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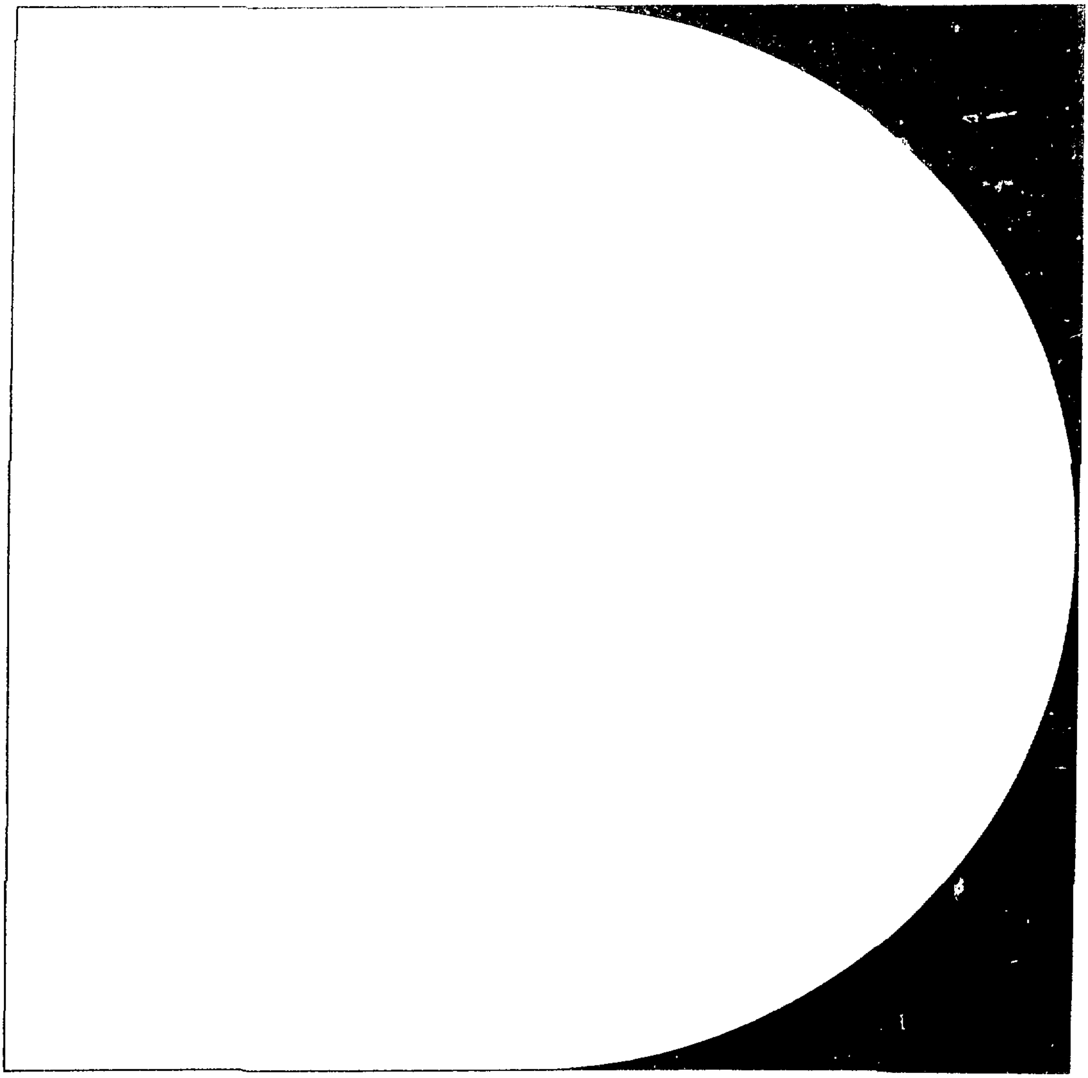

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THE LOW ENRICHED URANIUM FUEL CYCLE IN ONTARIO: A RESOURCE UTILIZATION STUDY

Nuclear Studies and Safety Department

Report No. 79011 February, 1979

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Abstract

The uncertainty of an assured long-term supply of low cost uranium has led to consideration of uranium-conserving alternate fuel cycles for use in CANDU reactors. Six fuel-cycle strategies are examined in terms of their uranium-conserving properties and their ease of commercialization for three assumed growth rates of installed nuclear capacity in Ontario.

The fuel-cycle strategies considered assume the continued use of the natural uranium fuel cycle up to the mid-1990's. At that time, the low-enriched uranium (LEU) cycle is gradually introduced into the existing power generation grid. In the mid-2020's one of four advanced cycles is introduced. The advanced cycles considered are: mixed-oxide, intermediate burn-up thorium (Pu topping), intermediate burn-up thorium (U topping), and LMFBR. Thus, four of the strategies consist of three fuel cycles, with the LEU as an intermediate cycle. For comparison purposes an all-natural-uranium strategy, and a natural uranium-LEU strategy (with no advanced cycle) are also included.

The cumulative and annual uranium requirements, fuel fabrication and reprocessing requirements and uranium enrichment requirements are presented for each strategy for each assumed growth rate of nuclear capacity. Also discussed are the effects of omitting the intermediate LEU cycle, and proceeding directly to an advanced cycle.

The three-cycle strategies involving the plutonium-topped thorium or the LMFBR cycles show the most potential for reducing uranium demand for any reasonable nuclear growth rate. The development of secondary industries is fairly smooth for each strategy. However, none of the fuel-cycle strategies considered has emerged as a clear, overall best-choice. A system economic analysis, based on the material throughput rates presented here, is recommended.

The use of the LEU fuel cycle as a stepping stone to an advanced cycle is shown to have numerous advantages over proceeding directly from the natural uranium cycle to an advanced cycle. Technical expertise necessary for the introduction of any of the advanced cycles would be gained by first introducing the LEU cycle. Furthermore, omitting the LEU cycle as an intermediate cycle would require more rapidly fluctuating throughput rates for the secondary industries, as well as higher annual and cumulative uranium requirements. Thus, in addition to reducing fuelling costs, the introduction of the LEU cycle would facilitate the later commercialization of an advanced cycle.

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TABLE OF CONTENTS

Page

Abstract i
Distribution ii

1. Introduction 1

2. Fuel Cycles and Strategies 3

3. Nuclear Capacity Growth Rates 7

4. Results 9
   4.1 Cumulative Uranium Requirements 9
   4.2 Annual Uranium Requirements 15
   4.3 Fuel Fabrication Requirements 18
   4.4 Irradiated Fuel Reprocessing Requirements 22
   4.5 Uranium Enrichment Requirements 24
   4.6 Total Available Plutonium 26
   4.7 Installed Capacity of LEU Reactors 27

5. Effects of Omitting the Intermediate LEU Cycle 31

6. Discussion of Results 34

7. Planned Future Studies 36

References 37

Appendix A - Introduction Rate of New Methods of Electricity Generation in Ontario A-1

LIST OF TABLES

Table		Page
2.1	Fuel Cycle Parameters	4
2.2	Process Yields and Delay Times	5
2.3	Fuel Cycle Strategies	6
4.1	Cumulative Uranium Requirements to the Year 2100	11
4.2	Total Available Plutonium in the Year 2100	26

LIST OF FIGURES

Figure		Page
3.1	Possible Trends for Installed Nuclear Generating Capacity in Ontario	8
4.1	Cumulative Uranium Requirements: Low Growth	12
4.2	Cumulative Uranium Requirements: Base Growth	13
4.3	Cumulative Uranium Requirements: High Growth	14
4.4	Annual Uranium Requirements	17
4.5	Fuel Fabrication Requirements: Low Growth	19
4.6	Fuel Fabrication Requirements: Base Growth	20
4.7	Fuel Fabrication Requirements: High Growth	21
4.8	Reprocessing Requirements for Plutonium Bearing Uranium Fuels	23
4.9	Uranium Enrichment Requirements	25
4.10	Installed Generating Capacity: All Strategies: Low Growth	28
4.11	Installed Generating Capacity: Nat. U-LEU-Th(U) or Pu Recycle: Base Growth	29
4.12	Installed Generating Capacity: Nat. U-LEU-Th(U) or Pu Recycle: High Growth	30
5.1	Cumulative Uranium Requirements: Base Growth	31
5.2	Annual Uranium Requirements: Base Growth	32
A.1	Fisher-Pry Model Applied to Introduction of Nuclear Power in Ontario	A-4
A.2	Introduction Rates of New Nuclear Technologies	A-5

THE LOW ENRICHED URANIUM FUEL CYCLE IN ONTARIO: A RESOURCE UTILIZATION STUDY

1. INTRODUCTION

The viability of a long-term nuclear program in Ontario has been questioned on the basis that a limited uranium supply will restrict future nuclear growth. However, it is likely that the ever-increasing worldwide demand for uranium will stimulate increased exploration, resulting in a continued uranium supply. It is also likely that increasing mining costs, and the need to exploit lower grade deposits, will result in increasing uranium prices. Thus, the depletion of presently known low-cost resources, and the subsequent need to develop higher-cost resources, will result in uranium prices increasing with time.

Previous studies by the Advanced Nuclear Concepts Section have shown that advanced fuel cycles possess the potential to sharply reduce uranium consumption (1,2), thereby reducing the depletion of low-cost reserves. However, the introduction of a uranium-conserving fuel cycle in Canada is likely to have only a minor effect on world uranium consumption, and hence, little effect on the world uranium price. Since the price of Canadian uranium will probably be similar to the world price, there seems little justification for commercializing an advanced fuel cycle unless that cycle is economically superior to the fuel cycle already in use. Static economic analyses have already shown that as uranium price increases, certain advanced fuel cycles will become economically superior to the presently used Nat. U cycle (3).

It seems then, that the decision to proceed in Ontario with a program based on one or more advanced fuel cycles is likely to be primarily influenced by economic considerations. A full economic analysis of a proposed generation system would be required to determine which advanced fuel cycle should be commercialized, and when it should be introduced. Such an analysis must include the potentially important effects of the economies of scale for new secondary industries necessary for the commercialization of a new fuel cycle. Capital requirements and prices for fuel fabrication, reprocessing and enrichment could vary significantly with the growth rate of the secondary industries, and could therefore have a large effect on the overall system economics. Therefore, prior to any system economic analysis, material throughput rates must be known for the secondary industries.

The purpose of the study described in this report was twofold. The first was to compare resource requirements for a number of different fuel cycle strategies for three assumed growth rates of installed nuclear capacity in Ontario. An evaluation of resource requirements such as cumulative and annual uranium mined is useful, because it demonstrates the potential for delaying the depletion of lower-cost uranium reserves if widespread adoption of advanced fuel cycles were to occur. Further, analyzing annual uranium requirements allows mining production capability to be evaluated as a limiting factor. The second goal was to compare the patterns of secondary industry development for the various strategies. This information will be used to establish plant-by-plant expansion rates for the various supporting industries. Hence, proper price levels can be established as preparation to a system economic analysis.

The study continues work reported in Reference 2, which presented results of two-fuel cycle studies. The study discussed here is different from prior two-cycle studies, in that the LEU cycle is introduced in the mid-1990's, and the date of introduction of the advanced cycles is pushed back to the mid-2020's. This was done because recent analysis (3) indicates that the LEU cycle will be economically feasible before the turn of the century and will provide a technological bridge to the more advanced cycles. The advanced cycles are also not expected to become economically attractive until the mid-2020's. Some important modifications have been made to the scenarios of Reference 2 in order to create scenarios which are as realistic as possible. The modifications include:

-three new growth estimates, incorporating Ontario Hydro's latest projection, Program Z;

-rates of introduction of new fuel cycles are restricted according to the Fisher-Pry model;

-review of fuel-cycle parameters;

-review of process yields and delay times;

-extension of study period to year 2100 to allow comparison of advanced cycles at maturity;

-evaluation of the effects of excluding the intermediate LEU cycle (i.e. proceeding directly from natural U cycle to advanced cycle in mid-2020's).

The simulation code FISS was used to produce all results. Minor modifications to the code were implemented to enable the simulation of three-cycle scenarios with an intermediate LEU cycle. The basic simulation rules under which FISS operates are outlined in Reference 2.

2. FUEL CYCLES AND STRATEGIES

Table 2.1 contains the important parameters of the six fuel cycles which are considered. The cycles are essentially the same as those of Reference 2. However, the reactor specific power for all the advanced cycles, except the LMFBR, has been reduced slightly to compensate for expected power-peaking problems. Also, the natural U-cycle burnup has been reduced from 7.5 MW.d/kg HE to 7.0 MW.d/kg HE, a value more representative of actual system achievement.

The yields and delay times of secondary industries are shown in Table 2.2. Process losses have been increased to 1%, which is representative of present conditions in existing industries.

Irradiated-fuel cooling for the LMFBR is 0.5 years greater than for the other cycles, causing an increased delay in the availability of reprocessed fissile material and hence increased demand for mined uranium. This has been done to compensate for the batch refuelling pattern of breeder reactors, as well as the difference in dwell times between the core and the blanket materials.

The reprocessing delay for the thorium cycles is only 0.2 years, reflecting the need to reprocess quickly, before there is a buildup of hard-gamma emitting isotopes.

The fuel cycle strategies which are considered are combinations of the cycles shown in Table 2.1. Four three-cycle strategies are considered, as well as an all-natural-U strategy, and a natural U-LEU strategy. Table 2.3 describes each of the six strategies. Load factors are shown to decrease as a function of time, reflecting an increase in the average age of reactors of a given type as well as the increased use of nuclear reactors in the load-following mode of operation. The load factor is assumed to decrease linearly between the two dates shown.

The rates of introduction of the LEU cycle and the advanced cycles have been restricted in order to realistically simulate the penetration of a new generation concept into the existing power grid. It has been shown elsewhere that restricted introduction rates also facilitate the orderly development of the secondary industries (2). Appendix A details the procedure for determining the introduction rates. Essentially, a fixed capacity of the new cycle is installed at the introduction date and maintained at a constant level for five years. After this time the fraction of total capacity generated by the new cycle increases at a fixed exponential rate, until the new additions of the new cycle equal the total system expansion. After this time only the new cycle can increase in capacity. (The exception is when additional LEU reactors are required to supply fissile material to the advanced cycle). The expansion rates of the new cycles, in MWe per annum, are therefore related to the growth of the total nuclear system.

TABLE 2.1: FUEL CYCLE PARAMETERS

	NATURAL UO_2 (NAT U)	LOW ENRICHED URANIUM (LEU)	MIXED OXIDE (Pu RECYCLE)	Pu TOPPED THORIUM (Th(Pu))	U-235 TOPPED THORIUM (Th(U))	FAST BREEDER OXIDE CYCLE (LMFBR)
REACTOR LIFE (yr)	30	30	30	30	30	30
EFFICIENCY (%)	30.5	30.5	30.5	30.5	30.5	38
SPECIFIC POWER (kW/kg)	29	24	24	24	24	29*
BURNUP (MW.d/kgHE)	7.0	21.0	17.0	27.0	27.0	21.7*
EQUILIBRIUM FISSILE TOPPING (g Fissile/kg HE)	-	-	0.0	3.5 Pu	3.2 U-235	0.0
EQUILIBRIUM NET FISSILE RECOVERY** (g Fissile/kg HE)	2.7 Pu	3.4 Pu	0.0	0.0	0.0	6.7 Pu*
FIRST CHARGE FISSILE TOPPING (g Fissile/kg HE)	-	-	3.6 Pu	25.6 Pu	23.5 U-235	53.4 Pu*
FUEL REPROCESSING	NO	NO	YES	YES	YES	YES

*weighted average of core and blankets

**for Nat U and LEU cycles, fissile material is contained in irradiated fuel, and is only recycled if it is required for an advanced cycle.

TABLE 2.2: PROCESS YIELDS AND DELAY TIMES

	YIELD	DELAY (yr)
SHIPPING FROM MINE	1.0	1.0 (1)
FUEL FABRICATION	0.99	0.5
IRRADIATED-FUEL COOLING	1.0	1.0 1.5 (LMFBR)
REPROCESSING	0.99 0.99	0.5 0.2 (Th CYCLES)
THORIUM RECYCLE	1.0 (2)	20
ENRICHMENT	.995	1.0
HEAVY WATER PRODUCTION	1.0	1.0

(1) This is an arbitrary value which allows for refining and a stockpile of fuel at each station.

(2) While not realistic, this is a convenient value, and does not affect uranium consumption.

TABLE 2.3: FUEL CYCLE STRATEGIES

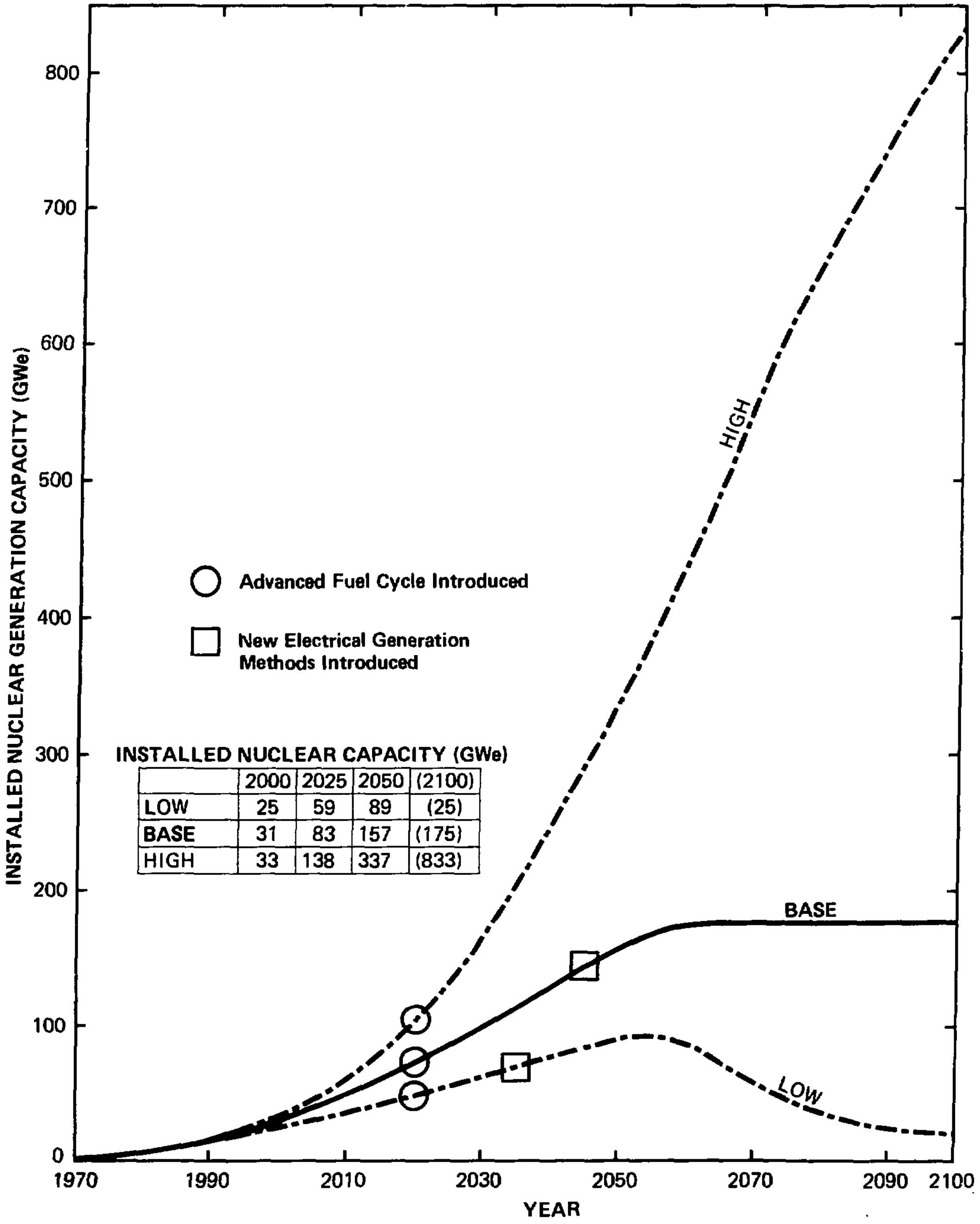
STRATEGY	1	2		3			4			5			6		
TITLE	NAT U	NAT U-LEU		NAT U-LEU-Pu RECYCLE			NAT U-LEU-Th(U)			NAT U-LEU-Th(Pu)			NAT U-LEU-LMFBR		
FUEL CYCLE INTRODUCTION DATE			1992		1992	2020		1992	2020		1992	2020		1992	2020
LOAD FACTOR PRIOR TO YEAR	.75 1995	.75 1995	.75 2025	.75 1995	.75 2025	.75 2050	.75 1995	.75 2025	.75 2050	.75 1995	.75 2025	.75 2050	.75 1995	.75 2025	.75 2050
LOAD FACTOR AFTER YEAR	.70 2010	.70 2010	.70 2045	.70 2010	.70 2045	.70 2070	.70 2010	.70 2045	.70 2070	.70 2010	.70 2045	.70 2070	.70 2010	.70 2045	.70 2070
REPROCESSING TO SUPPLY FISSILE MATERIAL TO ADVANCED CYCLE	NO	NO		YES	YES		NO	NO		YES	YES		YES	YES	
ADVANCED CYCLE FISSILE REPROCESSING						YES			YES			YES			YES
ADVANCED CYCLE FERTILE RECYCLE						NO			YES			YES			YES
URANIUM ENRICHMENT REQUIRED	NO	NO	YES (1.2%)	NO	YES (1.2%)	NO	NO	YES (1.2%)	YES (93%)	NO	YES (1.2%)	NO	NO	YES (1.2%)	NO

3. NUCLEAR CAPACITY GROWTH RATES

Each scenario was evaluated for three long-term estimates of installed nuclear capacity in Ontario. These are discussed elsewhere (4), and so will be described here only briefly. The low and high projections correspond respectively to the minimum and maximum levels of nuclear generating capacity deemed to be feasible. The base projection is an estimate of probable nuclear growth. The three estimates of total installed nuclear capacity are shown in Figure 3.1.

As seen in Figure 3.1, there is a large spread between the low and high estimates of nuclear growth. The primary reason for this is the large uncertainty in the future of nuclear power in Ontario. This in turn, stems mainly from recent downward trends in electrical demand growth, and from the unpredictable effects of public pressure and political uncertainty. Nevertheless, one might argue that the projections cover too wide a range to be of significant meaning. It may appear, for example, that the low growth projection is too low to warrant the development of an advanced cycle, or that the high growth projection requires an immediate move to an advanced cycle. In terms of resources, these thoughts may be correct. However, an economic assessment, with costs a function of resource depletion and support industry capacity, may prove otherwise. In other words, it may turn out that, on an economic basis, a thorium cycle would still be preferable even in a low growth situation. Since a system economic analysis has yet to be performed, such a possibility cannot be precluded. Furthermore, suppose the range of growth rates were narrowed, and, for example, a given strategy was shown to be superior for the low growth projection. It would be difficult to determine if the same advantage remained for an even lower growth rate, and so valuable information could be lost. Also, evaluating each scenario for the lower and upper bounds of growth may allow for easier interpolation if, in the near future, the long-term nuclear growth rate can be forecast with more confidence. Finally, the projections of nuclear growth were derived independently of considerations of resources or fuel-cycle economics. Each projection is believed to be a possibility. Narrowing the range would, therefore, reduce the completeness of resource or economic studies.

FIGURE 3.1
Possible Trends for Installed Nuclear Generating Capacity in Ontario



	2000	2025	2050	(2100)
LOW	25	59	89	(25)
BASE	31	83	157	(175)
HIGH	33	138	337	(833)

4. RESULTS

4.1 Cumulative Uranium Requirements

In long-term scenario studies, there is a tendency to compare results, such as cumulative uranium required, only at the end-point of the study. While this is a valid approach, considering the time-dependent behaviour of uranium requirements gives an indication of the relative timing, as well as the magnitude, of uranium savings for each strategy. Figures 4.1, 4.2 and 4.3 show this behaviour for each scenario and for each of the three growth projections.

An immediate observation is that the all-natural-U strategy is by far the most consuming. Substantial uranium savings can be achieved through the adoption of any of the other strategies. However, it should be noted that significant uranium savings are not achieved until about the year 2010. This is due to the restricted introduction rate of the LEU cycle, which causes delays in the accrual of resource benefits.

Since the third cycle is not introduced until the mid-2020's, significant differences in uranium consumption among the three-cycle strategies are not seen until about 2050. However, for all growth projections, the NAT U-LEU-LMFBR is ultimately the most uranium-conserving strategy, followed closely by NAT U-LEU-Th(Pu). In fact, prior to 2080, the NAT U-LEU-Th(Pu) strategy requires at most only 8% more cumulative uranium than the NAT U-LEU-LMFBR strategy. The NAT U-LEU-Th(U) strategy requires, to within 9%, the same cumulative uranium to the year 2100 as the NAT U-LEU-Pu RECYCLE strategy. However, the NAT U-LEU-Th(U) strategy requires more of its uranium at an earlier point in time. This occurs because of the thorium cycle's large pre-equilibrium requirement for highly enriched uranium (93% U-235). The effect of this on annual uranium requirements is discussed later.

Table 4.1 details the cumulative uranium requirements to the year 2100 for each scenario, and is included only to allow comparison of the strategies at a time when the full benefits of the advanced cycles can be felt. It is interesting to note that for the low growth case, the requirements for the NAT U-LEU-Th(Pu) strategy are identical to those of the NAT U-LEU-LMFBR. This is because the advanced reactors require no mined uranium (depleted uranium is used for the LMFBR's), and no additional LEU reactors are required to supply fissile material.

It is evident that the NAT U-LEU-LMFBR strategy demonstrates its uranium-conserving properties best in the base growth case, where installed nuclear capacity reaches a constant level in 2065. This is a somewhat fortuitous situation, because the Pu available in NAT U and LEU irradiated fuel is almost exactly the quantity required to supply the pre-equilibrium fissile charge for the breeders. The expansion rate of LMFBR capacity is such that the year at which all plutonium from irradiated fuel is used up is approximately the same year at which the breeder system becomes a net producer of plutonium. After this date, the start-up charge for new breeders is obtained from other breeders.

The situation is quite different in the high growth case. The breeder system expands at such a rapid pace, that the system never becomes a net plutonium producer. Thus, additional LEU reactors are required to supply fissile plutonium, bringing the uranium requirements closer to those of the other strategies.

It is likely, however, that the breeding efficiency of FBR's will improve in the long term, especially if a massive worldwide commitment is made to this technology. Hence, the present estimates of uranium consumption for the breeder scenario are probably conservative.

TABLE 4.1: CUMULATIVE URANIUM REQUIREMENTS TO THE YEAR 2100

STRATEGY	URANIUM MINED (Gg)			RATIO OF URANIUM MINED TO THAT FOR NAT U			RATIO OF URANIUM MINED TO THAT FOR NAT U-LEU-LMFBR		
	L	B	H	L	B	H	L	B	H
NAT U	724	1666	4798	1.00	1.00	1.00	2.18	3.11	2.42
NAT U-LEU	520	1155	3310	.72	.69	.69	1.57	2.15	1.67
NAT U-LEU-Pu RECYCLE	451	913	2476	.62	.55	.52	1.36	1.70	1.25
NAT U-LEU-Th(U)	414	846	2481	.57	.51	.52	1.25	1.58	1.25
NAT U-LEU-Th(Pu)	331	672	2164	.46	.40	.45	1.00	1.25	1.09
NAT U-LEU-LMFBR	331	536	1980	.46	.32	.41	1.00	1.00	1.00

L = LOW GROWTH
B = BASE GROWTH
H = HIGH GROWTH

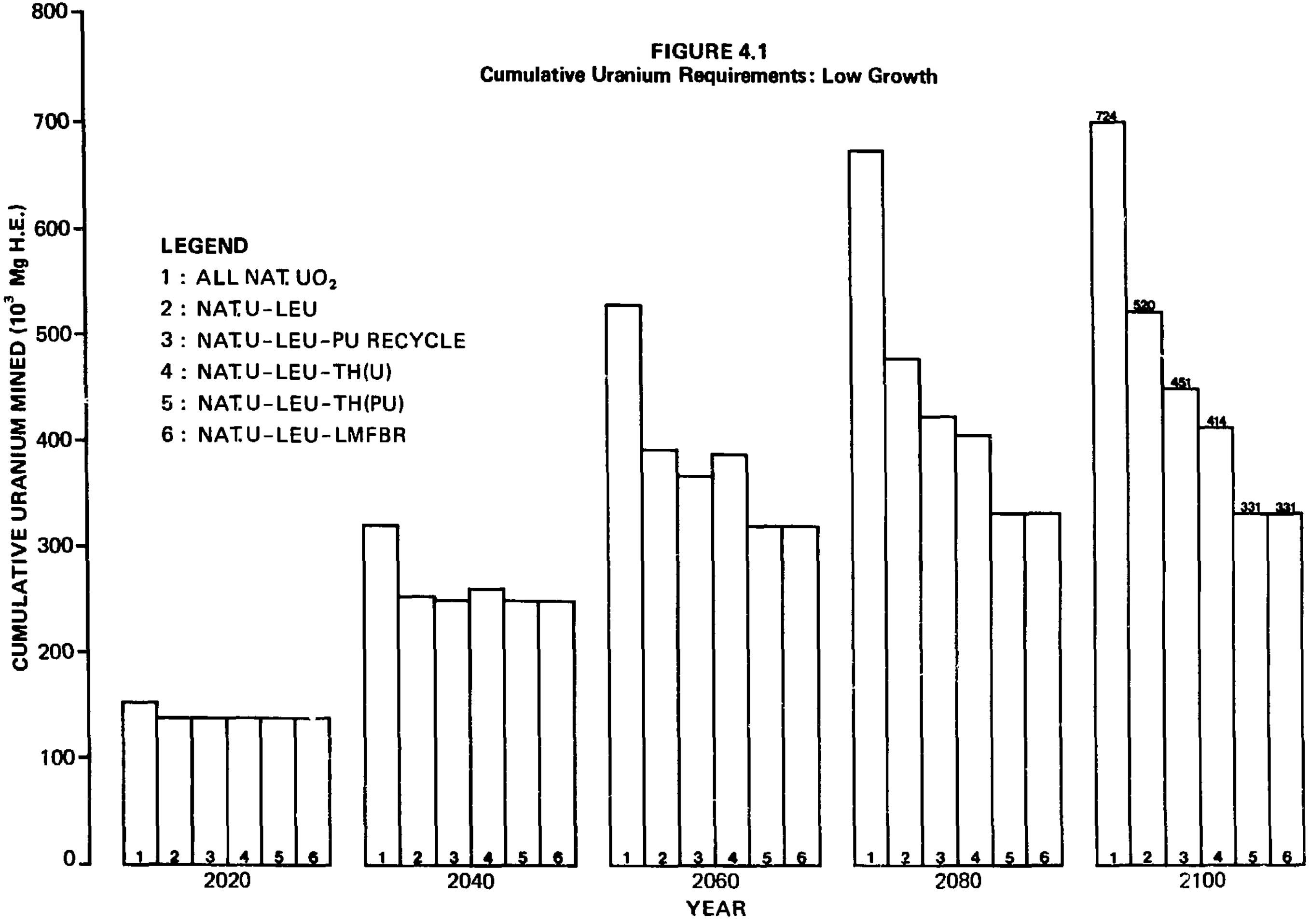


FIGURE 4.1
Cumulative Uranium Requirements: Low Growth

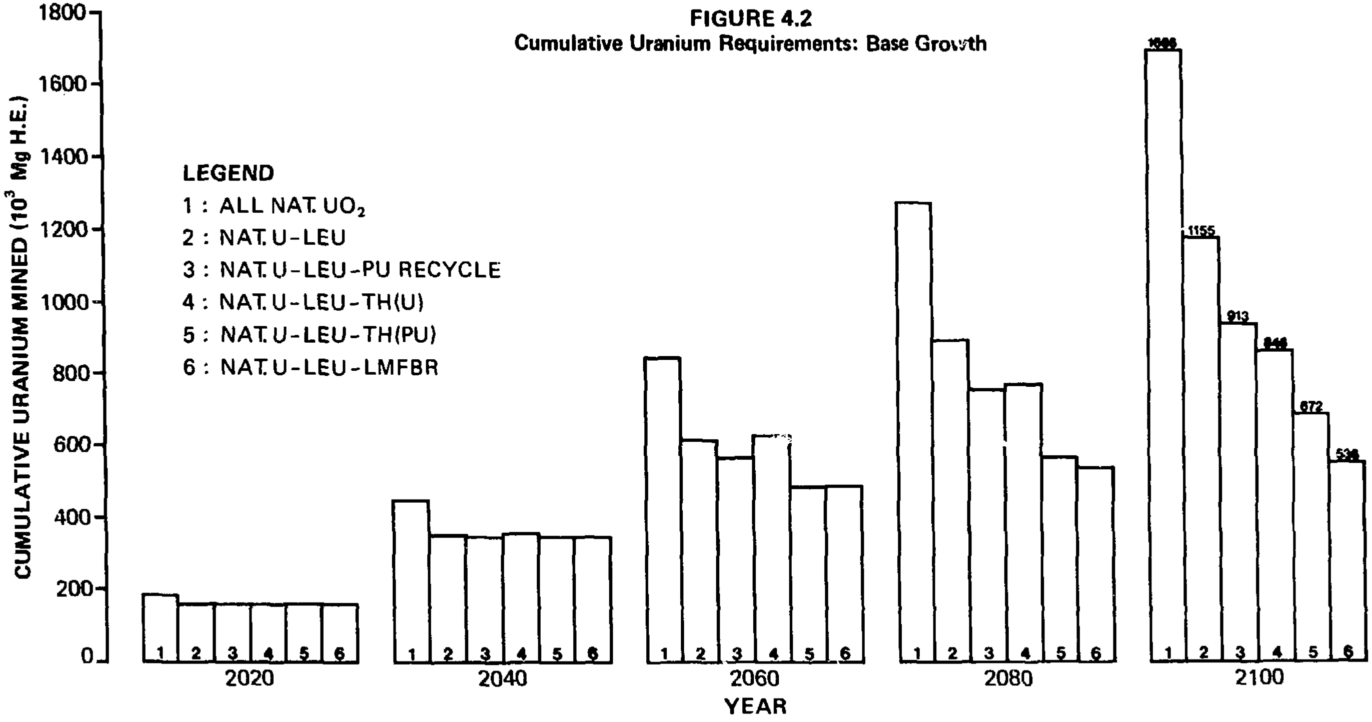


FIGURE 4.2
Cumulative Uranium Requirements: Base Growth

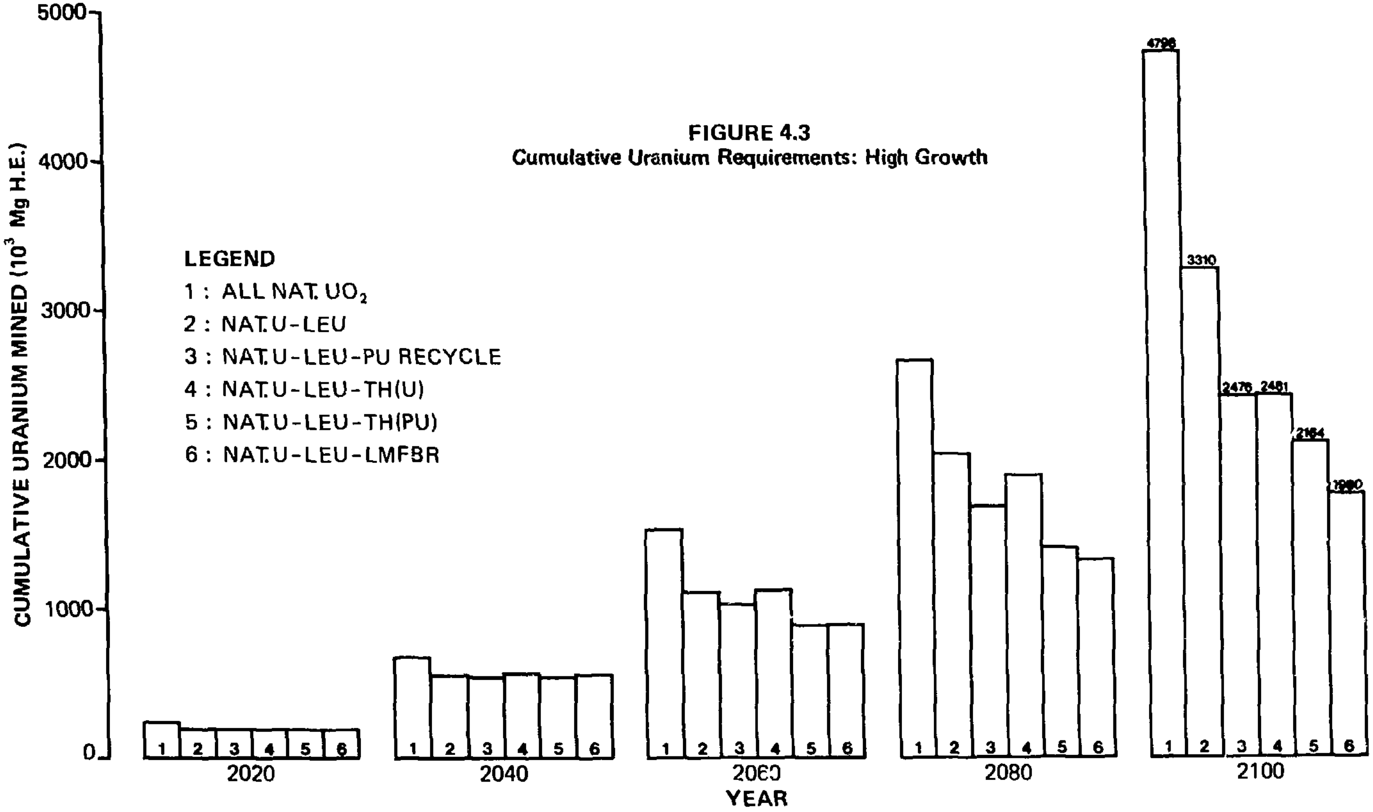


FIGURE 4.3
Cumulative Uranium Requirements: High Growth

4.2 Annual Uranium Requirements

The annual mined uranium requirements for each strategy and growth projection have been plotted on a common scale in Figure 4.4. This is to maintain a proper perspective on what might otherwise seem to be large variations in the annual requirements in the low and base growth cases. The most obvious feature is the reduction in annual mining capacity afforded by all the advanced strategies as compared to the all-natural-U strategy.

In general, the development of the mining industry is fairly smooth for each strategy. This is different from the scenarios of Reference 2, and is due to the inclusion of the intermediate LEU cycle, and the more realistic introduction rates of new cycles.

The large pre-equilibrium fissile requirement of the Th(U) cycle results in significantly higher annual requirements than for the other three-cycle strategies prior to about 2070. Thus, the NAT U-LEU-Th(U) strategy consumes much of its total cumulative uranium requirement at a relatively early time.

It can be seen that the system is independent of mined uranium only in the low growth case for only the NAT U-LEU-Th(Pu) and NAT U-LEU-LMFBR strategies. Zero uranium requirement is achieved in 2076 for each strategy. The NAT U-LEU-Th(U) strategy undergoes a 10 year period, from 2076 to 2085, of requiring no mined uranium. This occurs because the system generating capacity is decreasing, and a short-term supply of fissile material becomes available from decommissioned reactors.

The NAT U-LEU-LMFBR strategy almost reaches independence of mined uranium in the base growth case. The fact that it does not, however, indicates that the base growth projection's system expansion rate is slightly too rapid to allow the breeder system to become a net plutonium producer prior to the year when the breeder capacity levels off. Independence of mined uranium could conceivably be achieved by slightly manipulating the date and rate of introduction of breeder reactors, or by achieving a slightly higher overall breeding ratio. In the long-term it is conceivable that LMFBR's will operate with specifications superior to those used here. It should be noted, however, that if nuclear capacity growth turns out to be significantly greater than the base growth projection, or does not level off as in the base case, independence of mined uranium could not be achieved for the conservative breeder scenarios of the type considered here.

Also shown in Figure 4.4 is the projected 1990 uranium mining capability for Ontario (5). Based only on known reserves at existing and planned mines, the capability is expected to decline from 5540 Mg U/annum in 1990, to 4390 Mg U/annum in 2000. However, if a capacity of 5540 Mg U/annum could be maintained, and all mined uranium devoted to Ontario Hydro's use, annual demand would not exceed supply until at least 2003. In fact, for the low growth case, only the NAT U and NAT U-LEU-Th(U) strategies ever exceed an annual requirement of 5540 Mg U/annum. A previous estimate of Ontario's mining capability (6) predicted that the peak capability would be reached in 1985. If a trend can be inferred from two estimates, it is that the year at which peak production capability will be reached is moving further into the future. This trend reflects recently increased mining capacities and new discoveries.

To the end of the study period, strategies 2-6 for the base growth case require the mining capacity to be only slightly greater than double the expected 1990 peak capability. Since these strategies also require more cumulative uranium than is known to presently exist in Ontario's mines, it is clear that the additional capacity must come from new mines. It does not seem unreasonable to expect that, if uranium exploration is moderately successful, mining capability will at least double over the next 50 years.

In terms of an overall uranium-mining policy for Canada, the introduction of any of the advanced cycles offers potentially significant advantages. Reference 7 indicates that the annual total production capability in Canada from known centres could reach 12,600 Mg/a by 1990, and would then begin to slowly decline. The development of new centres after 1990 would be required to maintain a constant production capability.

The amount of uranium potentially available for export in a given year is the difference between production capability and domestic requirements. If the uranium price is sufficient to stimulate the development of new uranium production centres, then the reduction in annual requirements afforded by the advanced cycles would allow increased exports. This would allow Canada to maintain its position as a major supplier of uranium for a longer period of time.

The high nuclear growth projection would seem to require prohibitively large mining capacities, especially for the NAT U and NAT U-LEU strategies. However, it should be remembered that the high growth projection is an upper limit, and so the corresponding requirements of Figure 4.4 represent the worst case situations.

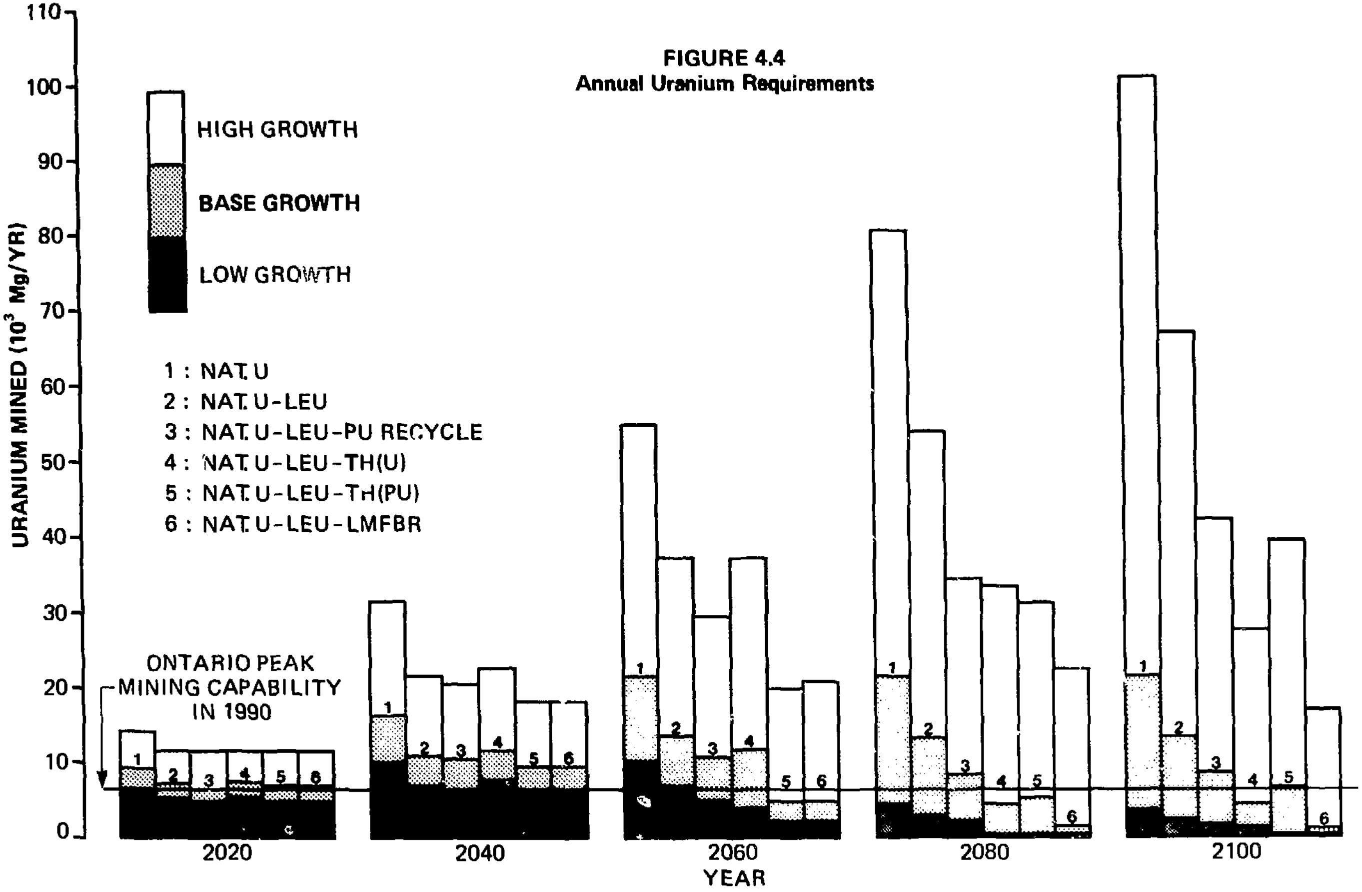


FIGURE 4.4
Annual Uranium Requirements

4.3 Fuel Fabrication Requirements

The total production capacity of the fuel fabrication industry is shown for each strategy and for each growth projection in Figures 4.5, 4.6 and 4.7. A breakdown, according to the type of fuel fabricated, is also included. Note that in each figure, the plots for the NAT U and NAT U-LEU strategies are on a different scale than for the three-cycle strategies.

Overall, the fabrication industry exhibits fairly smooth development. Due to the restricted introduction rates for new fuel cycles the total capacity for new types of fabrication plants is also seen to grow initially at a slow rate. Once a mature industry is achieved, there are no abrupt changes in production capacity.

For a given growth projection, the total fabrication capacity is roughly the same for all strategies, except the NAT U strategy. By 2040, the quantity of fuel fabricated for the NAT U strategy is approximately three times greater than for the others, and remains so to the end of the study period.

FIGURE 4.5
Fuel Fabrication Requirements: Low Growth

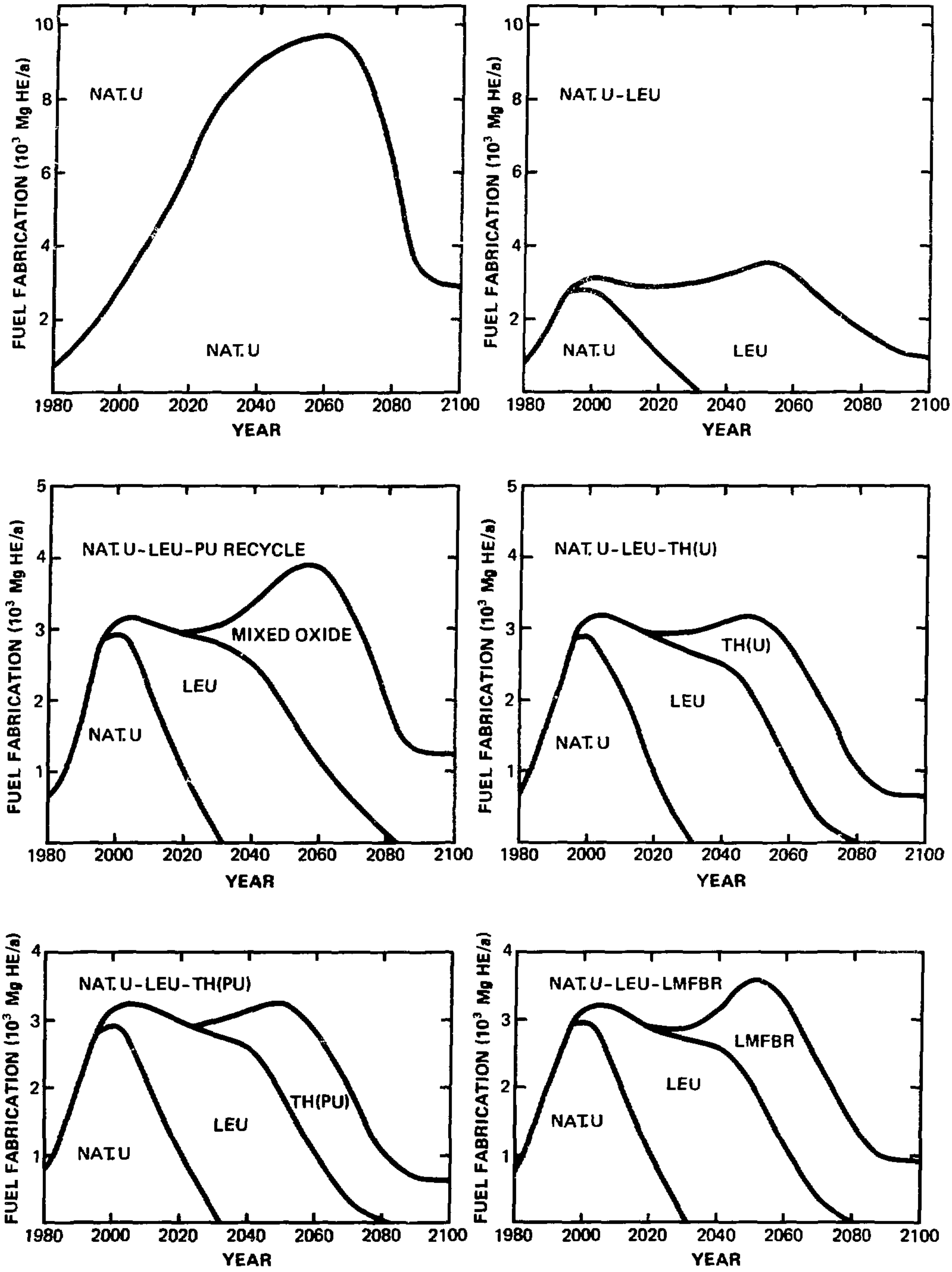


FIGURE 4.6
Fuel Fabrication Requirements: Base Growth

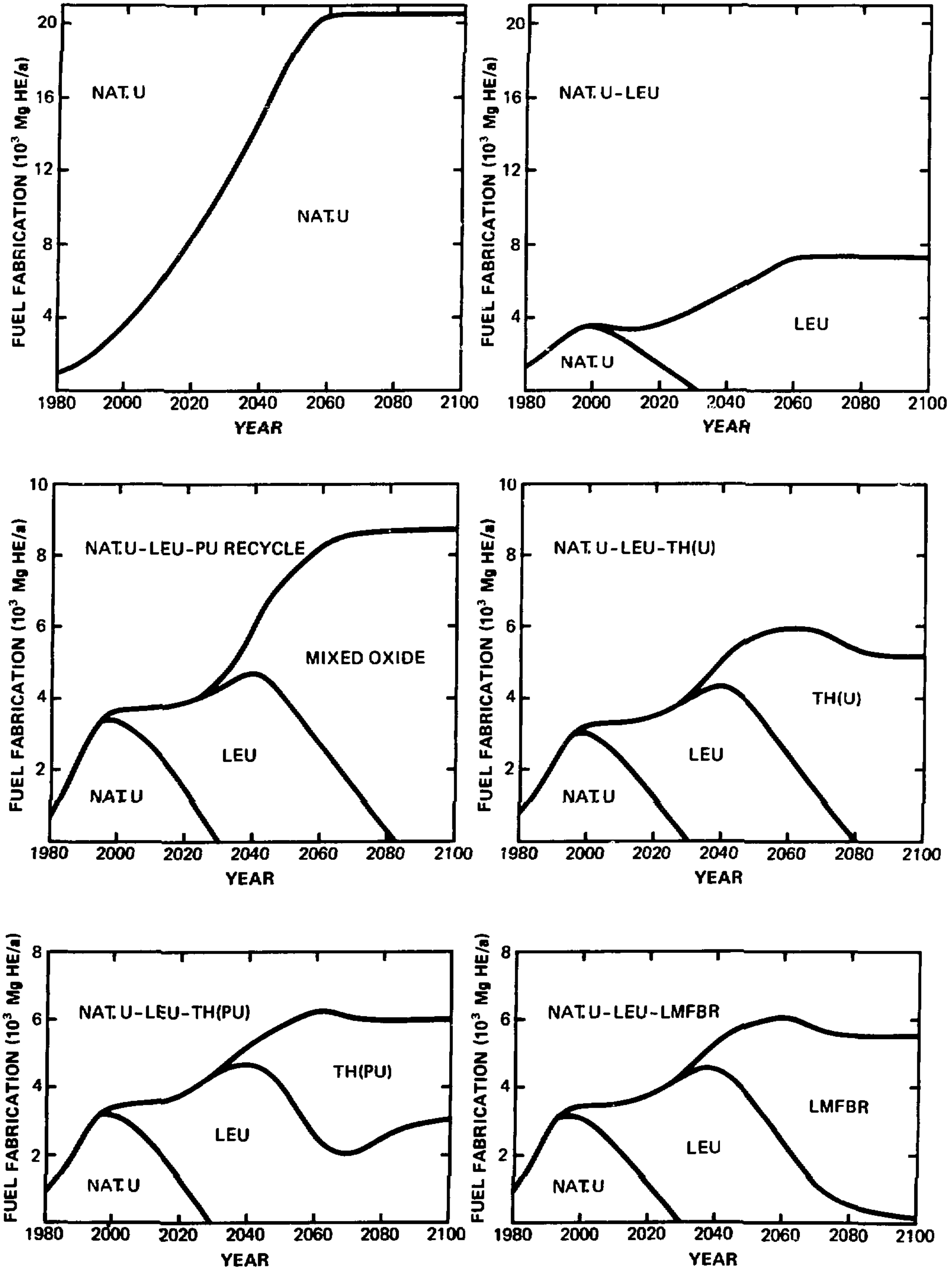
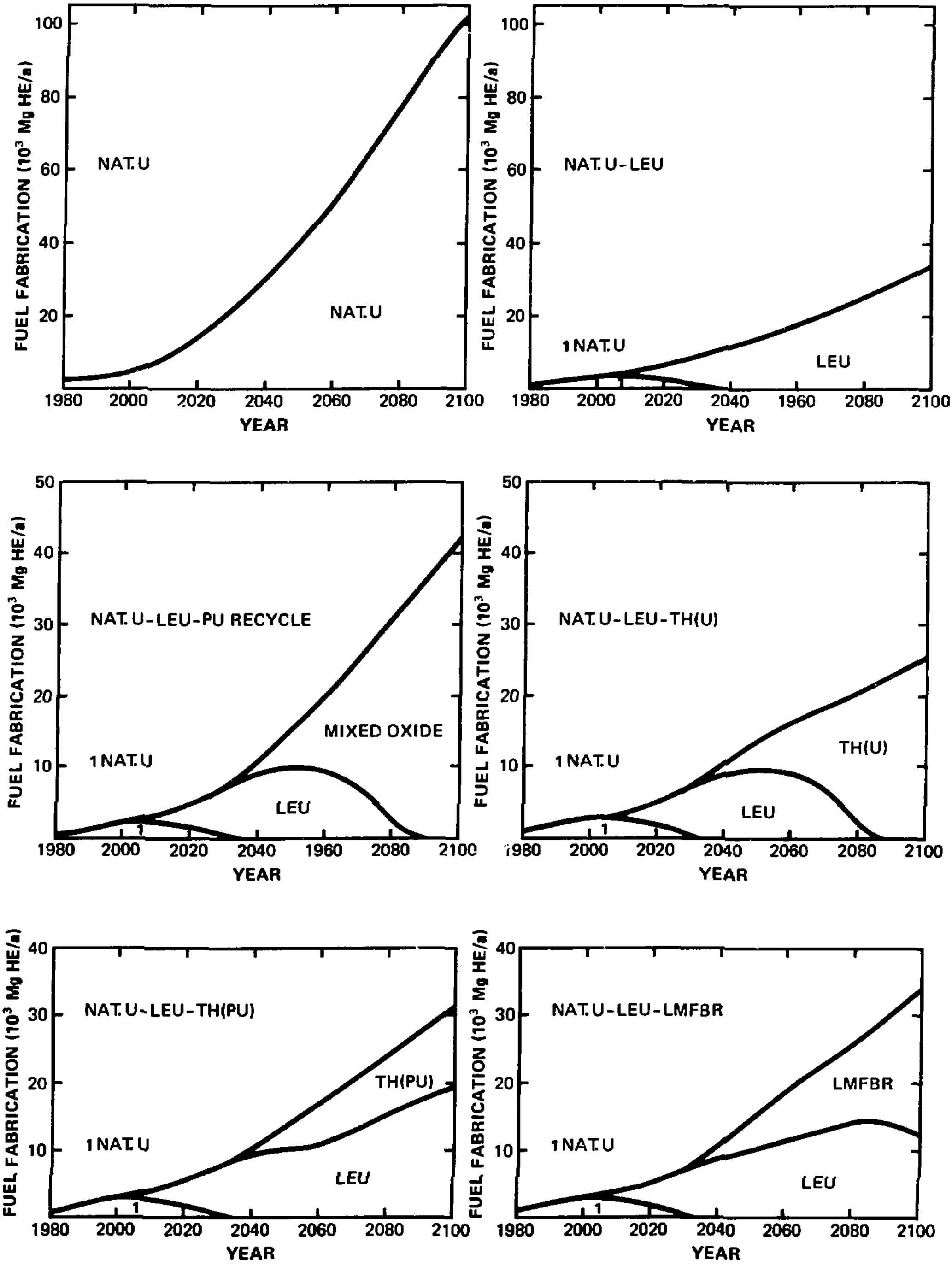


FIGURE 4.7
Fuel Fabrication Requirements: High Growth



4.4 Irradiated Fuel Reprocessing Requirements

The reprocessing requirements for plutonium-bearing uranium fuels are shown in Figure 4.8. The important feature is that in each case, the industry exhibits smooth development. Although the reprocessing capacity would seem to be 'peaky' for certain strategies, the peaks occur over a period of about 20 years, which is also the expected lifetime of reprocessing plants. Thus, peaks in reprocessing requirements can probably be accommodated by suitable scheduling of new plants.

Reprocessing capacities for thorium fuels are not shown in Figure 4.8. However, they can be inferred from Figures 4.5, 4.6 and 4.7, since thorium fabrication and reprocessing requirements show identical trends, with the only difference being a time interval of a few years.

The breakdown in Figure 4.8 according to fuel type allows commissioning dates for reprocessing plants to be specified for each type of fuel. For example, mixed oxide fuel can be reprocessed in plants identical to those for LEU fuel, but breeder and thorium fuels cannot. This may have a significant effect on the economics of each strategy, since the thorium and breeder strategies require maturation of essentially two reprocessing industries.

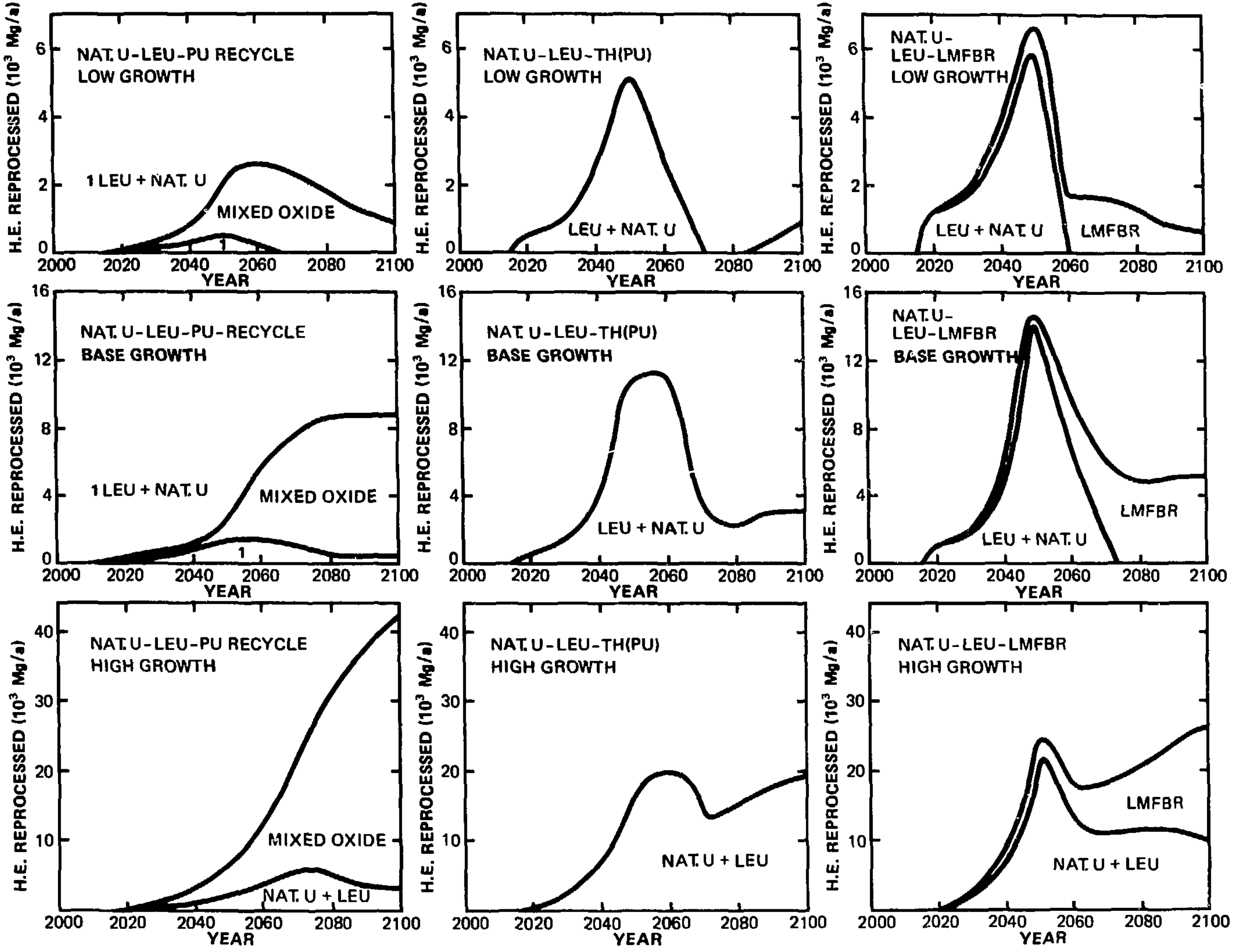


FIGURE 4.8
Reprocessing Requirements for Plutonium – Bearing Uranium Fuels

4.5 Uranium Enrichment Requirements

Figure 4.9 shows the uranium enrichment requirements for each strategy and each growth projection. The results are largely self-evident. The need for highly enriched uranium for the Th(U) cycle causes the enrichment requirements for the NAT U-LEU-Th(U) strategy to significantly exceed the requirements of the other strategies. The NAT U-LEU-Pu RECYCLE strategy consistently requires the lowest capacity of enrichment, and is independent of enrichment by 2075 for the low and base growth cases, and 2087 for the high growth case.

An enrichment plant of capacity 250 Mg SWU/a would be sufficient to fulfill the needs of all strategies to the year 2000 for any growth curve. The plant must be in-service by 1989. A maximum of 4 additional plants of capacity 1000 Mg SWU/a would be required by 2020. Thus, the development of the enrichment industry is seen to be gradual for any rate of nuclear growth, at least up to the introduction of the final fuel cycles.

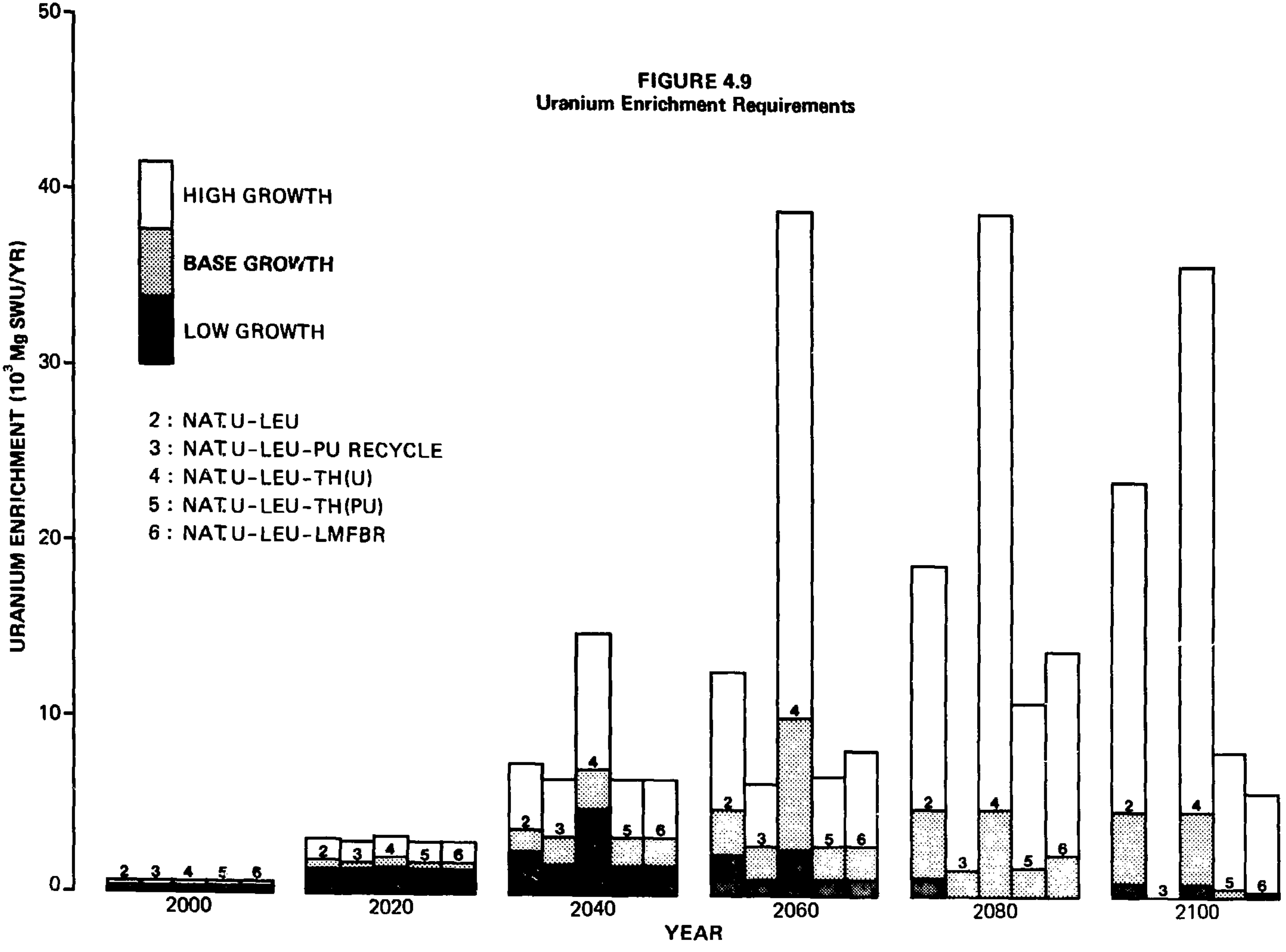


FIGURE 4.9
Uranium Enrichment Requirements

4.6 Total Available Plutonium

The total available plutonium is defined as separated fissile plutonium, plus fissile plutonium existing in irradiated fuel. Table 4.2 indicates the total plutonium available in the year 2100 for each strategy.

TABLE 4.2: TOTAL AVAILABLE PLUTONIUM IN THE YEAR 2100

	TOTAL AVAILABLE PLUTONIUM (Mg fissile)		
STRATEGY	LOW GROWTH	BASE GROWTH	HIGH GROWTH
ALL NAT U	1939	4317	12173
NAT U-LEU	984	2088	5831
NAT U-LEU-Pu RECYCLE	633	798	1218
NAT U-LEU-Th(U)	661	978	2049
NAT U-LEU-Th(Pu)	247	0	0
NAT U-LEU-LMFBR	859	585	7

For most strategies the buildup of available plutonium exhibits a monotonic increase with time. However, for the NAT U-LEU-Th(Pu) and NAT U-LEU-LMFBR strategies, this is not the case. For these strategies, introduction of the final fuel cycle causes a decrease in available plutonium as it is used as a supply of initial fissile material. In the NAT U-LEU-Th(Pu) strategy, all available plutonium is depleted by about 2060 in the base and high growth cases. In the NAT U-LEU-LMFBR strategy, the system is a net producer of plutonium only for the low and base growth cases. However, net production of plutonium for these cases is not achieved until 2060 and 2080, respectively. Thus, for the base growth case, LEU reactors are needed to the year 2080, and because premature decommissioning is not allowed, some LEU capacity exists right up to 2100.

In comparison to the Th(Pu) cycle, there are large amounts of plutonium left in Nat U and LEU irradiated fuel by the Th(U) and mixed-oxide cycles. Because the disposal cost of fuel bundles may exceed the cost of disposal of the reprocessing wastes from an equivalent number of bundles, these cycles could be penalized in terms of economics, unless the irradiated fuel is sold.

4.7 Installed Capacity of LEU Reactors

After the introduction of a third fuel cycle, new LEU reactors are commissioned only when needed to supply extra fissile material. This situation occurs only for the NAT U-LEU-Th(Pu) and NAT U-LEU-LMFBR strategies for the base and high growth cases. The situation for all other cases is illustrated in Figures 4.10, 4.11 and 4.12, which show a breakdown of installed capacity according to type of fuel cycle for each growth curve. These figures also demonstrate the extent to which the introduction rates of advanced fuel cycles are restricted.

The LEU capacity which must be maintained for the NAT U-LEU-Th(Pu) strategy is such that, in 2100, LEU reactors constitute 44% of the total nuclear capacity for base growth, and 58% for high growth. For the NAT U-LEU-LMFBR strategy, the corresponding figures are 2% and 36%. Thus, it can be seen that for the base growth case, only a minimal LEU capacity is required to supply plutonium to the breeders. It is for this reason that in the base growth situation, the cumulative uranium requirements of the breeder strategy compare most favourably with those of the other strategies.

FIGURE 4.10

Installed Generating Capacity: All Strategies: Low Growth

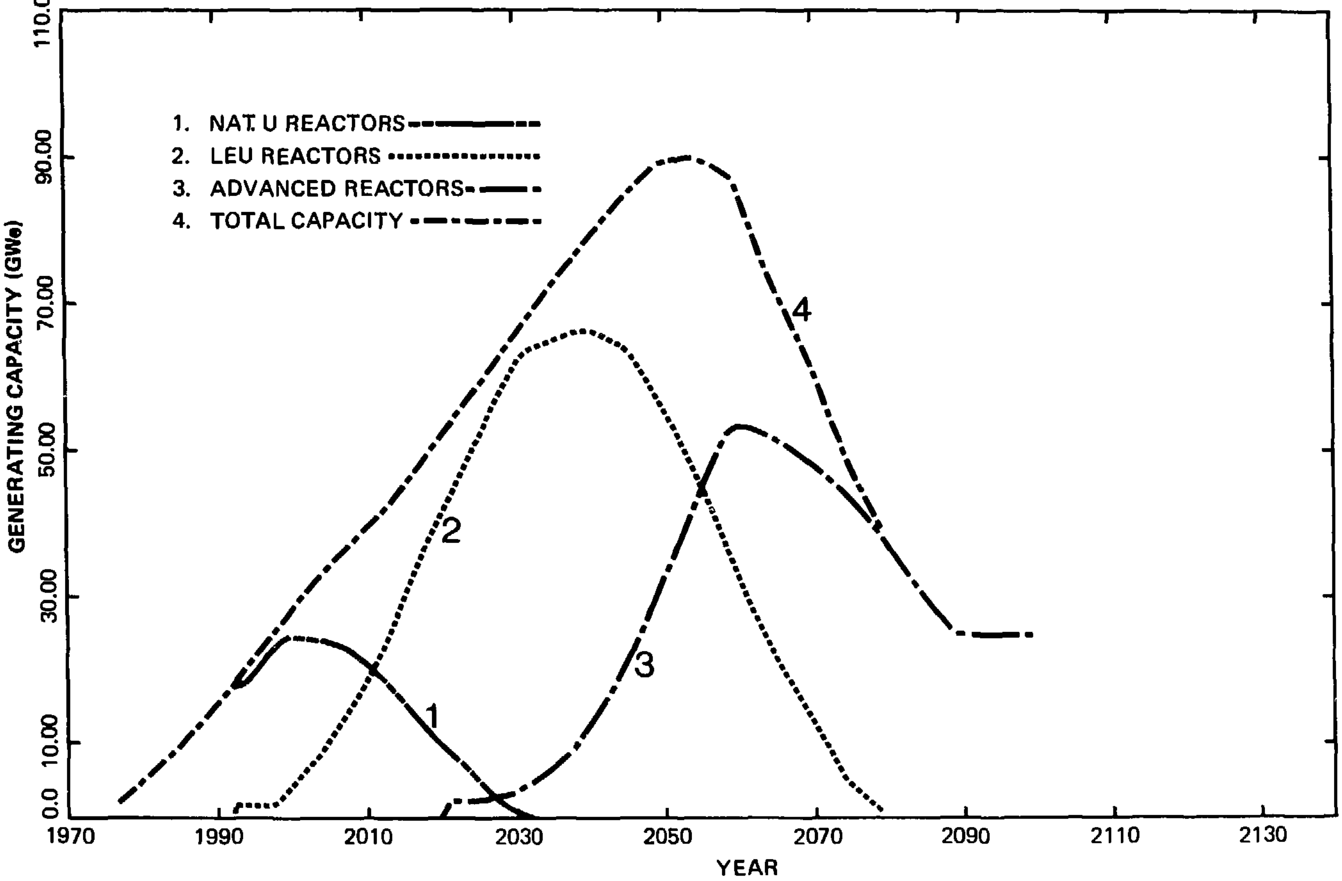


FIGURE 4.11
Installed Generating Capacity, Nat.U-LEU-TH(U) or PU Recycle, Base Growth

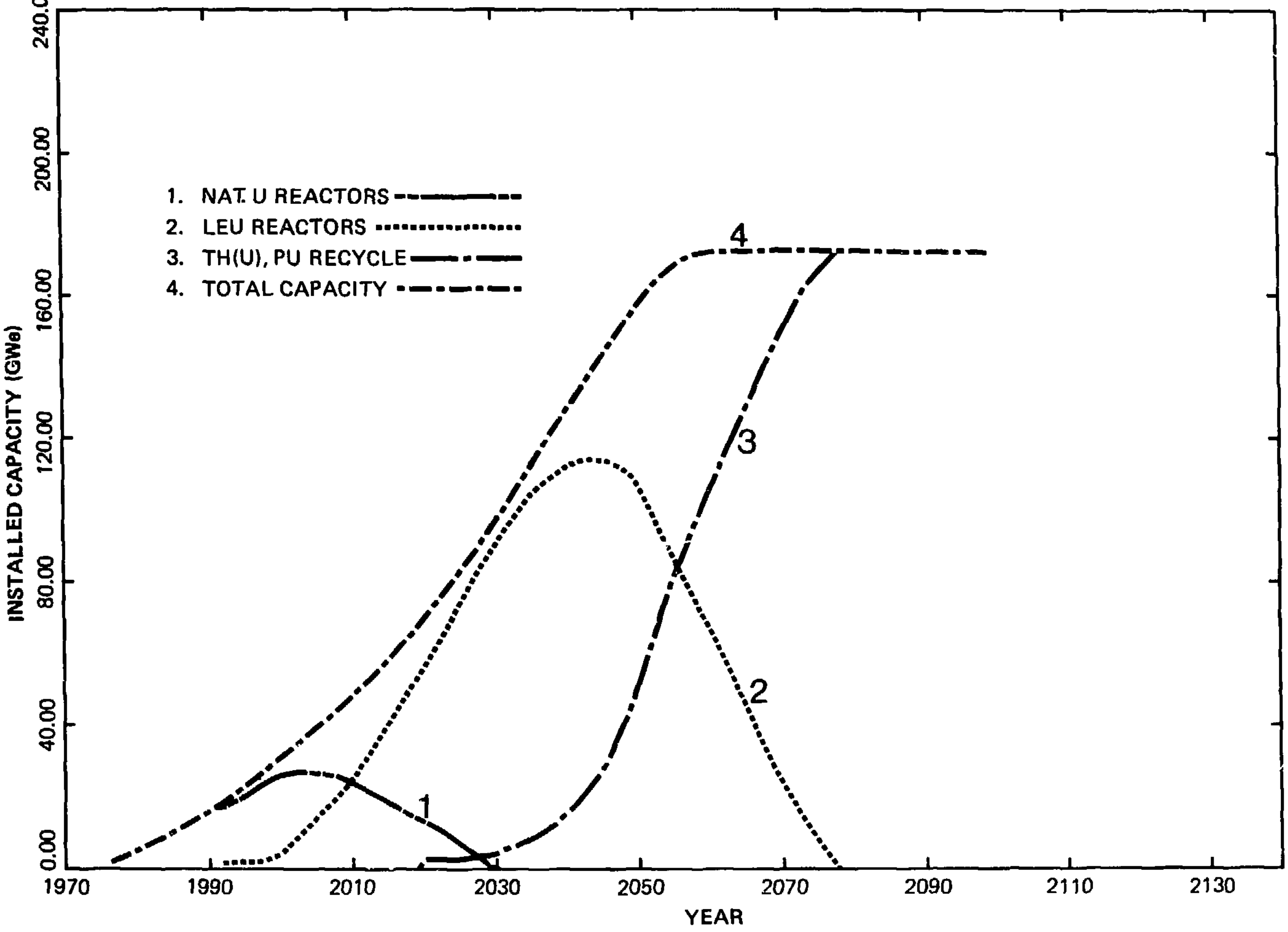
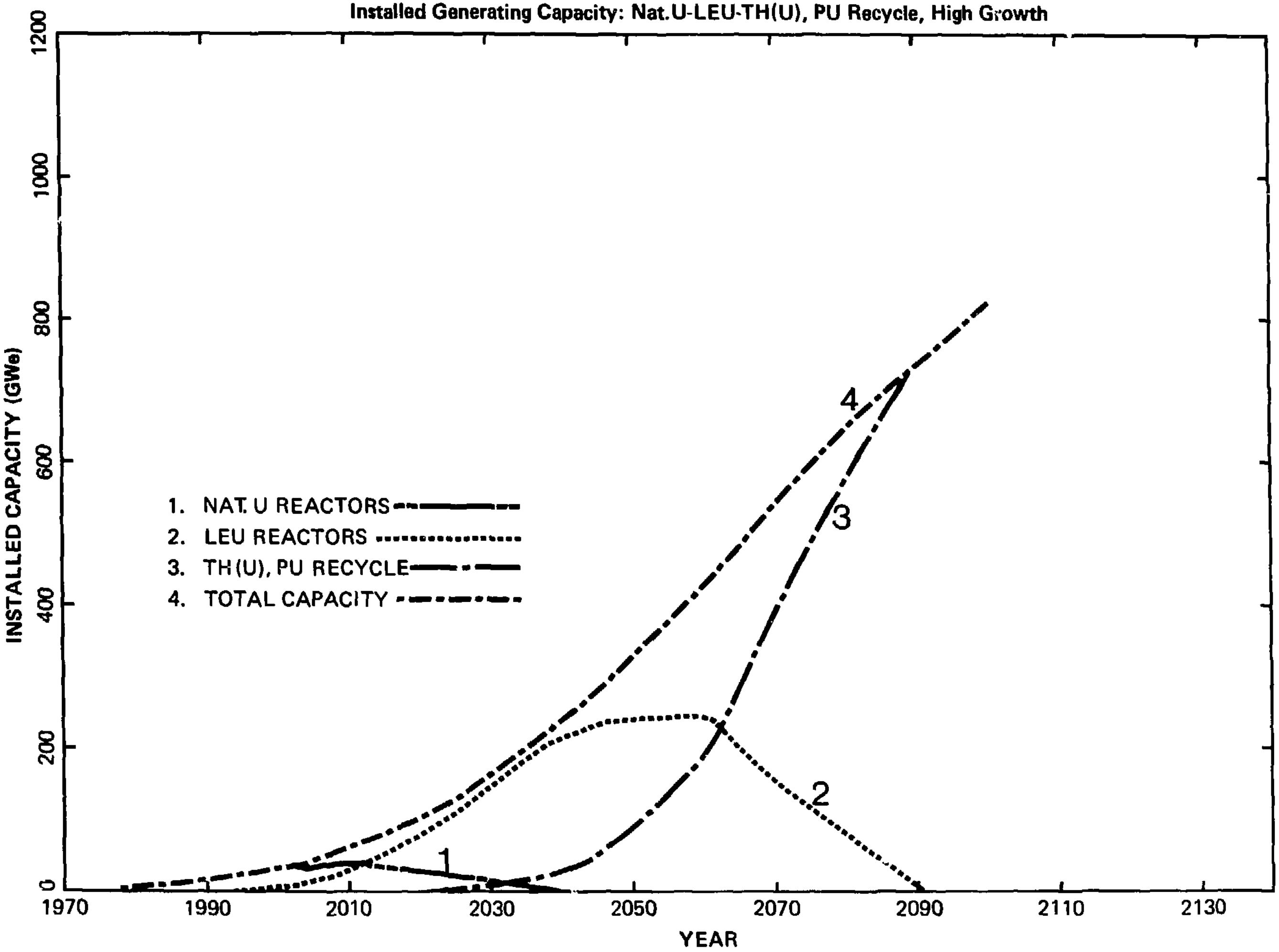


FIGURE 4.12
Installed Generating Capacity: Nat.U-LEU-TH(U), PU Recycle, High Growth



5. EFFECTS OF OMITTING THE INTERMEDIATE LEU CYCLE

The moderating effect of the intermediate LEU cycle is demonstrated in Figures 5.1 and 5.2, which compare the cumulative and annual uranium requirements of four pairs of strategies. Each two-cycle strategy is identical to the corresponding three-cycle strategy, except that the LEU cycle is omitted. The three-cycle strategies are the same as those of Table 2.3. Although Figures 5.1 and 5.2 are for only the base growth situation, identical trends occur for the low and high growth cases.

It is clear that for each strategy, omitting the LEU cycle causes an increase in cumulative uranium requirements. Furthermore, relatively more of the total requirement is consumed at an earlier time. This causes the annual uranium requirements to exhibit higher peaks and valleys.

The trends for supporting industries are similar. In each case, omission of the intermediate LEU cycle leads to greater peaks in supporting industry throughput rates. Thus, the LEU cycle, apart from conserving uranium resources, also moderates the level of secondary industry capacity required for the advanced fuel cycles.

FIGURE 5.1
Cumulative Uranium Requirements: Base Growth

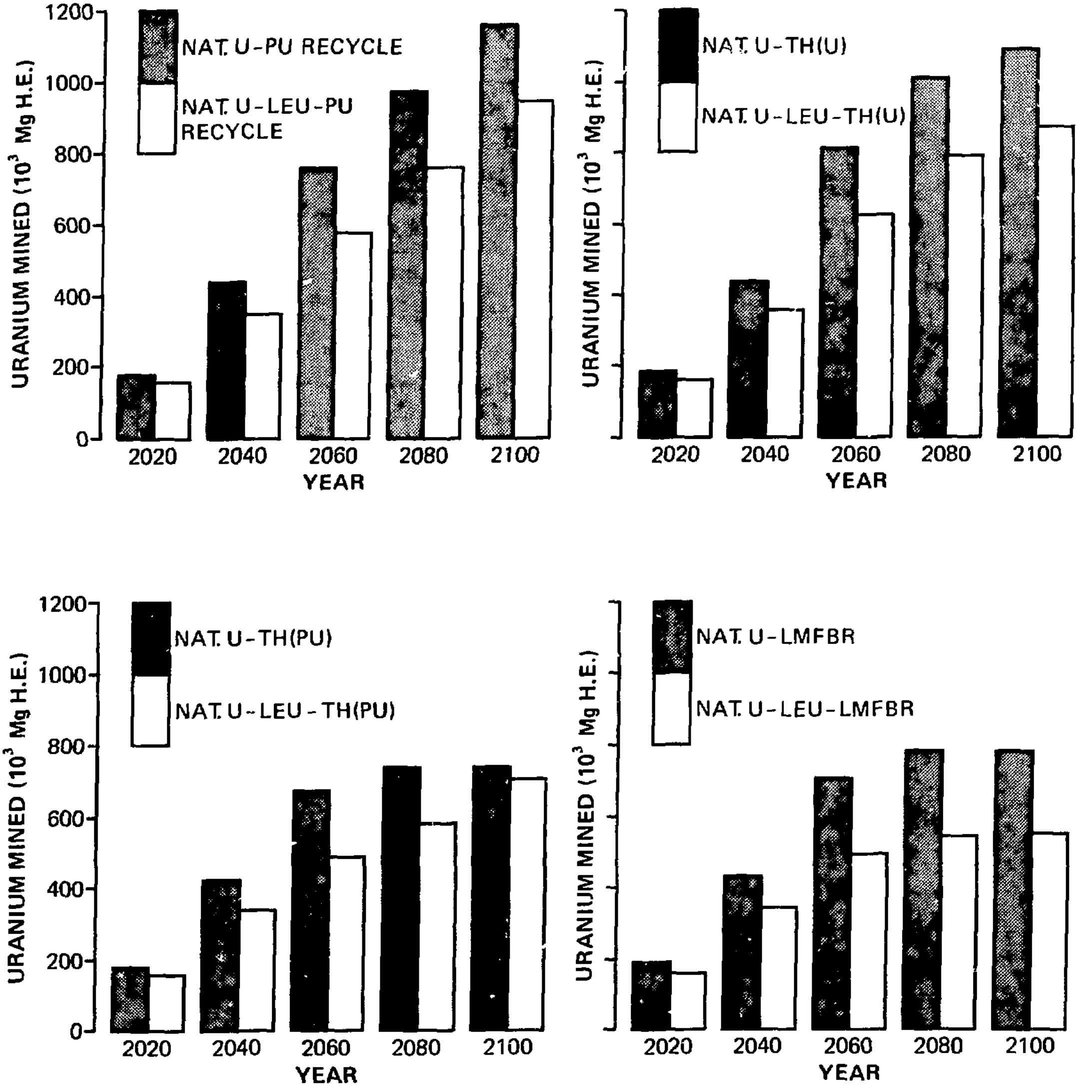
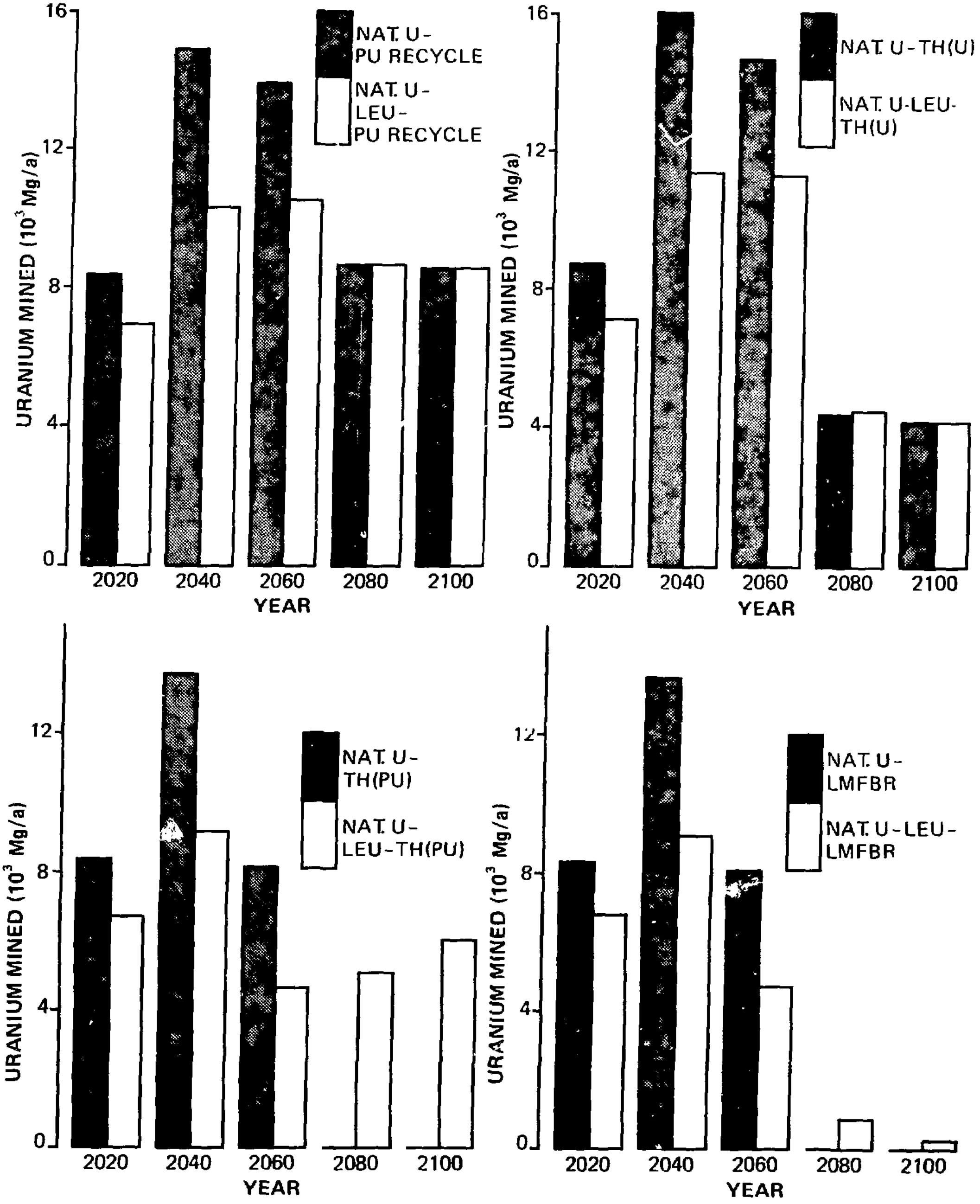


FIGURE 5.2
Annual Uranium Requirements: Base Growth



6. DISCUSSION OF RESULTS

The results presented in the previous sections indicate that the comparative performance of each strategy is relatively independent of nuclear capacity growth rate. That is, the rank of each strategy, in terms of uranium consumption and supporting industry development, remains essentially the same from low growth to high growth. Nevertheless, it is difficult to define any one strategy as the overall optimum.

Strategies 5 and 6, the NAT U-LEU-Th(Pu) and NAT U-LEU-LMFBR, are more uranium conserving than all the other strategies, and are essentially equivalent to each other. With the implementation of improvements to the LMFBR cycle, the NAT U-LEU-LMFBR strategy would compare even more favourably to the others. However, Strategies 3 and 4, the NAT U-LEU-Pu RECYCLE and NAT U-LEU-Th(U), are somewhat simpler. For example, each requires only one type of reprocessing facility, as compared to two for Strategies 5 and 6. Strategy 2, NAT U-LEU, is the simplest of the advanced strategies, but, of course, it requires more cumulative uranium and higher secondary industry throughput rates. Strategies 1-4 all require disposal of large amounts of irradiated fuel.

There is no doubt that significant resource savings can be achieved through the adoption of any of the advanced strategies. However, since no real upper limit can be placed on recoverable uranium reserves, the economics and commercial feasibility of each strategy will ultimately dictate which is the optimum choice for Ontario.

Perhaps the most significant of the results is the benefit provided by the intermediate LEU cycle. It was included as an intermediate cycle because it is likely that it could be implemented more quickly, and with fewer research and development costs than the other advanced cycles. Further, it would allow solutions to be found to technical problems which are also expected to occur for the more advanced cycles. However, the study discussed here has shown that the intermediate LEU cycle also has the significant effect of moderating the development of secondary industries upon the introduction of the more advanced fuel cycles. Thus, from a secondary industry point of view, the LEU cycle is desirable, regardless of the choice, if any, of a third fuel cycle.

It must be remembered, however, that adoption of the LEU cycle will not occur simply because it smoothes the way for the introduction of an advanced cycle, or because it uses resources more efficiently than the once-through natural U cycle. A more important consideration is its economic feasibility. Static economic analyses indicate that the LEU cycle is already economically superior to the natural U cycle (3). Thus, the major remaining concern regarding the LEU cycle, apart from potential technical problems, is to confirm the implications of the static economic analyses, by examining the economics of the LEU cycle in a growing nuclear system.

7. PLANNED FUTURE STUDIES

The next step in long-term strategy analysis is a dynamic study of the economics of the six fuel-cycle strategies discussed in this document. A review of the relevant economic parameters, taking into account maturity levels of secondary industries, is in progress. Based on the results of the present study, secondary industry plant sizes and in-service dates will be specified, allowing the establishment of proper price levels. The study will use the economic subroutines of the computer code FISS. However, the program will be modified to include features, such as time-dependent secondary industry unit costs, not available in the present version.

A slight modification will also be made to the rate of introduction of LEU reactors. Studies are presently underway to determine the most suitable scheme for introducing the LEU cycle into the generating system. The results of these studies will be incorporated into future system economic analyses.

The aim of the economic study will be to compare, on an economic basis, the various strategies for each nuclear growth rate. An analysis of cash flows for both publicly and privately owned components of the nuclear fuel cycle will be included. Thus, capital requirements for the total industry, not just the publicly owned portion, will be established. The economic effects of varying the introduction date of advanced cycles will be examined, with a view to determining the optimum introduction date. Close attention will also be paid to the economics of the LEU cycle, especially in terms of the timing of its introduction.

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APPENDIX A

INTRODUCTION RATE OF NEW METHODS OF ELECTRICITY GENERATION IN ONTARIO

Fisher and Pry (1) have developed a model which may be used to describe the rate at which a new technology captures the market held by an older, competing technology. The model has been shown to be successful in describing the penetration of synthetic fibers into the market held by natural fibers, the penetration of plastic versus leather and the penetration of synthetic versus natural rubber.

The model is based on the following three assumptions:

1. Many technological advances can be considered as competitive substitutions of one method of satisfying a need for another.
2. If a substitution has progressed as far as a few per cent of the total consumption, it will proceed to completion.
3. The fractional rate of fractional substitution of new for old is proportional to the remaining amount of the old left to be substituted.

The third assumption is characterized mathematically by the following equation:

$$\frac{1}{f} \cdot \frac{df}{dt} = 2\alpha \cdot (1 - f) \qquad (1)$$

where f is the fraction of the market held by the new technology, t is time and α is a rate constant. The solution to Equation 1 is given in two forms, as follows:

$$f = \frac{1}{2} \cdot \left[1 + \tanh \alpha (t - to)\right] \qquad (2)$$

$$f/(1 - f) = \exp\left[2\alpha \cdot (t - to)\right] \qquad (3)$$

Equation 3 is the more useful form of the solution, because, if the model is applicable, a plot on semi-logarithmic paper of $f/(1 - f)$ versus time will yield a straight line of slope 2α.

The purpose in describing the above model is to determine its usefulness as a method to predict the introduction rates of new methods of generating electricity in Ontario. Specifically, we are interested in defining the introduction rates of low-enriched uranium (LEU) CANDU reactors, beginning in 1992, advanced fuel cycle reactors, beginning in 2020, and a completely new method of electrical generation beginning in 2035 or 2045.

The applicability of the model can be determined by considering the introduction rate of CANDU(PHW) reactors in Ontario. Figure A.1 is a plot of $f/(1 - f)$ versus time, where f is the fraction of the total Ontario electric generating capacity which is provided by nuclear stations. The data was obtained from Ontario Hydro Power Resources Report No. 780301 and from System Planning's 'Program Z', which details in-service dates for new generation facilities. The result is a straight line, with slope corresponding to $\alpha = .0566$, indicating that the model is indeed applicable.

It will therefore be assumed that the Fisher-Pry model, with a suitable value of α, can be used to define the introduction rates of LEU and advanced reactors, and also of the new method of generating electricity. However, because the LEU fuel cycle is not really a brand new technology, it can probably be introduced at a relatively fast rate. Therefore, the rate constant, α, will be assumed to be 0.1132, or twice that describing the introduction of natural U CANDU reactors. For the advanced fuel cycle, and the new generation method, the value of α will be assumed to be 0.0566, which is equal to the value describing the introduction of natural U CANDU reactors.

According to the second assumption discussed earlier, the model is not applicable until the new technology has captured at least a few per cent of the market. Thus, initial values of installed capacity are required for each of the three new generation methods under consideration. For the LEU fuel cycle, it will be assumed that a 1250 MWe demonstration unit will be put in-service in 1992, but that no further LEU reactors will be built until 1998, after which time the construction rate will be defined by the Fisher-Pry model with $\alpha = .1132$. Similarly, for the advanced fuel cycle, it will be assumed that demonstration units totalling 2000 MWe will be put in-service in 2020, and that no further advanced reactors will be built until 2028. After 2028, the construction rate will be defined by the Fisher-Pry model with $\alpha = .0566$. For the new generation method, it will be assumed that demonstration units totalling 2500 MWe and 5000 MWe are put in-service at the appropriate year for the low growth and base growth cases respectively. These values correspond to $f = 1.7\%$, which is roughly the minimum value sufficient to maintain the model's applicability.

The initial values of f discussed above are important because for a given α, the time until <u>all</u> new generation facilities are of the new technology type <u>is</u> dependent on the initial value of f. The demonstration plants of 2000 MWe for the advanced reactors correspond to a smaller value of f than does the LEU demonstration plant size of 1250 MWe. Thus, apart from the slower introduction rate due to a lower value of α, the time until complete penetration by the advanced reactors is extended even further, simulating the delay which may be incurred due to the required buildup of support industries, such as reprocessing.

The rates of introduction predicted by the Fisher-Pry model for the LEU and advanced reactors are shown in Figure A.2 for each of the low, base and high growth cases. The curves are terminated at the time corresponding to complete penetration (i.e. all new facilities are of the given type). The introduction of the new method of generating electricity is indicated by the gradual decline of the nuclear growth curve in the base and low growth cases.

(1) J.C. FISHER, R.H. PRY 'A SIMPLE MODEL OF TECHNOLOGICAL CHANGE', INDUSTRIAL APPLICATIONS OF TECHNOLOGICAL FORECASTING ITS UTILIZATION IN R&D AND MANAGEMENT, ed. M.J. CETRON, C.A. RALPH, WILEY & SONS 1971 p. 290.

FIGURE A-1
Fisher-Pry Model Applied To Introduction of Nuclear Power in Ontario

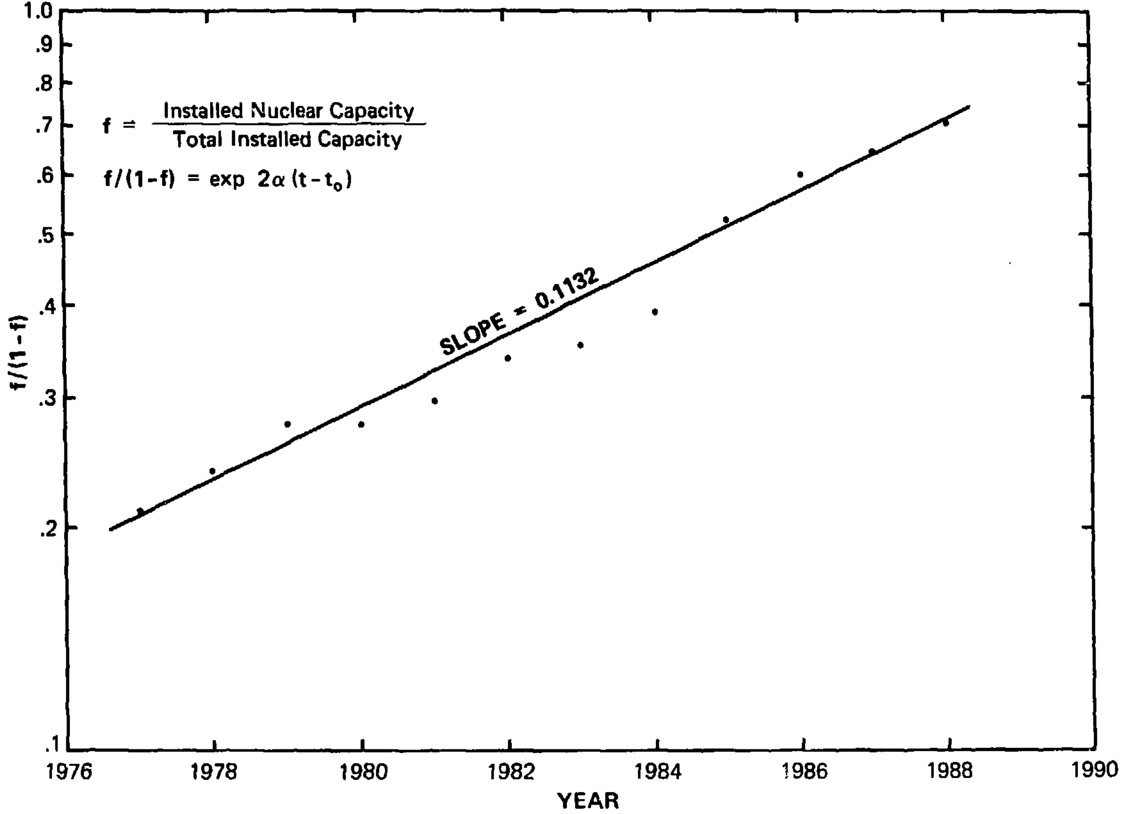

FIGURE A-2
Introduction Rates of New Nuclear Technologies