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ADVANCED FUEL CYCLES: A RATIONALE AND STRATEGY FOR ADOPTING THE LOW-ENRICHED-URANIUM FUEL CYCLE

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PREFACE

This report contains the text of a presentation to senior Ontario Hydro management on the results of a study of, "Advanced Fuel Cycles".

The first phase of the study was a preliminary review of the economics of a wide range of possible future fuel cycles. This review identified the most promising cycles and the most important parameters in the economic analysis. These key parameters included uranium price, fuel fabrication and reprocessing costs, and nuclear growth rates.

The next phase of the study was to thoroughly research each of these parameters, refine our earlier assumptions, and document the results. In parallel with these studies, we performed a detailed investigation of probable future uranium production capacity and ultimately recoverable uranium resources. The resulting data base set the scene for a comprehensive and sophisticated strategy analysis of future nuclear development in Ontario. This analysis addressed both resource utilization and economics. A technical report describing that strategy analysis has been published by G.H. Archinoff.* Archinoff's report provides more detail on how the study was conducted and references the extensive documentation produced as the study progressed.

This report is an executive over-view of the whole study. It briefly describes the possible advanced cycles. It also discusses each of the selection criteria for choosing a cycle for development, namely, resource utilization, economics, ease of implementation, and social acceptability. Finally, this report documents the results, conclusions and recommendations. The major recommendation is that a detailed study should be conducted with a view to the early implementation of the low-enriched-uranium fuel cycle.

As a summary document, this report draws on the efforts of many people. The study was under the outstanding leadership of W.J. Penn and, in its final stages, of Dr. R.A. Brown. The study was conducted by G.H. Archinoff, C. Blahnik, R.A. Bonalumi, C. Gordon, B.M. Guthrie, J.H.K. Lau, and myself.

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* G.H. Archinoff, "Future Fuel Cycles: A Resource Utilization and Economic Assessment," Report No. 80007, dated January, 1980.

Advanced Fuel Cycles:
A Rationale and Strategy for Adopting the
Low-Enriched-Uranium Fuel Cycle

1. INTRODUCTION

A study was initiated two years ago to review alternatives to the natural uranium fuel cycle. There were two questions which prompted the study:

(1) Are there sufficient uranium resources to ensure the long-term viability of Ontario Hydro's nuclear power program based on the natural uranium fuel cycle?

(2) Will advanced nuclear fuel cycles improve the economic competitiveness of nuclear power, particularly in the event uranium becomes increasingly expensive?

The uranium resource situation, and the potential costs and benefits of adopting a wide selection of advanced fuel cycles in the CANDU reactor, have now been investigated. The important conclusions, and resultant recommendations, which have emerged from this study are the subject of this presentation.

2. CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

(1) The uranium resource situation, from Ontario Hydro's point of view, is sound. The adoption of a fuel cycle which uses uranium more efficiently is desirable, but not essential. To justify the adoption of an advanced fuel cycle, there must be substantial economic incentives, as well as resource savings.

(2) The adoption of the low-enriched-uranium fuel cycle would significantly reduce future uranium requirements and result in substantial economic savings.

The annual uranium savings for a given reactor are approximately 34%. If (as assumed here) only new stations adopt the low-enriched-uranium cycle, the cumulative savings for the whole nuclear system, by the year 2030, would be about 18%. This means a reduction of between 40,000 and 60,000 tonnes in cumulative uranium requirements, depending on the nuclear growth rate.

The financial savings to the year 2030, would be between $1,200,000,000 and $2,600,000,000. These values are in 1980 dollars, present worthed to 1980. The savings represent 14% to 20% of Ontario Hydro's total expenditures on the nuclear fuel cycle, to the year 2030.

(3) The development costs for the low-enriched-uranium fuel cycle are small, the assurance of success is high, and the benefits are substantial.

2.2 Recommendations

(1) It is recommended that Ontario Hydro undertake a detailed study with the objective of committing an alternative replacement fuel management scheme, based on low-enriched-uranium fuel, for Bruce NGS B.

(2) It is recommended that the use of low-enriched-uranium fuel be made an option for the nuclear alternatives for the E15 station.

3. ASSESSMENT OF ADVANCED FUEL CYCLES

3.1 Advanced Fuel Cycle Options

Possible fuel cycles are:

(1) Natural Uranium (continuation of present fuel cycle)

(2) Low Enriched Uranium

(3) Plutonium Recycle

(4) Thorium Cycles with plutonium addition

(5) Thorium Cycles with uranium-235 addition

(6) Thorium Cycles that are self-sustaining (near-breeders)

The low-enriched-uranium cycle is a once-through fuel cycle. However, prior to fuel fabrication the uranium feed is enriched in the isotope uranium-235, from its natural concentration of 0.711% to between 1.0% and 1.2%. (We talk of "low" enrichment to contrast with light-water-reactor fuel which is typically enriched to between 2.0% and 3.5% uranium-235.) The enrichment increases the achievable fuel burn-up by a factor of between 2 and 3. This benefit is achieved at the expense of the enrichment charge and the loss of use of the enrichment-plant tails (that is, the uranium depleted in uranium-235). It will be seen later, that this fuel cycle provides a net benefit in both resource and economic terms.

Plutonium recycle involves adding fissile plutonium to the natural uranium feed, rather than increasing its uranium-235 concentration. Plutonium is not a naturally-occurring element, so the increased fuel burn-up is achieved at the expense of having to reprocess irradiated fuel, to retrieve the plutonium created in the reactor.

Thorium is not a fissile material. All thorium fuel cycles must be initiated by the addition of fissile material to the first load of fuel. The fissile material can be either highly-enriched uranium (that is, uranium containing approximately 93% uranium-235), or plutonium which has been obtained from reprocessing uranium fuel. The thorium fuel is reprocessed and the fissile isotope, uranium-233, is recovered. This isotope is recycled in new thorium fuel. The achievable burn-up in this fuel may be enhanced by the addition of plutonium, or of highly-enriched uranium. (This additional fissile material is often called "topping".) A cycle which requires no fissile addition is theoretically achievable. After the initial load of thorium fuel, sufficient fissile material is recovered from the irradiated fuel to enrich an identical quantity of new fuel. Hence the cycle is called, "self-sustaining." This cycle results in a low fuel burnup, and hence frequent reprocessing of the fuel. It is possible that the cycle will not be sustainable in practice and, in any case, it is economically far less attractive than the other thorium cycles. We do not, therefore, discuss the self-sustaining thorium cycle in the remainder of this presentation.

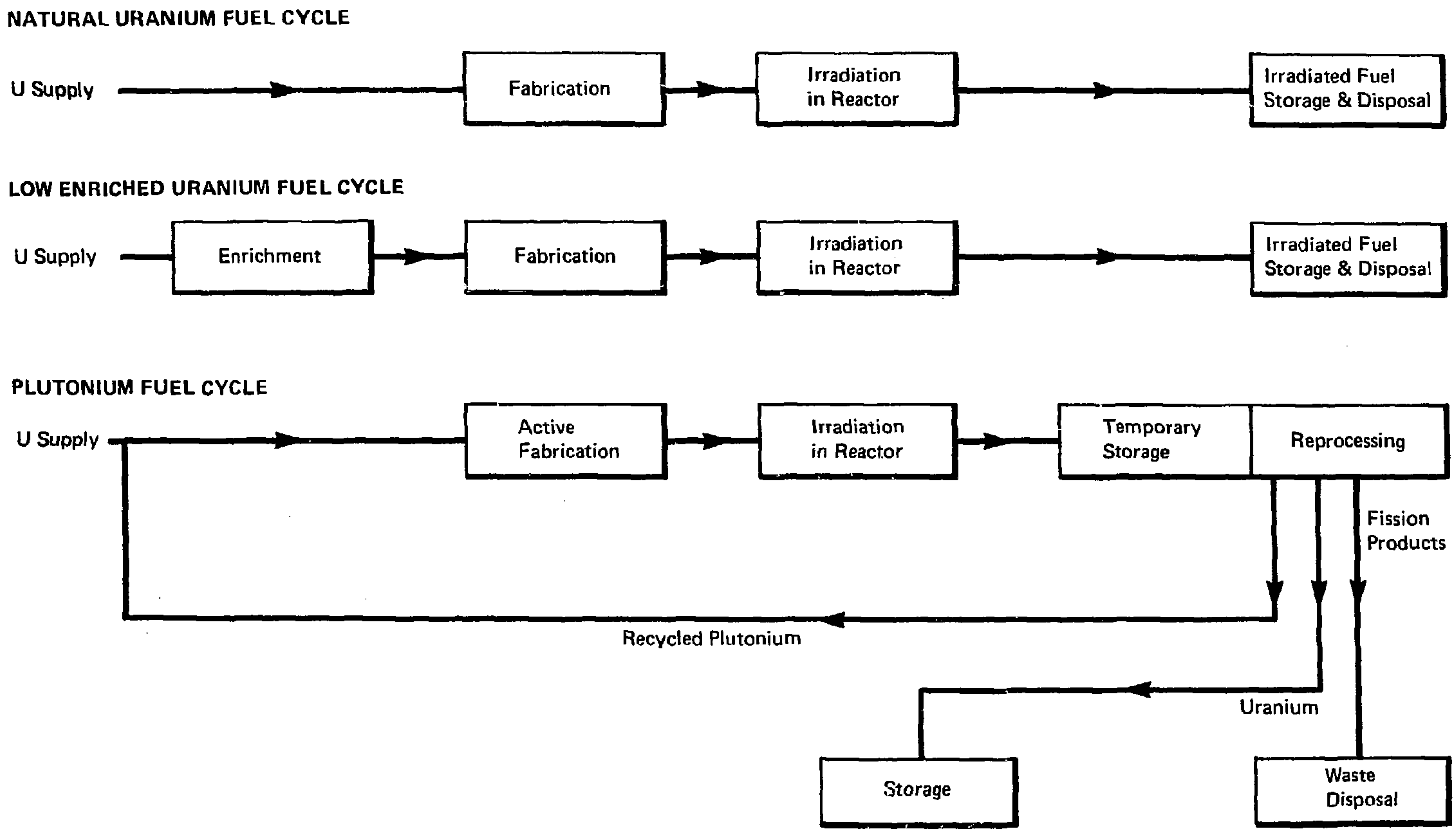
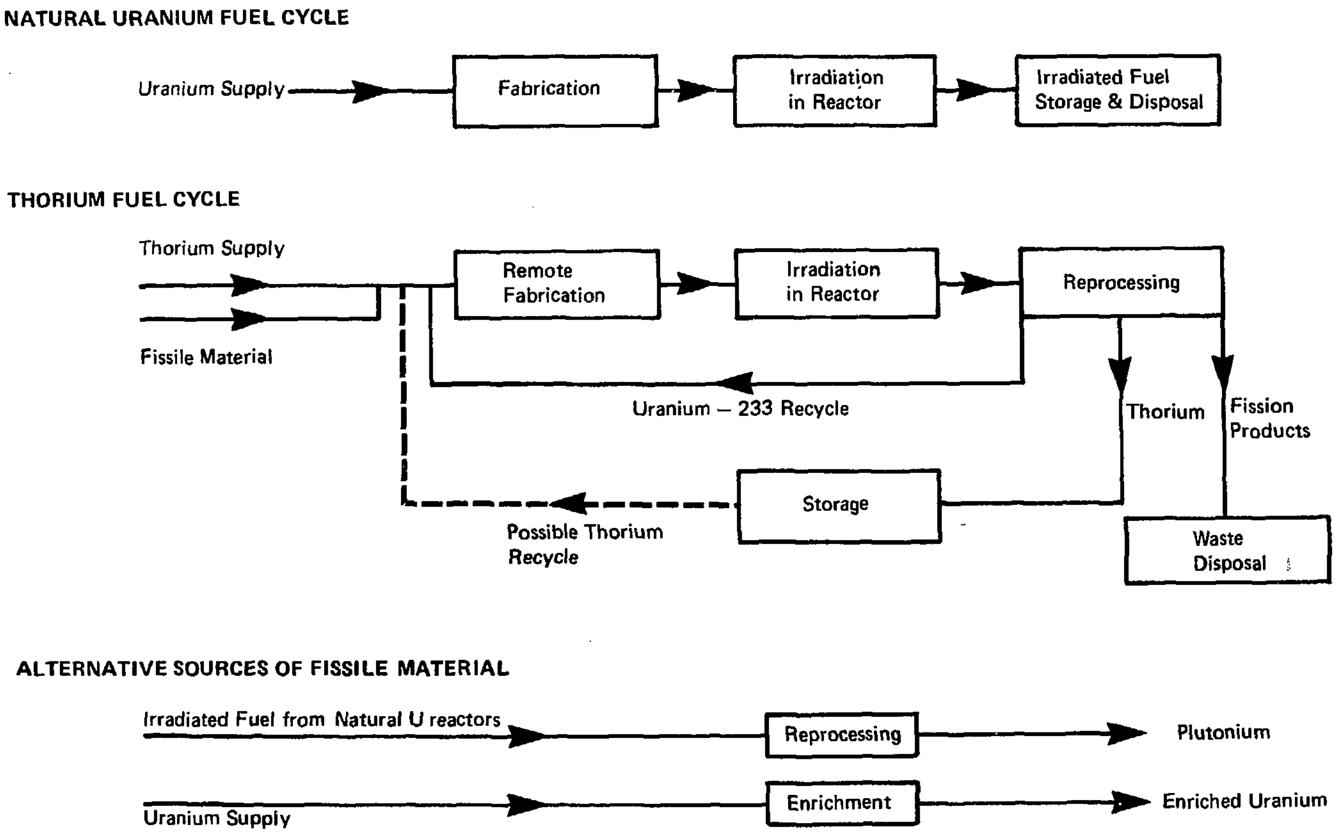


FIGURE 3.1-1

SCHEMATIC DIAGRAM OF NATURAL URANIUM, LOW ENRICHED URANIUM AND PLUTONIUM FUEL CYCLES

FIGURE 3.1-2
SCHEMATIC DIAGRAM OF NATURAL URANIUM & THORIUM FUEL CYCLES



3.2 Selection Criteria

Major criteria for assessing fuel cycles are:

(1) Resource Conservation

(2) Economics

(3) Ease of Implementation

(4) Social Acceptability

3.3 Comparison of Options

3.3.1 Resource Conservation

The critical resource for nuclear power production is uranium. For many years AECL's R&D on thorium cycles has been justified as insurance against uranium shortfalls, or very high uranium prices. As the uranium position has improved, the resource criterion has decreased in importance, and fuel cycles which are less conserving than thorium have attracted increasing attention.

The resource position must be examined from a resource base and a production capability point of view.

Resource Base

The resource position is illustrated in Figures 3.3-1 and 3.3-2. Figure 3.3-2 shows Ontario's estimated future uranium requirements.

The resource base over the last 4 years has been increasing at an annual rate of between 5 and 14%/annum.

Exploration is now at a higher rate in terms of dollar expenditures, and feet drilled, than it has ever been. There is, therefore, every expectation that the resource base will continue to expand.

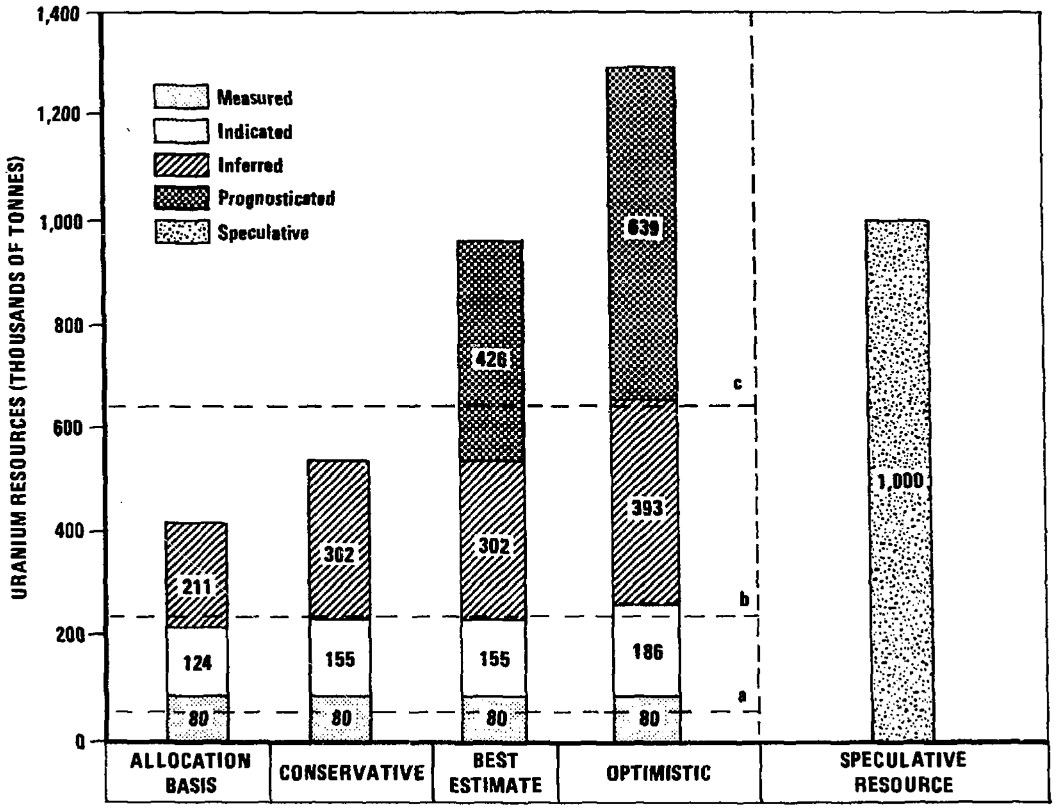
The reserve position is at least as good as many other essential commodities.

Production Capability

The Production Capability shown in Figure 3.3-3 is based only on known resources.

Exploration is currently at a high level, increasing both the known resources and the production capability.

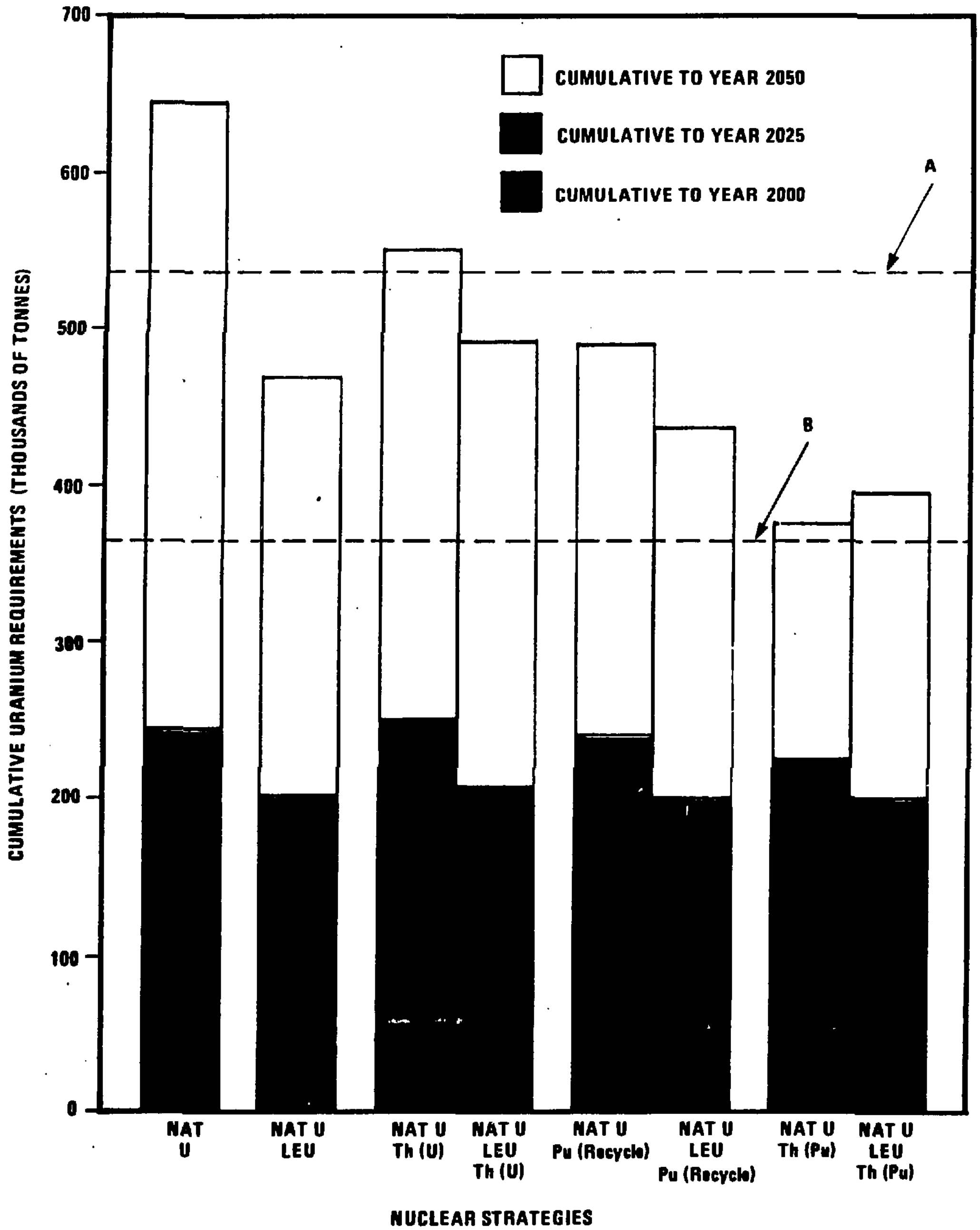
FIGURE 3.3-1
CANADA'S 1978 URANIUM RESOURCES (UP TO $175/kg U)



a, b, c: URANIUM REQUIREMENT UP TO THE YEARS 2000, 2025, AND 2050 RESPECTIVELY, FOR A NATURAL URANIUM, BASE GROWTH SCENARIO.

FIGURE 3.3-2

CUMULATIVE URANIUM REQUIREMENTS FOR BASE CASE INSTALLED CAPACITY



A – CANADIAN CONSERVATIVE URANIUM RESOURCE ESTIMATE (UP TO $175/KgU)

B – ONTARIO CONSERVATIVE URANIUM RESOURCE ESTIMATE (UP TO $175/KgU)

The production capability will only be achieved if the development of new uranium mines and mills proceeds without undue delays. This will occur if the potential producers can sign commercially attractive contracts for their uranium product.

The Federal Government policy is to assure uranium supplies for the domestic market, before allowing exports.

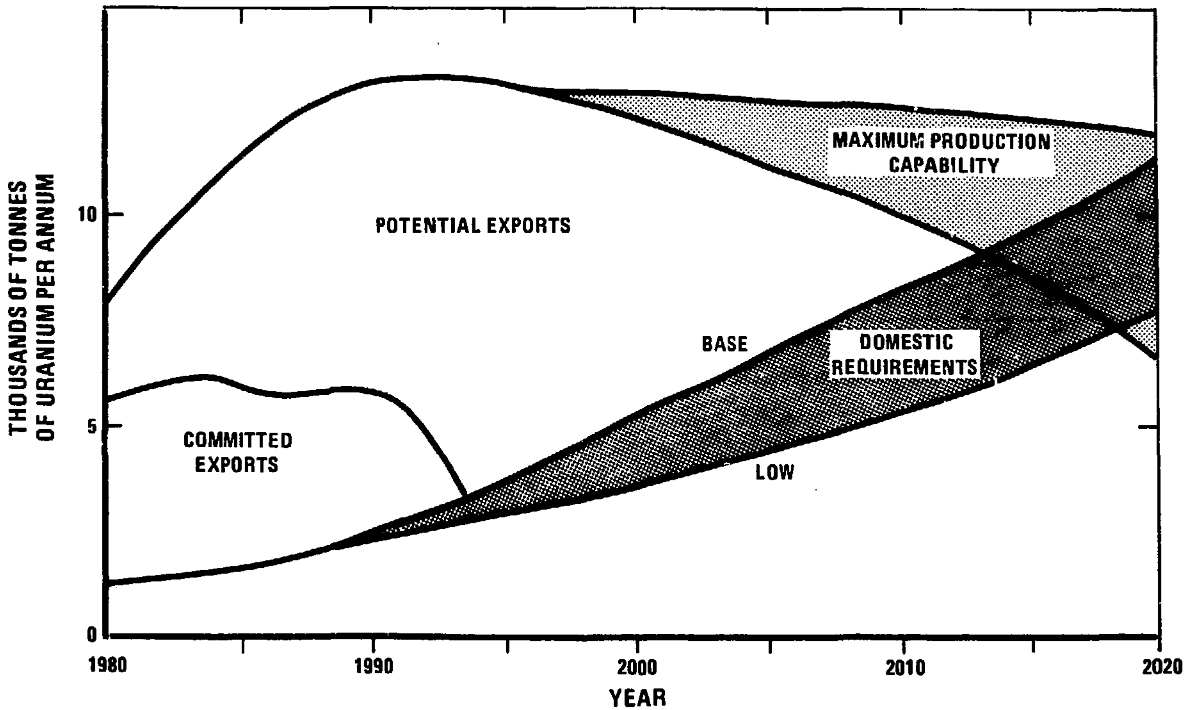
Present Ontario Hydro contracts provide for the bulk of the uranium requirements for the committed nuclear program. There is every indication more uranium can be secured as further nuclear installations are committed.

Conclusion

The resource base and the production capability situation lead us to the same conclusion.

A reduction in uranium requirements, for a given electrical output, is desirable. Nevertheless, the immediate development by Ontario Hydro of advanced fuel cycles cannot be justified solely on the basis of improving resource utilization. There must also be a significant economic incentive.

FIGURE 3.3-3
URANIUM PRODUCTION REQUIREMENTS AND CAPABILITY FOR CANADA AS OF 1978



3.3.2 Economics

In view of the satisfactory uranium situation, economics is the major criterion for evaluating the merits of research and development of advanced fuel cycles.

All the significant parameters were thoroughly analysed prior to conducting the economic study. These parameters include:

Nuclear Growth Rate
Uranium Price
Thorium Price
Uranium Enrichment Cost
Fuel Fabrication Cost
Fuel Reprocessing Cost

Low-Enriched-Uranium Fuel Cycle Costs

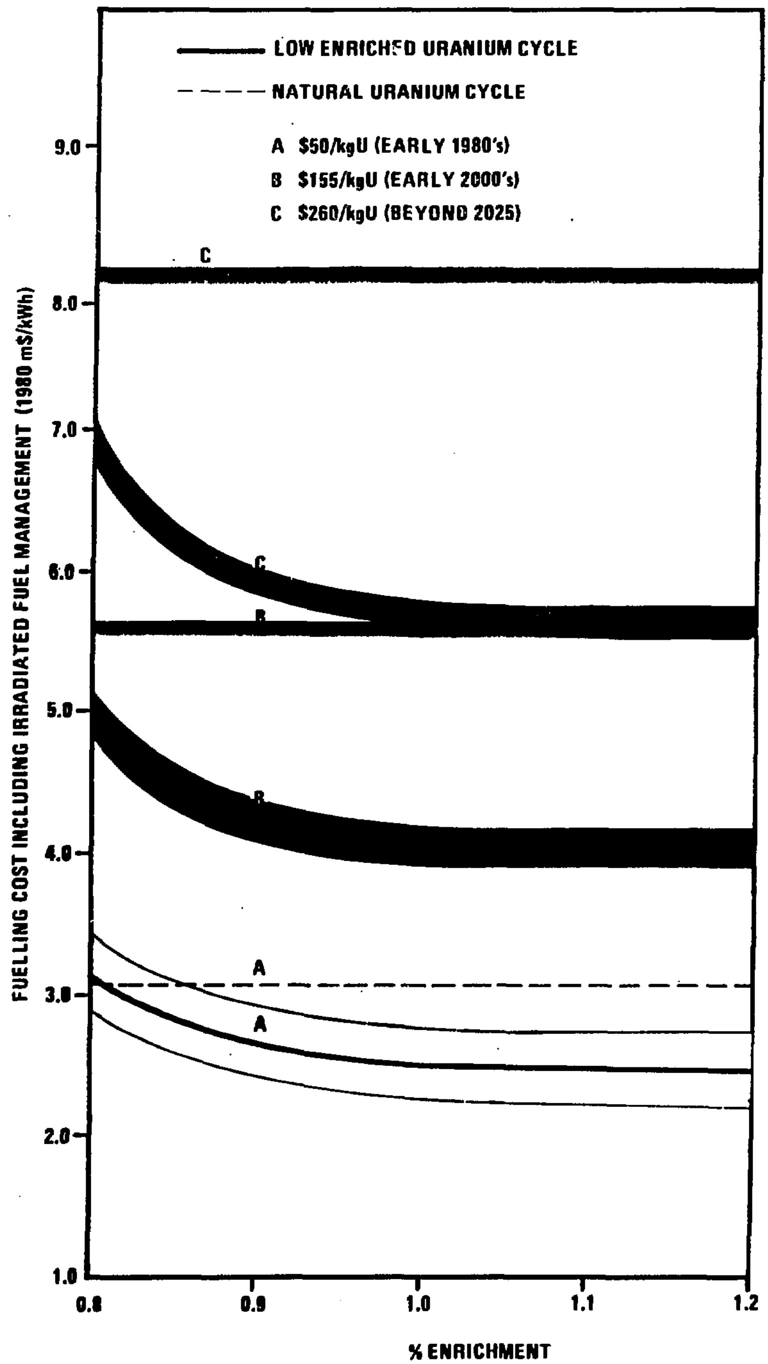
Figure 3.3-4 shows the low-enriched-uranium fuel cycle costs as a function of enrichment level, and also compares the costs to those of the natural-uranium fuel cycle.

An enrichment of 1.0% uranium-235 achieves very close to the maximum fuel savings. Above enrichments of 1.0% uranium-235, channel power peaking may necessitate a lower reactor specific power than in our present reactors. This would lead to a small increase in capital costs. The enrichment for minimum total unit energy cost is, therefore, close to 1.0% uranium-235.

The present average delivered price of uranium to Ontario Hydro is approximately 50$/kg. The present spot-price on the world market is approximately 110$/kg. There is expected to be some stability in uranium prices for the next few years, but then further price increases in real terms. It is also expected that, when new contracts come into effect in the late-1980's and beyond, the cost of uranium to Ontario Hydro will approach world-market levels. The expectation of uranium prices to Ontario Hydro of 155$/kg early in the next century is, therefore, reasonable. A return to prices of 50$/kg is extremely unlikely.

If the low-enriched-uranium fuel cycle is incorporated into the Darlington GS B design, and if that design was chosen for the E15 station, the economic savings for that one station would be between $600,000,000 and $680,000,000, depending on the precise movement of uranium prices. (The dollar values are in 1980 dollars, present worthed to 1994.) Those savings are equivalent to an 8.2% to 8.6% reduction in total unit energy cost.

FIGURE 3.3-4
FUELLING COSTS FOR ENRICHED URANIUM
CYCLES VS. ENRICHMENT



If there is a ten year delay in introducing the low-enriched-uranium fuel cycle, the savings will be significantly reduced.

Table 3.3-1

Economic Savings to the Year 2030 Due to the Low-Enriched-Uranium Fuel Cycle

	Economic Savings	
	Low Growth	Base Growth
Early Implementation	$1,200,000,000	$2,600,000,000
Ten Year Delay	$ 460,000,000	$1,200,000,000

Note: 1980 dollars, present worthed to 1980.

Advanced Fuel Cycle Costs

Figures 3.3-5 and 3.3-6 show the total unit energy costs for the entire Ontario Hydro nuclear system, for various strategies utilizing advanced fuel cycles. Only the most economically attractive of the thorium cycles are illustrated.

The strategies including low-enriched-uranium-fuelled stations assume that that cycle will be first introduced in 1994, and that beyond 2000 no further natural-uranium stations will be built. The more advanced cycles supplant the low-enriched-uranium cycle in 2025. For the strategies which do not include the low-enriched-uranium cycle, all nuclear stations built prior to 2010 operate on the natural-uranium cycle. Beginning in 2010, the more advanced cycles are introduced.

The costs for the fuel cycles involving reprocessing and active fabrication are highly dependent on:

1) Nuclear Growth Rate
2) Fuel Throughput
3) Maturity of the New Industries

The derivation of Figures 3.3-5 and 3.3-6 took the above factors into account by using a dynamic simulation of the nuclear generation system.

Figure 3.3-7 shows the cumulative dollar savings, as compared to using only natural-uranium-fuelled reactors, for each of the advanced-fuel-cycle options. (Fuel cycle introduction dates are as in Figures 3.3-5 and 3.3-6 above.)

FIGURE 3.3-5
TOTAL UNIT ENERGY COSTS FOR
ADVANCED FUEL CYCLE STRATEGIES
(BASE GROWTH)

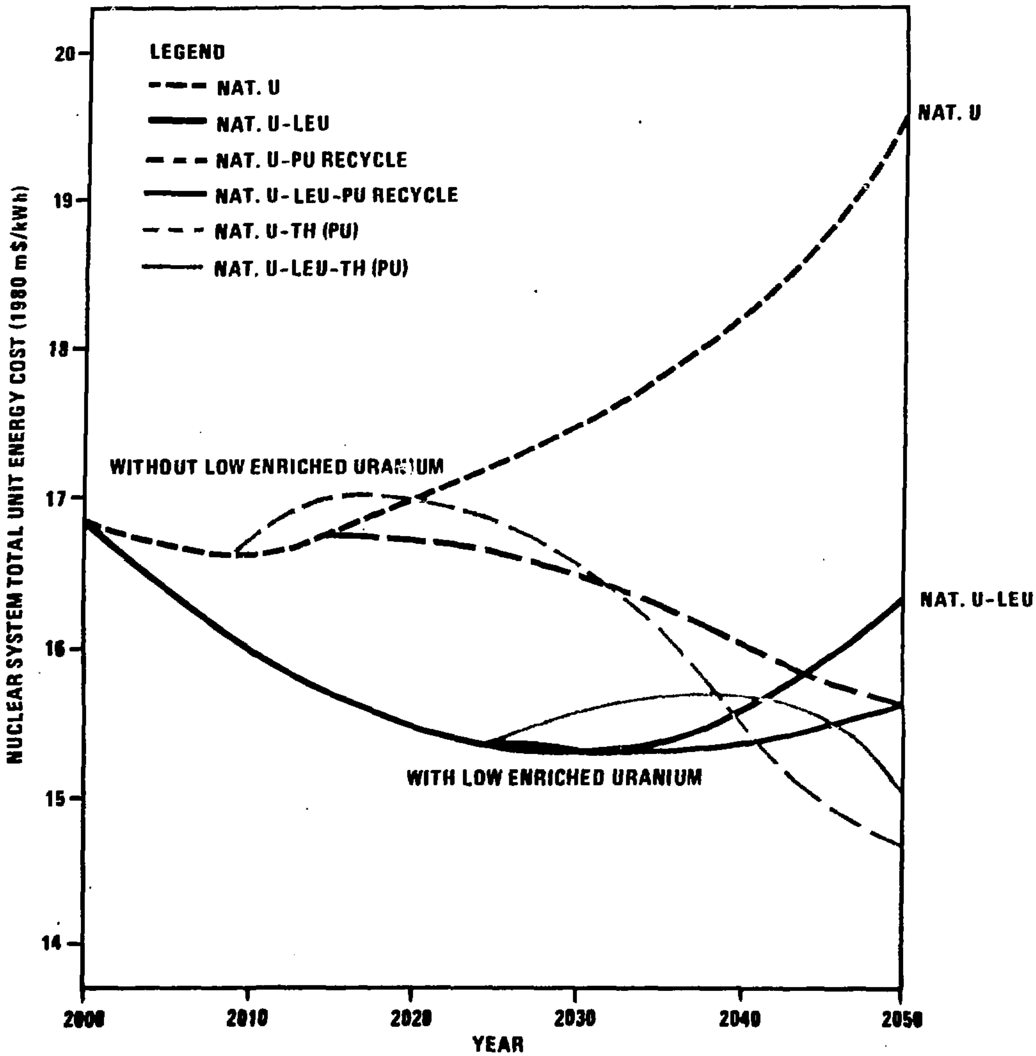


FIGURE 3.3-6
TOTAL UNIT ENERGY COSTS FOR
ADVANCED FUEL CYCLE STRATEGIES
(LOW GROWTH)

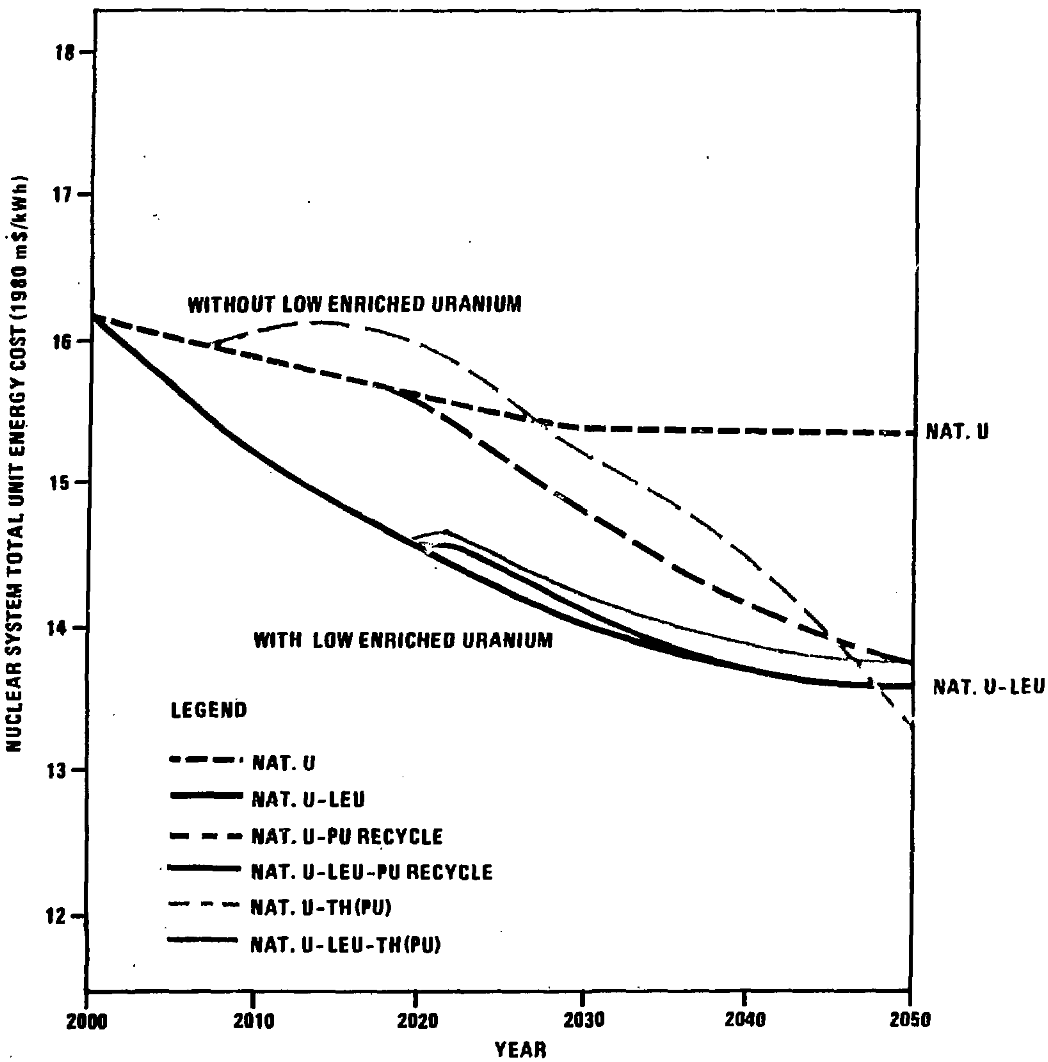
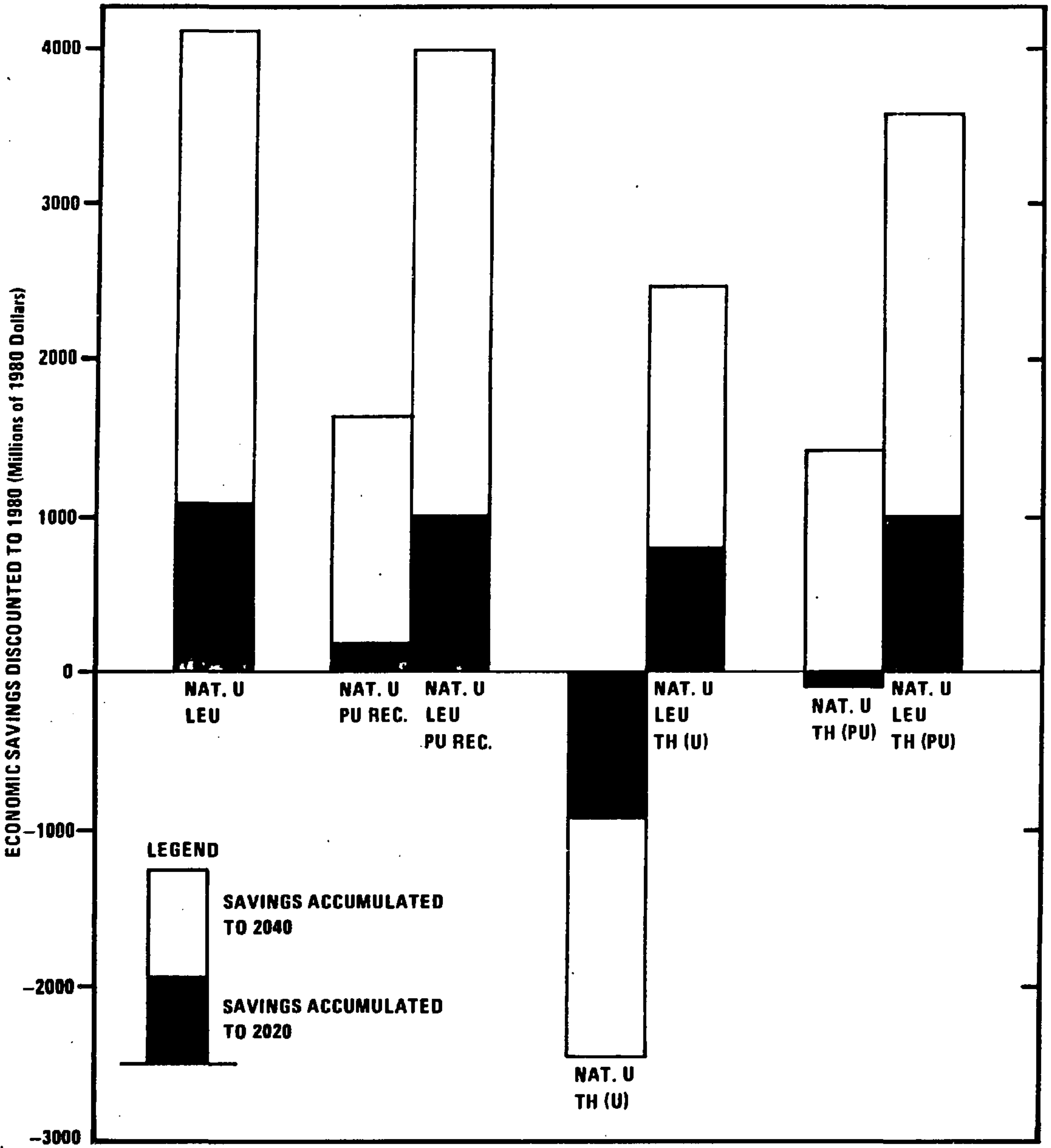


FIGURE 3.3-7
CUMULATIVE ECONOMIC SAVINGS DUE TO THE ADOPTION OF ADVANCED FUEL CYCLE STRATEGIES (BASE NUCLEAR GROWTH)



NOTE: Total Fuel Costs, discounted to 1980, for a Natural Uranium system are $9,000 Million from 2000 to 2020, and $18,000 Million from 2000 to 2040.

Conclusions

The following conclusions can be drawn from the economic analysis.

(1) The low-enriched-uranium fuel cycle shows significant economic savings over the natural-uranium cycle under existing conditions. There is very high confidence that the savings will increase substantially towards the end of the century and beyond. The more quickly the cycle is introduced, the greater will be the economic benefits.

(2) The low-enriched-uranium cycle shows greater economic benefits than any other advanced cycle until at least the year 2040, for the most probable nuclear growth rates and uranium prices. The early implementation of the cycle does not foreclose any of the longer-term options.

(3) The thorium cycle could be economic after the year 2025, but only if extremely high uranium prices occur (420$/kg by 2025). Therefore, there does not seem to be an economic justification for Ontario Hydro to pursue a vigorous R&D program on thorium fuel cycles at this time.

3.3.3 Ease of Implementation

The enriched-uranium cycle is more easily implemented than any other advanced fuel cycle.

The operating characteristics of a CANDU reactor fuelled with low-enriched-uranium can be predicted with confidence. There is only slightly less assurance about the characteristics of a plutonium recycle reactor. However, the reactor physics codes have not been thoroughly validated for thorium fuels. For thorium cycles, there is less confidence in the achievable burnup, probably more severe power-peaking problems, and possibly greater reactor control problems.

The fuel cycle service industries are in a mature state for the low-enriched-uranium cycle. There is only one additional process required, namely uranium enrichment, in addition to the processes already in place for the natural uranium cycle. Uranium enrichment is commercially established, with four major suppliers available. There is likely to be a buyers' market in this industry from now until at least the early 1990's.

A small facility for converting uranium hexafluoride, the standard product from an enrichment plant, to uranium oxide powder is available in Canada. This facility would have to be expanded, if a four-unit CANDU station was to be operated on low-enriched-uranium fuel.

The fuel fabrication lines presently being used in Canada to produce natural-uranium fuel are capable of processing uranium fuel enriched to 1.0% uranium-235. Modifications would be required for higher enrichments, but we have already seen that an enrichment of 1.0% is close to the economic optimum.

Plutonium recycle, and all the thorium cycles, require the commercial development of two new industries: reprocessing and active fuel fabrication. There are no facilities available for reprocessing CANDU fuel, and very few which can reprocess light water reactor and gas-cooled reactor fuels. Substantial research and development would be required before CANDU reprocessing facilities could be constructed.

Likewise, there is only a laboratory facility available at Chalk River Nuclear Laboratories for the fabrication of plutonium-bearing CANDU fuels. The toxicity of plutonium requires the total containment of the fabrication process. This results in major differences between the existing natural-uranium fabrication lines and those which would be required to produce plutonium-bearing fuel. Significant development would, therefore, be necessary for plutonium recycle.

The thorium fuel cycle involves the recycle of uranium-233. There are high-energy gamma rays associated with the recycled material, so the fuel fabrication process must not only be contained, as for plutonium recycle, but also heavily shielded. The development problems are thus substantially greater for the thorium fuel cycle, than for plutonium recycle.

3.3.4 Social Acceptability

It is likely that most countries with substantial nuclear power programs will, in the longer-term, develop advanced fuel cycles which entail reprocessing. In a world of dwindling energy resources, the energy potential of the plutonium in irradiated fuel is too substantial to ignore. However, at the present time, the social and political climate in a number of countries, including Canada, is not favourable to a major development effort on fuel reprocessing. This constraint does not apply to the low-enriched-uranium fuel cycle. In fact, features of the low-enriched-uranium cycle may have social, as well as economic, merit.

The availability of a domestic uranium-enrichment service is not essential, perhaps not even desirable, during the introduction of a low-enriched-uranium cycle, when the enrichment requirements are very limited. There is a buyers' market for enrichment services with suppliers in the U.S.A., France, Britain, and the USSR. There is, therefore, no political risk associated with a short-term dependence on a foreign supplier.

As the low-enriched-uranium program expands, the domestic demand could well be a catalyst for the development of a Canadian enrichment capability. This could occur towards the end of the century, when the world demand for enrichment is increasing more rapidly and new facilities will be required. This would be a socially-desirable secondary industry. It would create employment and result in the export of a higher-grade material. This could add, by the end of this century, some 500 million dollars per annum to the export value of Canadian uranium.

4. STRATEGY FOR ADOPTING THE LOW-ENRICHED-URANIUM CYCLE

4.1 Assessment of Technical Feasibility

The assessment of the technical feasibility of low-enriched-uranium reactors is, so far, based on calculations. Confidence in the calculations is justified because validated codes have been used, and because of the experience gained with natural-uranium-fuelled reactors. The calculations will be confirmed by an appropriate physics and fuel experimental program.

Most of the calculations have been based on the Bruce NGS B reactor, with enrichments in the range from 0.75% to 1.2% uranium-235.

The following preliminary conclusions have been reached for 850 MWe reactors, including Bruce GS B:

(1) Reactor physics calculations show that the achievable fuel burnups are as follows:

Natural uranium	0.71% U-235	166 MWh/kg U
Low Enriched	0.80% U-235	240 MWh/kg U
Low Enriched	0.90% U-235	325 MWh/kg U
Low Enriched	1.00% U-235	390 MWh/kg U

The higher burnups achievable with the enriched fuel will improve fuelling-machine-reserve margins.

(2) Fuel management schemes are available which will result in acceptable refuelling peaking factors with the enriched fuel. These schemes involve fuelling in the direction of coolant flow.

(3) The use of enriched fuel will not increase the fuel defect rate.

(4) Regarding control system assessment: the worth of the zone controllers is smaller in an enriched, than in a natural core. Nevertheless, the study of refuelling transients has shown that the natural-reactor control system is adequate for low-enriched-uranium operation.

(5) None of the areas of accident analysis are of major concern:

- the loss-of-coolant accidents have approximately the same reactivity balance with enriched fuel, as with natural-uranium fuel.

- in the case of loss-of-regulation, the present design of the in-core protective system against regional overpower should be adequate for use with enriched-uranium fuel.

4.2 Fuel Cycle Services

The fuel cycle services required for the low-enriched-uranium cycle are:

- enrichment,
- conversion and fuel fabrication,
- transportation.

Uranium enrichment can be readily purchased from diverse sources. The other fuel cycle services required are available in Ontario. There are, therefore, no supply problems which prevent the early commitment to a low-enriched-uranium fuel cycle.

The low-enriched-uranium fuel cycle, because of the higher fuel burnup, reduces the volume of irradiated fuel to less than half of that of the natural-uranium fuel cycle. This will reduce the storage volume and, hence, also reduce the requirement for additional irradiated fuel bays and/or interim storage capacity. It will also tend to reduce the transportation requirements and also the radiation exposure of personnel associated with the handling of irradiated-fuel.

4.3 Necessary Development Work

The low-enriched-uranium fuel cycle is a logical progression from the present natural-uranium fuel: no major development effort is required.

Review and optimization of reactor design will be performed, as part of the normal design procedure for any new station. Minor design changes may be needed in the following areas, to take full advantage of the low-enriched-uranium fuel cycle:

- Mechanical components for fuel handling, which are associated with downstream refuelling (latches, fuel carrier tube);
- Core layout (location of adjusters and other reactivity devices);
- Regional overpower protection and control systems associated with downstream fuelling and optimized core layout;
- Support services for criticality control, material control, and security, in storage facilities and irradiated-fuel bays.

Experimental confirmations are required in the following areas:

- Physics measurements (reactivity, power peaking);
- Reliability of fuel handling components in the downstream fuelling mode;
- Fuel performance at high burnups.

Development of the fuel supply route will include some changes in the following areas:

- Regulatory criteria
- Tendering policies
- Inventory control
- Minor process developments in the conversion stage.

The preceding development tasks are only extensions of past experience, and there is every reason to believe that they will be successful. The incremental development costs are small compared to the economic benefits associated with adopting the low-enriched-uranium fuel cycle.

4.4 Strategy of Introduction

4.4.1 Enriched Uranium Fuel for Bruce GS B

The use of low-enriched-uranium fuel is an attractive option for Bruce GS B and it is proposed that this should be the first Ontario Hydro station to take advantage of the fuel cycle.

It may be desirable for Bruce GS B, using the low-enriched cycle, to be fuelled in the direction of coolant flow (unlike the present reference fuelling scheme which is against the coolant flow). The optimum enrichment level will be close to 0.9% uranium-235. This entails adoption of a 2/4 bundle shift scheme (rather than the reference 4/8 scheme). Using this scheme, the fuelling-machine margins will be better than they would be using natural-uranium fuel.

In order to allow the introduction of low-enriched fuel as early as possible the following actions are required:

- immediate review of licensing requirements and associated safety studies;
- immediate review of the downstream fuelling capability and reliability;
- commitment in 1980 to procure enriched fuel (especially the enrichment services).

Advantages of this proposal are:

- there would be immediate reductions in fuelling costs, the reductions increasing to about 1 m$/kWh by the end of the century;
- the fuel-management scheme would provide increased fuelling-machine-reserve margins;
- the low-enriched-uranium fuel cycle would be demonstrated on a commercial scale, without a major capital commitment.

4.4.2 Enriched-Uranium Fuel for the E15 Station

The E15 station is the first opportunity to plan for the use of low-enriched-uranium fuel from the preliminary engineering phase. Enrichments of up to 1.2% uranium-235 could be considered, although the optimum enrichment will probably be 1.0% uranium-235.

Enrichment in the E15 station would take full advantage of the significant reductions in fuelling cost previously discussed.

The reactor would still be capable of economic operation on natural-uranium fuel if, for any unforeseeable reason, the use of that fuel became desirable in the future.

5. Concluding Remarks

In closing, we would just like to again touch upon the major conclusions.

The low-enriched-uranium fuel cycle reduces cumulative uranium requirements to the year 2030 by an estimated 40,000 to 60,000 metric tonnes. The financial savings by the same date are in the range $1,200,000,000. to $2,600,000,000. These values are in 1980 dollars, present worthed to 1980.

The low-enriched-uranium cycle is more economically attractive than any other advanced fuel cycle, at least until the year 2025, and more probably until 2040. Adoption of the cycle does not, however, foreclose any of the other longer-term options.

Finally, the low-enriched-uranium fuel cycle is unique amongst the possible advanced fuel cycles in requiring very little research and development effort.