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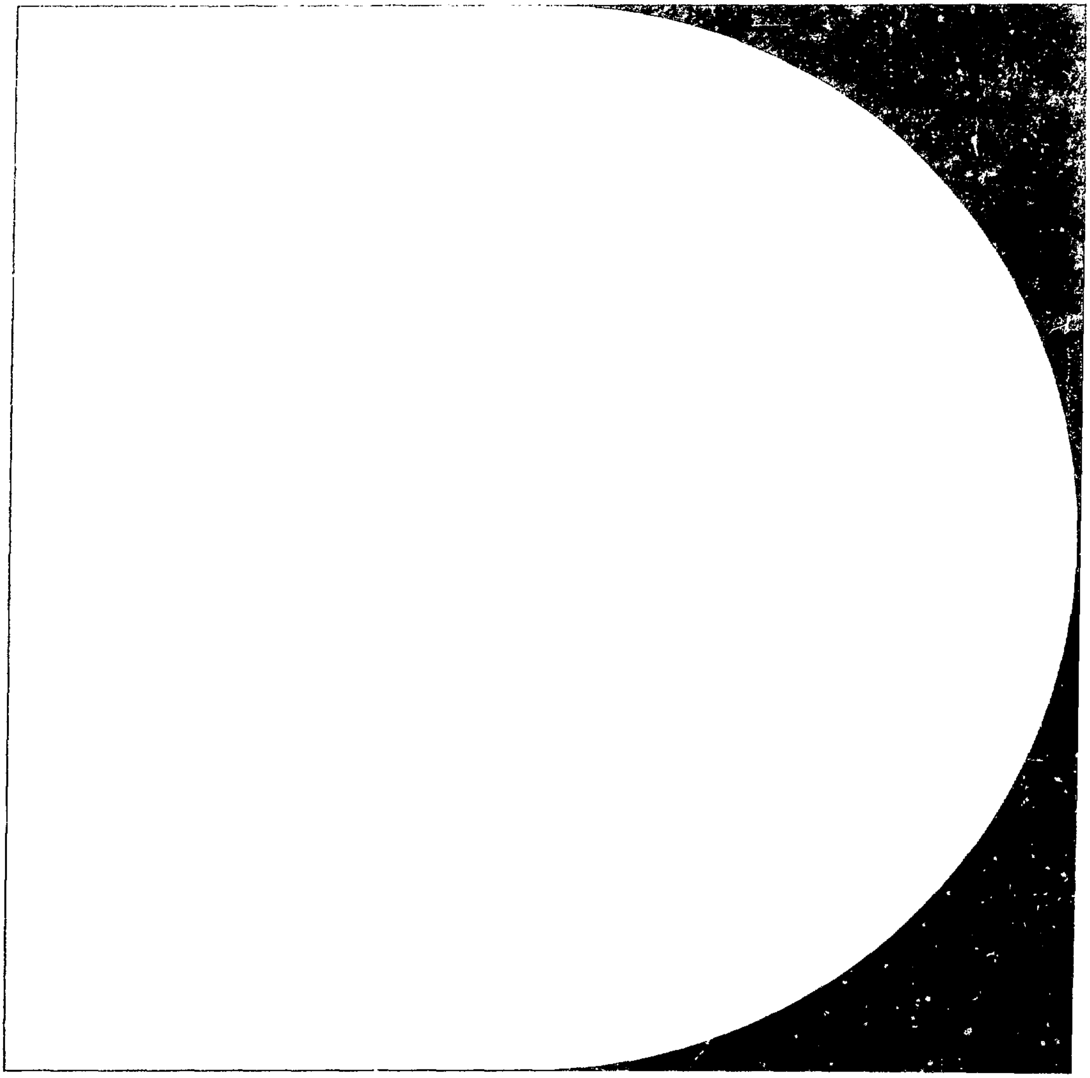

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ALTERNATIVE FUEL CYCLES: WHICH OPTIONS TO DEVELOP?

Nuclear Studies & Safety Department

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ABSTRACT

Uranium resource utilization and economic considerations provide incentives to study alternative fuel cycles as future options to the PHWR natural uranium cycle.

Preliminary studies to define the most favourable alternatives and their possible introduction dates are discussed. The important and uncertain components which influence option selection are reviewed including: nuclear capacity growth, uranium availability and demand, economic potential and required technological developments.

Finally, a summary of Ontario Hydro's program to further assess cycle selection and define development needs is given.

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1.0 Introduction

CANDU PHWR's with the once-through natural uranium fuel cycle have been commercially successful in Ontario since the early 1970's. One of the main reasons for their economic advantage over fossil-fuelled generating stations is the current abundance of low cost uranium in Ontario. Since uranium is indigenous to Ontario and fossil-fuels are not, long range forecasts have suggested that nuclear power should constitute up to two-thirds of the installed generating capacity in the province following the turn of the century.

Ontario Hydro has secured uranium supplies for much of the life of its presently committed nuclear stations. However, it is not possible to confidently estimate the availability or price of uranium after the turn of the century. Ontario Hydro has, therefore, been examining alternative CANDU fuel cycles and reactor systems which give improved uranium utilization. Cycles that offer protection against rising uranium prices, which would erode the present economic advantage of the CANDU PHWR, are of particular interest.

Studies have shown that a wide range of uranium savings is possible, although these savings do not occur dramatically, but accrue over long periods. The largest savings are associated with cycles or systems requiring significant technological development, and which are economic only at high uranium prices. Such systems provide insurance against extreme price escalation (possibly caused by supply problems). Because of the low cost of fuel relative to the total energy cost, the overall economic advantage of CANDU PHW's is retained.

Economic considerations will most likely determine the future adoption of any alternative to the natural uranium cycle, and its introduction time. Thus, judgment of the time at which the uranium supply might fall short of matching future requirements and uranium price movement, are of paramount importance. Uranium requirements depend on the growth of installed nuclear capacity in Ontario and Canada. This growth has a widening range of uncertainty as we look further into the future. Uranium price movement (in real terms) will be determined by world demand and supply capabilities in the future.

Currently, the annual uranium requirements of Canada's nuclear power program are relatively small compared with the estimated potential production capability from low cost resources. However, as the installed nuclear capacity grows, there is concern that annual demand could exceed supply if the natural uranium once-through cycle is retained indefinitely. There are several reasons why annual production capability, rather than quantity of uranium resource in the ground, could limit a rapidly expanding nuclear power program. Apart from concerns of acquiring equipment, manpower and investment capital, there are problems associated with developing sites in remote and hostile terrain. Changing regulatory requirements to meet necessary safety standards at specific sites could delay the establishment of new production centres. It is estimated that in the future it could take between 10 and 15 years to establish new production centres following the initial discovery of an economic deposit.

While the future annual domestic requirements for uranium are forecast to increase exponentially, mining companies with apparent surplus capacity in the near term will need incentives to invest and plan for relatively long term returns. Otherwise, only those production facilities to meet the near term market demands will occur.

Uranium export tied to success in finding new economic deposits and availability of production capacity, could provide the necessary incentives and significantly help Canada's future balance of payments. Such a policy, however, risks depletion of our economic resource at too great a rate and unfavourably impacting on our future electrical generation costs.

In summary, several important questions require analysis in the future planning of Ontario's nuclear program:

1. What is the estimated range of installed nuclear capacity in Ontario and Canada up to the year 2000 and beyond?

2. What level of confidence do we have that uranium resources will continue to be discovered? Can they be economically developed to satisfy future requirements?

3. Is annual uranium production capability likely to limit nuclear growth in the long term?

4. Will future uranium exports have an unfavourable or beneficial impact on our nuclear power program?

5. Which alternative CANDU fuel cycles or reactor systems should be developed to reduce uranium requirements and minimize the possibility of fissile material shortages?

6. Which alternative fuel cycles show the most economic potential, and how high must uranium prices rise for that potential to be realized?

7. When in time should options to the natural uranium cycle be available?

The Advanced Nuclear Concepts section (Figure 1) was formed at Ontario Hydro in 1977 to study these questions. The alternative cycles and systems under study are:

(A) CANDU PHWR with,

- Natural Uranium
- Low Enriched Uranium (LEU)
- Uranium Enriched with Plutonium (MIXED OXIDE)
- Thorium with Plutonium Topping
- Thorium with U-235 Topping
- Thorium Self-Sufficient Cycle

(B) LMFBR with a Depleted Uranium/Plutonium Cycle.

A program of studies is proceeding in three phases:

- Preliminary Review
- Consolidation Studies
- Detailed Appraisal

This report summarizes the results of the first phase, "Preliminary Review", and provides a progress report on the continuing "Consolidation" studies. The "Detailed Appraisal" of selected cycles has only reached the planning stage.

Table 1 summarizes the contents of this three phase program. The bibliography lists the reports which detail the results produced to date.

2.0 Cycle Selection and Preliminary Results

2.1 Cycle Selection Process

It has been widely acknowledged that the CANDU PHWR is capable of operating with a wide range of fuel cycles including the LEU, MIXED OXIDE and a variety of THORIUM fuels without radical design change. It has also been estimated that the time to develop these options to commercial application, will range from 15 to 25 years. The recycle mixed oxide and thorium cycles will require development of reprocessing, semi-remote or remote fuel fabrication and waste management facilities. Assuming the desire for Canadian self-sufficiency, the LEU cycle will require the development of an appropriate uranium separation technology which would also be required for the U-235 topped thorium cycle. The advisability of building a

Canadian uranium enrichment plant and analysis of its benefits to the domestic nuclear program and national balance of payments is a central issue.

To determine which cycles should receive priority and what development programs might be recommended, the following three groups of factors have to be analysed.

- Forecast Factors
- System Technology Factors
- Institutional Factors

It is believed that these groups of factors will collectively influence the decision to adopt an alternative to the present cycle. However, those associated with economics and risk of reliable performance may have greatest significance.

The "Forecast Factors" influence fuel cycle ranking, applicability, penetration rate into the generating system, and desirable introduction date. These factors are inter-related and contain uncertain values. They include:

- Growth of Installed Nuclear Capacity
- Uranium Resource Levels and Production Rates
- Cycle and System Uranium Requirements
- Economics of Alternative Cycles and Systems

The "System Technology Factors" are associated with the results of development projects and engineering analysis. They are not uncertain in the same sense as the Forecast factors. They will influence the choice of cycles and control the timing and mode of their actual introduction. They include:

- Difficulty in Reactor Design and Operation
- Commercialization problems in the Fuel Cycle Service Industry
- Opportunities that the Alternative Cycles offer to Reduce Station Capital Costs
- Steps to Implement Alternative Cycles into the Generating System
- Reactor and Fuel Cycle Safety Provisions

The "Institutional Factors", which include resistance to weapons proliferation and social acceptance of the need for new technologies, may also influence the adequacy and flow of development funds. These factors therefore affect timing and possibly choice of cycle to be developed.

2.2 Results of Preliminary Review

In the preliminary review, consideration was given only to the "Forecast Factors" and possible reactor design difficulties which could add to capital costs. References 1 to 8 provide the detail of these studies and this report will only note the highlights which led to the interim conclusions presented in Section 3.0. Section 4.0 reports progress made in the "Consolidation" phase of Ontario Hydro's program, which aims to examine all assumptions made in earlier studies and confirm the choice of cycles for detailed study.

2.3 Nuclear Growth Assumptions

Figure 2 shows the variation of installed nuclear capacity assumed for Ontario. At the time of the preliminary review, the long range forecast (LRF48A)* suggested a need for 46 GWe by the year 2000. The "Base growth" estimate following year 2000 was postulated to be somewhat less than in the 1990's at 2.5 GWe/year. After the year 2040, zero growth was assumed.

Any projection so far into the future is highly speculative. However, many of the alternative fuel cycles cannot be made commercially available until the early part of the next century. Without simulating a period significantly beyond that, it is not possible to determine the impact such cycles could have on the uranium requirements. The purpose of these very distant projections is to obtain perspective on the relative improvements in uranium utilization, eliminate options on the basis of need, and select a minimum of two cycles which serve to meet all contingencies in the time frame of 20 to 40 years.

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* Section 4.1 discusses recent estimates for the growth of installed nuclear generating capacity in Ontario and Canada. These estimates are lower than those extrapolated from the earlier forecast, LRF48A. Studies (Reference 15) performed using the current estimates of future installed capacity, confirm the ranking of the alternative fuel cycles relative to uranium availability and demand which is discussed in the following section.

Figure 2 also shows a range of growths used for sensitivity studies, which were performed to determine effects on cumulative and annual uranium requirements, fuel fabrication, reprocessing and uranium enrichment needs. In addition, the importance of fissile losses and delays in recycling were studied. The range of growths shown in Figure 2 is sufficiently large that it probably encompasses the actual growth rate that will be experienced.

2.4 Uranium Availability and Requirements

Figure 3, shows the cumulative uranium requirements at various times for each fuel cycle with the "base case" power demand. In all cases, the natural uranium cycle is used until 1999 after which new stations utilize the alternative cycle shown, subject only to the availability of appropriate fissile material. Existing stations are not converted but are replaced by the alternative fuel cycle reactors at the end of their 30 year life. Figure 3 also shows the Ontario and Canadian uranium resource estimates in the "measured", "indicated" and "inferred" categories thought recoverable up to $160/kgU. Simple addition of these different categories is a questionable practice. Uranium resource appraisors may not agree with this type of comparison of requirements and resources. However, the graphical comparison is presented to provide perspective rather than reliability. Section 4.2 discusses further interpretations of possible resource availability and demand.

The conclusions from Figure 3 are:

1. Alternative fuel cycles do not provide significant mined uranium savings until 20 years after introduction.

2. In the long term (> 40 years), the CANDU thorium self-sufficient cycles and the LMFBR operating on the depleted uranium/plutonium metal cycle show significant advantages. They show the potential to essentially remove any dependence on mined uranium following 50 years of operation.

3. By 2070, uranium requirements, relative to the natural cycle, are reduced by 23%, 46% and 57 to 77% by the LEU, mixed oxide and thorium cycles respectively.

4. Assuming modest annual gains (say 5%) in the uranium resource level continue, and that exports are constrained, it is suspected that development of the self sustaining cycles or LMFBR are not an early requirement for Ontario.

Figure 4, shows that the ranking of the alternative fuel cycles is not sensitive to the magnitude and growth of installed nuclear capacity. If the high growth scenario were to occur, the need to develop one of the thorium cycles or the LMFBR becomes more obvious. At the high growth rate, Ontario would have used 1.5 million tonnes of uranium by 2070 if it continued to build natural uranium reactors. This quantity approximates to three times the "conservative" value of discovered uranium resource in Canada today at present economic recovery costs. The LMFBR shows a clear advantage in uranium utilization at high nuclear growth rates. There is little difference in the U-235 and plutonium topped thorium cycles at high growth rates. However, the unavailability of plutonium, and the consequent need to build natural CANDU's to provide this fissile material, makes the Pu-Th cycle a slightly higher consumer of mined uranium. For the low growth scenario, it does not appear that development of the CANDU thorium cycles or LMFBR is necessary.

It was noted earlier that maximum uranium production capacity might limit nuclear growth, rather than total resource. Figure 5 shows the annual uranium requirements of some of the fuel cycle strategies for Ontario. By way of comparison, the estimated maximum Ontario production rate (~ 6 GgU/year) is shown. Future Canadian production capacity could rise to double this figure by the 1990's provided markets for uranium are established and incentives to invest in the mines development are made available (Ref. 10).

The significant advantage of the various fuel cycle strategies is largely self evident in Figure 5. The annual requirements of the natural uranium cycle steadily climb and reach values in excess of estimated maximum capability for all mining companies in Canada by 2020. This conclusion is based on resource levels thought to exist today and does not allow for any export. The levelling of demand at 2040 is directly related to the onset of zero growth in nuclear capacity. Figure 5 points to the need to develop options to the natural cycle which slow down the growth of annual requirements. If one takes a pessimistic view of the future of the mining industry, cycles which have reduced requirements with time should be developed. The development of the LMFBR or Th(U)SS cycle will theoretically free Ontario of mined uranium needs by the middle of the next century. Because of the high pre-equilibrium fissile consumption of the Th(U)SS cycle, significantly more mined uranium is required in the first quarter of the next century than by the Th(Pu)SS cycle, which uses plutonium from reprocessed irradiated natural uranium fuel.

2.5 Reactor Design and Station Requirements

Preliminary studies (References 2 and 8) have been performed to identify necessary station and reactor design changes appropriate to each alternative CANDU fuel cycle, and their attendant incremental capital costs.

Station facilities for alternative cycles which are different from those associated with the natural uranium cycle are:

- Fresh Fuel Storage and Inspection
- Fuelling Machine
- Irradiated Fuel Storage
- Safeguards
- Operation and Maintenance

Reactor design changes can be expected for:

- Control and Flattening
- Channel Power Peaking
- Fuel
- Reactivity Limitations
- Instrumentation

The extent of these changes will depend on the particular fuel cycles considered. Most of these changes involve modification of existing techniques or the use of methods which will be developed for reprocessing and remote fabrication. They will add to station costs, but can be expected to be off-set by potential improvements in station design made possible by the increased reactivity provided by enrichment. Examples include: higher primary system pressure, increased station cycle efficiency, and reduced lattice pitch. The possibility of these potential cost reductions is to be investigated in the third phase ("Detailed Appraisal") of Ontario Hydro's program.

Increased channel power peaking, associated with enriched fuel cycles, is considered to be an important problem to overcome before it can be confirmed that CANDU's can utilize all fuel cycles. This problem arises because, for a given flux level, enriched fuel generates substantially more power and changes more rapidly with burnup than natural fuel. Variations in channel power due to refuelling are therefore larger for the alternative cycles, and methods to limit the peak channel power are needed.

Methods of doing this include:

(a) Reduction of reactor specific power.

(b) Reduction in number of bundles shifted per channel visit.

(c) Use of burnable poisons.

(d) Fuel management involving radial shuffling.

(e) Fuel design changes.

(f) Sophisticated control of macroscopic power distributions.

Only detailed studies will determine what combinations of these methods will be adequate and economically optimum. A combination of items (a) and (b) could represent a preferred approach since these items require the least R&D.

Figure 6 shows the variation of power peaking with the number of bundles shifted for a variety of fuel cycles. High fuel burnups from the alternative fuel cycles will permit fewer bundle shifts per channel than for the natural uranium cycle for the same fuelling machine demand. However, this will not reduce the power peaking to the natural fuel levels and lower reactor specific powers will be needed.

Table 2 shows the bundle shifting schemes and the reduction in specific power (ie increased number of fuel channels) necessary to reduce peak channel powers to the Bruce GS A license limit. The bundle shift schemes result in the same refuelling demand as for natural fuel in Bruce A. A range of specific power reductions and corresponding capital cost increments are given in Table 2. This range allows for possible non-symmetric burnup distributions caused by catchup or localized refuelling of groups of adjacent channels.

From our preliminary review of the required station and reactor design changes, we conclude that the added capital cost will approximate to $15M for a low enriched uranium cycle and, $25M for either plutonium or thorium cycles in a 850 MWe PHWR. Detailed design is required to improve these estimates.

Other technical aspects of CANDU thorium cycles were also reviewed (Reference 8). From this review we concluded that the development of the intermediate burnup cycle would be preferable to either the self-sufficient or high burnup cycles.

The self-sufficient cycle, SSTC, suffers from reactivity limitations and may not be achievable if fissile losses in fuel processing are 1% or more. This cycle is also estimated to have high Total Unit Energy Costs (TUEC) and, therefore, to be non-competitive until uranium prices reach very high levels.

In summary, the SSTC probably requires:

(a) Superpure D_2O ($> 99.95\%$)

(b) Low cross-section, enriched Zr alloy development

(c) Low specific power for economy

(d) Fissile losses $< 1\%$

(e) High fissile inventories

(f) Large reprocessing requirements.

The high burnup thorium cycle, HBTC, probably requires:

(a) High reactivity and sophisticated control systems

(b) High specific power to be economic

(c) New fuel design

(d) High fuel performance

(e) Extended time to reach the final system equilibrium cycle.

2.6 Economic Analysis

The key economic questions are:

(a) Which advanced fuel cycles show the most economic potential?

(b) How high must uranium prices go for that potential to be realized?

(c) At what time can we expect those prices to occur?

Current fuel bundle designs for CANDU(PHW) reactors have been assumed appropriate for all cycles. Preliminary cost estimates of the fuel cycle services are given in Table 3. The costs are based on an assessment of the available literature and discussions with knowledgeable persons in the industry. These cost estimates, in common with all assumptions made in the preliminary studies, are being thoroughly examined in the "consolidation" phase of studies at Ontario Hydro.

Fuelling costs, with the added capital cost increments associated with reactor and station design changes for the alternative cycles (Section 2.5), were calculated using data from Table 3 and a range of uranium prices. The calculations included carrying charges on inventory, and burnup variations due to changing isotopic compositions (References 3, 4, 5).

Discounted cash flow analyses were performed for each cycle, for a range of enrichments and U_3O_8 prices, to provide levelized fuel costs over a 30 year reactor life. The economically optimum enrichments were obtained as a function of uranium price and their fuel cycle costs are presented in Figure 7. The costs given are in constant 1978 dollars.

The LEU cycle has the lowest fuelling cost for a wide range of U_3O_8 prices (between 15 and 107$/lb). The current average price of uranium is about $20/lb so the LEU cycle is already competitive with the natural cycle. The Th-Pu-U233 cycle offers the highest potential in the long term when U_3O_8 prices exceed $107/lb.

The optimum enrichment for the LEU cycle (based on economic considerations), was found to slowly vary from 1.1 to 1.2% U-235 as the U_3O_8 price rises from 40 to 100$/lb. The thorium cycle with the lowest fuelling cost is the intermediate burnup cycle. It has an equilibrium burnup between 28-35 MWd/kg HE and requires a fissile topping in the range 0.3 to 0.6%.

The optimum enrichment for the $(Pu,U)O_2$ cycle is about 0.3-0.4% fissile Pu/kg HE. This cycle appears to offer significantly less potential than the other alternative fuel cycles.

An estimate of the future variation in U_3O_8 price is required to predict possible introduction dates and periods for which the alternative cycles might be most economic. Only very approximate estimates of future uranium prices can be made.

Since this is a subject of crucial importance in selecting which alternatives should be developed, it is receiving further attention in our "consolidation" studies.

For periods beyond the next ten years, uranium price is particularly speculative and involves many issues including problems of development in remote areas, increasing regulatory controls and governmental policy. Uranium price will be determined by world market forces and our studies assume that a two-tier Canadian price policy will not occur. The general concensus amongst uranium resource advisors is that the long-term price might reasonably be expected to be within the following scenarios. This however cannot be rigorously justified.

The scenarios are:

Scenario 1: U_3O_8 price 45$/lb in 1985, 2%/annum escalation beyond 1985.

Scenario 2: U_3O_8 price 45$/lb in 1985, 3%/annum escalation beyond 1985.

Figures 8 and 9 show the present worth savings in TUEC which would be realized if either Scenario 1 or 2 occurred. These figures suggest that the savings in TUEC from the LEU cycle, range between 0.5 and 1.0 m$/kWh during the latter part of this century and the first decades of the next. The figures also suggest that the plutonium initiated thorium cycle will be commercially competitive starting sometime between 2015 and 2030.

3.0 Preliminary Conclusions

Based on the information available, there does not appear to be an immediate concern for the viability and continuing economic competitiveness of the natural uranium CANDU cycle, relative to other forms of electric generation in Ontario. However, there is sufficient uncertainty in the availability of low cost uranium by the turn of the century, that it is prudent to identify development programs which will provide flexibility of choice of fuel cycles in the future. Which options should be developed first, appears to be largely determined by economics and judgment of the efforts which should be made to conserve uranium. Uranium price movements which will be set by world demand, attainable production rates, and the extent of future low cost discoveries, will determine which cycles will be committed and when. Our studies suggest:

1. The Low Enriched Uranium (LEU) cycle should be developed for commercial operation in PHWR's in the period 1990-2020.
2. The Intermediate Burnup Thorium Cycle using plutonium should be developed as an option, but the very earliest that it is likely to be commercially attractive is the year 2015.
3. In the event that nuclear growth is high in the next century, the LMFBR operating on the plutonium/depleted

uranium cycle may be attractive and it, therefore, warrants further study.

Other reasons for interest in pursuing further study of the LMFBR are:

- Low system fissile inventory;
- Can burn all actinides efficiently;
- Low man-rem load in station;
- Safety due to the low enthalpy system;
- Reduced reliance on Zirconium supply;
- Future world-wide technological support.

4.0 Consolidation Studies

In the "consolidation" phase of our studies we are updating the forecast factors and cost assumptions. The intent is to document the rationale for all assumptions, incorporate information from current EMR, NURE and INFCE studies, and produce a data-base handbook. Further strategy and economic evaluations will be performed to confirm the preliminary conclusions. This section of the report provides a summary of recent progress.

4.1 Current Estimates of Installed Nuclear Capacity

In the last quarter of 1977 the primary electric demand in the province dropped below the previous year. The December 1977 peak was lower than the previous year, an event which had not occurred since the 1929-1932 period. Weather conditions were not the reasons. Monthly demands have generally been lower than revised forecasts for 1978 and appear to reflect the weakness in the Canadian economy which has grown at less than its potential rate for three years.

The decline in the fourth quarter of 1977 is seen as a radical departure from the past, and emerging long range forecasts are sharply lowered from LRF48A.

The reasons for the change in outlook in the mid-term are twofold:

(a) A less optimistic economic outlook.
(b) The impact of electricity price increases and conservation.

For the longer term (1990's), sharply lower forecasts of population growth in Ontario combine with a projected increase in the importance of a conserver society (as a social objective) and reinforce the mid-term considerations.

A new long range forecast is expected to be officially adopted during 1979. Compared with the historical increase of more than 6%/year, interim studies suggest the Ontario East system primary peak demand growth might decline gradually from 5.5% in 1987 to 4.5% in 2007.

Table 4 lists the installed nuclear capacities thought likely to occur by the year 2000 for all Canadian provinces. This data is speculative, but reflects an appreciation recently acquired through informal discussions with other utilities. Table 5 lists our revised (Reference 9) very long term estimates of installed nuclear capacity for Ontario. The rationale for the "base" nuclear growth estimate is given in Table 6. These very distant trends are needed to rank the long term advantages of alternative fuel cycles. The "low" and "high" boundaries given in Table 5 are maximum conceivable limits and are used only for the purpose of sensitivity studies in selecting fuel cycles for development.

4.2 Progress in Uranium Supply and Demand Interpretation

Energy, Mines and Resources Canada published the latest uranium resource data in June 1978 (Reference 10). The best estimates of uranium quantities contained in the designated geologic categories are:

Category	Tonnes U (x 10^3)	
Measured	82	mineable up to $160/KgU
Indicated	107	
Inferred	318	
Prognosticated	388	
Speculative	700	

The definitions of the categories (see Appendix) vary from well defined in the case of "measured", to "unknown", but thought to exist, for the "speculative" category. While the values represent best estimates of contained uranium, the nature of the information is such that there is decreasing confidence in the quantities reported in going from the measured to the speculative quantities. How can a nuclear policy planner use such data? Figure 10 attempts, with the aid of confidence weighting factors discussed in Reference 11, to place some perspective on this resource data. Superimposed on this resource schematic are the cumulative amounts of uranium required for the high and low estimates of the Canadian installed capacity shown in Table 4. These are the cumulative quantities required to fuel all reactors committed by year 2000 for 30 years, and allows for the 1978 export commitment of 68 GgU. It should be noted that the speculative category is not included in this perspective but is treated as a potential addition. It is also to be noted that the resource base represents todays knowledge of expectation for "low" cost uranium, does not include resources mineable at more than $160/kg or any account of continuing success in future exploration. A 5% growth in the total resource base per annum is considered a reasonable expectation, although only time will confirm this, and show how long it can be maintained. The confidence weightings used to illustrate the possible range in resource quantity are:

(a) Allocation Basis: Measured, Indicated and Inferred in the ratio of 1.0, 0.8, and 0.7 respectively (this conforms to the export guideline formula and ensures adequate domestic allocation by each active mining company).

(b) Conservative: Measured, Indicated and Inferred in the ratio of 1.0, 1.0 and 1.0 respectively (No Prognosticated).

(c) Best Estimate: EMR's best estimate of quantities most likely in the four categories, ie Measured, Indicated, Inferred and Prognosticated.

(d) Optimistic: Maximum quantities of Measured, Indicated, Inferred and Prognosticated in the ratio of 1.0, 1.2, 1.3 and 1.5 respectively.

It is concluded from Figure 10 that,

(1) The likely quantities of economic uranium in the ground are sufficient for Canada's nuclear capacity commitment to the year 2000.

(2) The possible extent of Canada's uranium resource and the likely near-term excess to domestic requirements are incentives for continued exports.

(3) The need to develop highly uranium conserving fuel cycles is not urgent.

Resource experts advise (Reference 12) that the best and most accurate illustration of the uranium supply situation is a comparison of projected annual requirements with projected annual production capabilities. Figure 11 provides such an illustration together with production requirements if Canada were to supply 10% of the world's future needs.

The domestic high and low requirements correspond to estimates of the Canadian installed nuclear capacity given in Table 4 assuming the percentage growth rate from year 2000 to 2020 for Canada will be the same as Ontario (see Table 5). The maximum attainable production from economically mineable deposits is based on the 1977 resource appraisal (Reference 10) updated by recent advice from EMR (13). The maximum capability that could be developed is now considered to be approximately 13500 tonnes/year by 1990. Without the benefit of future new discoveries and production centres, the maximum production capability will decline as the known centres are mined out and lower grade ores start to predominate. Currently, the capability is estimated to decline to 50-90% of its maximum by the year 2020. As part of the Canadian INFCE contribution, EMR are performing a mine by mine analysis to improve definition of this decline.

Presently, Canada's uranium exports amount to more than 15% of the world's requirements and in the future, as requirements rapidly grow, EMR consider 10% as a reasonable goal. Figure 11 shows how Canada's annual uranium production would need to increase to maintain 10% of the world's market. This curve is based on the world's low nuclear growth estimate in reference 14, which requires 180,000 and 300,000 MgU/annum approximately by year 2000 and 2020 respectively.

From Figure 11, it can be concluded that,

(1) There is an apparent surplus to domestic needs until at least 2005 assuming a high Canadian nuclear power growth scenario. If the assumed low nuclear growth occurs in Canada, the apparent surplus could extend to 2020 or later.

(2) Without a continuing export market there would be no incentive to attain the predicted maximum production potential by 1990, unless government policies to stockpile are introduced to ensure future domestic needs.

(3) Known uranium resources will permit modest export. However, very aggressive exploration and production centre development will be required to meet the goal of supplying 10% of the world's uranium needs after 1990.

(4) Development of fuel cycles which will reduce future annual uranium requirements becomes more important when world needs are considered. A policy to guarantee that future domestic annual requirements are met will be needed if exports progressively increase.

4.3 Uranium Requirements in the Long Term

Further studies have been performed to determine the relative advantages of alternative fuel cycles and systems to conserve uranium in the long term (Reference 15). These studies are based on our revised estimates for very long term nuclear growth in Ontario given in Table 5. Based on our preliminary conclusions, we assume a three-fuel cycle strategy in the future, ie: Natural Uranium - LEU - Advanced Cycle or System. The Low Enriched Uranium (LEU) cycle is first introduced in 1992 followed by the Advanced Cycles in 2020. The Fisher and Pry (Reference 16) model is used to describe the system penetration rate of the LEU and Advanced cycles. This model has been shown to simulate the actual introduction rate of natural CANDU PHWR's into the total Ontario electric generating system very well.

This study confirmed the ranking of the alternative cycles to conserve uranium shown in Figure 3, 4 and 5. Figures 12 and 13 show the long term cumulative and annual uranium requirements for the following three-cycle stragegies in comparison with an all natural uranium strategy.

(a) Natural U - LEU - Th(Pu)

(b) Natural U - LEU - LMFBR (U/Pu)

In summary, these three-cycle strategies reduce (in the long term) the cumulative and annual requirements to 40 and 45% respectively of that needed for the natural cycle. The cumulative and maximum annual uranium requirements could be reduced to 700 GgU and 9.5 GgU/a respectively for Ontario during the next century if either of strategies (a) or (b) were deployed. Figures 14 and 15 compare uranium requirements of the three-cycle stragegy (a) with that needed if the LEU cycle is simply omitted, but the advanced cycles are still introduced in the year 2020. The impact of introducing the LEU cycle is shown on Figure 15 since it limits Ontario's maximum annual uranium requirement to 9.5 instead of 14 GgU/a.

Figure 16 shows the estimated uranium separative work requirements for various strategies during the next century.

4.4 Progress in Economic Evaluations

Significant progress has been made in estimating the cost of fabricating fuel for the various cycles (Reference 17), and in estimating future uranium price movement. A detailed review of reprocessing costs, uranium enrichment price, station capital costs, OM&A and waste management costs is in progress.

Compared with our preliminary studies, we have found shortcomings in the cost estimates of both natural and enriched uranium fabricated fuels, when all processes from mine to reactor are considered, and volume through-put is properly recognized. In our previous discounted cash flow calculation of fuelling cost, we had used fabrication costs of $44 and $50/kgU for natural and LEU fuels. We believe more realistic costs, which include refining, conversion, scrap recycle and uranium purification, to be $49 and $85/kgU (reducing to $75/kgU at maturity), respectively.

These increases in estimated fuel fabrication cost raise the levelized fuelling costs previously given in Figure 7. They also increase the price of U_3O_8 at which the natural and LEU cycles have equal fuelling cost to $20/lb.

However, at higher U_3O_8 prices, the fuelling cost advantage of the LEU cycle over the natural cycle is little changed from that shown in Figure 7. This is due to the insensitivity to LEU fabrication costs, as compared to the higher importance of U_3O_8 price, in the determination of levelized fuelling costs.

Figure 17 compares the fuelling costs of the natural and LEU cycles as a function of both enrichment and U_3O_8 price. There is negligible variation in fuelling cost with enrichment above 1.0 weight percent.

At a uranium price of $60/lb, the LEU cycle gives 0.6m$/kWh saving and, when the price of U_3O_8 rises to $100/lb, the fuelling cost savings amount to 1.2m$/kWh in current values. When these savings might occur depends on the rate at which the U_3O_8 price increases with time.

Figure 18 shows the estimated trend in the average U_3O_8 price together with the scenarios assumed in our preliminary studies. The estimated price movement is a function of the rate of nuclear growth and therefore uranium requirement, and the ability to supply the demand. The curves in Figure 18 are based on a recent US analysis. In adopting this data we assume that the US uranium supply and demand will determine future world prices.

Figure 18 appears to support our previous assumption that the U_3O_8 price will increase in real terms at approximately 2%/annum. This provides further evidence that the LEU cycle will likely provide the lowest CANDU fuelling cost until the second or third decade of the next century.

Detailed engineering studies are planned to further assess the economics of the LEU CANDU fuel cycle. These studies will include an evaluation of U-235 separation technology, the potential for an optimized reactor to reduce station capital costs, and an understanding of the problems of converting an existing reactor core to the LEU cycle. The conversion of an existing unit is considered a desirable step to demonstrate the cycle reliability.

5.0 Overview

In summary, studies performed at Ontario Hydro during the last twelve months suggest:

- Canada's near term (pre-year 2000) installed nuclear capacity is expected to be lower than previously predicted.
- Canada's uranium resources are probably sufficient to fuel all domestic reactors committed by 2000 for a 30-year life using natural uranium. Recent uranium finds in Saskatchewan show high promise and potential for increased exports and favourable balance of payments.
- Domestic requirements will likely need a maximum uranium production capability of approximately 7000 Te/a by year 2000.
- A maximum uranium production potential of 13500 Te/a in the 1990's is possible based on assessments of known deposits and expected uranium occurrences.
- After 1990, annual uranium production might limit uranium exports. Aggressive development of new production centres and fuel cycles with lower requirements are needed to attain future uranium export goals.
- The LEU cycle is the earliest economic alternative to the natural uranium CANDU cycle. It is competitive at current uranium prices.
- Uranium price is expected to rise to $50-70/lb (1978 $'s) by 2000. At $60/lb, the LEU cycle saves 0.6 m$/kWh.
- When uranium price exceeds $100/lb (2020-2030), the intermediate burnup Pu/Th cycle becomes economic. Due to uncertainities in the 21st century, this cycle should receive continuing study.
- The LMFBR should also be studied in the event that required nuclear growth is very high in the next century.

6.0 References

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Appendix

Definitions of Uranium Resource Categories

This appendix gives the definitions of the uranium resource categories: Measured, Indicated, Inferred, Prognosticated and Speculative, as classified by Energy, Mines and Resources Canada. The following definitions are excerpts from Reference 10.

Measured (Proven) comprises ore from which tonnage is computed from dimensions revealed in outcrops, trenches, workings, or drill holes, and for which the 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 refer 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 a 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, the 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.

Speculative resources refer to estimated tonnages in deposits thought to exist on the basis of indirect indications and geological extrapolations in virgin areas or in areas where only occurrences are known.

TABLE 1
ONTARIO HYDRO'S
ALTERNATIVE FUEL CYCLES PROGRAM

• PRELIMINARY STUDIES	Compare & Select Cycles
• CONSOLIDATION STUDIES	*Analyse Assumptions* Data Handbook Preparation Confirm Preliminary Results
• *DETAILED STUDIES*	*Station Design* Fuel Cycle Requirements *Economic Appraisal* Introduction Strategy

TABLE 2
COST OF SOLVING CHANNEL POWER PEAKING IN ADVANCED FUEL CYCLES

FUEL CYCLE	INITIAL FISSILE W/O	BURN UP MWD/kg	BUNDLE SHIFT*	% INCREASE IN CHANNELS MINIMUM	MAXIMUM	ADDED COST, $M.** 850 MWe PHWR
ENRICHED U	1.1	17	2/4	3	11	5 – 19
Pu/U	0.3					
Th – SS	1.59	12	4	1	9	2 – 15
Th – U235	2.42	30	2	0	7	0 – 12
Th – Pu	2.44	25	2	2	10	3 – 17

* For similar refuelling demand as natural cycle.

** *Relative to natural uranium cycle, Bruce A design.*

TABLE 3
COST ASSUMPTIONS

FABRICATION COST:	
Fuel is Natural Uranium	44$/kg U
Fuel is Enriched Uranium	50$/kg HE
Fuel contains Plutonium	120$/kg HE
Fuel contains U-233	160$/kg HE
REPROCESSING COST:	
Uranium Fuels	187$/kg HE
Thorium Fuels	206$/kg HE
ENRICHMENT COST	100$/S.W.U.
THORIUM COST	44$/kg ThO_2

TABLE 4
ESTIMATED CANADIAN INSTALLED NUCLEAR CAPACITY
(GWe BY YEAR 2000)

PROVINCE	BEST ESTIMATE	RANGE
ONTARIO	31.0	25 – 33
QUEBEC	5.2	3.5 – 6.9
MARITIMES	2.4	1.2 – 4.0
WESTERN PROVINCES	3.0	0 – 8.4
TOTALS	41.6	29.7 – 52.3

TABLE 5
1979 LONG-TERM ESTIMATES OF INSTALLED NUCLEAR CAPACITY IN ONTARIO
(GWe)

YEAR GROWTH	2000	2025	2050	2100
LOW*	25	59	89	25
BASE	31	83	157	175
HIGH*	33	138	337	833

*MAXIMUM CONCEIVABLE LIMITS

TABLE 6
RATIONALE FOR ONTARIO BASE NUCLEAR GROWTH ESTIMATE

- LOAD GROWTH TO 2000 IDENTICAL TO 1978 OH FORECAST
- NUCLEAR GROWTH TO 2000 IDENTICAL TO 1978 OPTION (Z)
- LOAD GROWTH AFTER 2000 BASED ON SLOWLY DECLINING GROWTH RATES OF:
  - POPULATION
  - TOTAL ENERGY DEMAND PER CAPITA
  - ELECTRICITY DEMAND PER CAPITA
  - ELECTRICITY'S PORTION OF TOTAL ENERGY SUPPLY
- *NUCLEAR CAPACITY IS 50% OF TOTAL FROM 2000 TO 2045*
- NUCLEAR CAPACITY REMAINS CONSTANT AT 175 GWe AFTER 2055

FIGURE 1
DESIGN & DEVELOPMENT DIVISION

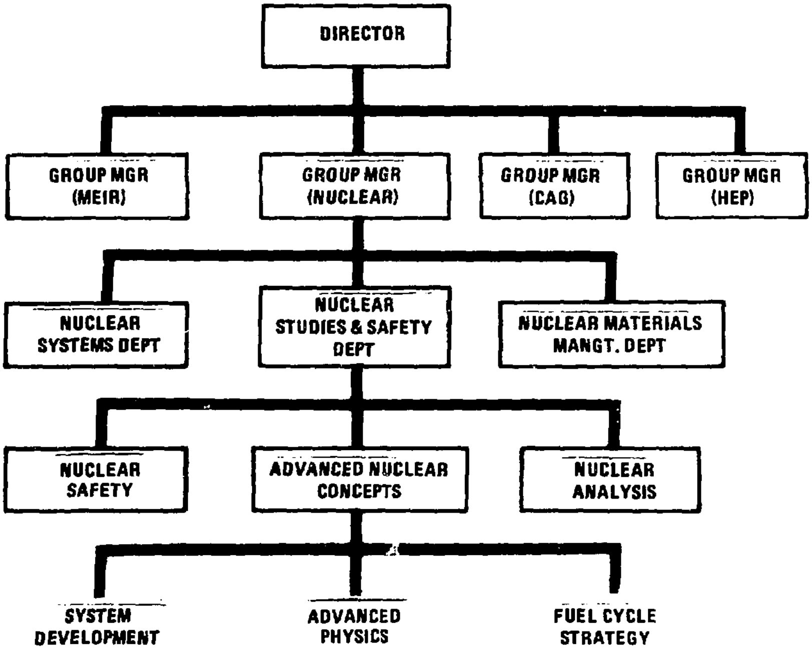


FIGURE 2
NUCLEAR INSTALLED CAPACITY ALTERNATIVES FOR ONTARIO
(PRELIMINARY ASSUMPTIONS)

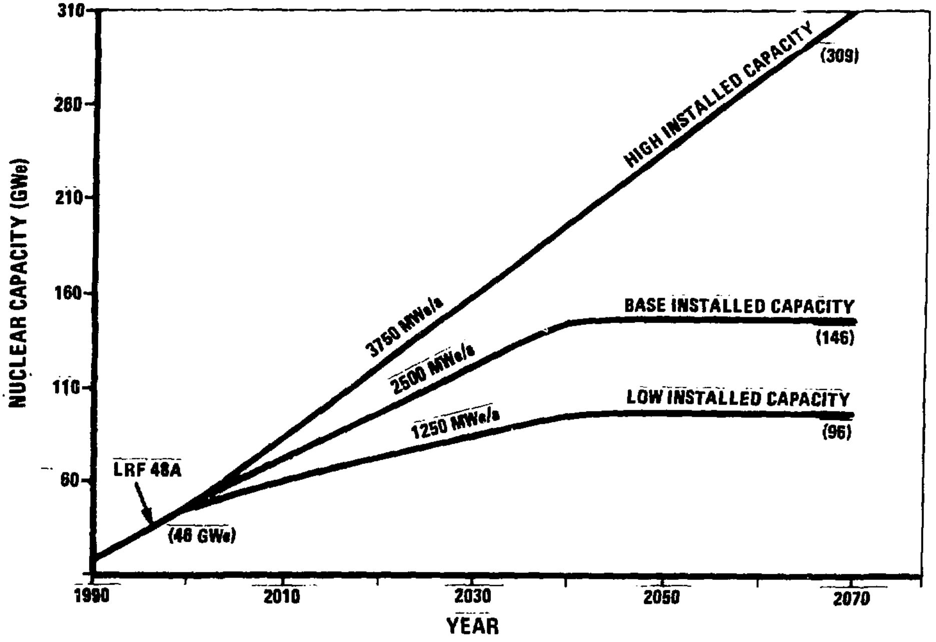


FIGURE 3
CUMULATIVE URANIUM REQUIREMENTS FOR THE BASE CASE POWER DEMAND

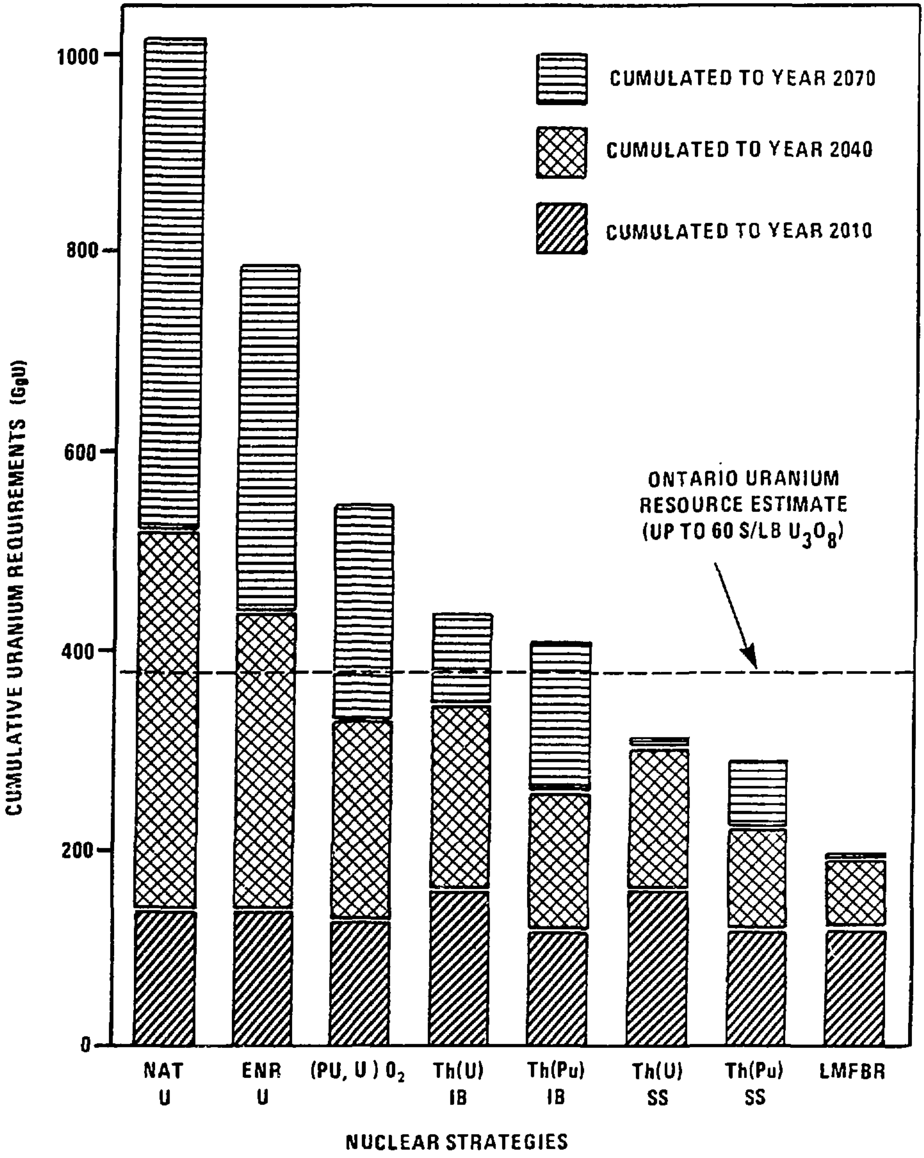


FIGURE 4
URANIUM REQUIREMENTS: SENSITIVITY TO INSTALLED CAPACITY

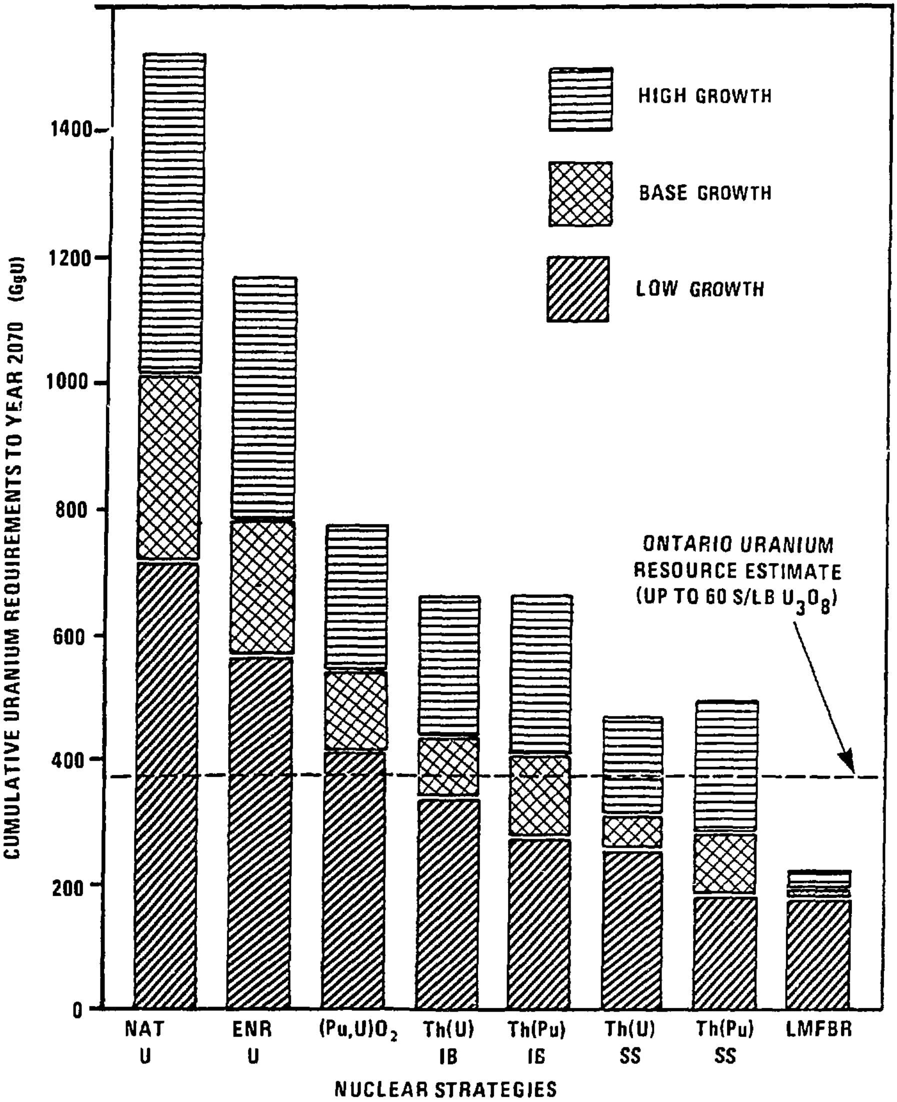


FIGURE 5
ANNUAL URANIUM REQUIREMENT

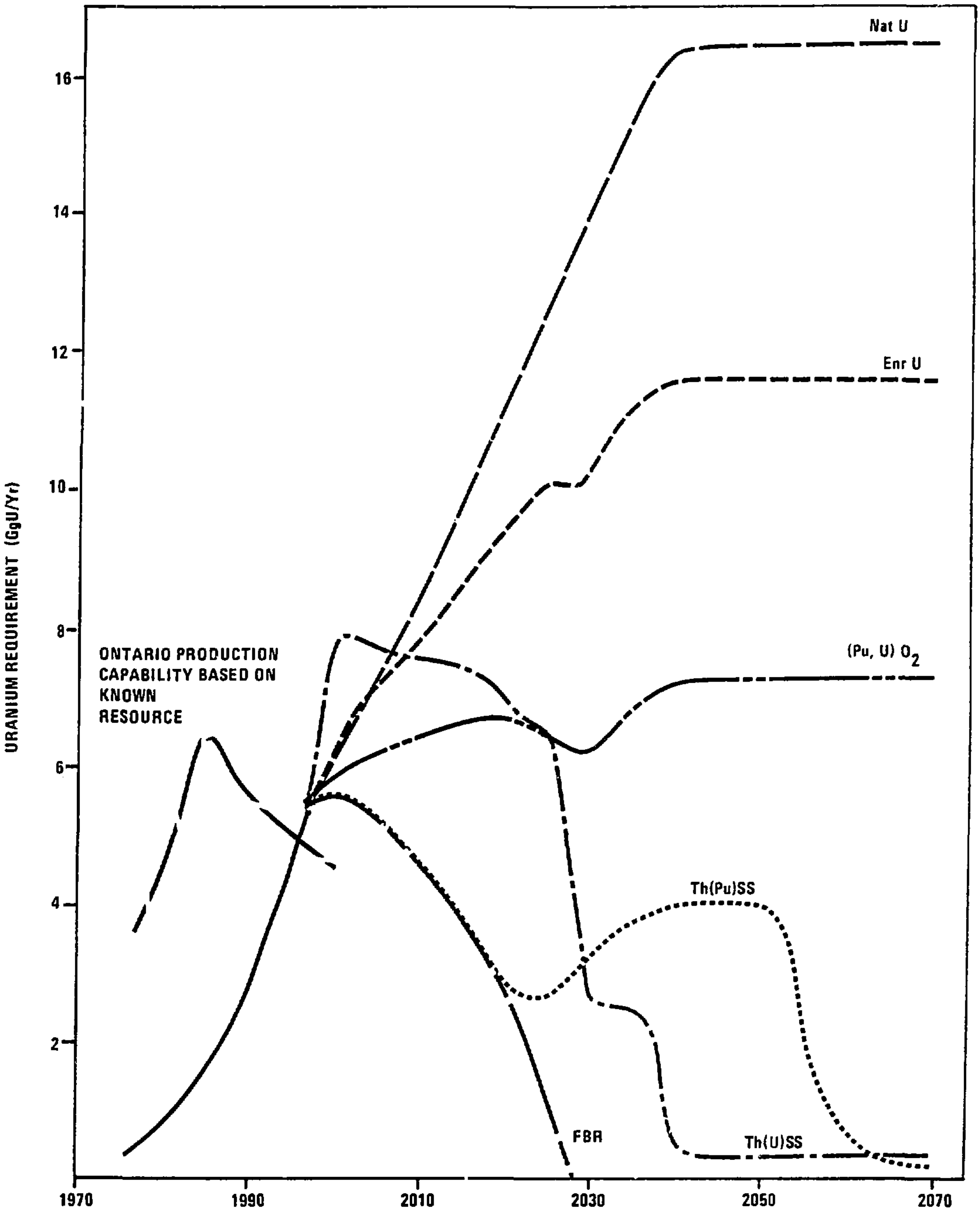
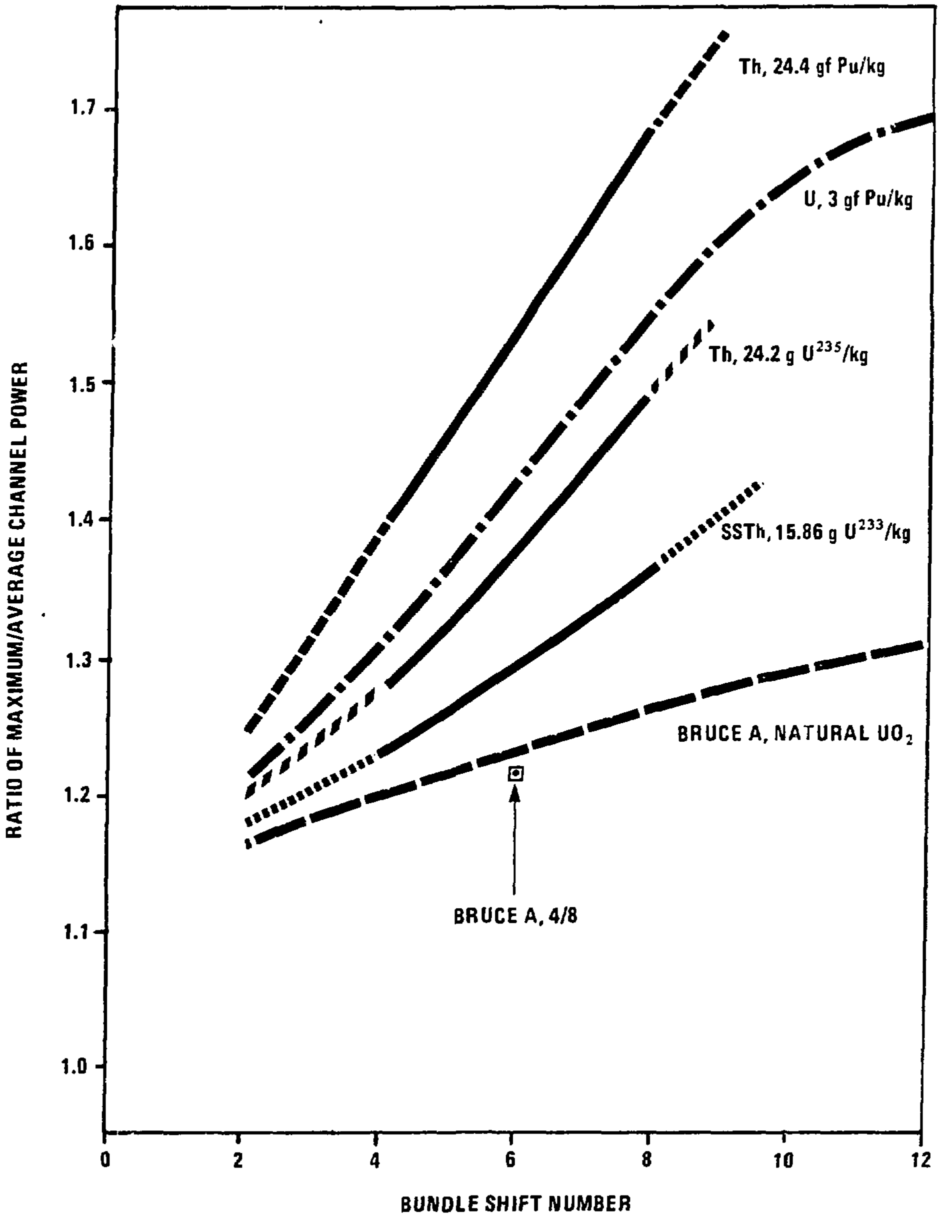


FIGURE 6 CHANNEL POWER PEAKING, A COMPARISON OF ALTERNATE CYCLES



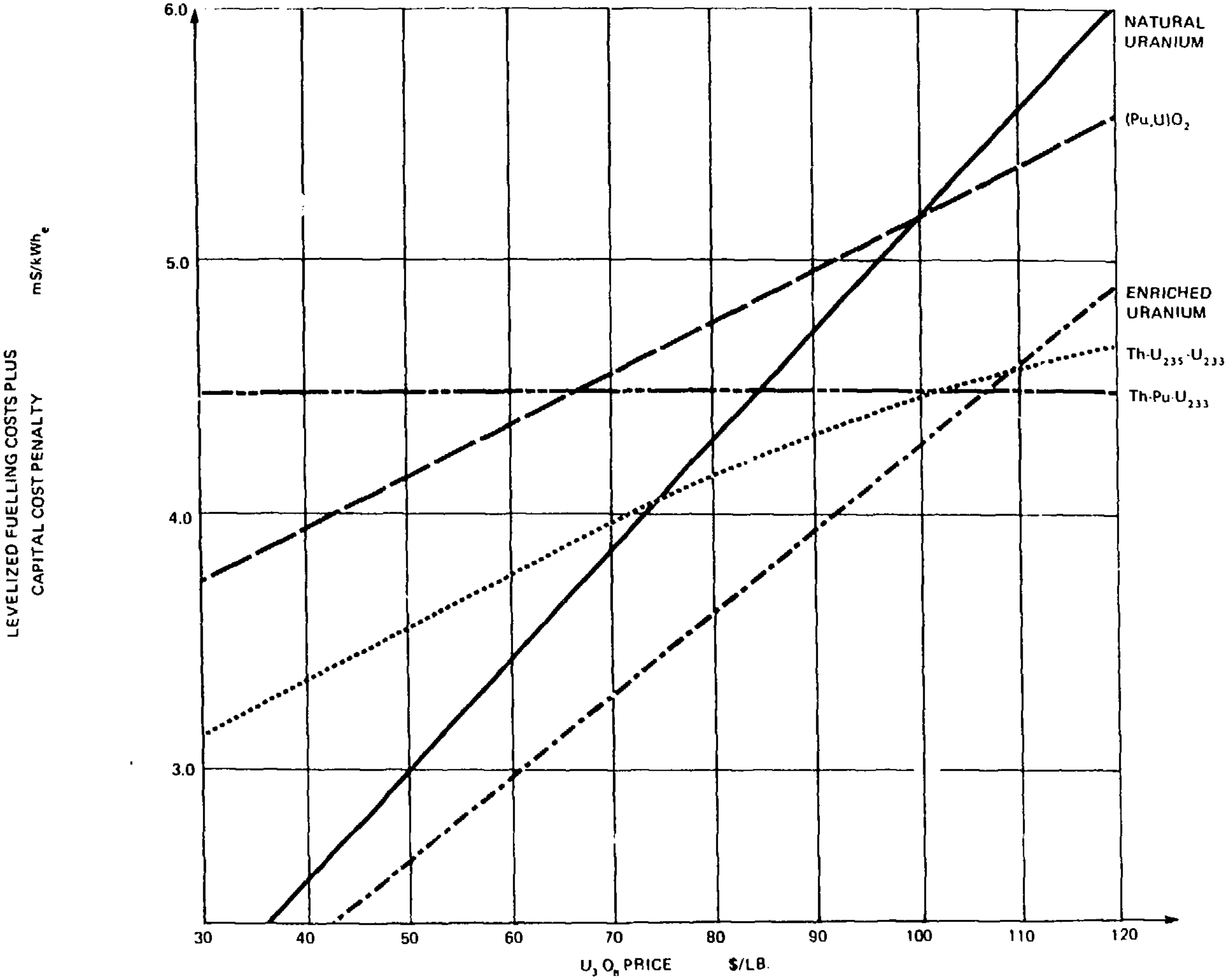


FIGURE 7
FUELLING COSTS PLUS CAPITAL COST PENALTIES FOR ADVANCED FUEL CYCLES

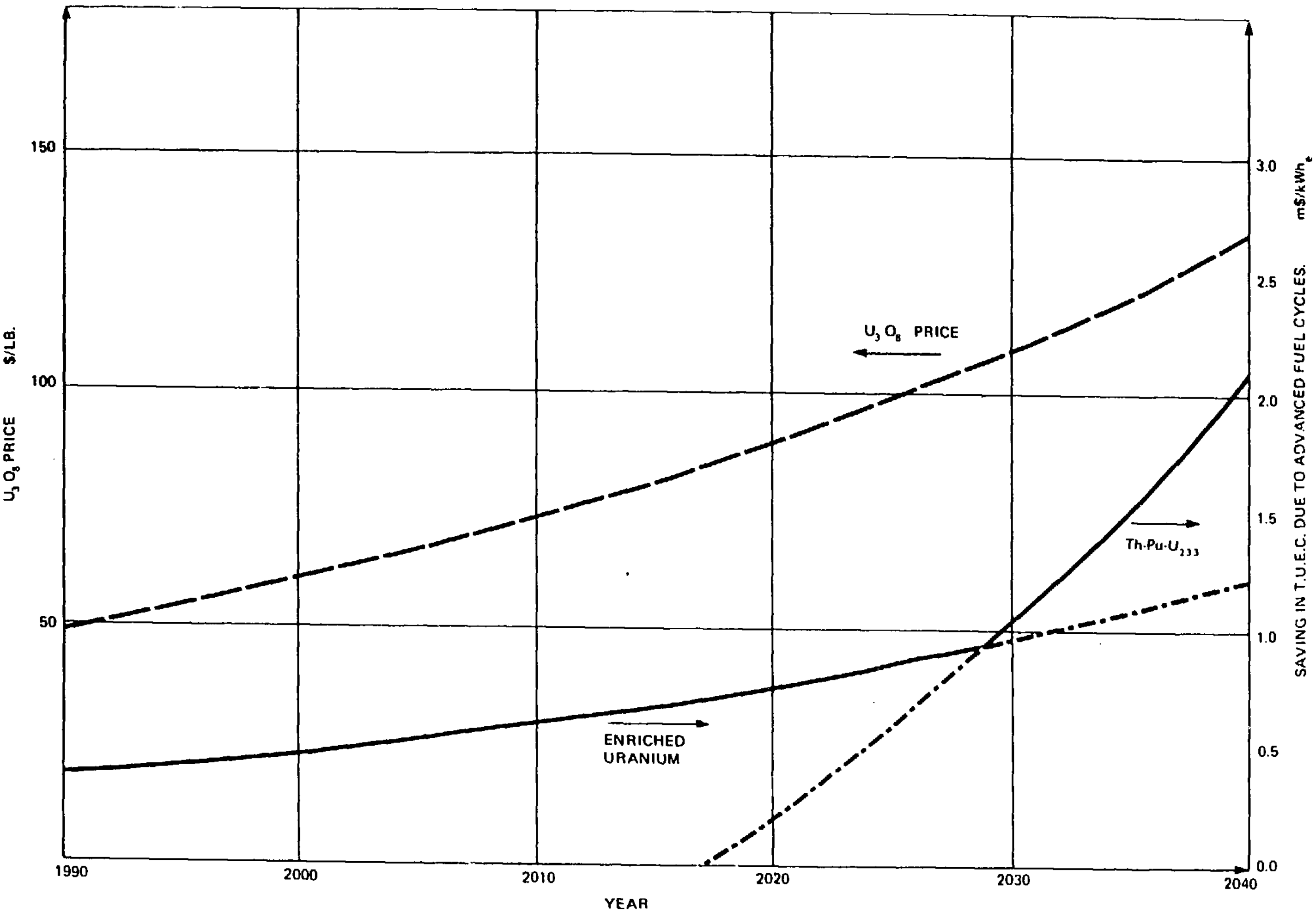


FIGURE 8
SAVINGS IN T.U.E.C. DUE TO ADVANCED FUEL CYCLES

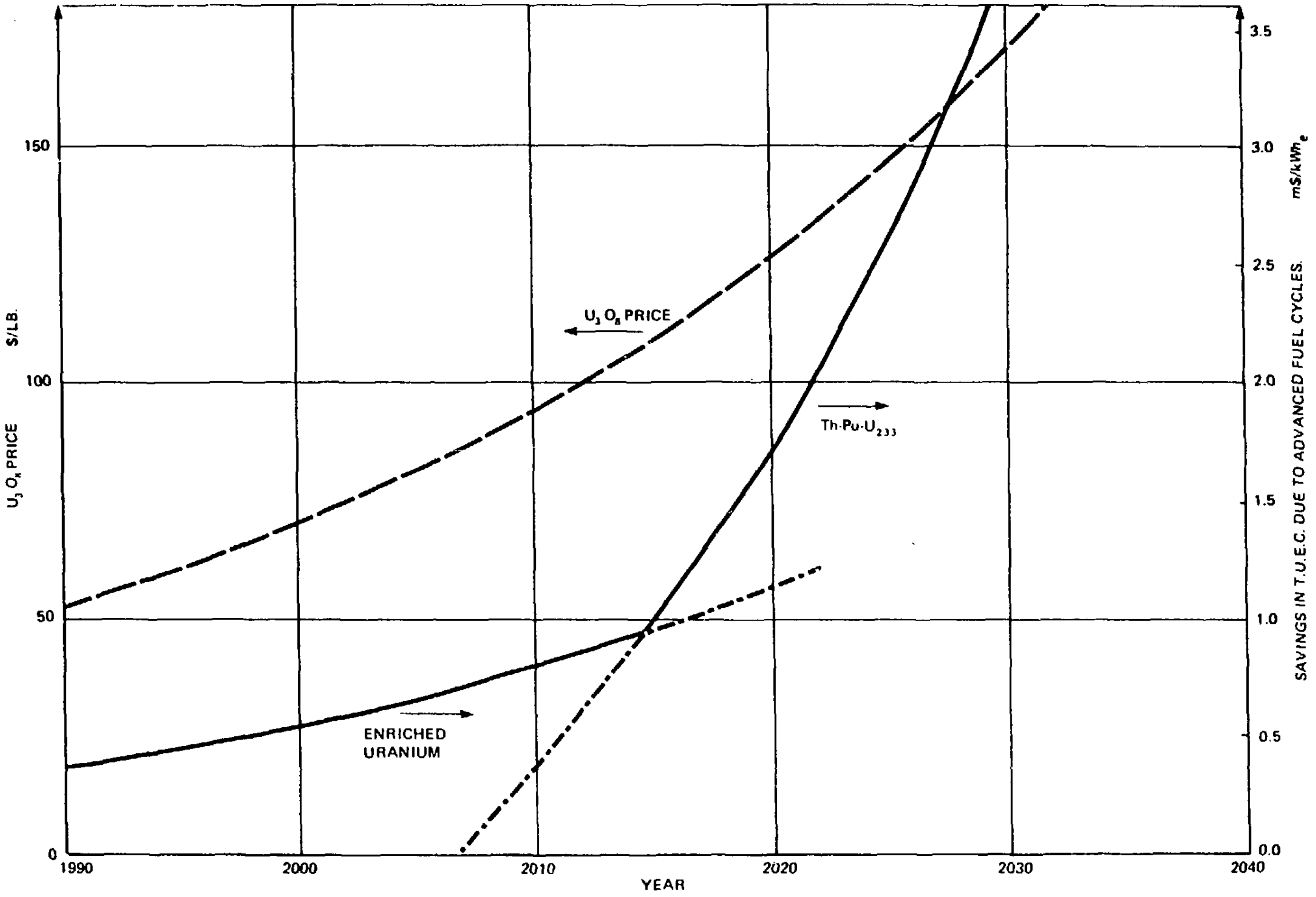


FIGURE 9
SAVINGS IN T.U.E.C. DUE TO ADVANCED FUEL CYCLES

FIGURE 10
CANADA'S 1977 URANIUM RESOURCE (UP TO $160/kgU)

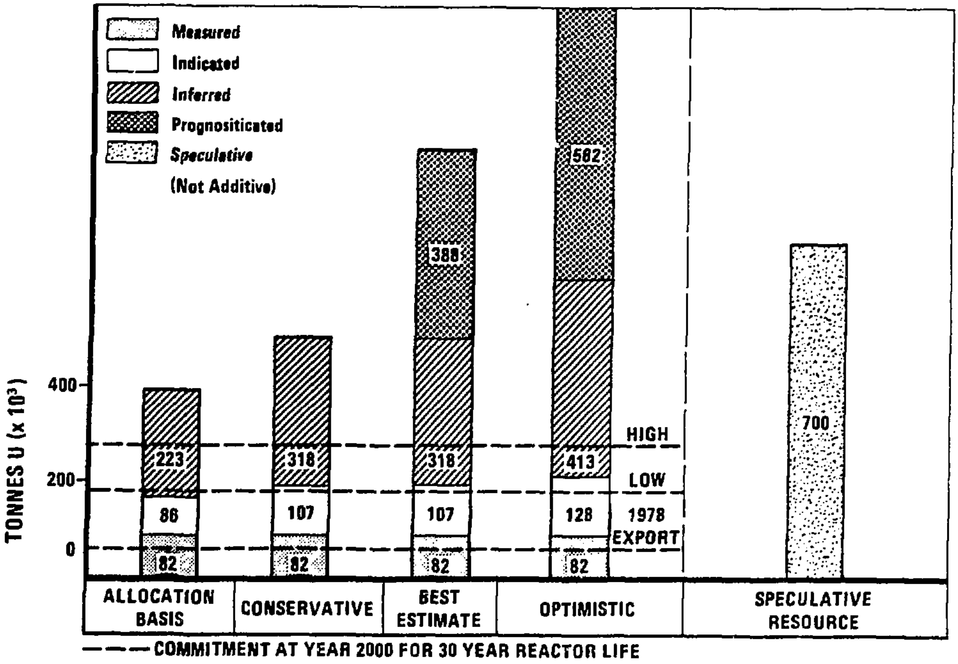


FIGURE 11
URANIUM PRODUCTION REQUIREMENTS AND CAPABILITY FOR CANADA AS OF 1978

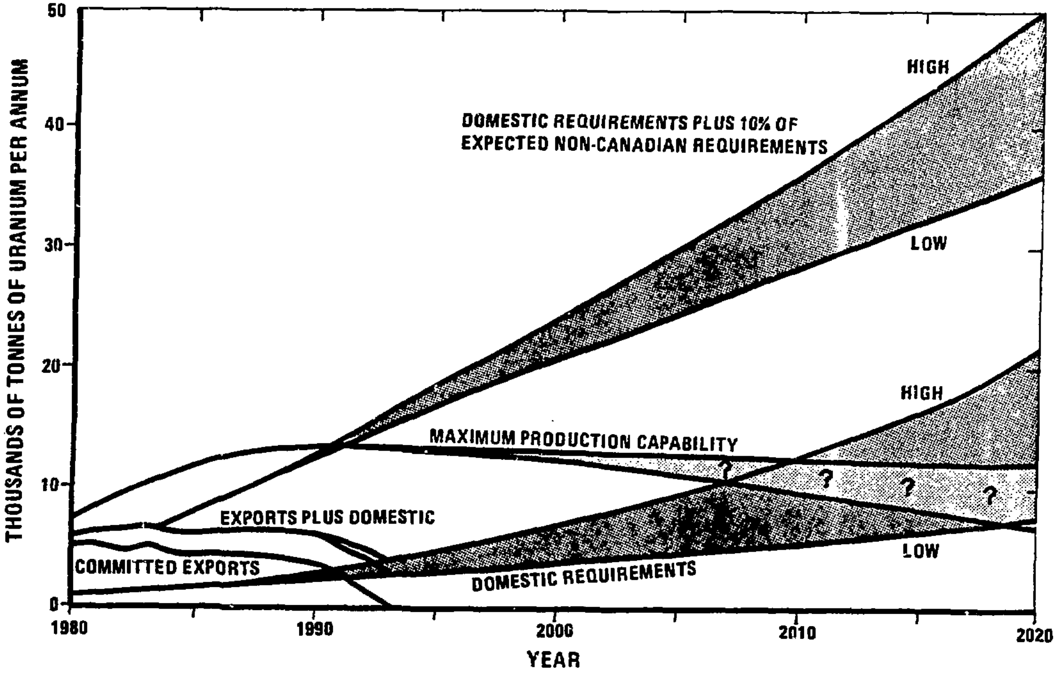


FIGURE 12
CUMULATIVE URANIUM REQUIREMENTS FOR BASE NUCLEAR GROWTH
(3 CYCLE SCENARIOS)

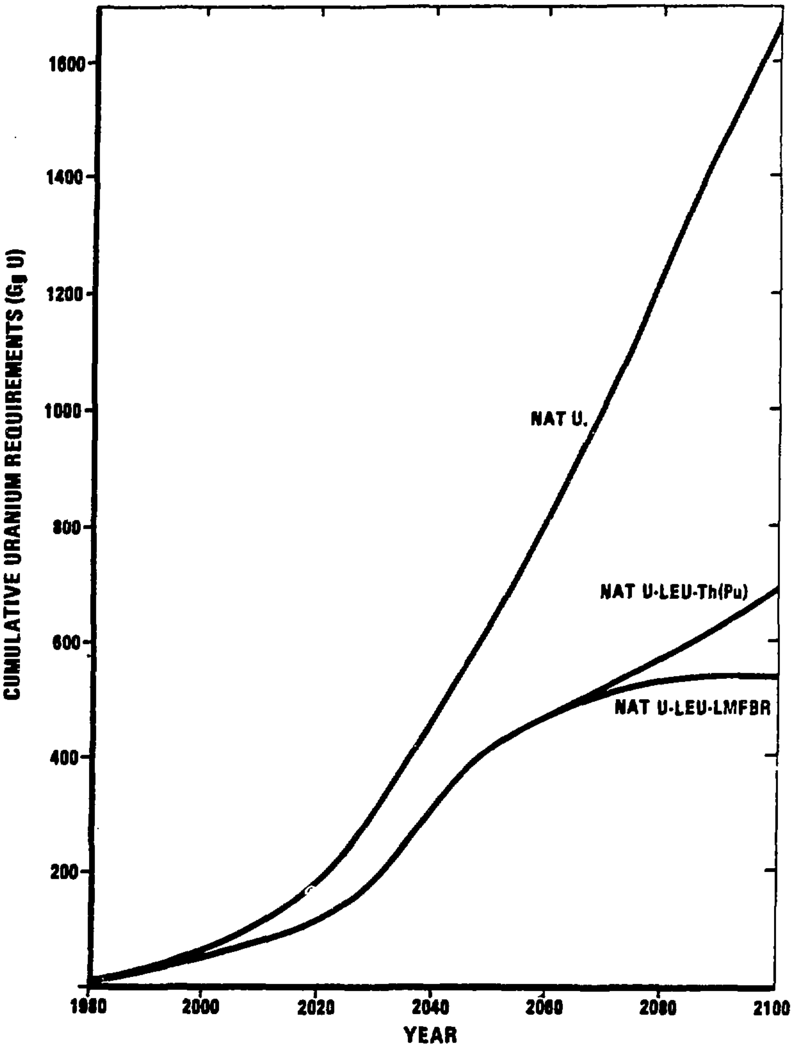


FIGURE 13
ANNUAL URANIUM REQUIREMENTS FOR
BASE NUCLEAR GROWTH
(3 CYCLE SCENARIOS)

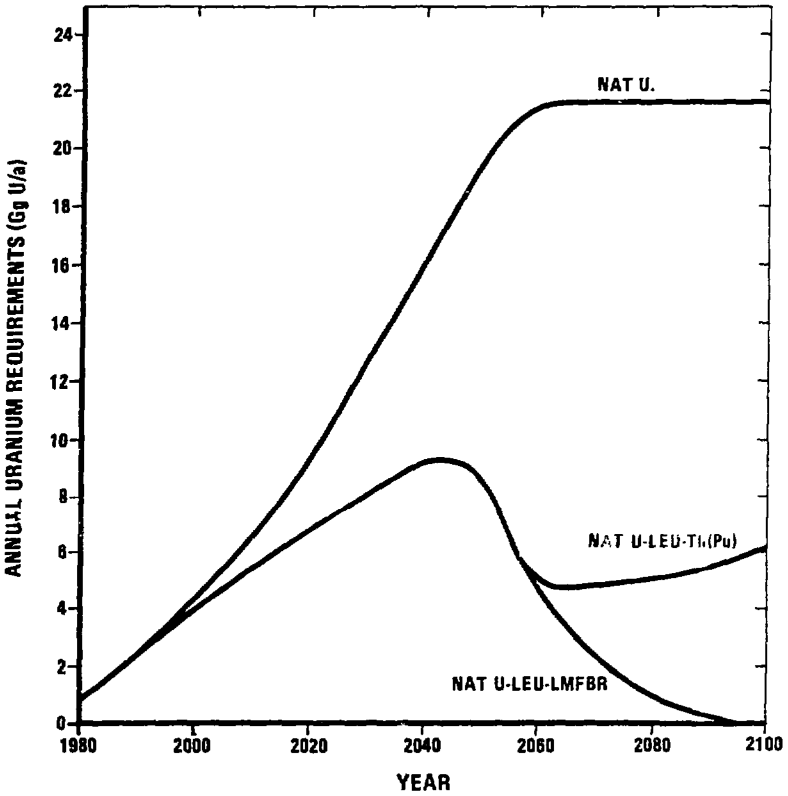


FIGURE 14
COMPARISON OF TWO-CYCLE vs. THREE-CYCLE STRATEGY
– CUMULATIVE URANIUM REQUIREMENTS FOR BASE NUCLEAR GROWTH –

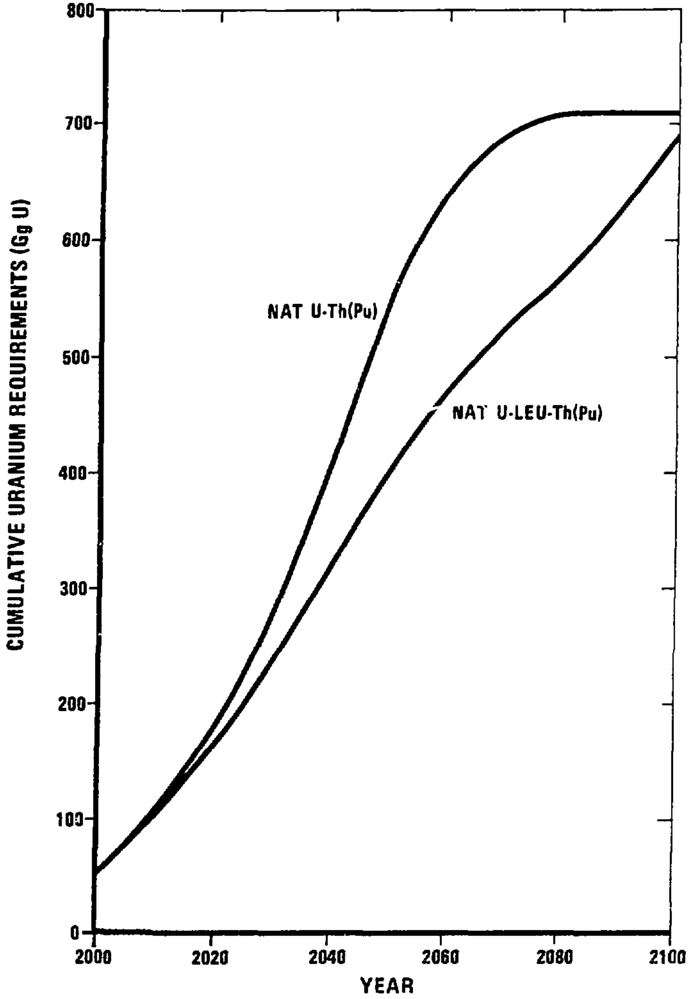


FIGURE 15
COMPARISON OF TWO-CYCLE vs. THREE-CYCLE STRATEGY
– ANNUAL URANIUM REQUIREMENTS FOR BASE NUCLEAR GROWTH –

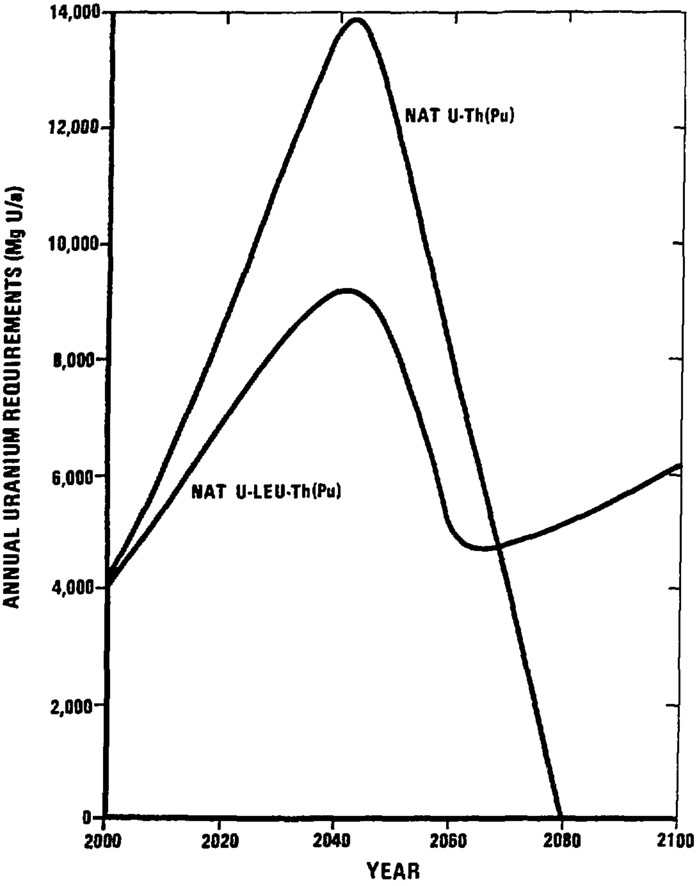


FIGURE 16
URANIUM ENRICHMENT REQUIREMENTS
FOR BASE NUCLEAR GROWTH

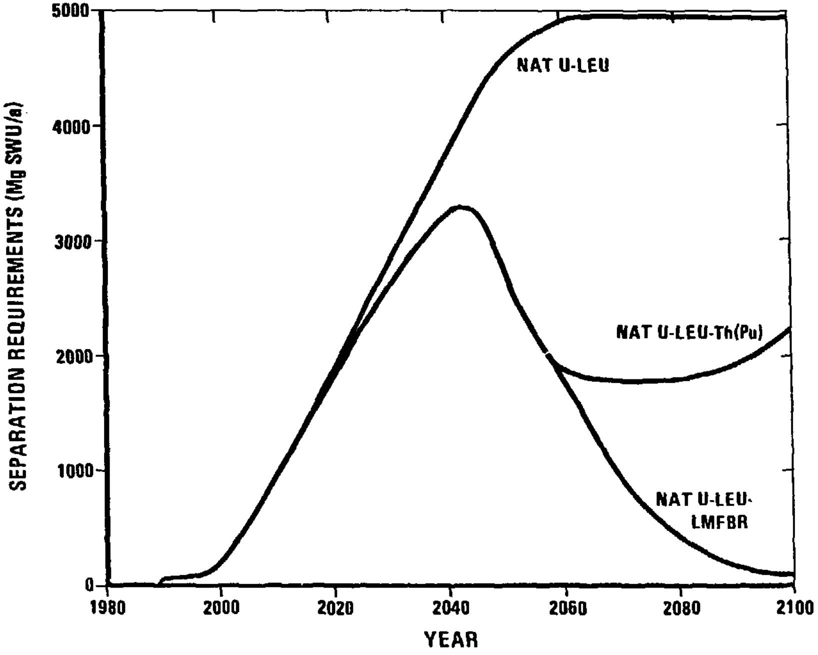


FIGURE 17
FUELLING COSTS FOR ENRICHED URANIUM CYCLES vs ENRICHMENT

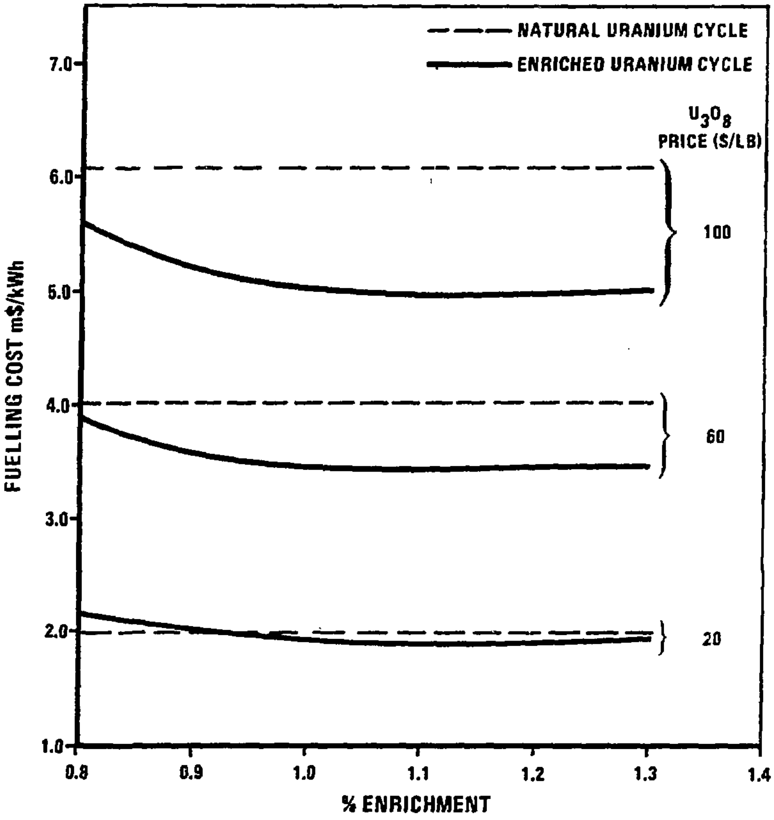


FIGURE 18
ESTIMATED TREND IN AVERAGE U_3O_8 WORLD PRICE
(1978 DOLLARS)