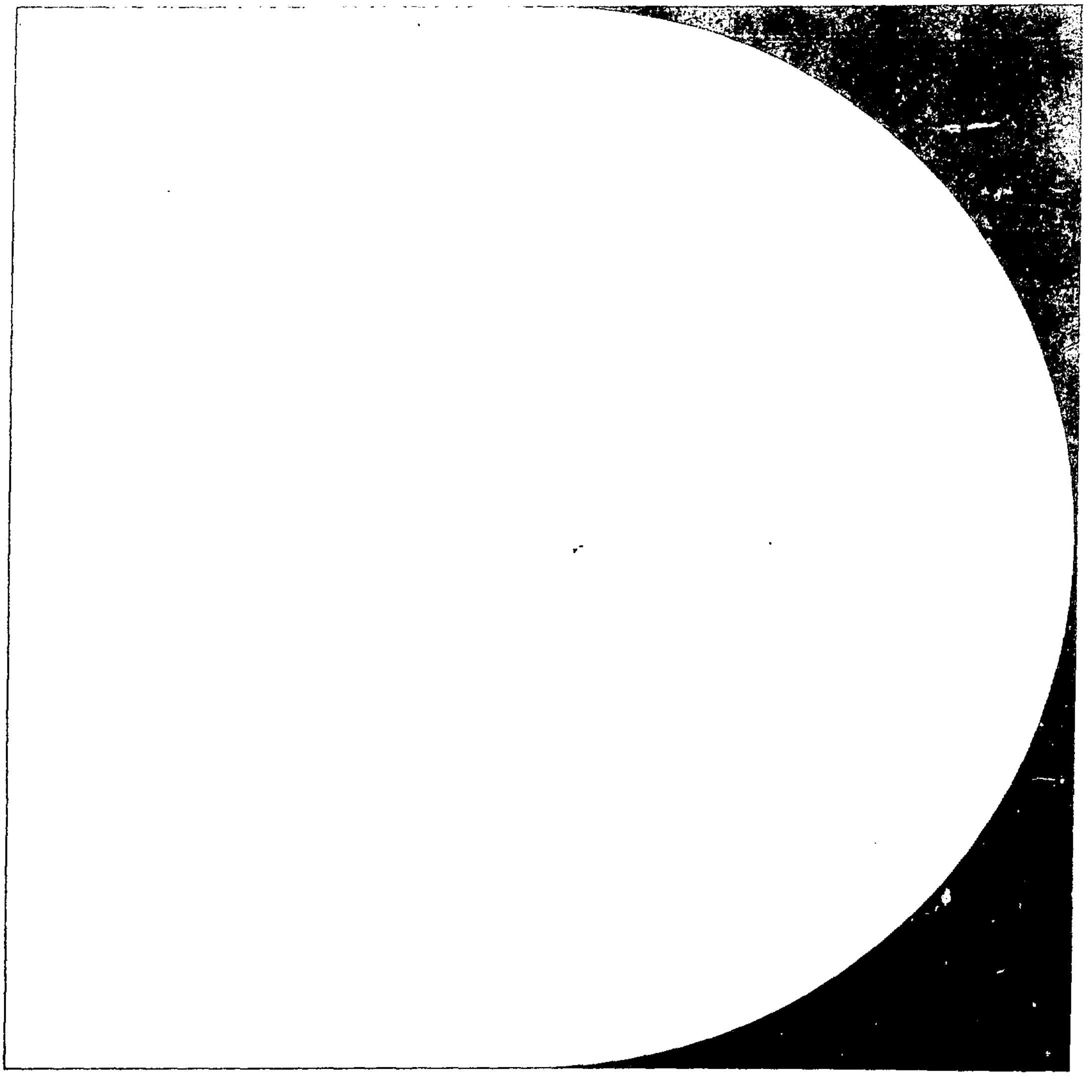

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IMPLICATIONS OF USING ALTERNATE FUEL CYCLES TO MEET ONTARIO'S NUCLEAR POWER DEMAND

Nuclear Studies and Safety Department

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Abstract

Considerable uncertainty in the assurance of the future uranium supply in the next century leads to the prudent assumption that the supply might be limited. With this view, the use of alternate fuel cycles to meet an assumed nuclear capacity growth rate in Ontario is then examined. Two criteria are used:

i) The ability of the alternate fuel cycles to lessen the uranium demand.

ii) The ease of commercialization.

The nuclear strategies considered assume the use of the natural uranium cycle and, starting in the year 2000, the gradual introduction of an alternate fuel cycle. The alternate fuel cycles reviewed are the enriched uranium cycle, the mixed oxide cycle and a variety of thorium cycles. The cumulative uranium requirement to the year 2070, and the growth and size of the reprocessing and fuel fabrication industries are discussed in detail. Sensitivity analyses on nuclear capacity growth rate, recycling loss and delay time are also described.

The CANDU self-sustaining thorium cycles and the fast breeder offer the greatest opportunities to limit the uranium demand. But they require substantial developmental work before commercialization. Of the alternate CANDU fuel cycles considered, the once-through enriched uranium cycle offers advantages in:

(a) Reducing uranium requirement.

(b) Requiring less developmental work to commercialize.

(c) Providing a technological bridge to lead in to other alternatives (thorium cycles or fast breeder).

(d) Delaying the need for the thorium cycle and fast breeder.

(e) Providing decision points in the nuclear strategey so as to respond to future uncertainties.

(f) Reducing present fuelling cost.

It is recommended that further detailed studies on its use should be initiated.

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1. Introduction

Ontario Hydro is planning to use nuclear energy for a large portion of its base load generating capacity. It has secured uranium for most of the life of its presently committed and operating stations. Nuclear strategies adopted for the future will depend not only on socio-economic considerations but also on resource needs. Two important factors are:

(1) The uranium demand in the long term.

(2) The availability of uranium to supply the demand.

The uranium supply situation after the turn of the century is largely unknown. Both uranium availability and price are uncertain because they depend on exploration success, environmental factors, the possible need for new mining techniques and government policy both at home and abroad. Clearly, these influences on uranium supply in the next century are very difficult to predict. In this report, we take the view that the uranium supply might be limited. Having adopted this prudent view, we seek to provide insurance against the risk of future uranium shortfall. We proceed to examine alternate CANDU fuel cycles based on two criteria:

(1) The ability to reduce uranium demand.

(2) The ease of commercialization.

The prime objective of examining alternatives is not to set one of these alternatives in place, but to provide guidance to required developmental work. Accordingly, future developmental tasks can be selected so as to give to the people of Ontario, by the turn of the century, the widest latitude for energy decisions as can reasonably be possible.

2. Uranium Supply

This chapter provides a brief review, based on References 1 - 5, of the future uranium supply.

One of the most comprehensive estimate of the uranium resources in Canada is made by Energy Mines and Resources, Canada (EMR). Tables 2.1 and 2.2 are results of EMR's 1976 assessment (1). Table 2.1 shows the quantities of uranium in four categories; measured, indicated, inferred and prognosticated*. The definitions of these resource categories are given in Appendix 1. Table 2.2 illustrates the distribution of these resources by province.

Of the measured, indicated and inferred categories, 370 GgU is estimated to be in Ontario. This figure, however, does not represent the amount of uranium available to Ontario Hydro. New uranium deposits are expected to be found with continued exploration. Also, if the market price increases more rapidly than production costs, the resource level will increase, since an increasing number of low grade deposits will become economically recoverable.

On the other hand, the resource categories represent levels of decreasing confidence that the stated quantities of uranium exist, and that they can be mined within the price range shown. Considering that almost 87% of the 370 GgU is in the indicated and the inferred categories, there is a significant uncertainty in the amount of uranium that can be mined.

It is worth noting that even when low grade deposits become economically attractive, they require proportional increases in the mining capacity to mine the same quantity as high grade deposits. Limitations on the rate at which uranium is recoverable could lead to a temporary shortfall in meeting uranium demand.

Figure 2.1 shows the potential uranium production capability in Ontario (4). The projection is based on the known reserve. The decline after 1986 is due to the exhaustion of presently developed mines. If the decline is to be avoided, uranium, in the indicated, inferred or prognosticated categories, must prove mineable, and must be put into production to make up for the depleted capacity.

While we have been concentrating on the uranium resource and production in Ontario, it must also be remembered that Ontario Hydro is not restricted to purchase uranium from Ontario. Conversely, the Ontario producers can, within government export restrictions, sell on the world market.

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*Results of the 1977 assessment by EMR (6) indicate that the total resources in the four categories have increased by about 7% over those reported in 1976. This data was not available in time to be incorporated here. However, the conclusions of this report are unaffected by the new assessment.

Table 2.1

1976 Estimate of the Canadian Uranium Resources

	Tonnes Uranium			
	Measured	Indicated	Inferred	Prognosticated
Recoverable Up To 60 $/lb U_3O_8	83,000	99,000	307,000	349,000

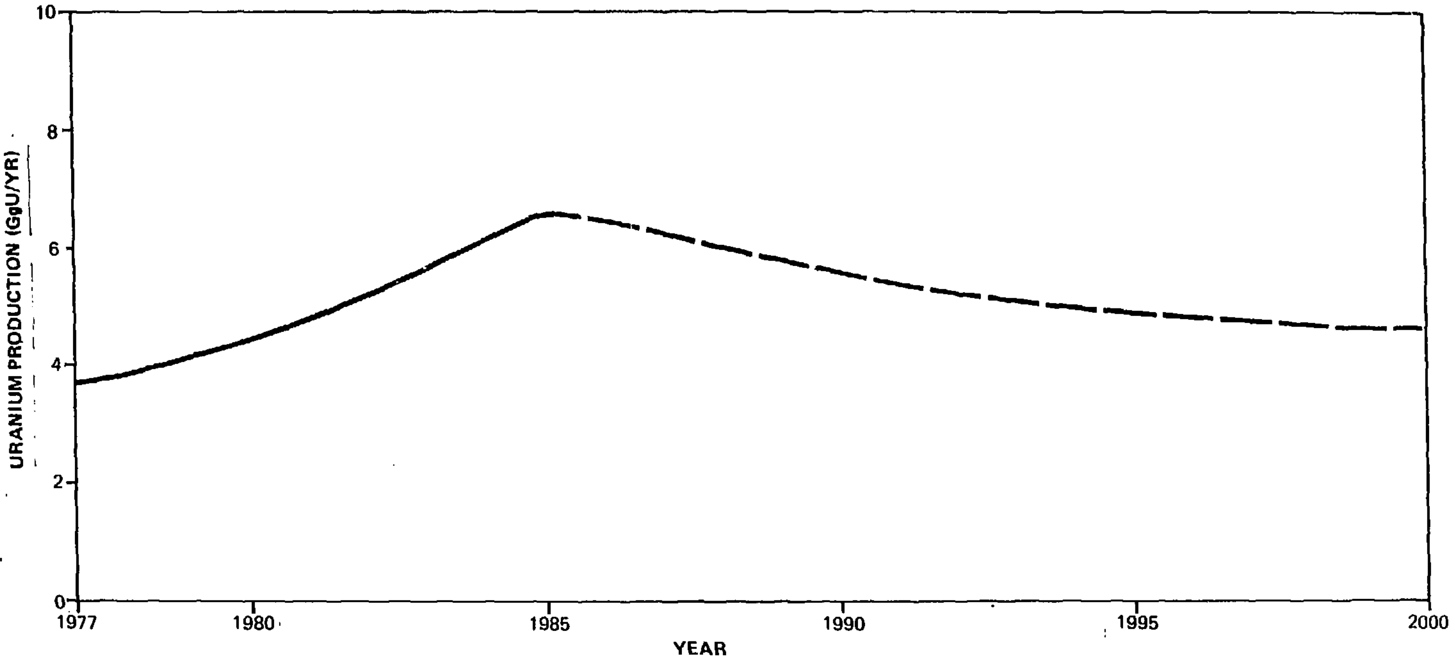
Table 2.2

Distribution of Resources by Province

	Ontario	Saskatchewan	Others
Measured	59%	37%	4%
Indicated	77%	21%	2%
Inferred	80%	19%	1%

- This table is for resources up to 60 $/lb U_3O_8 and estimated in 1976.
- The measured, plus indicated, plus inferred, resources in Ontario total 370,000 tonnes (370 Gg) of uranium.

FIGURE 2.1
ONTARIO PRODUCTION CAPABILITY BASED ON KNOWN RESERVES



With respect to the world uranium resources in the measured plus indicated categories, Reference 5 indicates that Canada ranks fourth behind the United States, South Africa and Australia. For the inferred plus prognosticated resources, Canada ranks second behind the United States. It is also second to the United States in the current world production of uranium, a position which is expected to be continued at least until the mid 1980's. Hence, the Canadian supply position appears to be strong relative to other countries.

There are many other factors which further affect the assurance of future uranium supply. These include:

(1) Government policy on nuclear power.
(2) Public opinion on nuclear power and uranium mining.
(3) Nuclear capacity growth rate.
(4) Economics of alternate power sources.
(5) Import and export policies of Canada and other major uranium producing countries.
(6) Federal and provincial tax laws.
(7) Availability of skilled labour for mining.
(8) Site conditions.

The resources and production capacity are adequate for the currently operating and committed generating stations in Ontario. However, the long-term supply (after the turn of the century) is uncertain. Consequently, the resource figures and the estimated production capability must only be viewed as broad reference points. Because of the uncertainties, it is prudent to assume that the uranium supply in the future might be limited. This report, therefore, proceeds to examine alternate fuel cycles and their ability to reduce the uranium requirement.

3. Uranium Demand

The uranium requirement depends on the installed nuclear capacity and on the types of fuel cycles and reactors which are utilized.

3.1 Installed Nuclear Capacity

Figure 3.1 illustrates the installed nuclear capacity which is assumed for Ontario and designated as the base case. It is identical to Ontario Hydro's long range load forecast LRF-48A up to the year 2000. From 2000 to 2040, the capacity growth is assumed to be 2500 MWe/a. This is followed by a no growth period to the year 2070.

Projection of the installed nuclear capacity so far into the future is highly speculative. However, many of the fuel cycles require 20-30 year R&D before they can be fully commercialized. Without simulating a period significantly beyond that, their impacts on uranium demand cannot be completely evaluated.

In a later chapter, the sensitivity of the results to variations in the predicted growth rate, including the recently revised forecast to year 2000, will be investigated.

3.2 Nuclear Strategies

Table 3.1 lists the seven nuclear strategies considered for Ontario. The fuel cycle characteristics and reactor data are given in Tables 3.2, 3.3 and 3.4 (References 7 and 8). All alternate fuel cycles involve oxide fuel and are assumed to be utilized in CANDU PHW reactors.

Strategy 1 assumes the continuing use of the natural uranium cycle. All other strategies also assume the use of the natural uranium cycle. However, in the year 2000, alternate fuel cycles are introduced into the system.

The low enriched uranium cycle (1.2% U-235) in strategy 2 is a once-through cycle. The mixed oxide cycle in strategy 3 involves multiple recycling of plutonium. The thorium cycles use as the fissile source, either enriched uranium (93% U-235) from an enrichment plant or plutonium from the reprocessing of natural uranium fuel. The intermediate burnup thorium cycles have a burnup of 27 MWd/kgHE, and the self-sustaining cycles have a burnup of 13 MWd/kgHE. Self-sustaining is used to denote that at system equilibrium, fissile make-up from external sources is required only to compensate for recycle losses.

FIGURE 3.1
ONTARIO NUCLEAR CAPACITY (BASE CASE ASSUMPTION)

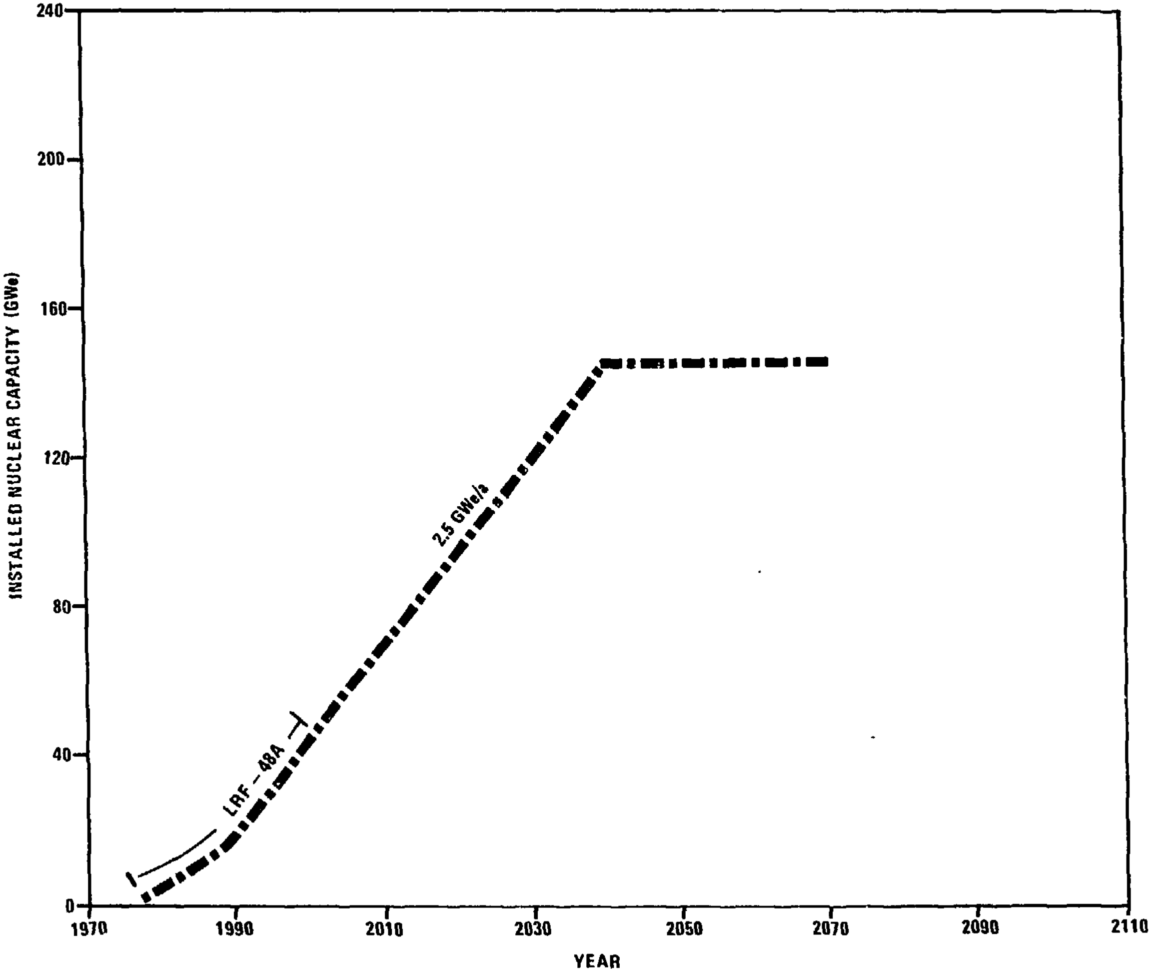


Table 3.1

Nuclear Strategies

Strategy	Fuel Cycle
1	Natural UO_2
2	U-235 Enriched UO_2
3	$(Pu,U)O_2$
4	Th(Pu)IB*
5	Th(Pu)SS*
6	Th(U-235)IB
7	Th(U-235)SS

* IB= Intermediate Burnup
SS = Self-sustaining

All thorium cycles use oxide fuel

Table 3.2

CANDU PHWR Fuel Cycles and Reactor Data

	FUEL CYCLE						
				Thorium Intermediate Burnup		Thorium Self-Sustaining	
				Topping		Topping	
	Nat UO_2	U-235 Enriched UO_2	$(Pu,U)O_2$	U-235	Pu	U-235	Pu
Reactor life (years)	30	30	30	30	30	30	30
Efficiency(%)	30.5	30.5	30.5	30.5	30.5	30.5	30.5
Specific Power (kW/kgHE)	29	29	29	29	29	29	29
Burnup (MWd/kgHE)	7.5	21	17	27	27	13	13
Equilibrium Net Fissile Feed (g Fissile/kgHE)	7.1 U-235	12 U-235	7.1 U-235	3.2 U-235	3.5 Pu	0.0	0.0
Equilibrium Net Fissile Production (g Fissile/kgHE)	2.7 Pu	3.4 Pu	-	-	-	-	-
First Charge* (g Fissile/kgHE)	7.1 U-235	12 U-235	3.6 Pu 7.1 U-235	23.5 U-235	25.6 Pu	21.5 U-235	23.4 Pu
Fuel Reprocessing	No	No	Yes	Yes	Yes	Yes	Yes

*Includes any extra fissile material consumed in the pre-equilibrium period.

Table 3.3

Process Delay Time and Yield Factors*

Item	Delay (years)	Yield Factor
Mines (Uranium or Thorium)	0.65	1.0
Fuel Fabrication (Natural Uranium or Alternative Fuel)	0.5	0.993
Fuel Reprocessing (Natural Uranium or Alternative Fuel)	1.0	0.999
Uranium Enrichment	1.0	0.995
D_2O Plant	Delivery to reactor 1.0 years before startup	

*Future experience is required to determine the magnitude of many of the parameters in this table.

Table 3.4

Uranium Enrichment and Other Data

Enrichment in Natural Uranium (%)	0.71
Enrichment in Tails Assay (%)	0.2
Uranium Enrichment Required for External Fissile Feed in Fabrication of $(U,Th)O_2$ Fuel (%)	93
U-233 Equivalent to Pu (g U-233/g Pu)	0.735
U-233 Equivalent to U-235 (g U-233/g U-235)	0.8

This report concentrates mainly on strategies with two fuel cycles. It enables the impacts of the different fuel cycles to be highlighted. However, strategies involving three or more fuel cycles offer advantages in technological transition and material feed requirements. Some of these features are discussed qualitatively in a later chapter.

In simulating the strategies, no constraint is applied on the availability of enrichment services, reprocessing or fuel fabrication facilities. All alternate fuel cycles are to supply the additional nuclear capacity demand after the year 2000, subject only to the following three constraints:

(1) Existing reactors cannot be replaced before the end of their 30 year life.

(2) After the alternate fuel cycles are initiated, natural uranium reactors are built only when they are needed to supply fissile plutonium. Therefore, in strategies (3), (4) and (5), the installed capacity of the alternate fuel cycle reactors, which are plutonium enriched, is constrained by limitations in the fissile plutonium supply.

(3) The irradiated fuel accumulated from the natural uranium reactors that are built before the year 2000 represents a source of plutonium inventory. This study assumes that all plutonium enriched systems will first utilize this inventory to minimize the need to build more natural uranium reactors.

For the mixed oxide and thorium cycles, some extra fissile material in excess of the normal equilibrium consumption must be utilized during the pre-equilibrium period. In this report, for calculational convenience, it is assumed that the pre-equilibrium fissile usage is consumed in the first fuel charge. Such a 'first charge' approximation only slightly penalizes the alternate fuel cycles because the extra fissile material is largely consumed in the first few years of operation. For instance, in the thorium cycles, more than 60% of the extra fissile material is used up during the first three operational years (Reference 9).

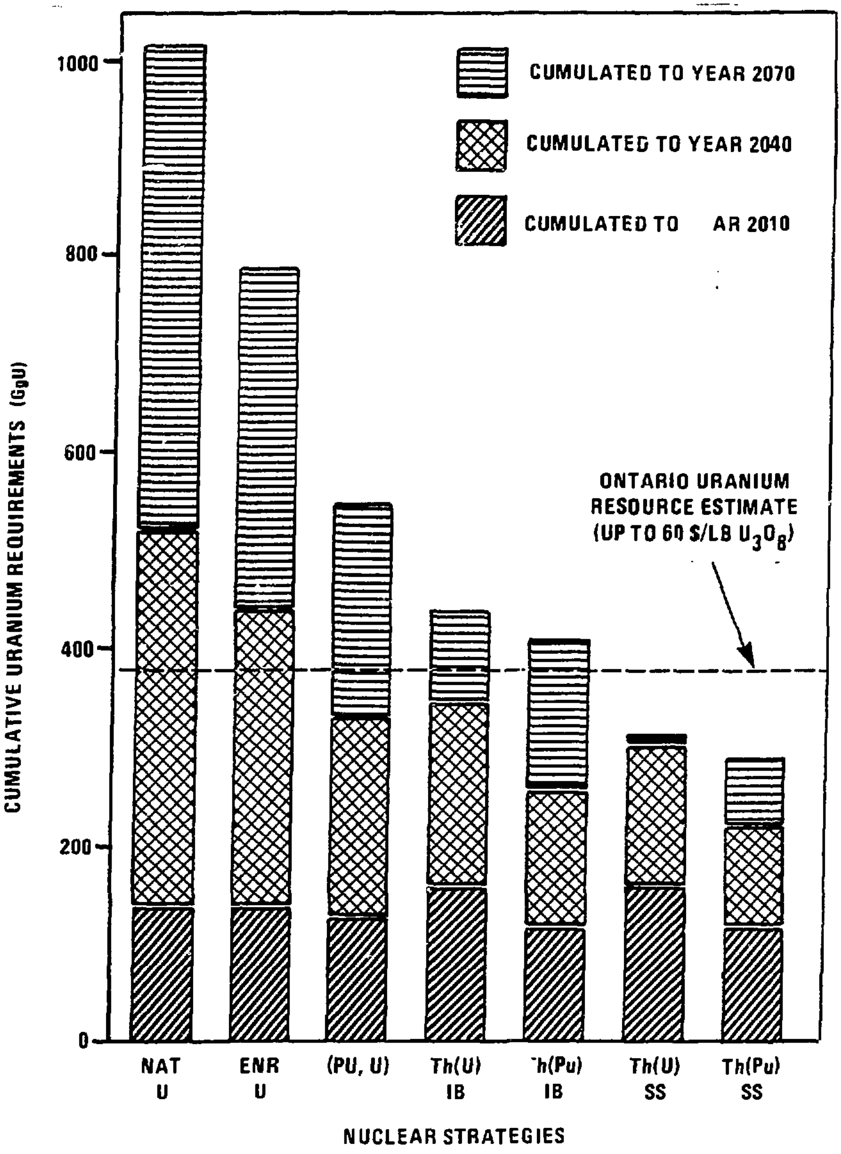
The strategies were simulated using the computer code 'FISS' which was developed at Whiteshell Nuclear Research Establishment (Reference 10).

3.3 Cumulative Uranium Requirements

Figure 3.2 shows the cumulative uranium requirements of the strategies to the years 2010, 2040 and 2070. As a point of reference, the 1976 EMR estimate of the Ontario uranium resource of 370 thousand tonnes of uranium is indicated.

FIGURE 3.2

CUMULATIVE URANIUM REQUIREMENTS FOR THE BASE CASE
INSTALLED CAPACITY



It can be observed that the self-sustaining thorium cycles offer the greatest opportunities to limit uranium consumption. Relative to the natural uranium cycle, enriching natural uranium with uranium-235 can reduce the total requirement by about 23%. Recycling plutonium increases the saving to 46% and the use of thorium cycles effects savings in the range of 57% to 77%.

It is only after the year 2010 that there begins a marked divergence in the cumulative uranium consumption of the strategies. This long induction period implies that if an alternate fuel cycle is to be used to avoid a potential uranium shortage, then it must be introduced well ahead of the time that such a shortage is expected.

The choice of using enriched uranium or plutonium as the enrichment material for the thorium cycles has very little effect on the total uranium consumption by the year 2070. Choosing plutonium utilizes the plutonium inventory. However, after the inventory is exhausted, the continued use of plutonium requires that a portion of the installed nuclear capacity must be filled by natural uranium reactors which supply the plutonium. This mix of thorium-plutonium and natural uranium fuelled reactors uses more uranium than would a system composed entirely of thorium-uranium 235 fuelled reactors. Optimum strategy to minimize uranium consumption would be to switch to uranium-235 as the enrichment material when the plutonium inventory has been used.

3.4 Time Extension

Table 3.5 is used to illustrate the effect of the resource uncertainty on the impact of the alternate fuel cycle strategies. It tabulates the extra time that a particular strategy can be pursued, relative to the natural uranium strategy, before a given amount of uranium resource is consumed. Three resource figures of 200 GgU, 370 GgU and 500 GgU are considered. The range is not meant to be a prediction, but is used to illustrate the effects of uncertainty. Where necessary, extrapolation beyond 2070 on the base case installed capacity is done assuming that the no growth period continues indefinitely.

There is one striking observation. If the resource is severely limited at, say, 200 GgU, alternate fuel cycles, which start in the year 2000, cannot alleviate the resource demand to any significant extent. At best, they can extend the usage by a maximum of 19 years (to 2035). If the resource figure is higher, and hence the impact of the alternate fuel cycles can be accrued with time, the time extension is progressively longer. As shown, for the self-sustaining thorium cycles, the constant installed capacity can be sustained for more than two centuries.

Table 3.5

The Time Extension Provided by Alternate Fuel Cycles Relative to the Natural Uranium Cycle For Various Uranium Resource Levels

Strategy	Time Extension (Years)*		
	Uranium Resource 200 GgU	Uranium Resource 370 GgU	Uranium Resource 500 GgU
Nat. Uranium Strategy consumes by year:	2016	2030	2039
Enriched U	1	4	10
(Pu,U)	5	16	25
Th (Pu) IB	14	31	~ 52
Th (Pu) SS	19	> 400	> 800
TH (U-235) IB	0	17	~ 80
Th (U-235) SS	1	> 200	> 800

*Where necessary, extrapolation beyond 2070 is done assuming that the no growth period continues.

3.5 Annual Uranium Mining Requirements

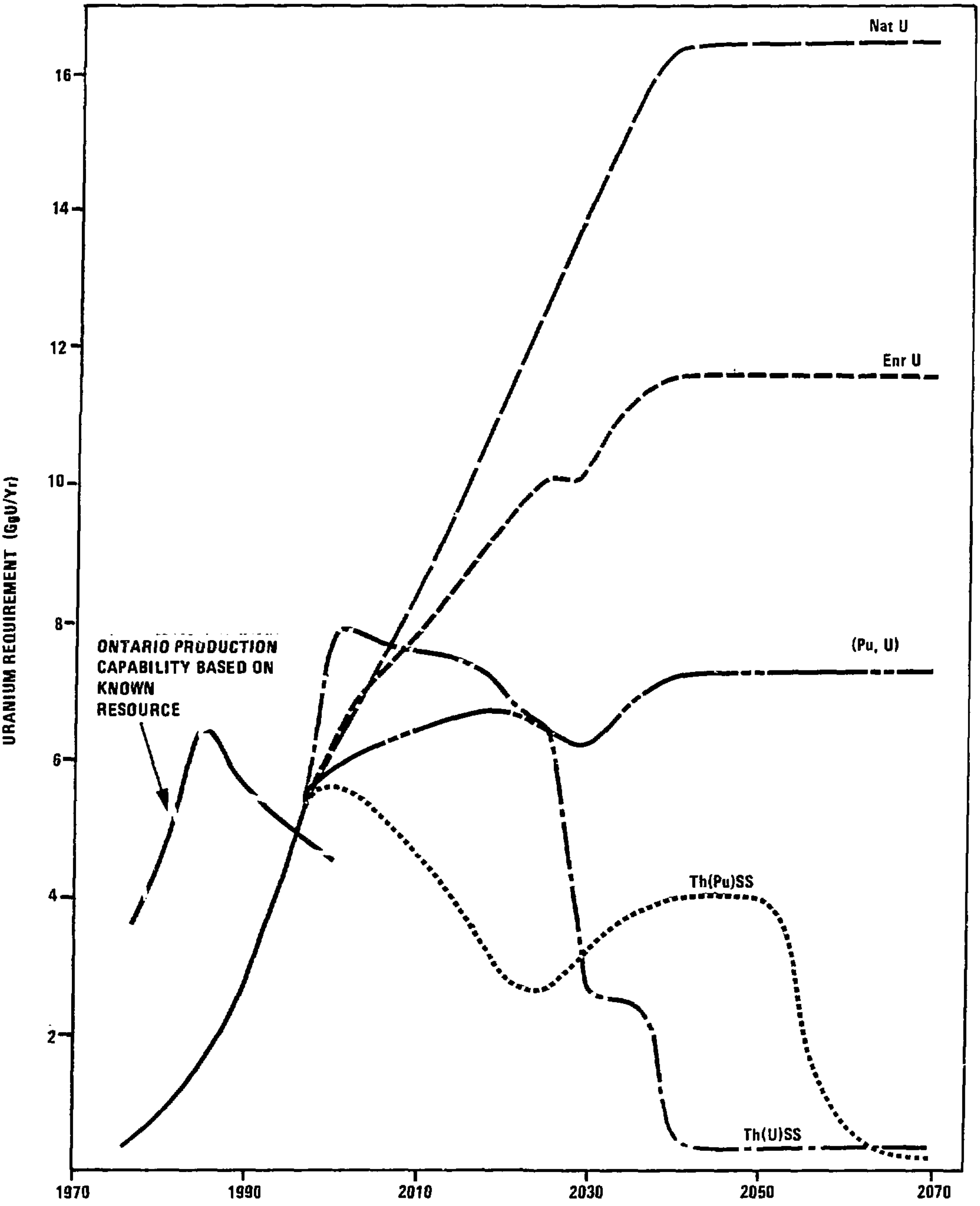
It was pointed out earlier that the uranium production capacity may be a limiting factor long before the total resource is depleted. Figure 3.3 shows the annual uranium requirements of some of the strategies. By way of comparison, the Ontario production capability, based on the presently known reserve, is also shown.

The advantages of the alternate fuel cycles in reducing the annual mining requirements are largely self-evident. To continue with the natural uranium cycle poses the most stringent demand on the production capacity. It requires by the year 2040, about 2-1/2 times the 1985 peak production level expected in Ontario.

Although the choice of using enriched uranium or plutonium as the fissile source for the thorium cycles does not result in any significant difference in the total uranium consumption, the timing of the consumption is quite different. The high pre-equilibrium fissile consumption of the thorium cycles results in a large fissile requirement in the 2000-2020 time period. If this is supplied by uranium-235, the uranium requirement actually rises above that of the natural uranium strategy from 1997 to 2007. If the fissile source is supplied by plutonium, (because it can be retrieved from the plutonium inventory), the production requirement actually decreases and starts upwards only when this plutonium source is depleted.

It can be seen that the use of plutonium can lessen the production requirement more in the 2000-2025 time period. In contrast, the use of uranium-235 can better reduce the requirement from 2030 onwards. Therefore, the choice of enrichment material for the thorium cycles must also be selected by considering the future trend in uranium production capability.

FIGURE 3.3
ANNUAL URANIUM REQUIREMENT



4. Fuel Cycle Services

4.1 General

In simulating the strategies, no constraint was imposed on the availability of enrichment services, fuel reprocessing or fabrication capacities. It should be noted that both uranium enrichment and fuel reprocessing represent new industries to Canada. Likewise, the fabrication of alternate cycle fuel, be it plutonium and/or uranium-233 enriched, is quite different from the fabrication of natural uranium fuel.

With new industry, there is a definite limitation on how fast the industry can initially expand. This is in addition to the normal constraints imposed on the growth of an established industry. By and large, the expansion rate depends on a range of factors, including:

(1) Economics
(2) Manpower and other resource availability
(3) Government policy
(4) Stage of Maturity of the industry
(5) Public opinion
(6) Availability of capital
(7) Material supply
(8) Availability of sites

However, once the technology is satisfactory demonstrated, the economy of scale will encourage the capacity to be increased in larger steps. In summary, there is some uncertainty in the feasible growth rate of a new fuel cycle service industry.

In this chapter, the capacities of the support industries required by the strategies are presented. The discussion will stress on two issues:

1. Industrial growth must be orderly. Therefore, peaky requirements, ie, rapid increases followed by rapid decreases, are undesirable.

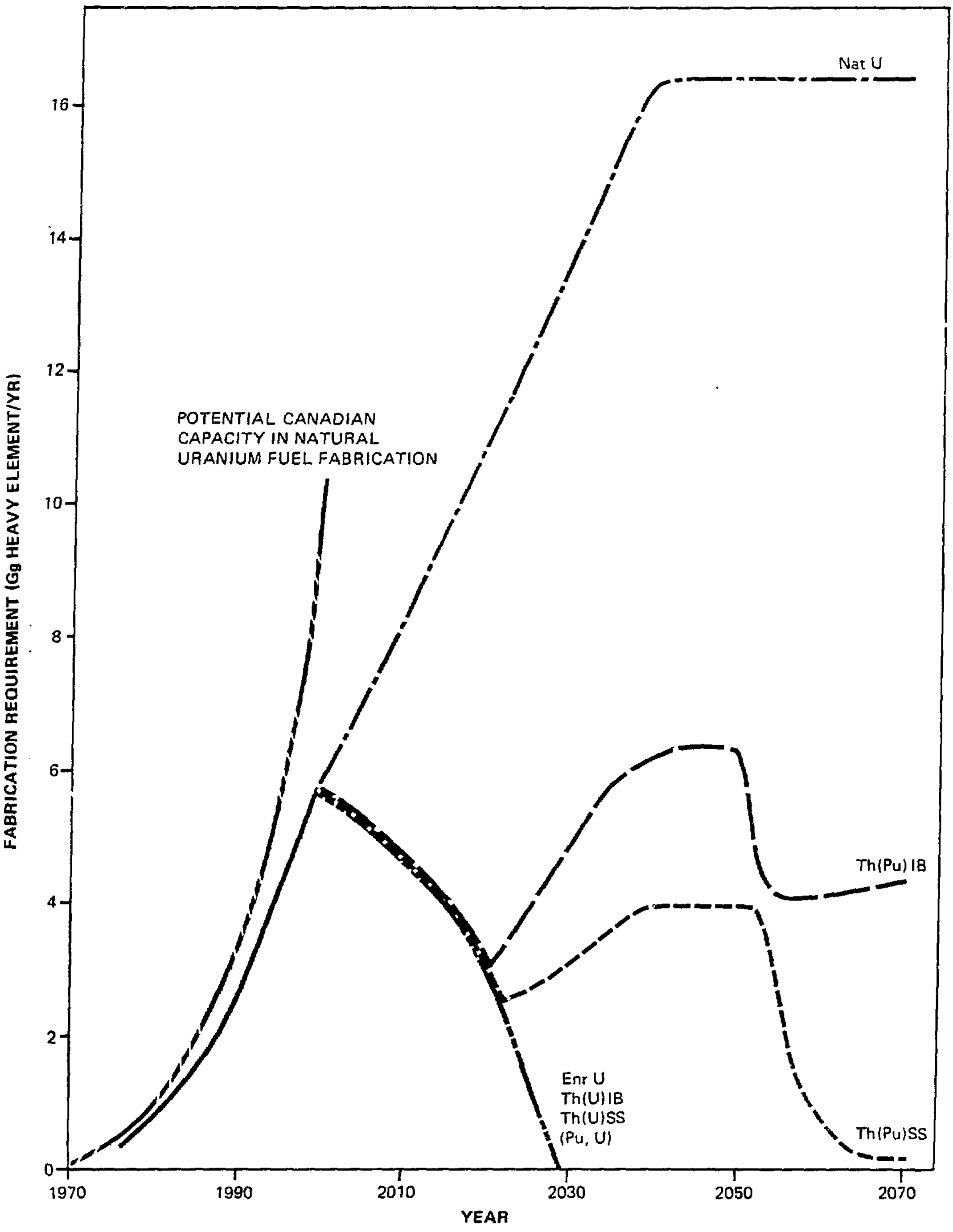
2. Inter-comparison of the requirements of the fuel cycle service industries can provide some overall perspective on the relative ease of commercialization of the different fuel cycles.

4.2 Fuel Fabrication and Reprocessing Requirements

4.2.1 Fuel Fabrication Requirements

The natural uranium fuel fabrication requirements for some of the strategies are illustrated on Figure 4.1. By way of comparison, the projected potential of the Canadian fabrication industry up to the year 2000 is also shown (11).

FIGURE 4.1
FABRICATION REQUIREMENT FOR NATURAL URANIUM FUEL



For the uranium-235 enriched thorium strategies, no additional natural uranium reactor is required after the year 2000. The fabrication requirements therefore decrease. They reach zero in 2030 when the last of the natural uranium reactors are decommissioned at the end of their assumed 30 year life.

The mixed oxide $(Pu,U)O_2$ strategy also behaves in a similar manner. This shows that the plutonium inventory is a sufficient fissile source for the mixed oxide cycle within the study period.

Figure 4.2 plots the fabrication requirements for the alternate cycle fuel. Because the self-sustaining thorium cycles have lower burnups than the intermediate burnup cycles, their fabrication requirements are higher. This can be seen by comparing the curves of strategies Th(U)SS and Th(U)IB.

4.2.2 Reprocessing Requirements

The reprocessing requirements for the natural uranium fuel are plotted on Figure 4.3. The requirements for the alternative fuel reprocessing are shown on Figure 4.4. The main features are very similar to those of the fabrication requirements. It must be noted however that for the plutonium enriched thorium strategies, where a mix of natural uranium and thorium reactors is required, there are two peaks in the reprocessing requirements for the natural uranium fuel. The peak about the year 2020 is due to the additions of natural uranium reactors when the plutonium inventory is depleted. The peak about 2050 is the delayed effect of the decrease in the nuclear capacity growth rate.

4.2.3 Some Observations

(a) The fabrication industry for natural uranium fuel can likely meet the demand even if the use of the natural uranium cycle is continued.

(b) Alternate fuel cycles can significantly reduce the fabrication requirement for natural uranium fuel. However, the reductions are offset by the addition of a new demand - the fabrication of alternative fuel.

(c) Of all the alternative fuels considered, the enriched uranium fuel is the simplest to fabricate. Other fuels, which contain plutonium and/or U-233, require either remote or semi-remote operation.

(d) When plutonium is used as the enrichment material for the thorium cycles, they require two types of reprocessing:

FIGURE 4.2
ALTERNATIVE FUEL FABRICATION REQUIREMENT

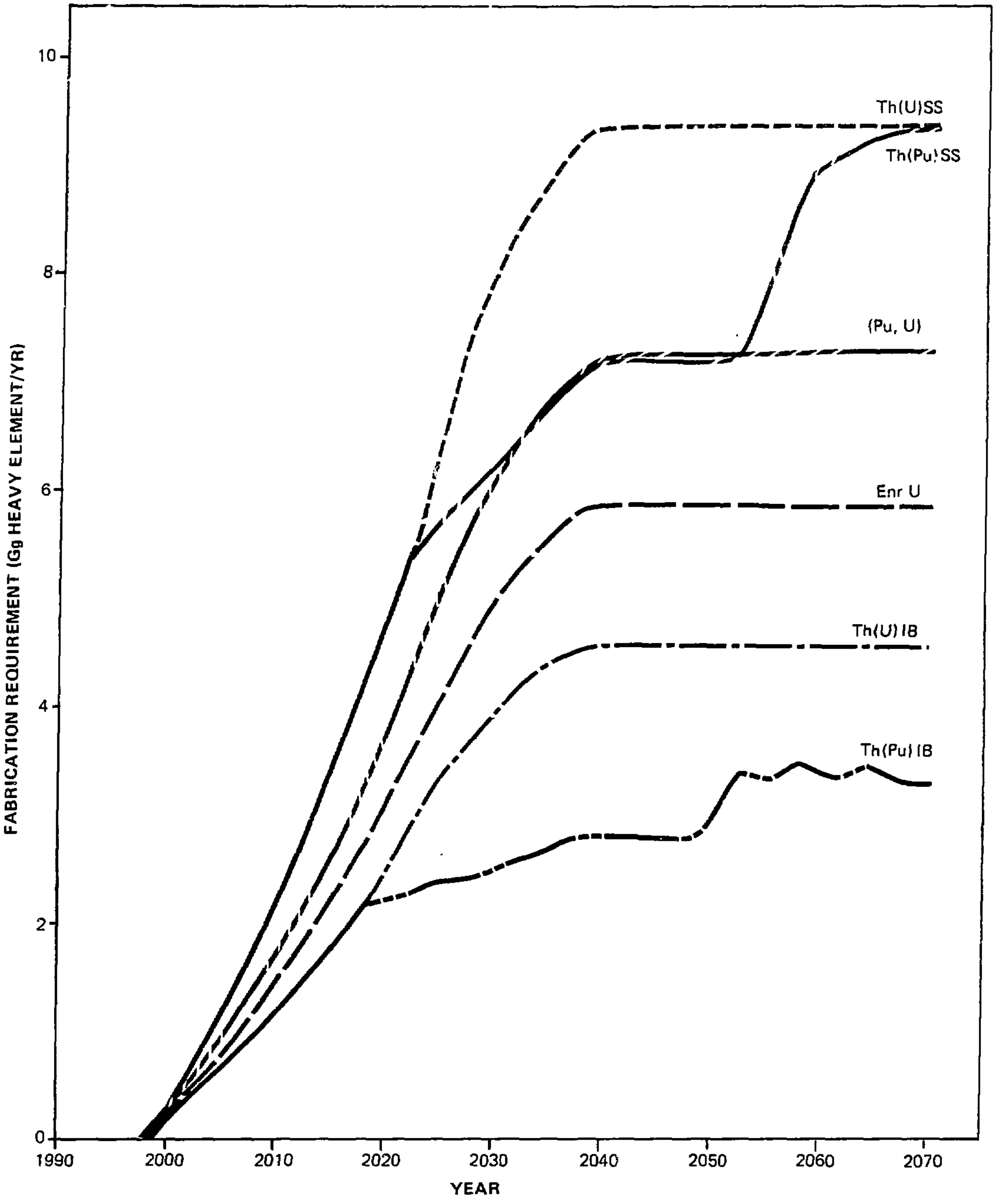


FIGURE 4.3
REPROCESSING REQUIREMENT FOR IRRADIATED NATURAL URANIUM FUEL

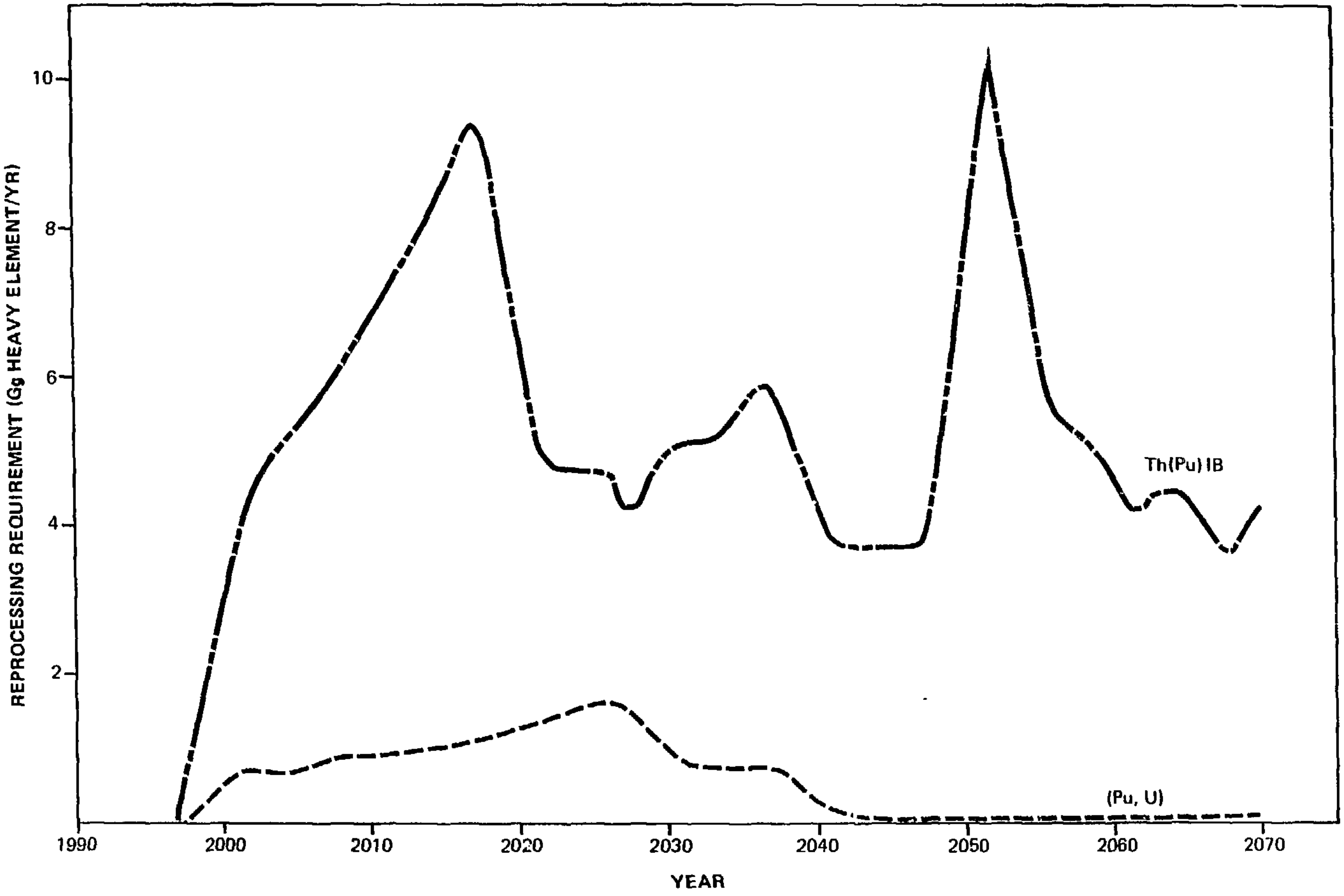
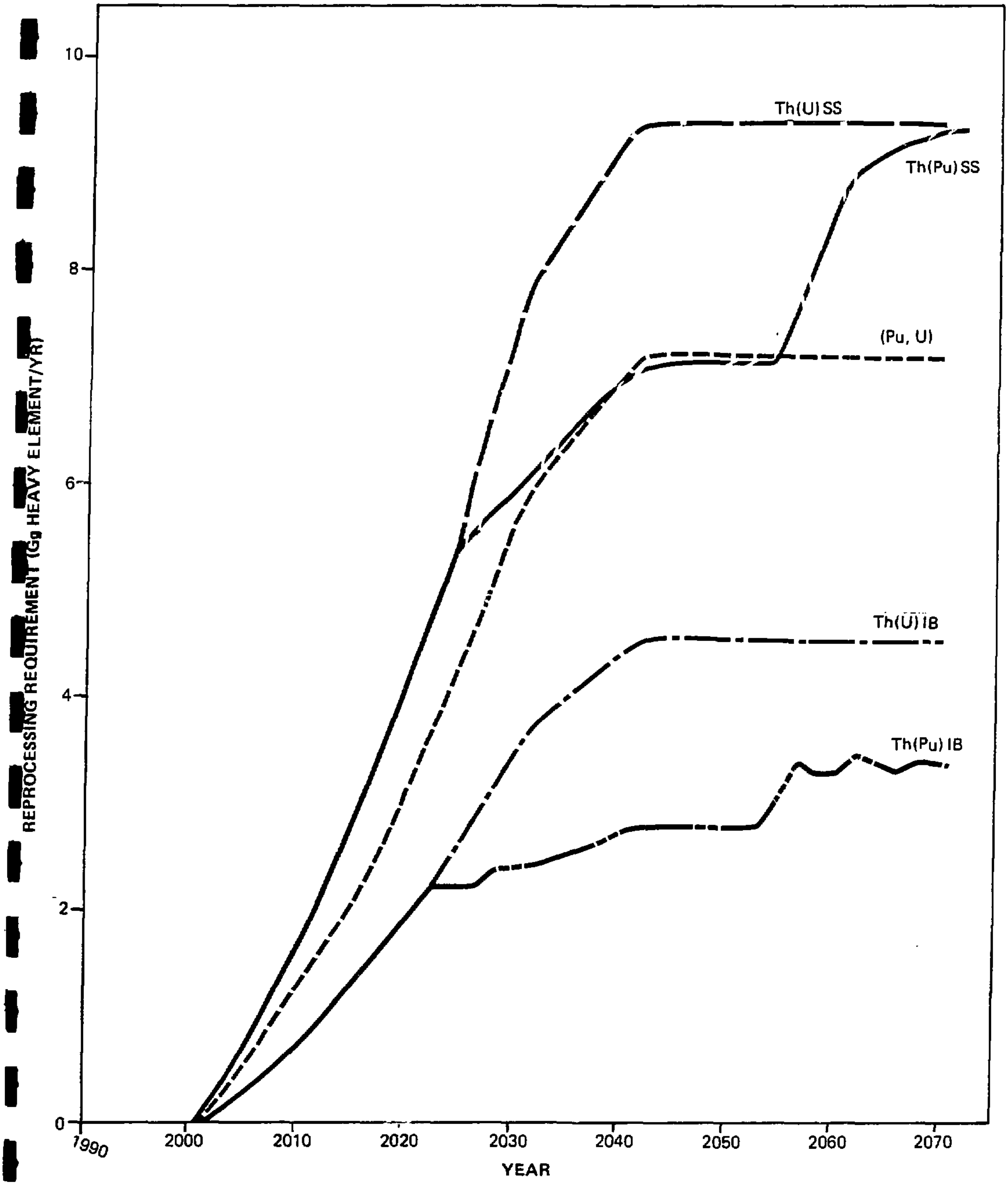


FIGURE 4.4
ALTERNATIVE FUEL REPROCESSING REQUIREMENT



i) Natural uranium irradiated fuel to obtain the plutonium; and

ii) U-233 bearing thoria fuel.

In contrast, the uranium enriched thorium cycles require only the reprocessing of U-233 bearing thoria fuel and the mixed oxide cycle requires only the reprocessing of natural uranium irradiated fuel*.

(e) Compared to the self-sustaining thorium cycles, the intermediate burnup thorium cycles demand less fuel reprocessing and fabrication facilities. Therefore, from an industrial viewpoint, they would be more easily implemented.

(f) Rapid increases in the requirements do occur when some alternate fuel cycles are introduced. Of particular concern is the peaky characteristic of the reprocessing requirements for the plutonium enriched thorium cycles. We found that reductions in the rate of introducing the alternate fuel cycles, and in the rate of change of their installed capacities, can permit more orderly development of the service industries. Analysis along these lines was conducted and is discussed in the next section.

4.2.4 Additional Constraints Applied on the Installed Capacities of the Alternate Fuel Cycle Reactors

Some peaks and rapid increases in the fabrication and reprocessing requirements do occur when some alternate fuel cycles are introduced. For more orderly developments of these service industries, additional constraints on the installed capacities of the alternate fuel cycle reactors must be applied. Because the 'peaky' characteristic is the most severe for the two plutonium enriched thorium cycles, they are considered in the following discussions.

Figure 4.5 shows the installed capacities of the plutonium enriched, intermediate-burnup, thorium reactors before and after the constraints are added. It is worth noting that in the constrained case, the installed capacity is smoother and is strictly increasing. Also, because a smaller installed capacity of thorium reactors is committed in the early part of the study period, it is less efficient in reducing the uranium demand. In fact, the cumulative uranium requirement to 2070 is higher in the constrained case by about 10%, representing an increase from 408 to 447 GgU.

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*Note that the reprocessing of mixed oxide irradiated fuel is similar, if not identical, to the reprocessing of natural uranium irradiated fuel.

FIGURE 4.5
INSTALLED CAPACITY OF THORIUM REACTORS

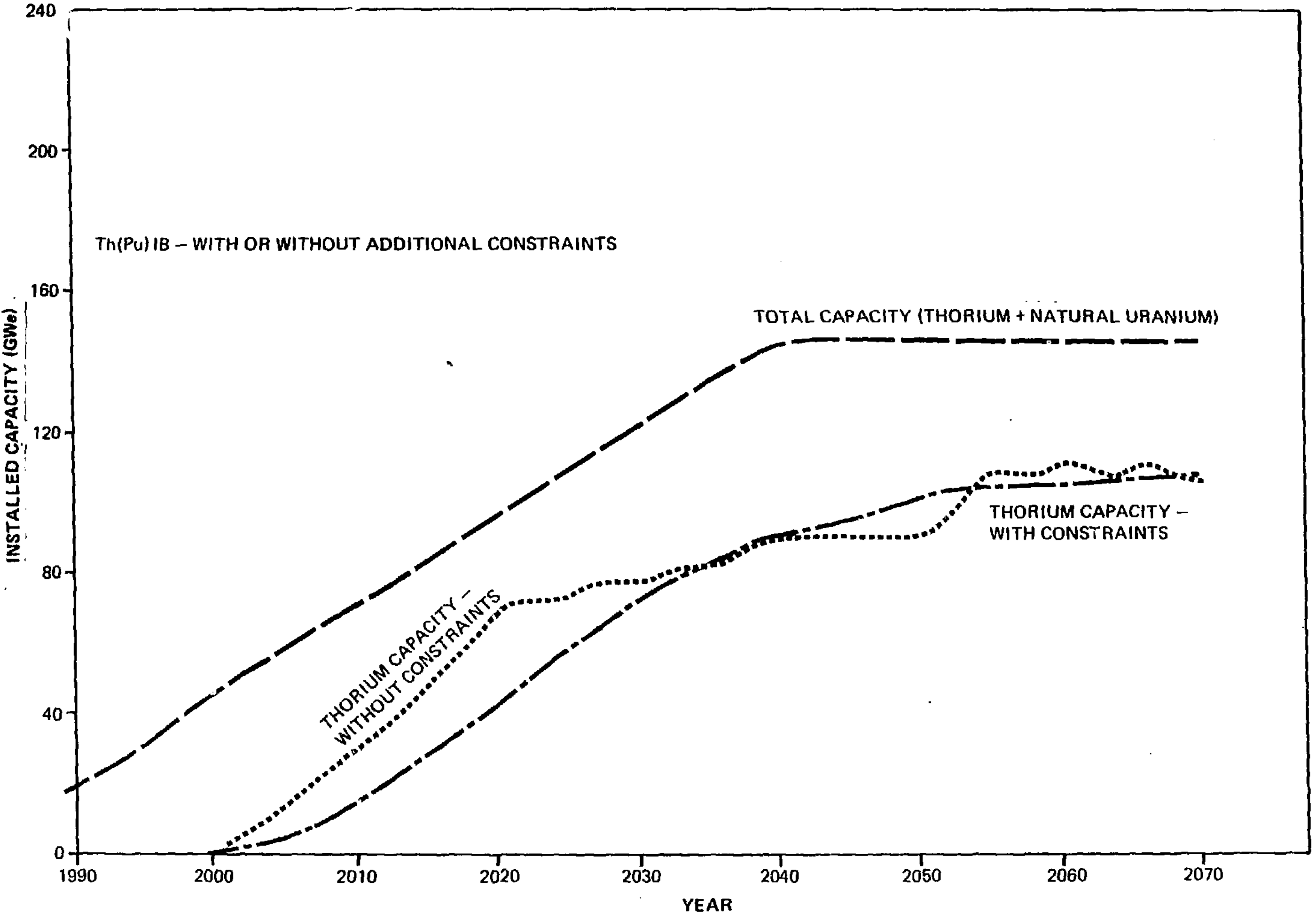


FIGURE 4.6
NATURAL URANIUM FUEL REPROCESSING REQUIREMENT

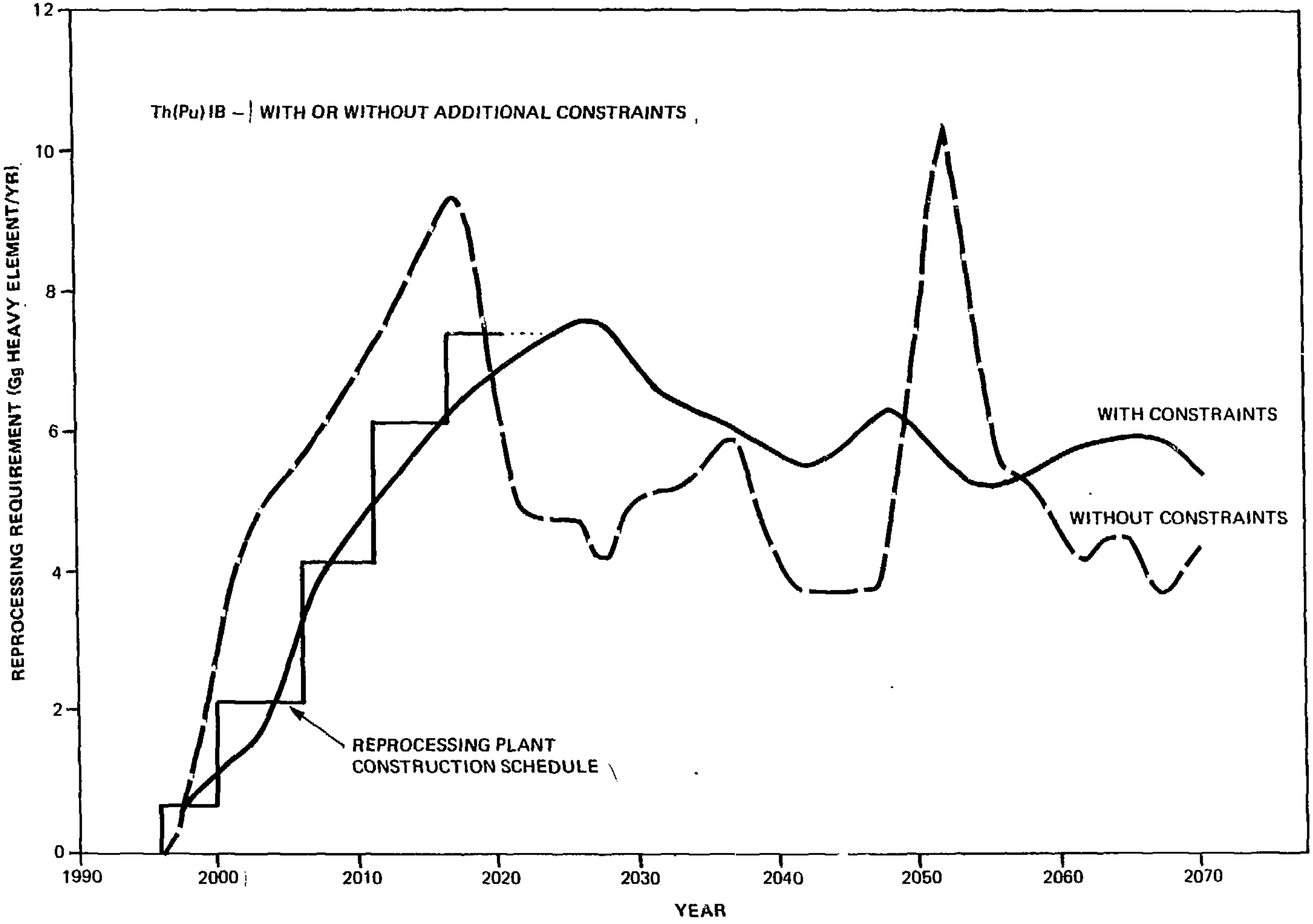


Figure 4.6 contrasts the natural uranium fuel reprocessing requirement with and without the additional constraint. By way of highlighting the orderly development of the industry in the constrained case, a reprocessing plant construction schedule, satisfying the requirement, is also shown. This is not a prediction and is only used to provide some perspective.

With the additional constraint on the self-sustaining thorium cycle, there is an increase in the cumulative uranium requirement of about 20% by the year 2070. In general, without the additional constraint, the calculated savings in uranium from the alternate fuel cycle strategies are on the optimistic side. However, the constraint increases the cumulative uranium requirement by, at worst, about 20%.

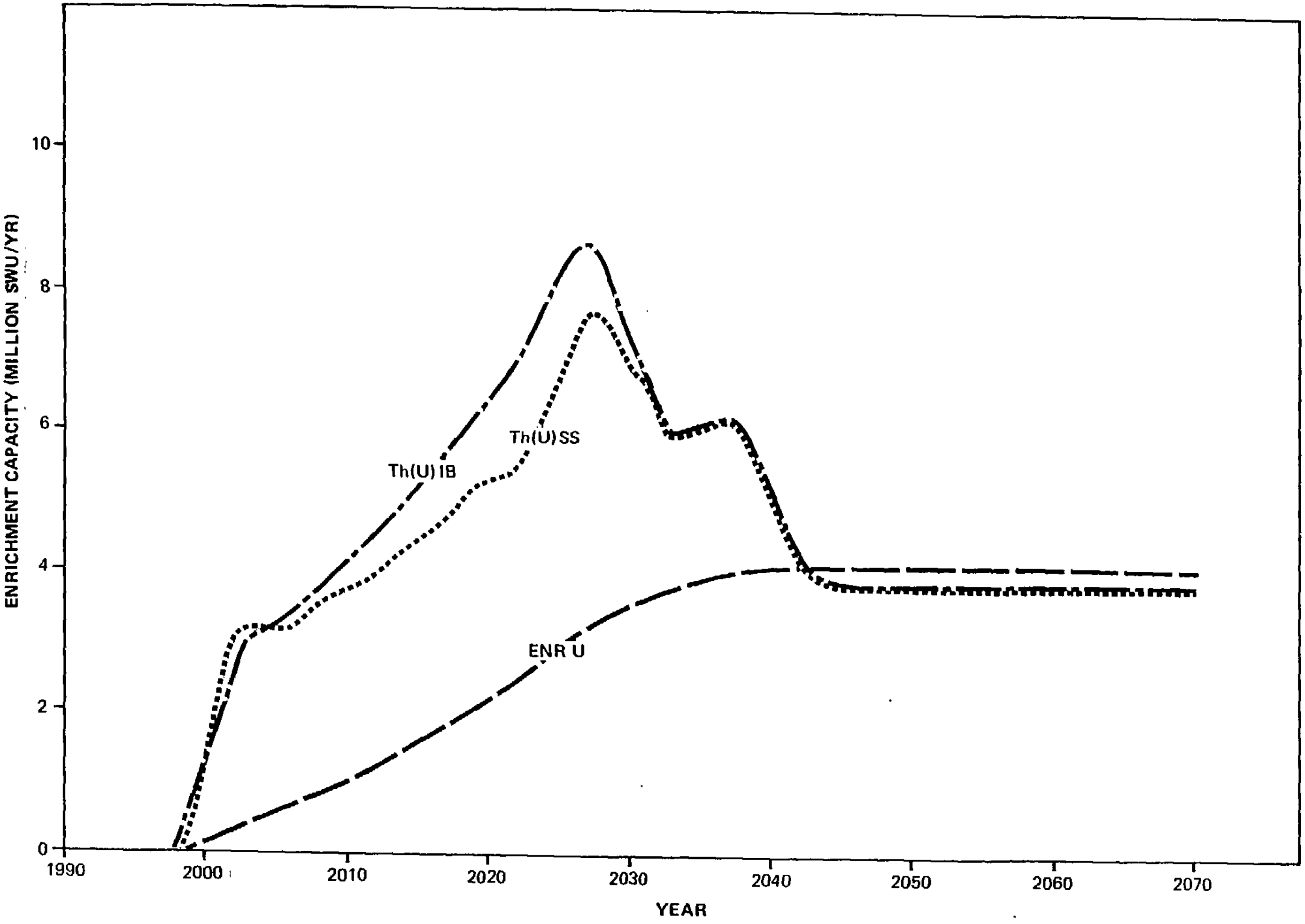
4.3 Uranium Enrichment

Figure 4.7 shows the required uranium enrichment capacity. It demonstrates that, for all cases, a maximum capacity of 9 million kg SWU/yr is sufficient to meet the expected demands.

There appears to be no commercial feasibility problem in establishing the 9 million SWU/yr capacity in Canada in the future. Although the technology of enriching uranium is new to Canada, it has already been well established in many countries. For commercial reasons, these countries would probably be reluctant to transfer the technology directly to Canada. However, it is quite conceivable that by a combination of technological exchanges, purchases and development, an enrichment plant could be constructed in Canada within the next 20 years. As late as 1976, the construction of a uranium enrichment plant in Canada was proposed by Canadif (Reference 12). So there has been interest in such a project. Moreover, the required capacity is relatively modest. In various countries today, some proposed plants have already reached a capacity of 9 million SWU/yr (12).

It was earlier noted that the optimum thorium strategy to minimize uranium consumption would be to switch to uranium-235 enrichment after using up the plutonium inventory. It is evident that such a strategy will require the reprocessing of two types of fuel (natural uranium and thoria fuel) as well as an enrichment capability. In total, when compared to the other fuel cycles, it requires one extra technology, which makes it more difficult to commercialize. Besides, if U-235 is the choice of enrichment material, unless the uranium supply is severely limited, the plutonium will probably not be utilized and an option exists in selling the plutonium in the form of irradiated fuel to other countries which utilize plutonium. From the standpoint of ease of commercialization, this thorium strategy, although optimum in conserving uranium, is likely not preferred and is therefore not considered in this report.

FIGURE 4.7
URANIUM ENRICHMENT CAPACITY REQUIRED



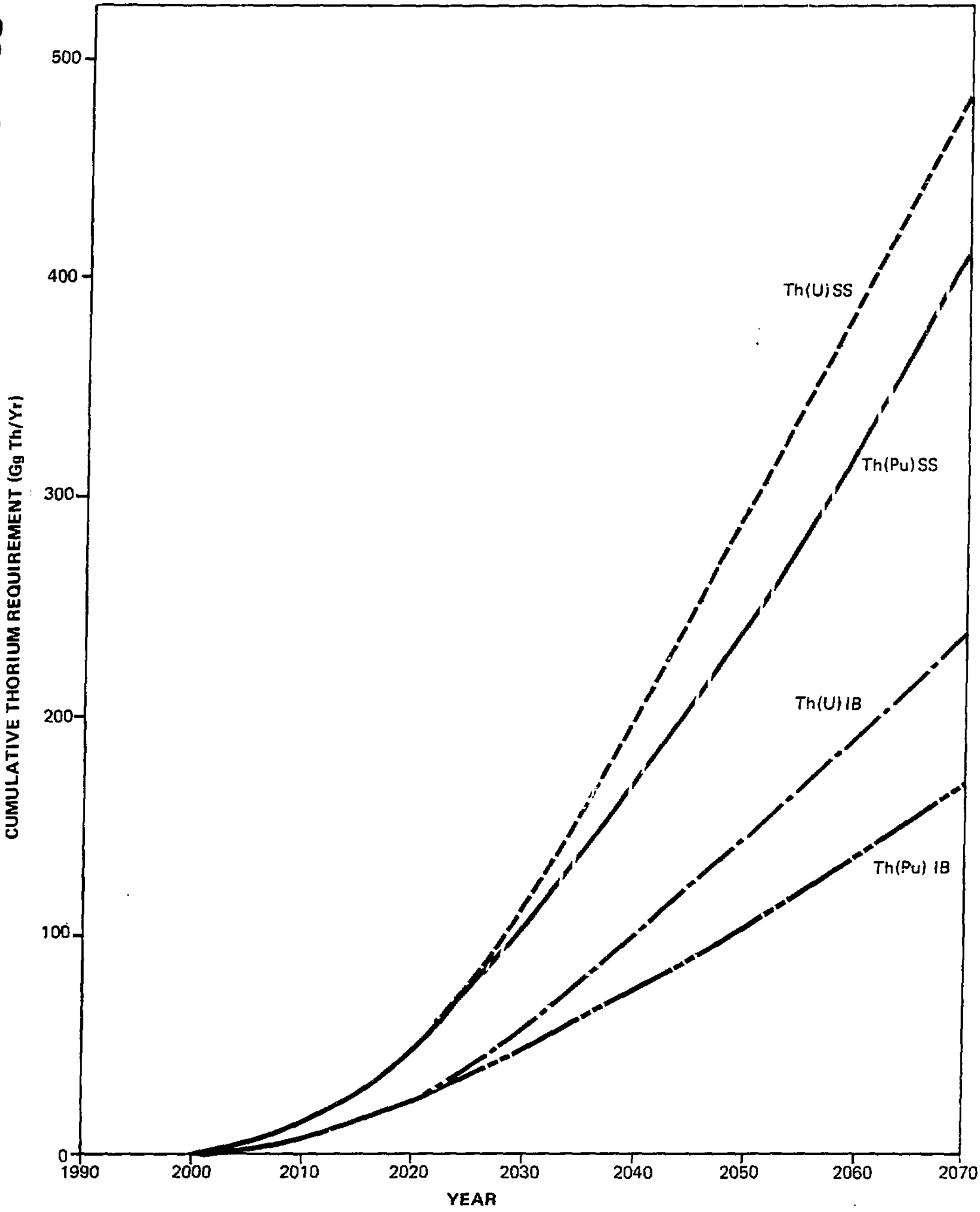
4.4 Thorium Requirements

Figure 4.8 plots the cumulative thorium mining requirements. No recycling of the thorium is considered. The intermediate burnup thorium cycles require less thorium than the corresponding self-sustaining cycles.

It is generally believed that the abundance of thorium in the earth's crust is about 3 times that of uranium. However, the commercial demand for thorium, at the present, is low. Therefore, no extensive resource delineation has been made in Canada. Based on what has already been delineated or is considered probable on the basis of the delineations, the thorium resource estimate is around 200 Gg (13).

If this figure is used as a reference, then the cumulative thorium requirements of some strategies will deplete this resource before 2070. However, because the irradiated thoria fuel must be reprocessed to obtain its fissile content, it would be attractive to recycle also the fertile thorium, from a resource saving and possibly from a waste management point of view. If thorium is recycled, the requirements can be reduced by up to a factor of 10 depending on the cooling and delay time. Thorium supply does not appear to pose any problem within the study period.

FIGURE 4.8
CUMULATIVE THORIUM REQUIREMENT TO THE YEAR 2070



5. Sensitivity Analysis

5.1 General

The bulk of the uranium consumption in many alternate fuel cycle reactors occurs at the beginning of the reactor life. Equilibrium operation, and subsequently future generation reactors, require much less uranium. Therefore, the uranium consumption of an alternate fuel cycle strategy in a given period is highly dependent on the nuclear capacity growth rate. For example, during a very fast growth rate, the uranium-235 initiated, self-sustaining thorium cycle can have higher uranium consumption than the all natural uranium strategy. This is demonstrated by the Th(U)SS strategy on Figure 3.3 within the period 1999 to 2015.

Because of uncertainties in the long term installed nuclear capacity, this chapter examines the sensitivity of the uranium consumption to the assumed growth rate. Also discussed are the effects of recycling loss and delay time during the reprocessing and fuel fabrication stages.

5.2 Sensitivity to Nuclear Capacity Growth Rate

5.2.1 Variations in the Nuclear Growth Rate After the Year 2000

Figure 5.1 illustrates the range of nuclear capacity growth rates chosen for the sensitivity study.

The lower bound is represented by an installed capacity which has an annual increase of 1250 MWe from the year 2000 to 2040. This is then followed by a no growth period to the year 2070. The upper bound is designated as the high installed capacity which has an annual increase of 3750 MWe from the year 2000 to 2070. At 2070, these curves span an installed capacity from 96 to 309 GWe. The range is sufficiently large that it likely encompasses the actual growth rate that will be experienced.

Figure 5.2 plots the cumulative uranium requirements for the three capacity growth rates. It shows that the overall ranking of the strategies, by uranium consumption, is not significantly different for the different growth rates. The self-sustaining thorium cycles still provide the best opportunity to limit uranium requirement.

It was noted earlier that the Th(U) system consumes less uranium than the corresponding Th(Pu)-natural uranium system. However, the latter, using the plutonium in the stockpiled natural uranium irradiated fuel, has the benefit of an instant fissile source without additional uranium consumption. As evident from Figure 5.2, for the base case and low installed capacities, the plutonium inventory exceeds any saving that

FIGURE 5.1

NUCLEAR INSTALLED CAPACITY ALTERNATIVES FOR ONTARIO

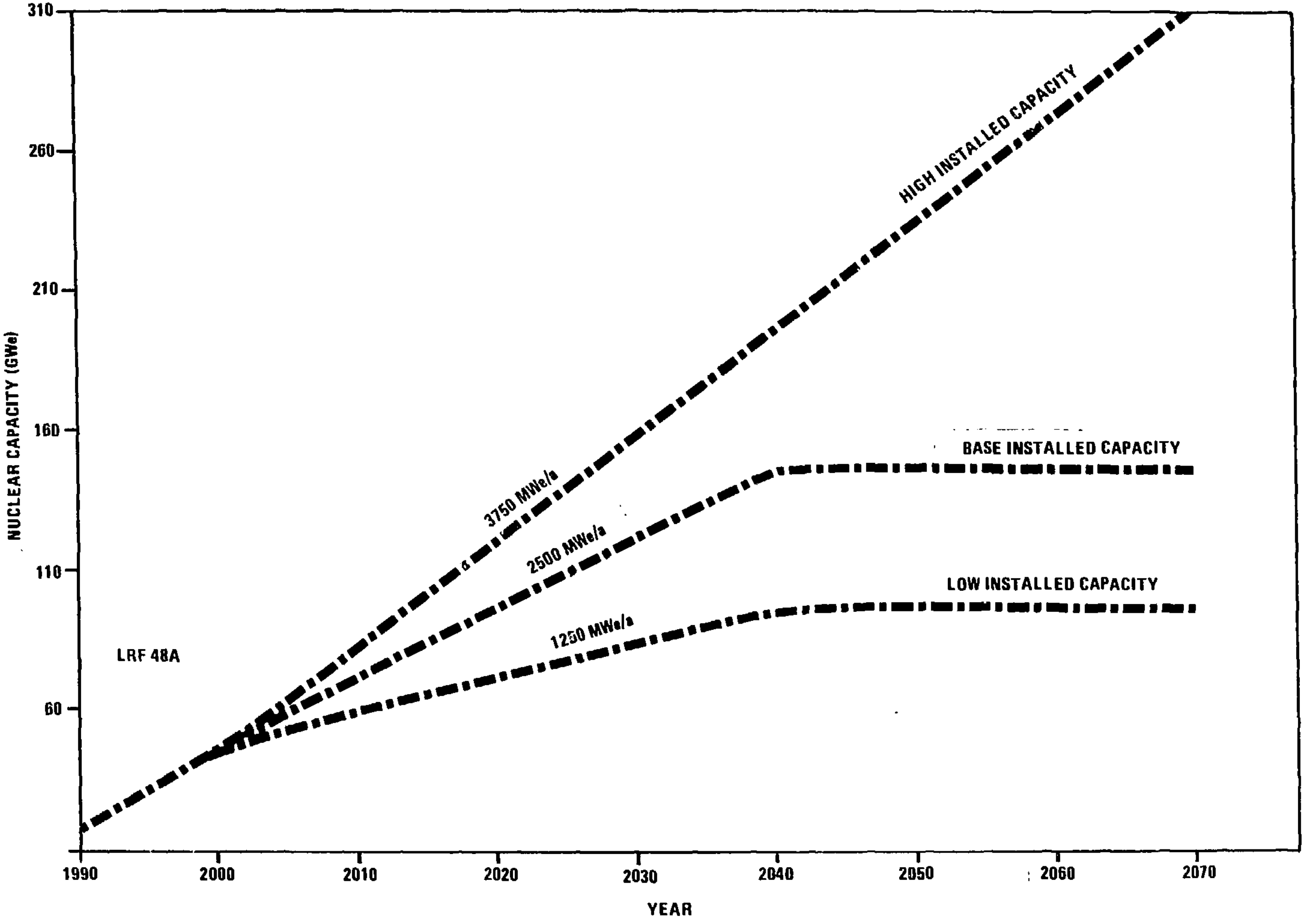
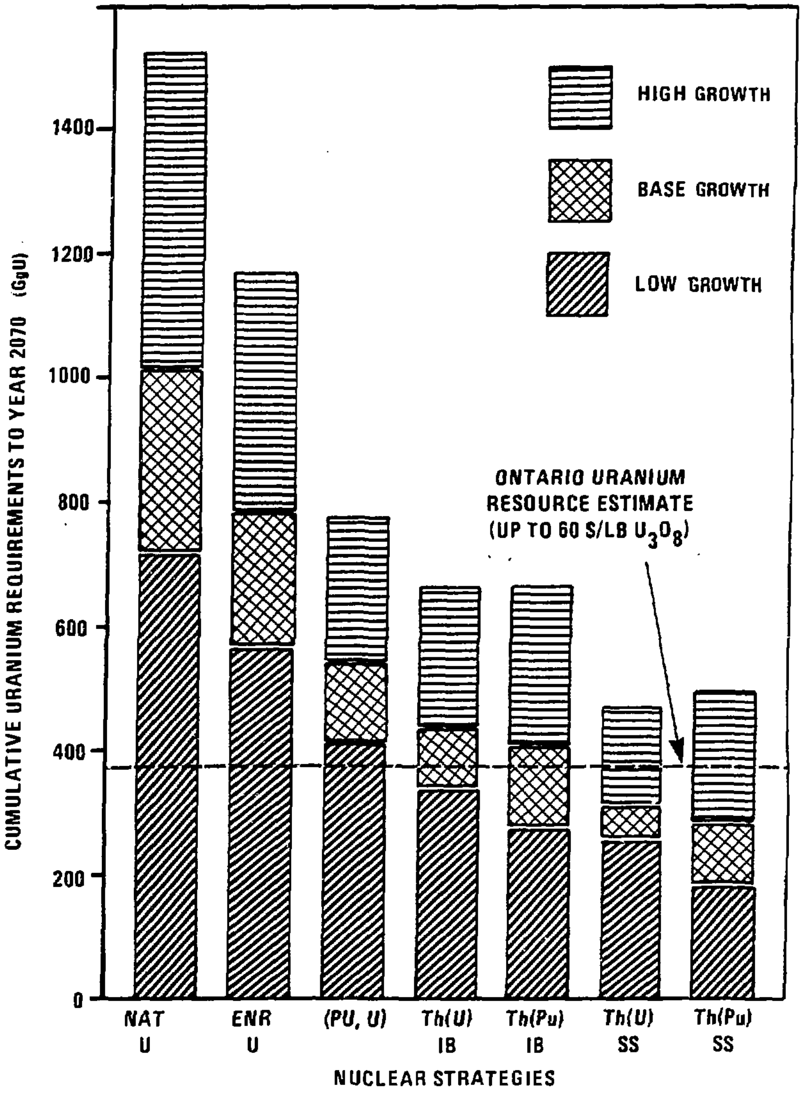


FIGURE 5.2
URANIUM REQUIREMENTS: SENSITIVITY TO INSTALLED CAPACITY



the Th(U) system has over the Th(Pu)-natural uranium system in the study period. The latter therefore consumes less uranium. However, with the high installed capacity, the situation is reversed by the year 2070, so that the Th(Pu)-natural uranium system is shown to consume more uranium. Nevertheless, any difference in the uranium requirement between the two systems is not significant.

5.2.2 Effects of a Zero Growth Period

To show the effect of a zero growth rate, a Base Continuous installed capacity was analysed. As shown on Figure 5.3, it is identical to the base case except that the zero growth is replaced by a constant growth of 2500 MWe/yr.

Table 5.1 shows the cumulative uranium consumption for the base case and the Base Continuous growth rates. It is evident that the no growth period, starting in 2040, decreases the cumulative uranium consumption. At 2070, the percentage decrease is relatively small for the natural uranium cycle (~ 12%), but becomes more significant in the thorium fuel cycles (up to ~ 21%). The self-sustaining thorium cycles are shown to be particularly effective in low/zero growth conditions.

5.2.3 Growth Rate Decrease in the Period 1978-2000

A common feature of all growth rates considered so far is that the installed capacity in the pre-2000 period is based on Ontario Hydro forecast LRF-48A. Estimates of nuclear capacity growth rate have in the past year declined in many places, including Ontario. The 1978 load forecast made recently by Ontario Hydro shows a reduction in the installed nuclear capacity at the year 2000 of approximately 11 GWe.

To evaluate the effect of the reduced growth rate in the pre-2000 period, a Reduced Base growth shown on Figure 5.4 was chosen. The installed capacity at 2000 is reduced by about 11 GWe from the base case. A comparison of the cumulative uranium consumption to 2070 is given on Figure 5.5.

It is shown that the lower growth rate in the pre-2000 period results in 10-17% reductions in the total uranium consumption of the strategies. The reductions in the Th(Pu) strategies are consistently smaller than their corresponding Th(U)SS strategies. For instance, in the base case, the difference between the requirements of the Th(Pu)SS and Th(U)SS strategies is 25 GgU. For the Reduced Based growth, the difference is narrowed to 1 GgU. This is evidently caused by the smaller plutonium inventory with the Reduced growth rate. However, it should be noted that the ranking of the strategies, by uranium consumption, is not different for the two different growth rates.

FIGURE 5.3
NUCLEAR CAPACITY ALTERNATIVES

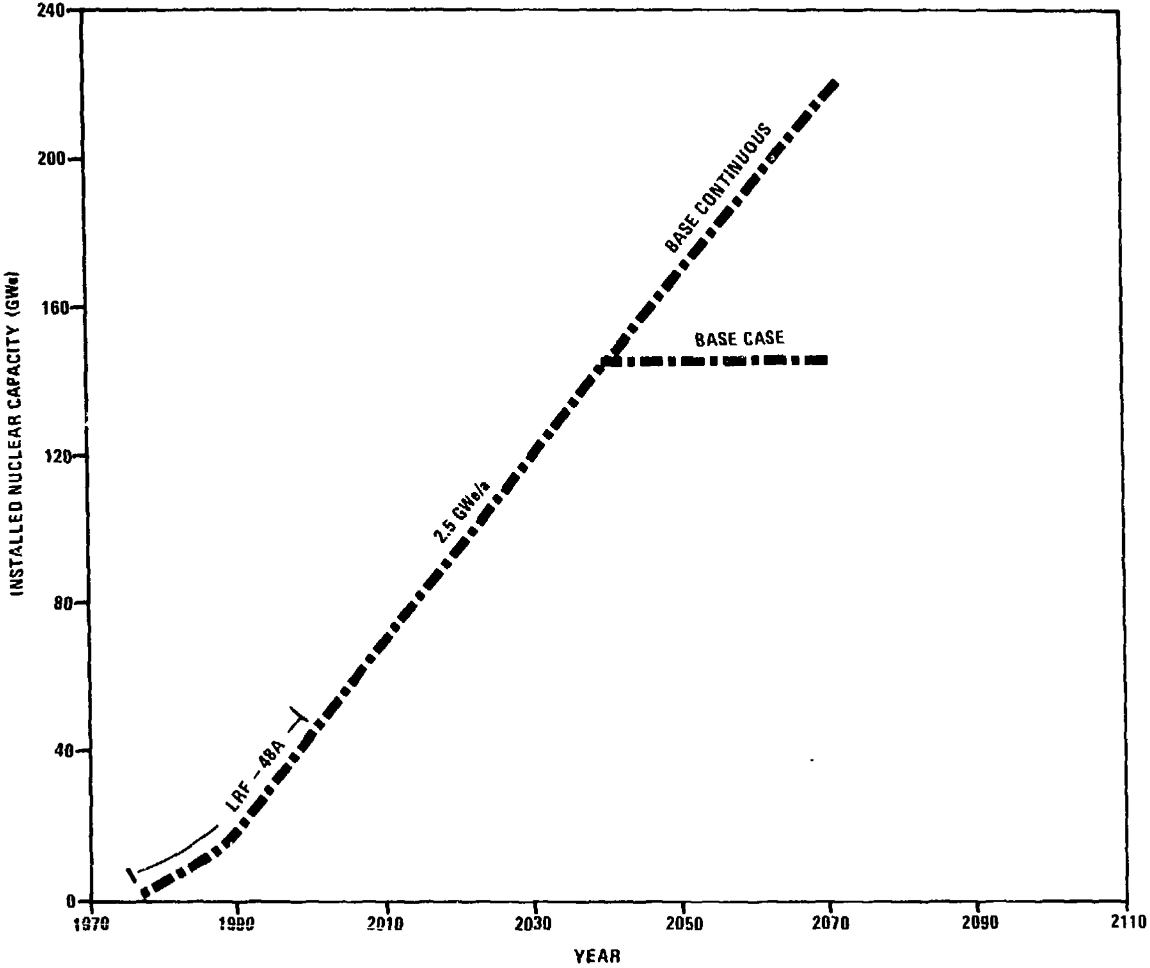


Table 5.1

Effect of A Zero Growth Period on Uranium Consumption

Nuclear Strategies	Cumulative Uranium Consumption (GgU) Base Continuous Installed Capacity	Base Case Installed Capacity	% Decrease
1) Natural Uranium	1159	1015	12.4
2) Enriched Uranium	899	786	12.6
3) (Pu,U)	611	545	10.8
4) Th(Pu)IB	496	408	17.7
5) Th(Pu)SS	363	288	20.7
6) Th(U)IB	526	438	16.7
7) Th(U)SS	384	313	18.5

FIGURE 5.4

NUCLEAR CAPACITY ALTERNATIVES

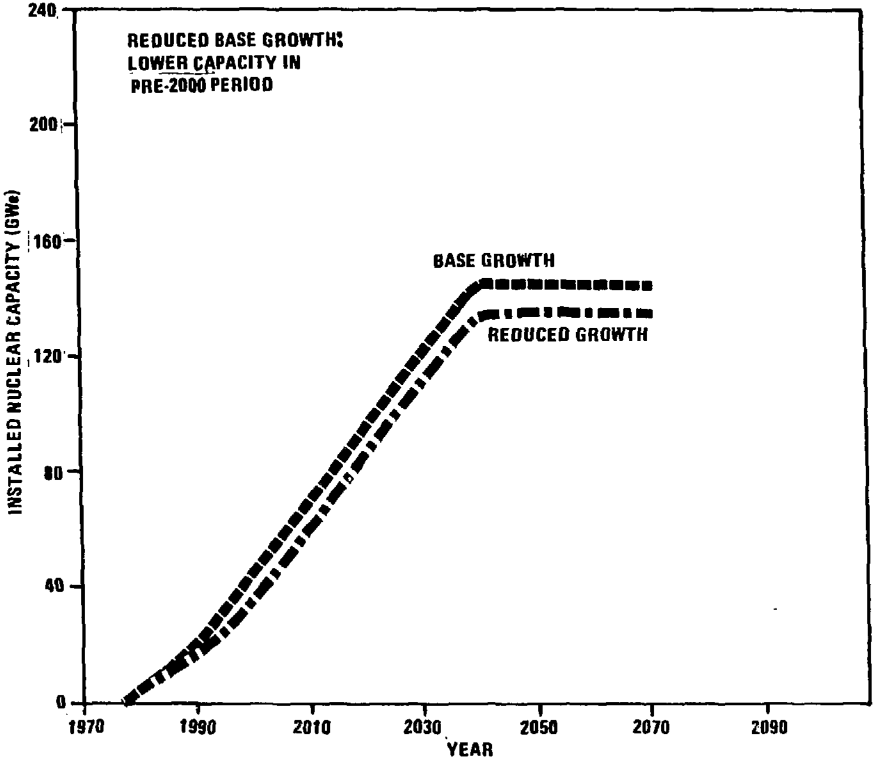
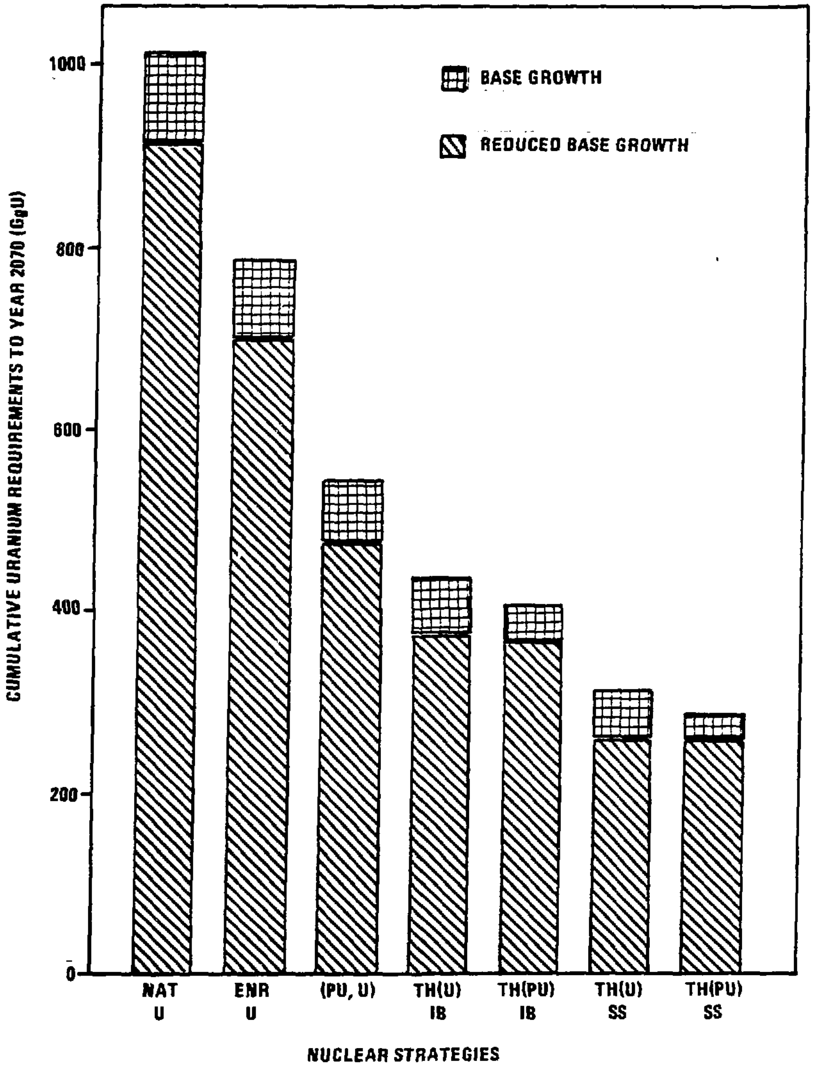


FIGURE 5.5

CUMULATIVE URANIUM REQUIREMENTS TO 2070
FOR THE BASE AND REDUCED GROWTH RATE



5.2.4 Some Observations

(a) Uncertainties in the nuclear capacity growth rate results in a significant variation in the total uranium requirements by the year 2070. In particular, continuing with the natural uranium cycle has variations between 720 GgU and 1520 GgU.

(b) Alternate fuel cycles can significantly reduce the uranium requirements. The relative ranking of the cycles, by uranium consumption, is not significantly different for the different growth rates.

(c) Changes in the relative merits (in reducing uranium requirement) between the uranium-235 and plutonium enriched thorium strategies occur for different growth rates. In general, a higher growth rate than the base case after the year 2000 and a lower growth rate in the pre-2000 period tend to favour the use of uranium-235 as the enrichment material. Nevertheless, our studies indicates that, within the study period, any advantage of one enrichment choice over the other is small.

(d) The self-sustaining thorium cycle offers the greatest opportunity to limit uranium consumption. This cycle is particularly effective for low nuclear growth rates.

5.3 Sensitivity to Recycling Loss and Recycling Delay Time

Figures 5.6 and 5.7 show the effects of recycling loss and recycling delay time on four of the thorium cycle strategies. The recycling loss includes that during both reprocessing and fabrication. The delay time is the period between fissile material being discharged from a thorium reactor and the time it is refabricated into new fuel and loaded into the same or another reactor.

The effect on uranium consumption is naturally greater for the self-sustaining cycles which have a lower burnup and undergo more frequent reprocessing. If the reprocessing loss is high but the delay time is short (or vice versa), the effect on uranium savings is modest. The uranium savings relative to the natural uranium cycle are about 7% less for the intermediate burnup thorium cycle and about 12% less for the self-sustaining cycle in the worst conditions shown on Figure 5.6. But if both parameters are large, say 3% loss and 3.5 year delay, then the reductions in uranium savings reach 11% for the intermediate burnup cycle and about 22% for the self-sustaining cycle (Figure 5.7).

FIGURE 5.6
SENSITIVITY OF URANIUM REQUIREMENT TO RECYCLING LOSS AND DELAY TIME

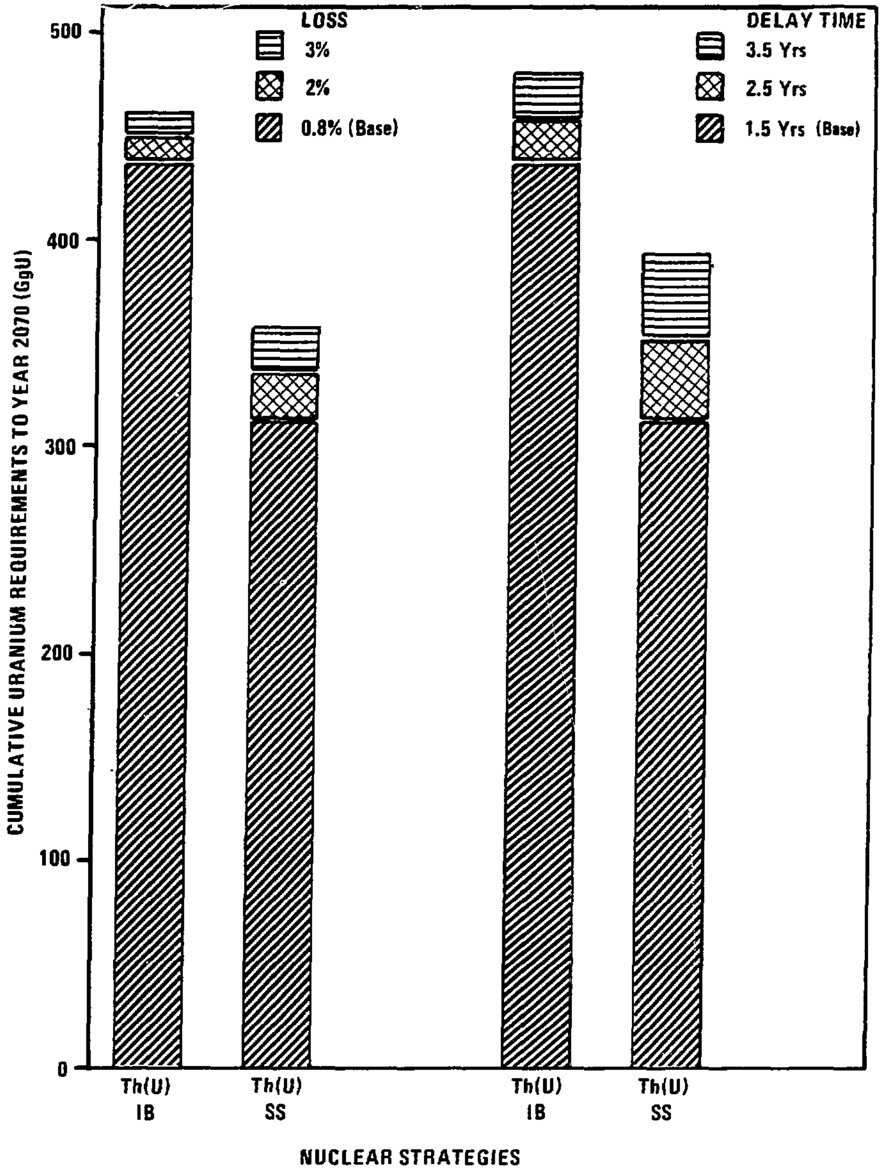
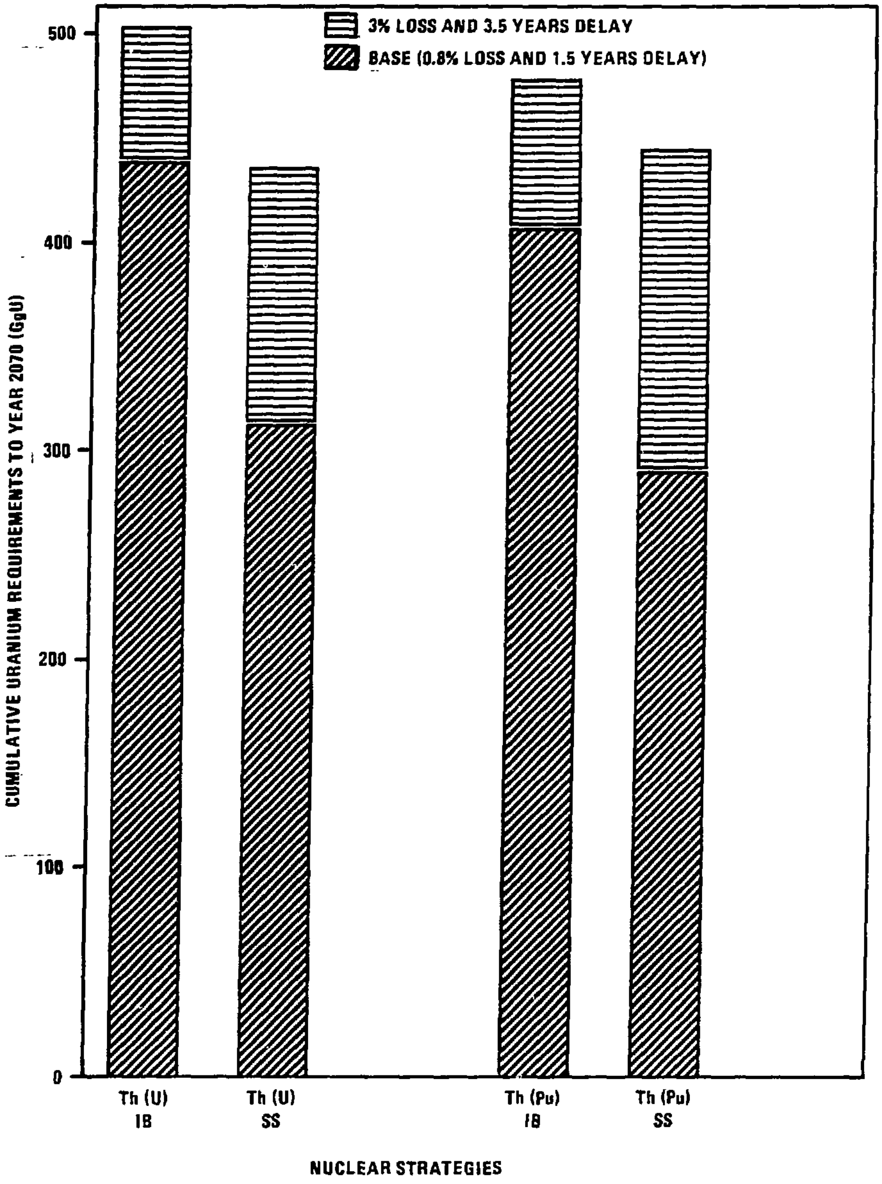


FIGURE 5.7
URANIUM REQUIREMENT FOR 3% RECYCLE LOSS
AND 1.5 YEARS DELAY



6. Optimum Strategy

It has been shown that alternate fuel cycles can add to energy security by lowering the uranium requirement. Of the simple strategies studied here, the self-sustaining thorium cycles are shown to offer the best opportunities to reduce the uranium demand.

Reference 14 describes corresponding results for strategies using fast breeder reactors in Ontario. The uranium saving of fast breeders is shown to be comparable to or even better than the self-sustaining thorium cycles. For completeness, the fast breeders are therefore included in the discussion that follows.

From the standpoints of uranium utilization and ease of commercialization, what is the best strategy for nuclear power production?

One obvious pathway is to continue with the natural uranium cycle. When the need is foreseen, one of the self-sustaining thorium cycles or fast breeder will then be employed.

However, as shown earlier, the resource impact of the alternate fuel cycles is gradual so that marked divergence in the uranium requirement from the natural uranium cycle does not occur until 10 - 20 years after their implementation. There is also a predicted 20 - 30 year R&D delay time for the commercialization of the thorium cycle or fast breeder. In view of these facts, the need must be forecast approximately 40 years in advance. Since uranium consumption depends on the nuclear-electric growth rate, and both the growth rate and the uranium supply are very uncertain, any prediction of the need and optimum timing to implement the thorium cycles or the fast breeder is very difficult.

Moreover, it must be realized that a pathway which changes from the natural uranium to a thorium cycle or FBR's requires a considerable technological change all at once. For the thorium cycles, it requires:

i) The thorium-uranium-233 fuel fabrication and reprocessing industries.

ii) The natural uranium fuel reprocessing industry when plutonium enrichment is used.

iii) The uranium enrichment technology when uranium-235 is used.

For the fast breeder, the natural uranium fuel reprocessing, the mixed oxide fuel fabrication, as well as the fast breeder reactor technology are required.

Because of these complexities, it is considered desirable that intermediate cycles be used in order to achieve a gradual technological advancement. They would also allow more possible decision points so that, dependent on future events, necessary changes in policy and strategy can be made without drastic reversals.

Two possible pathways are outlined on Figure 6.1. They will be discussed in qualitative terms.

The first pathway starts with the mixed oxide $(Pu,U)O_2$ cycle. This cycle is simpler to develop than the thorium cycles. It also provides working experience in the natural uranium fuel reprocessing industry as well as the $(Pu,U)O_2$ fabrication industry. Both industries are required for the fast breeder while the former industry is necessary for the thorium cycle with plutonium enrichment.

It should be noted that an intermediate burnup thorium cycle precedes the self-sustaining cycle in the selection. This is because the intermediate burnup cycle require less reprocessing and fuel fabrication requirement. Its uranium requirement is also less sensitive to recycling loss and delay time, both parameters which are required to be confirmed by future experience.

The second pathway starts with the once-through enriched uranium cycle, which is the simplest alternative to the current natural uranium cycle. Since uranium enrichment facility would eventually be needed, this cycle could naturally lead to the thorium cycles with uranium-235 enrichment.

Moreover, the irradiated enriched uranium fuel will have a 20% higher concentration of plutonium than the natural uranium irradiated fuel. Thus, future plutonium recovery costs and required reprocessing plant capacity will be smaller. It was noted earlier that an additional constraint on the installed capacity of plutonium enriched thorium reactors must be imposed in order to obtain an orderly development of the reprocessing industry. The preceding use of the enriched uranium cycle can facilitate the plutonium enriched thorium cycles and the fast breeder by reducing the cost of, and also the demand for, reprocessing.

There is another aspect of flexibility in the two pathways which is not illustrated on Figure 6.1. The fast breeders can, if desired, be employed as 'fuel factories' in parallel with the mixed oxide cycle $(Pu,U)O_2$ reactors or the plutonium enriched thorium cycle reactors. In this mode, the prime function of the fast breeder is not to generate power, but to generate the plutonium required for the plutonium burners.

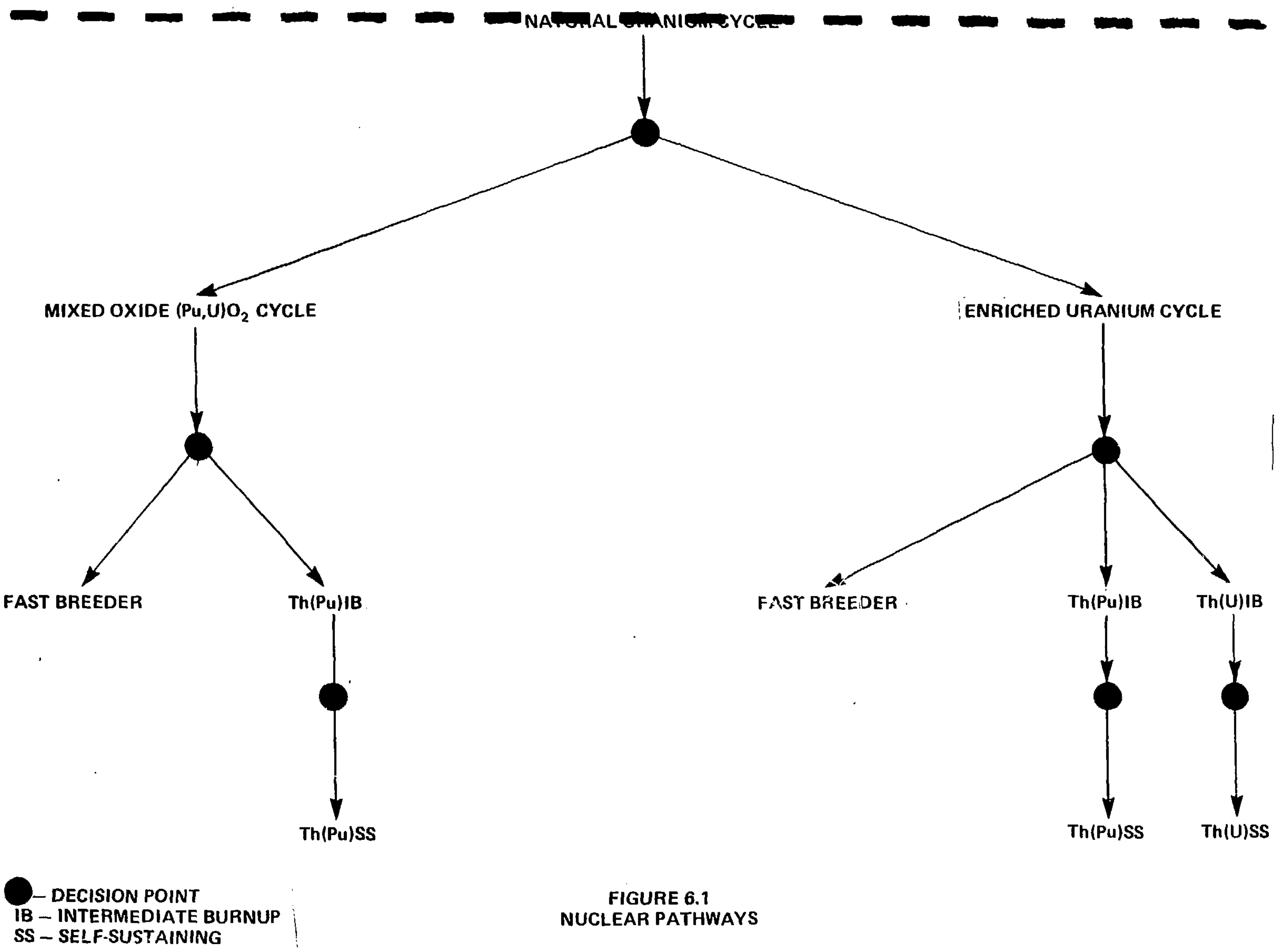


FIGURE 6.1
NUCLEAR PATHWAYS

All strategies in this study assume the introduction of alternate fuel cycles in the year 2000. While this provides a common ground for comparing the impacts of each cycle, it must be noted that the realistic commercialization date for the thorium cycles and fast breeder will probably be in the period 2015 - 2020. The commercialization of the mixed oxide cycle can possibly be achieved in 2005, whereas the enriched uranium cycle could be implemented in the early 1990's. Because these two simpler cycles can also conserve uranium relative to the natural uranium cycle, using either one of them as the intermediate step permits an earlier transition to a higher uranium saving system. Hence, it delays the need for, and optimum introduction date of, the thorium cycles or the fast breeder.

References 15 and 16 examine the economic potential of the alternate fuel cycles. It is concluded that in the short to mid-term (i.e. from the present to the early twenty-first century), the enriched uranium cycle shows the best economic prospect of reducing the fuelling cost. In the long term (i.e. early to mid twenty-first century), the intermediate burnup, plutonium enriched thorium cycle has the highest economic potential of the CANDU cycles considered. Hence, the findings in this report, based on resource utilization and the ease of commercialization, complement the economic results. The evidence points in favour to the once-through enriched uranium cycle as the intermediate cycle for adoption.

7.0 Conclusions and Recommendations

- Within the range of nuclear growth rates considered for Ontario, continuing with the natural uranium cycle requires 720 to 1520 Gg of uranium by the year 2070. Whether the uranium mining industry and the uranium resource base can sustain these demands is at present uncertain. However, based on today's resource estimate, there is a possibility of a uranium supply shortfall occurring before the middle of the next century.

- Alternate fuel cycles and fast breeders can significantly reduce the uranium requirements. Of the options considered, self-sustaining thorium cycles and fast breeders offer the greatest opportunities to limit the uranium demand.

- The many possible alternate fuel cycles, including choices of enrichment material, lead to a wide variation in uranium demands, requirements for fuel cycle services and need for technological development. Each alternate fuel cycle has its advantages (or disadvantages) depending on future situations. The optimum choice and introduction date of alternate fuel cycles in Ontario is dependent on: the future uranium supply, the future growth rate, progress in reprocessing and active fabrication technology and, many other socio-economic considerations.

- Because thorium cycles and fast breeders require substantial technological development, an intermediate fuel cycle is desirable to ease their commercialization. This cycle would reduce uranium requirements and act as a technological bridge. It would also delay the need for the thorium cycles or fast breeder. Hence it would 'buy' more time for development, provide more decision points and allow a more flexible nuclear strategy which could respond to future uncertainty.

- Two possible intermediate cycles are suggested: the mixed oxide $(Pu,U)O_2$ cycle and the enriched uranium cycle. Of the two cycles, the enriched uranium cycle is economically and technically preferable. It is recommended that further detailed studies on the use of the enriched CANDU uranium cycle should be undertaken.

Acknowledgements

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Appendix 1

Definitions of Uranium Resource Categories

This appendix gives the definitions of the uranium resource categories: Measured, Indicated, Inferred and Prognosticated, as classified by Energy, Mines and Resources Canada. The following definitions are excerpts from Reference 1.

Measured (Proven) 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 the size, shape and mineral content are well established. It must be stated whether the tonnage and grade refers to in-situ or to recoverable ore, with recovery factors shown and explained.

Indicated (Probable) comprises ore for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projections 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) 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 upon the characteristics and knowledge of the orebodies.

Prognosticated Resources comprise estimated tonnage of deposits which are located beyond specific limits established for inferred ore. They may include tonnages of portions of identified orebodies or of concealed satellite orebodies, 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.