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A SURVEY OF CONSIDERATIONS INVOLVED IN INTRODUCING CANDU REACTORS INTO THE UNITED STATES

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ABSTRACT

The important issues that must be considered in a decision to utilize CANDU reactors in the U.S. are identified in this report. Economic considerations, including both power costs and fuel utilization, are discussed for the near and longer term. Safety and licensing considerations are reviewed for CANDU-PHW reactors in general. The important issues, now and in the future, associated with power generation costs are the capital costs of CANDUs and the factors that impact capital cost comparisons. Fuel utilization advantages for the CANDU depend upon assumptions regarding fuel recycle at present, but the primary issue in the longer term is the utilization of the thorium cycle in the CANDU. Certain safety features of the CANDU are identified as intrinsic to the concept and these features must be examined more fully regarding licensability in the U.S.

PREFACE - THE CANDU CONCEPT

The current Canadian CANDU power reactors differ from U.S. light water reactors (LWRs) primarily on two counts: the CANDU reactors are cooled and moderated with heavy water (D_2O) and they are fueled with natural uranium. The use of D_2O with its relatively small capture cross section yields an inherent advantage in the neutron economy of the reactor. The good neutron economy in turn permits the use of natural uranium as fuel, so no enrichment process is required. These two basic features have led to a reactor design that is significantly different from LWRs. Some of the characteristics of the CANDU design are illustrated in Fig. a.

Heavy water moderator, at atmospheric pressure, is contained in a light calandria reactor vessel. Pressure tubes passing through the calandria contain the fuel elements and the pressurized heavy water coolant. The entire reactor assembly is oriented with the major axis of the cylindrical calandria vessel parallel to the floor.

A fuel assembly is shown in Fig. b. This particular illustration depicts a 37 element fuel bundle. Each bundle is about 20 in. long. These bundles are designed to facilitate on-power refueling. Automated refueling machines move the fuel bundles in a series of steps progressively through the reactor as burnup proceeds. With natural uranium as fuel, relatively low fuel burnup (less than 10,000 MWD/t) and low excess reactivity margins are characteristic of the CANDU design.

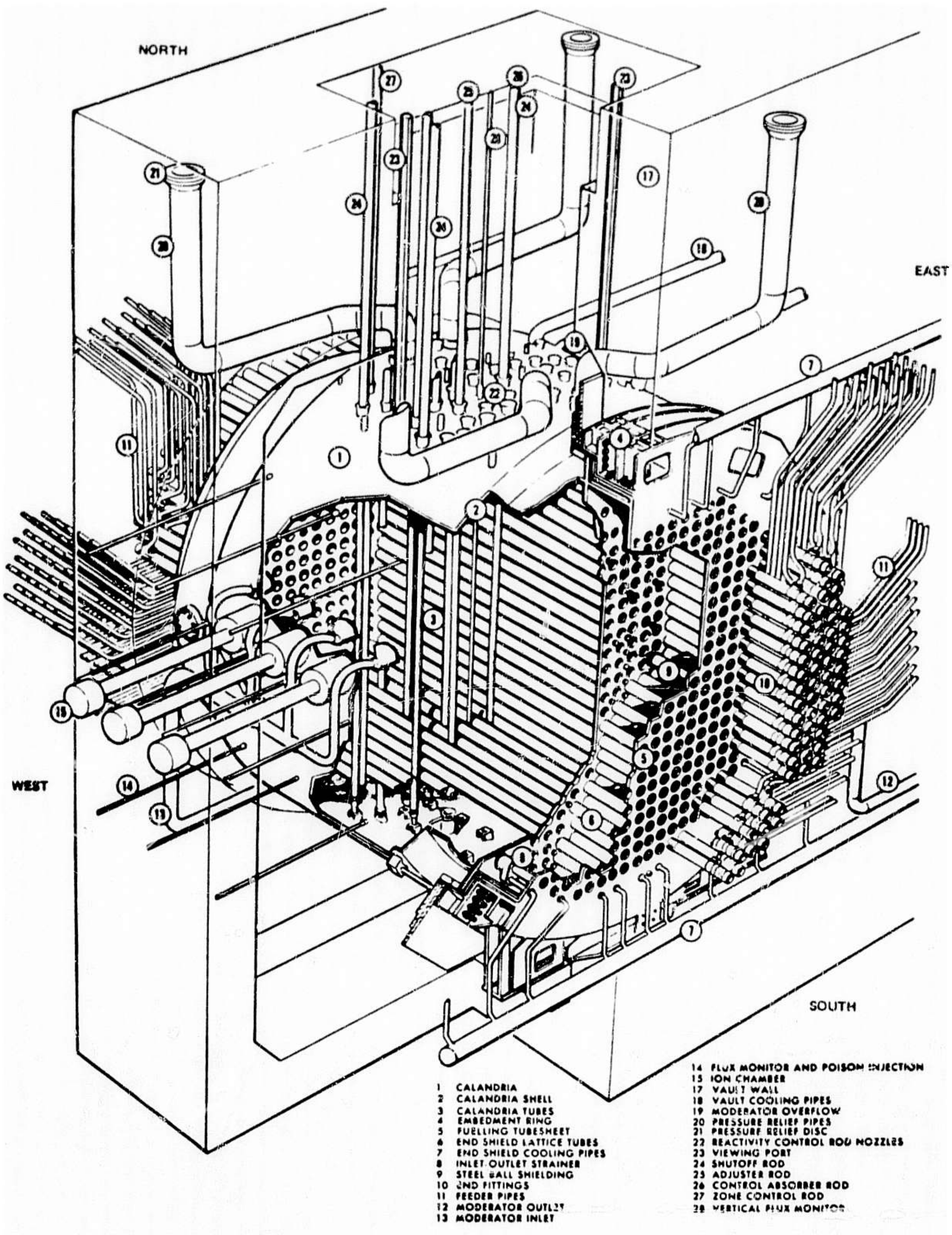

Fig. a. CANDU Reactor Assembly.
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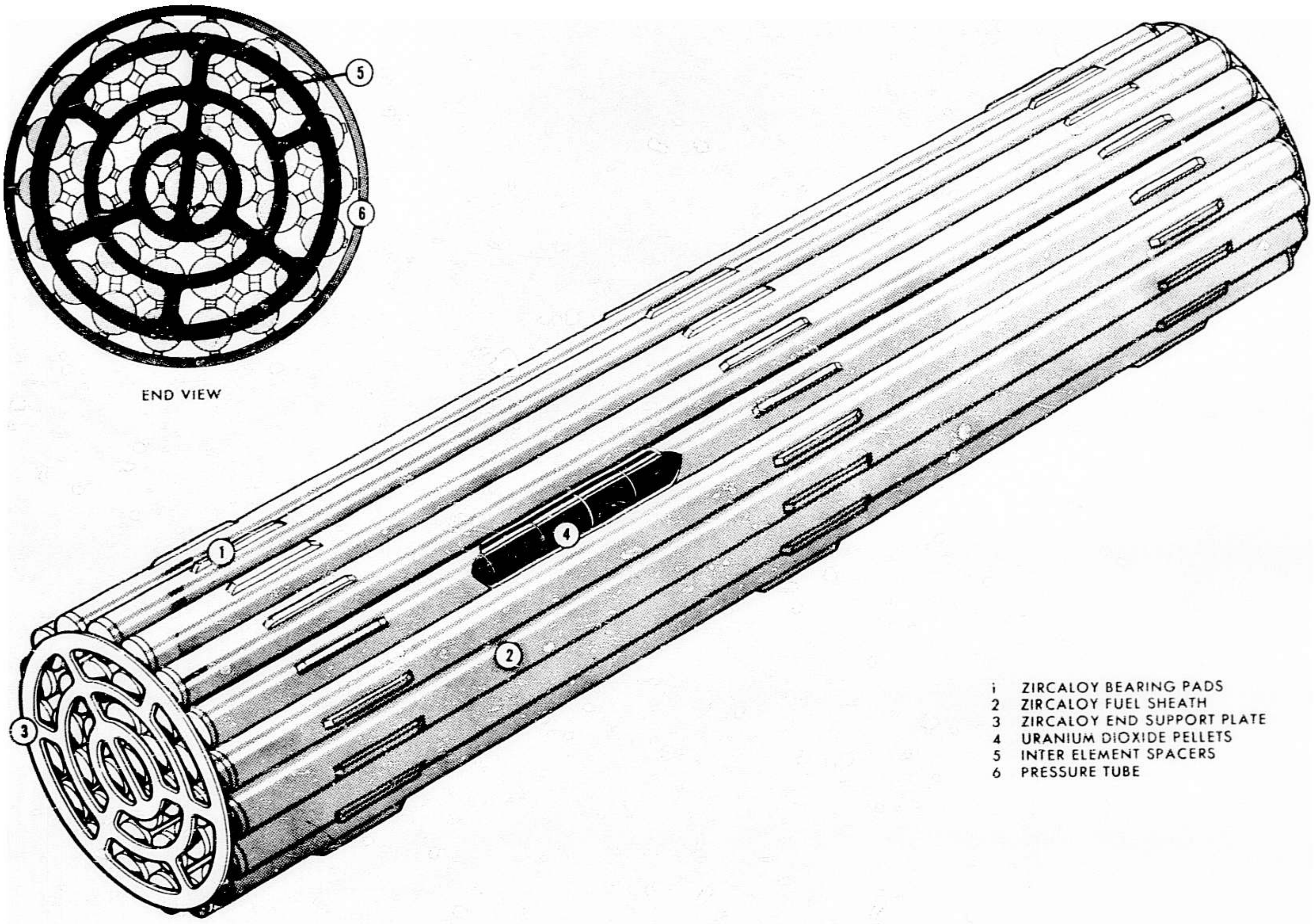

Fig. b. Thirty-Seven Element Fuel Bundle.
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SUMMARY

This report presents the results of a very brief survey of the issues that would require consideration in any future decision to utilize CANDU reactors in the U.S.

The report is divided into two parts: I. Current Issues and II. Longer-Term Issues.

The discussion under Current Issues is divided into two main parts: Economic Considerations, and Licensing Considerations. The economic considerations include both power costs and fuel utilization.

Current power costs were compared directly using data from the Pickering plant (for CANDUs), and from Commonwealth Edison and Consolidated Edison (for LWRs), after placing the data on a common basis to the extent possible. No significant difference in the power cost was identified. The Pickering capital costs are higher, but the information base for capital costs and capacity factors is very limited for CANDUs. The cost of heavy water has increased by roughly a factor of two (to $110-120/kg) over the past decade, much less than the increase in other plant capital costs over the same period; it now contributes about 20% to the overall power cost, and may for a number of reasons contribute a smaller fraction in the future. Fuel costs tend to run at least 1-2 mills/kWhr less in CANDUs than in LWRs; because of counter balancing effects this differential can be expected to remain fairly constant in the future.

Fuel utilization comparisons depend upon the recycle scheme and the tails assay selected for comparison. The basic CANDU throwaway cycle has a fuel utilization (tons U_3O_8 per year) essentially identical to the LWR with uranium but not the plutonium recycled assuming the tails assay of 0.2%. If no recycle is allowed in either case CANDUs use about 20% less fuel. For complete recycle in both cases (plutonium in CANDUs and U+Pu in LWRs) CANDUs use about 40% less fuel, but the economic incentive to recycle in CANDUs is considerably less than in LWRs because of the much smaller fissile content in the CANDU spent fuel. LWRs on recycle use about 20% less fuel than CANDUs on a throwaway cycle. Thus it is not possible to point to an unambiguous advantage in fuel utilization for either system as the situation now stands. The relative advantages are likely to be in the range of ±20%, and dependent upon the future developments with respect to recycle.

The licensing issues, that may have to be considered if the current CANDU reactors are to be implemented in the U.S., derive mainly from the fact that most of the U.S. Licensing Regulations and Regulatory Guides have evolved predominantly around the current generation of LWRs. Some of these licensing issues are intrinsic to the CANDU concept; others are not. Probably the main intrinsic safety related characteristics of the NSSS are associated with the coolant pressure tube feature of CANDU, and the associated on-line refueling capability. The system may be designed for minimal sensitivity to rupture of any single primary coolant component. Considerations associated with the functioning of the emergency cooling system appear to be less constraining than for LWRs. However, irradiation damage to the pressure tubes, potential pressure tube failure, positive void-reactivity effect, and potential small-scale LOCAs during on-line refueling operations, may necessitate detailed licensing reviews. Non-intrinsic safety related characteristics, i.e.,

features that may be modified to accommodate U.S. safety requirements, include the use of computers for certain control functions in the CANDU plant, use of separate vacuum building for containment, and redundancy of various auxiliary and engineered safeguards systems. Licensability considerations would include evaluation of the overall safety analysis approach and the assumptions that are made with respect to hypothetical accidents, and reliability of plant protection systems.

Turning to longer-term issues, definite conclusions regarding future relative power generation costs are not possible, but the important factors influencing these costs can be identified. Capital costs will remain the dominant costs and the factors that must be examined include costs associated with modifying CANDU reactors to meet U.S. standards and regulations, use of enriched fuel cycles to reduce the heavy water inventory, and the potential plant performance of CANDU reactor operating in the U.S. environment. The portion of capital costs attributed to heavy water is not expected to increase, but heavy water production capacity would have to be installed to support CANDU type reactors operating in the U.S. and a large capital expenditure would be required. Relative fuel cycle cost estimates for CANDU reactors and LWRs indicate that a small differential of 1-2 mills/kWhr in favor of CANDU reactors is likely to continue in the 1980's. This differential is relatively insensitive to large U_3O_8 price changes and it is partially offset by heavy water upkeep costs.

The potential for uranium resource conservation in the current CANDU-PHW reactors, by themselves, is little different than current reactors in the U.S. and it is the thorium fuel cycle that is to be considered for possible long term fuel utilization benefits.

The use of thorium in CANDU reactors can substantially improve fuel utilization. A self-sufficient thorium cycle (conversion ratio of 1.0 at equilibrium cycle) is feasible at a low burnup (10 MWD/kgHM) provided that the fabrication and reprocessing losses can be kept below 1%. Total power generation costs are affected by design parameters such as specific power, lattice pitch, burnup and type of coolant. Economic optimization of the CANDU-thorium cycle reactor necessarily involves design trade-offs that impact the fuel utilization characteristics. Unless the uranium price becomes very high ($\sim$\$150/lb U_3O_8) and the fabrication cost of ^{233}U bearing fuel can be kept low (<\$100/kgHM), it appears that there is no economic incentive to consider conversion ratios greater than 0.9-0.95, and if the reprocessing and refabrication costs turn out to be very high, the optimum will be less than 0.9. Even if uranium conservation becomes a critical issue, the role of thermal near-breeders in an expanding power economy is problematical. Since thermal breeders (CANDU near-breeders or LWBRs) are at best self-sufficient, and then only in their equilibrium condition, they could supply power indefinitely only to a non-growth power system with a fixed equilibrium nuclear power capacity. Furthermore, the introduction of thermal breeders over the next several decades appears unlikely to significantly affect the rate of uranium usage during that period because thermal breeders require loadings for the initial core and for the transition to the equilibrium cycle equivalent to about 15 annual loadings for uranium cycle reactors. Hence, in a growing power economy, any benefit from thermal breeders could not be realized in the intermediate future, in which period the currently estimated reserves of high grade uranium may well all be consumed.

I. CURRENT ISSUES

A. Economics

Power generation costs, and somewhat less directly, resource utilization, are the major economic factors. Some actual cost and fuel utilization data are available for currently operating CANDU-PHW reactors. These data can be compared with similar data for current generation light water reactors in the U.S. to give some information on the relative economics of the two concepts. By far the most important factors influencing current power costs are associated with capital costs, and the most important current issues therefore relate to the factors that influence these costs. Fueling requirements are compared but relative fuel utilization advantages are not clearly evident, nor do these considerations substantially affect current power costs.

A.1. Power Generation Costs

A.1.1. Capital Costs

The capital fixed charges are the largest contributor to overall power generation costs. For the CANDU reactors, the portion is ~75% and for LWR's, it is ~60-70%. Yet, it is difficult to make a direct, unequivocal comparison of capital costs. There are no LWR's operating in Canada and there are no CANDU reactors in the U.S., but capital costs are impacted by several factors that are dependent on the local economic and industrial environment. These costs have risen rapidly the past few years with the major contributing factors being additional regulatory (safety and environmental) requirements, material and equipment price escalations, cost of labor and capital, and construction and licensing delays. A total of 62 LWR's have been constructed in the U.S., while only one CANDU plant, the Pickering plant, is operating in Canada.

Perhaps the most useful information at this time is to simply display, as is done in Fig. 1, the information available on capital costs for LWR's constructed in the U.S. and for CANDU reactors constructed in Canada. In this figure, all costs are given as a function of the initial year of plant operation. The CANDU capital costs[1,2] are shown as the average cost for a four-unit station over the time all units are put on-line. These costs include the initial inventory of heavy water. The data for LWR plants for each year through the year 1976 are the average of actual capital costs reported by the operating utilities.[3]

The total capital cost of the four-unit (500 MW(e) each) Pickering station, including heavy water, was \$364/kW(e). The heavy water inventory required is about one metric ton per MW(e) and the initial inventory was costed at \$66/kg giving \$66/kW(e). The average LWR capital cost in the U.S. over the time Pickering became operational was ~ \$200/kW(e). This capital cost differential may be somewhat misleading, however. In addition to the local factors impacting capital costs that were mentioned above, Pickering was the first large unit of its kind, while many of the LWR units were constructed under early turnkey contracts. The latter two considerations would tend to emphasize capital cost differentials in favor of LWRs. Thus, from the existing data, it is difficult to draw a definite conclusion on capital cost differences between the two reactor concepts.

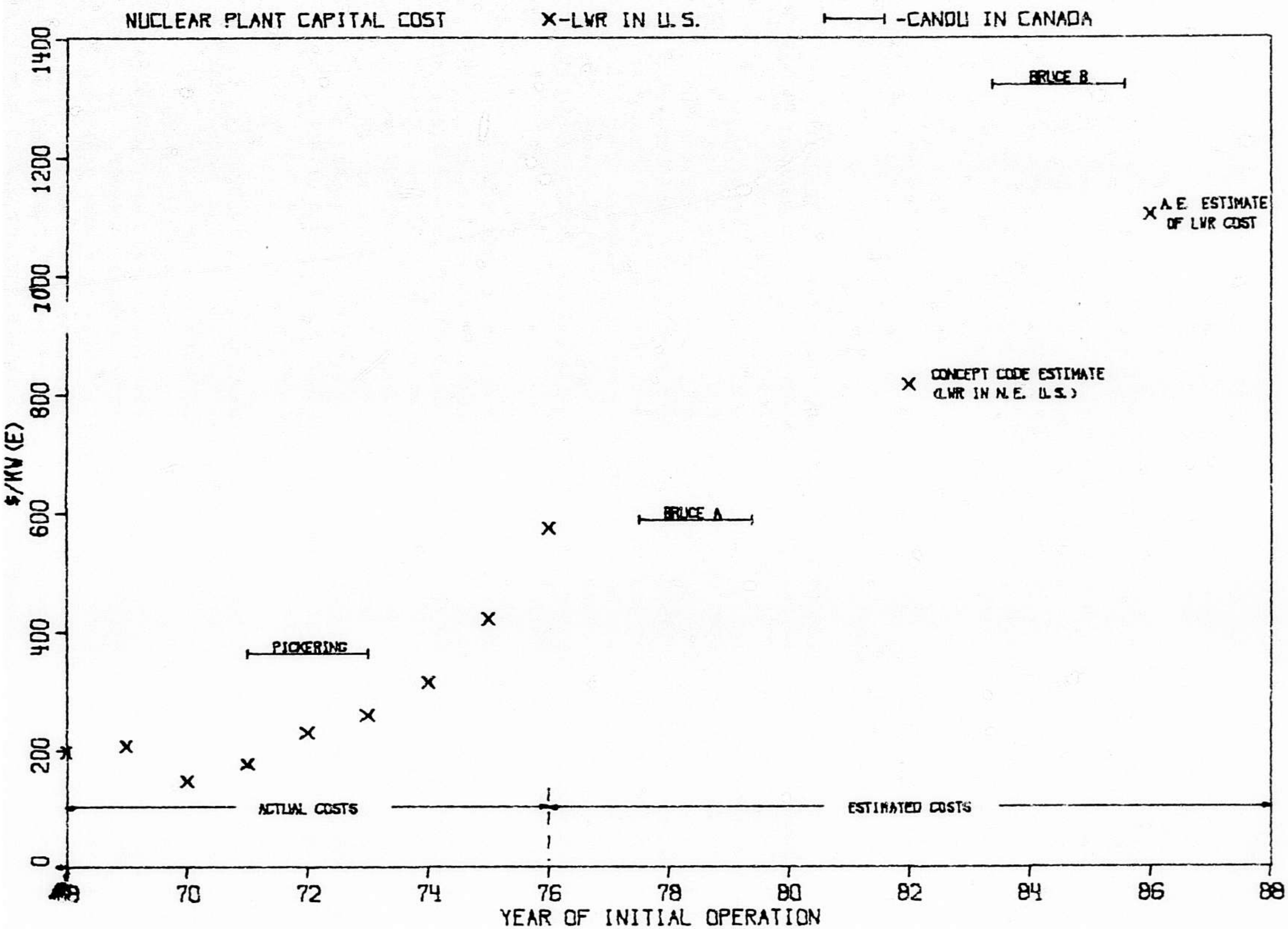

Fig. 1. Capital Costs for LWRs in the U.S. and CANDUs in Canada.
ANL Neg. No. 116-77-62.

A.1.2. Capacity Factors

Fixed charge costs are directly proportional to capital costs and inversely proportional to the capacity factor. Thus, a high capacity factor would discount high capital costs. In addition, operation and maintenance operational costs are semi-variable costs - i.e., these costs will be incurred at an annual rate generally independent of the level of plant operations - so to a considerable extent these power costs are also inversely proportional to the capacity factor.

Data available on CANDU operations is limited to the single Pickering station and it is summarized in Table I.A.1. The capacity factor averaged over the lifetime of Units No. 1 and 2 is 85% for each unit, a relatively high level of performance. All units considered, nearly two-thirds of the operating experience at Pickering has been accomplished at a capacity of 80% or more. The average lifetime capacity factor for the four-unit station is 75%.

TABLE I.A.1. Capacity Factors Reported for the Four-Unit Pickering CANDU Plant (Ref. 1)

Unit	On-Line	Capacity Factor (%) for Year: 1972[a]	1973	1974	1975	to 6/76	Lifetime Capacity Factor
No. 1	7/71	72.3	92.5	72.0	80.2	97.0	81.9
No. 2	12/71	82.2	69.0	88.4	86.0	88.6	82.2
No. 3	6/72	91.3	85.1	42.7[b]	57.5[b]	97.8	69.1
No. 4	6/73	-	90.1	93.9	23.8[b]	46.8[b]	62.1
						Weighted Average:	75%

[a]Excludes impact of labor dispute.

[b]Low capacity factors as a result of pressure tube replacements.

The Pickering capacity factors are compared with lifetime capacity factors reported[4] for 62 LWR's in the U.S. in Fig. 2. Three-fourths of the U.S. LWR's have achieved a capacity factor greater than 50%, but only about 10% have achieved capacity factors around 80%. However, several factors cast uncertainty on a direct comparison of capacity factors for the two reactor concepts.

First, the statistics on CANDU operations have not really developed as they have to date for LWR's and future comparisons with LWR's could change significantly as more operating experience is accumulated.

Secondly, plant availability, as well as capacity factor, must be considered in a realistic comparison. Plant availability for LWR's in the U.S. is generally 15-20% greater than the capacity factor.[5] Capacity

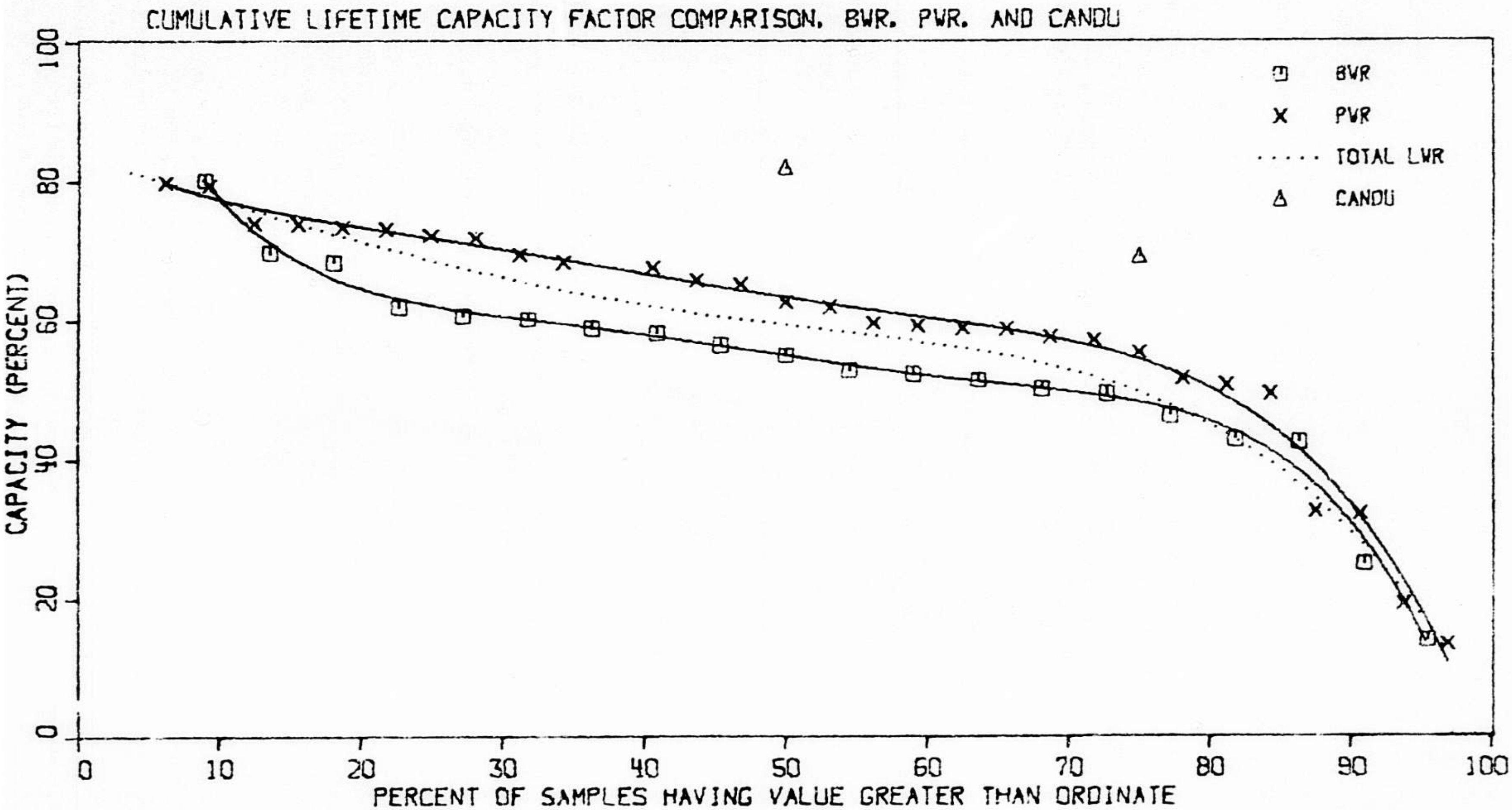

Fig. 2. Cumulative Lifetime Capacity Factors for LWRs and the CANDU Pickering Plant. ANL Neg. No. 116-77-64.

factors are less than the actual plant availability due to the nature of the load demand, the number and characteristics of the reactor plants available to a utility, and the mode of operation chosen by the utility. Hence, an equitable comparison of plant performance should be based on plant availability. (Plant availablity data for Pickering were not available for this study.)

Finally, plant availability and capacity factors are also impacted by licensing and inspection regulations and these factors may be different for CANDU's operating in the U.S. and for CANDU's operating in Canada. The important issue is whether or not CANDU plants have the inherent capability of achieving a higher availability factor than LWR plants. This aspect will be discussed further in Section C.

A.1.3. Heavy Water Costs

Heavy water costs contribute about 20% of the total power costs. The upkeep costs apparently are small and the heavy water cost appears to be an issue only with respect to its effect on total capital costs. The initial inventory of heavy water for the Pickering plant was costed at $66/kg. The current price (1975), both in the U.S. and Canada, is $110-120/kg.[6] The price has increased by approximately a factor of two over the past ten years, much less than the increase in overall capital costs. Heavy water costs are sensitive primarily to the cost of power since steam generation costs contribute 40% of the overall cost. Heavy water plants, both in the U.S. and Canada, have used coal as the source of energy, and hence, the D_2O costs have been sensitive to the price of coal. Most recently, heavy water in Canada is being produced with power supplied by nuclear plants and heavy water prices may stabilize in the future.

A.1.4. Fuel Costs

The current CANDU-PHW reactors operating with natural uranium fuel characteristically demonstrate a low fuel cost of $\sim$1 mill/kWhr for the present burnup of 7.5 MWD/kg.[1] CANDU fuel costs are primarily functions of the price of U_3O_8 and the cost of fuel fabrication. For the low uranium feed prices prevailing over the past few years, uranium costs contributed 30-35%. The fuel cost component of the total power generation cost is only $\sim$10%. The fuel cost differential between CANDU and LWR's is 1-2 mills/kWhr and is partially offset by the heavy water upkeep cost in the CANDU plant. This differential is of the order of the uncertainty in capital cost estimates. Thus, at the present time, fuel costs are important, but they are not a major issue. Future fuel costs and sensitivity to various factors are discussed in Section II.

A.1.5. Total Power Generation Costs

The component costs of power generation and factors impacting these costs were reviewed briefly above and it is evident that a directly equivalent comparison of the power generation costs associated with heavy water reactors and light water reactors would be difficult to establish. Power generation cost data for operating heavy water reactors are available for only one generating station, the data is based on reactors constructed and operated in Canada, and extrapolation of this data to the U.S. environment necessarily involves some degree of uncertainty. Nor can a representative cost of light water reactor power generation be assigned with certainty. Reported power generation costs for light water reactors in the U.S. vary significantly among the various utilities and these costs have been rising rapidly over the past few years. The procedures used to estimate costs, the number and sizes of reactor plants, the period of construction, and the actual operating history must be considered in order to properly qualify a cost comparison.

Recent estimates of actual power generation costs for the Pickering CANDU Generating Station-A are given in Table I.A.2 along with two representative light water reactor power cost estimates. To the extent possible, the data have been placed on a common basis to facilitate a comparison.

TABLE I.A.2. Typical Power Generation Costs (mills/kWhr) for Operating Light Water Reactors and CANDU Heavy-Water Reactors

	CANDU Pickering Units 1,2,3,4,[a]	Commonwealth Edison Dresden 2,3; Zion 1 Quad Cities 1,2[b]	Consolidated Edison Indian Point 2[c]
Fixed Charges:[d]			
Capital	6.75 (7.20)[e]	5.19 (3.88)[e]	7.04 (6.01)[e]
D_2O[f]	1.49 (1.59)[e]	-	-
Operational Costs:			
Operation & Maintenance	1.10	2.02	1.28
Fuel	0.98	2.01	3.49
D_2O Upkeep[g]	0.35	-	-
Total	10.67 (11.22)[e]	9.13 (7.91)[e]	11.81 (11.19)[e]

[a]Unit 1 on-line 7/71, Unit 2 on-line 12/71, Unit 3 on-line 6/72, Unit 4 on-line 6/73. Total capacity 2056 MW(e). Cost data as of March 1975.

[b]Dresden 2 on-line 8/70, Dresden 3 on-line 10/71, Quad Cities 1 on-line 8/72, Quad Cities 2 on-line 10/72, Zion 1 on-line 6/73. Total capacity 4300 MW(e). Cost data for 1974.

[c]On-line 9/73. Capacity 873 MW(e). Cost data for 7/74-6/75.

[d]A fixed charge rate of 16% and the actual capacity factor achieved for the period indicated have been used for all calculations.

[e]Cost assuming a 75% capacity factor for all reactors.

[f]Initial inventory costed at $66 kg D_2O. The fact that D_2O is a non-depreciating capital cost and subject to a slightly different fixed charge rate has been ignored here. A fixed charge rate of 16% has been applied to the D_2O capital cost.

[g]Makeup D_2O costed at ~$110/kg.

The CANDU costs presented in Table I.A.2 represent the average costs for four 500 MW(e) units as of March 1975.[1] These units were operated base load and had achieved an actual capacity factor of about 80% for the cost period reported. As discussed above, the total capital cost, including the initial D_2O inventory, was $364/kW(e) for the four-unit station. The CANDU fixed charge costs have been computed with a fixed charge rate of 16% in Table I.A.2 to make possible a direct comparison with reactors operated by private utilities in the U.S. The portion of the total capital costs assigned to interest costs during construction (∿15%) and the interest rate assumed (7.5%) is similar to indirect capital cost experience for reactors constructed in the U.S. during the same period.[7] The Pickering units came on-line over a period of two years, mid-1971 for Unit No. 1 to mid-1973 for Unit No. 4. The estimated power generation cost is about 11 mills/kWhr with the largest fraction (∿75%) due to capital costs.

The cost data for the five Commonwealth Edison light water reactors represent costs for LWR units brought on-line over approximately the same period as the Pickering station. The Dresden and Quad Cities units are parts of multiple unit stations and all five units are operated as base load plants. Thus, a capital cost comparison between Pickering and these five units can be justified on these accounts at least. The capital costs for the two earlier plants, Dresden 2 and 3, are about $144/kW(e), for the two Quad Cities units about $156/kW(e), and for the Zion 1 unit on-line in mid-1973, about $250/kW(e).[4] The actual capacity factor reported for the cost period (1974) is 56%. The estimated power generation cost is about 9 mills/kWHr with capital costs contributing 57%. The fuel costs are 2 mills/kWhr compared to 1 mill/kWhr reported for Pickering.

Cost data[9] for Consolidated Edison's Indian Point 2 unit are also included in Table I.A.2 to demonstrate the variability of power generation costs. Indian Point 2 is part of a multiple unit station, operated as base load, and constructed under turnkey contract for $250/kW(e). It came on-line late in 1973. The actual capacity factor was 64% for the cost period (July 1974 to June 1975) and the total power costs were about 12 mills/kWhr, with fueling costs at 3.5 mills/kWhr.

The important observations to be made from the data presented in Table I.A.2 are:

1. Fixed charge costs are the dominant power costs, especially for the CANDU station.

2. CANDU capital costs, in the case of the Pickering station, appear to be $150-175/kW(e) greater than LWR's constructed over the same period.

3. Heavy water costs account for about 40% of the capital cost differential between CANDU and LWR's.

4. Fuel costs for the CANDU reactors are low relative to LWR's.

The impact on fixed charges of assumptions regarding capacity factors is also illustrated in Table I.A.2. If a capacity factor of 75% is assumed for all reactors (CANDU's and LWR's), LWR costs are reduced significantly (to ∿8 mills/kWhr for the Commonwealth Edison reactors compared to ∿11 mills/kWhr for the CANDU-Pickering station and the Indian Point 2 LWR). The importance of factors influencing capacity factors is evident.

If a general conclusion regarding total power generation costs is warranted, it is that no significant difference between LWR's and CANDU's can be established at this time. The identification of any differential is precluded primarily by uncertainties in establishing an equivalent capital cost comparison.

It should be noted that all the observations on costs made here are without the consideration of certain industry introduction costs, i.e., costs associated with licensing the CANDU concept and costs associated with establishing heavy water production capacity.

A.2. Fuel Utilization

Commercial reactor designs are optimized for minimum power cost in the prevailing economic and resource environment. As uranium resources become more scarce and as uranium prices increase, fuel design and management schemes would reoptimize accordingly. However, such design evolution would not be likely on a short time scale because of the incentives to retain proven designs. These include reliable fuel performance and standard procedures for safety analysis, licensing, and fuel cycle manufacturing processes. Hence, comparisons of the fuel utilization for current designs might be expected to be applicable at least through the early 1980's.

In Table I.A.3, reactor characteristics and fuel cycle requirements are compared for the LWR, CANDU,[10-13] and the HTGR[14,15] for different recycle schemes. The LWR parameters are an average of the values for BWR's and PWR's.

The uranium requirement for the CANDU once-through cycle is 168 ST U_3O_8/GWe-yr. The U_3O_8 requirements for the LWR, however, depend on the tails assay in the enriching process and the recycle scheme. Fuel utilization becomes an important issue when the uranium price is very high, in which case economic considerations will tend to lower the tails assay. Apart from enrichment capacity limitations, the optimum tails assay (which minimizes the enrichment cost plus feed cost) is a function of the natural uranium feed to separative work cost ratio.[16] The optimum tails assay is about 0.29% for \$8/lb U_3O_8 and \$36/kgSWU. The economic optimum changes to 0.21% for the current costs of \$24/lb U_3O_8 and \$55/kgSWU. Tails assays of 0.2 and 0.3% have been selected for fuel utilization comparisons.

There are both economic and fuel conservation incentives to recycle in the LWR because the discharge fuel still contains a relatively high fissile fraction. Even if a decision is made not to recycle plutonium, it is possible that the spent fuel would still be reprocessed and at least the uranium recycled. For the case of uranium recycle only and 0.2% tails assay, the U_3O_8 requirements for the LWR (163 ST U_3O_8/GWe-yr) are almost identical to 168 ST U_3O_8/GWe-yr for the CANDU basic cycle (natural uranium once-through). The reasons for this are:

TABLE I.A.3. Current Reactor Characteristics and Fuel Utilization (at 80% Capacity Factor)

Reactor Type	LWR			CANDU		HTGR	
Fuel Cycle Option	No Recycle	U Recycle	U & Pu Recycle	No Recycle	Pu Recycle	No Recycle	^{233}U Recycle
Thermal efficiency, %		33		30.5		39	
Specific power, kWth/kgHM		32.1		26		77.1	
Discharge burnup, MWD/kgHM		30.5		7.5	16.0	90.0	
Fuel residence time, yrs		3.25		1.0	2.1	4.0	
Equilibrium cycle loading[a] MTHM/GWe-yr	29.0	29.0	21.8(U) 7.3(Pu)	127.7	59.8	0.62(U) 7.70(Th)	0.62(U) 7.70(Th)
Fissile enrichment, % HM	3.0	3.0	3.0(U) 3.5(Pu)	0.71	0.71 +0.31	93(U)	85(U)
Equilibrium cycle discharge							
^{235}U, % HM	0.86	0.86	0.75	0.22	0.11	0.6	0.6
Fissile Pu, % HM	0.61	0.61	0.89	0.27	0.35	-	-
^{233}U, % HM	-	-	-	-	-	2.2	2.3
U requirement,[b] ST U_3O_8/GWe-hr							
at 0.2% tails assay	210	163	129	168	79	149	87
at 0.3% tails assay	251	203	159	-	-	185	108
Sep. work Req.,[b] MTSWU/GWe-hr							
at 0.2% tails assay	126	121	91	-	-	148	86
at 0.3% tails assay	100	97	73	-	-	125	73
Approximate Conversion Ratio		0.61			0.74		0.66

[a]The data are shown separately for each type of fuel if the loading consists of more than one type.

[b]Allowances are made for losses during fabrication and reprocessing.

(a) The CANDU discharge ^{235}U enrichment is about 0.2%, which is identical to the tails assay assumed in the enriching process. Hence, the wastage rate of the mined uranium is about the same for both reactor types.

(b) The better neutron economy (higher conversion ratio) in CANDU is partially offset by the lower thermal efficiency.

(c) Even though the conversion ratio is higher in CANDU, the total plutonium utilization in situ is not. The fission fraction in plutonium is about the same for both reactor types (∿40%). However, the fissile plutonium discharge rate is higher in CANDU. (340 kg/GWe-yr for CANDU at 7.5 MWD/kg as compared to 180 kg/GWe-yr for LWR).

For self-generated plutonium recycle the U_3O_8 requirements are reduced by about 20% for LWR and about 50% for CANDU. The difference in the plutonium recycle credit is due to the higher plutonium production in CANDU.

As shown in Table I.A.3, the U_3O_8 requirements for the HTGR are lower than either the LWR or CANDU for the basic uranium cycle. For the self-generated recycle case, the U_3O_8 requirements for the HTGR are lower than the LWR and slightly higher than the CANDU. In Fig. 3, the uranium requirements are compared for the LWR, CANDU and the HTGR with and without recycle allowances. A 0.2% tails assay is used for the fuel utilization comparison in the figure. If 0.3% tails assay is taken, the U_3O_8 requirements for the LWR and the HTGR would be increased by 20-25%. CANDU requirements are not affected.

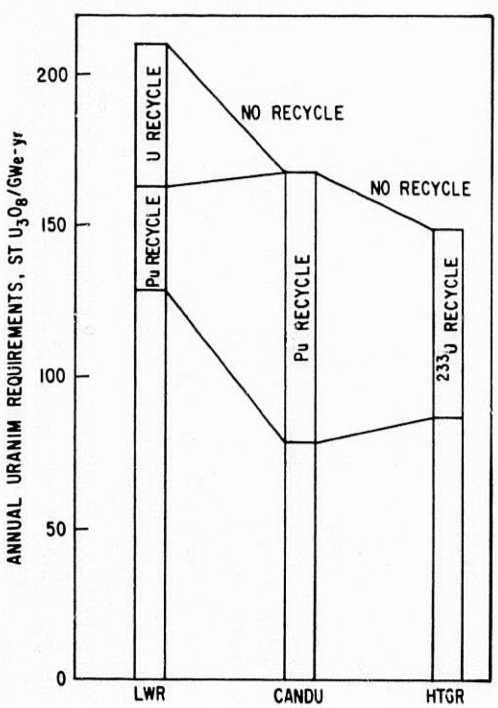

Fig. 3

Comparison of Annual Uranium Requirements (capacity factor = 80%, tails assay = 0.2%).
ANL Neg. No. 116-77-55.

A.3. Summary

From available data, it is difficult to identify a significant difference in total power generation costs for current CANDU-PHW reactors and LWR's. Capital costs, the largest portion of power costs, are the most difficult costs to determine and to compare. The plant capacity factor impacts directly on fixed charge costs and the higher capacity factor achieved by the CANDU reactors, if inherently characteristic of the reactor type, would offset initial higher capital costs. Heavy water costs contribute about 20% of the initial capital cost, but operational upkeep costs are apparently small. The CANDU fuel costs are small and 1-2 mills/kWhr less than LWR fuel costs. The fuel cost differential is partially offset by heavy water upkeep costs, but the difference in operational power costs is probably less than the current uncertainty in estimates of the capital costs. Thus the most important issues regarding current power generation costs center on factors influencing capital costs and the plant capacity factor. The factors that influence CANDU capital costs are the same as those controlling LWR capital costs (cost escalations, fixed charge rates, construction delays, etc.). The factors that impact the plant capacity factor may include inherent characteristics of the CANDU plant (e.g., on-line refueling versus difficulty of inspectability) as well as characteristics of plant performance basically unrelated to reactor type.

Conclusions regarding fuel utilization are coupled to economic considerations and recycle capability. For a basic uranium cycle (uranium recycle for LWR, once-through cycle for CANDU and no recycle for HTGR) and an economically optimized tails assay of 0.2%, the CANDU U_3O_8 requirements are not less than either the LWR or HTGR. For the self-generated recycle case (plutonium recycle for LWR and CANDU, and ^{233}U recycle for HTGR), the CANDU U_3O_8 requirements are 20% less than the LWR, but about 10% greater than the HTGR. Thus, it is difficult to identify a distinct fuel utilization advantage for current CANDU reactors. Should fuel utilization become an important issue, the discussion must turn to advanced fuel cycles, including the use of thorium; current fuel cycles bear only marginally on this point.

B. Licensing Considerations for CANDU Reactors

B.1. Introduction

The regulatory issues, that may have to be considered if CANDU reactors are to be constructed in the U.S., derive mainly from the fact that most of the U.S. Licensing Regulations and Regulatory Guides have evolved predominantly around the current generation of Light Water Reactor (LWR) power plants. Design characteristics, which are typical for the CANDU reactors and different from current LWRs, may therefore require some special attention in that some of them may not have been addressed up to now in the U.S. Regulatory process. An example is the use of zircaloy as part of the primary coolant pressure boundary (such as is the case for the CANDU in-core pressure tubes), which did not have to be addressed for LWRs. The primary issue then is not whether CANDU reactors meet adequate safety standards (they, no doubt, do), but rather how much effort is required to introduce the CANDU technology into the U.S. regulatory environment, as determined by U.S. NRC regulatory procedures, practices, criteria, guidelines, and standards.

In evaluating the safety aspects of CANDU-PHW reactors with respect to licensability in the U.S., it is desirable to clearly distinguish design characteristics that are intrinsic to the Nuclear Steam Supply System (NSSS) from those that are non-intrinsic (i.e., pertaining to subsystems of a more peripheral nature), and that could therefore be modified relatively easily without changing any of the principal characteristics of the NSSS. In the latter category are the design characteristics associated with such systems as containment, most parts of the control and plant protection, auxiliary feed water supply, most engineered safeguards, etc.

B.2. Safety-Related Intrinsic Characteristics of the NSSS

Table I.B.1 gives a list of some of the important safety-related characteristics intrinsic to CANDU-PHW reactors. Some of the implications of these characteristics listed in Table I.B.1 will be briefly discussed:

The fact that the primary coolant pressure boundary consists solely of tubes is one of the most obvious differences between CANDU reactors and LWRs of current U.S. design. This makes it possible to design the system for large tolerance to rupture of any single primary coolant pressure bearing component. It should be noted, however, that the pressure tubes are exposed to the full neutron flux, so that some degree of embrittlement may be expected with time. This may require some attention in that the probability of pressure tube-to-tube failure propagation has to be shown to be very low at any point in the life of the reactor. In LWRs, none of the stress-bearing components in the primary coolant boundary are exposed to the full neutron flux. It should be kept in mind, however, that the probability of catastrophic failure of a pressure tube in a CANDU reactor can be made extremely low, in view of the following considerations:

(1) the tube-wall thickness is smaller than the critical crack size for catastrophic failure ("leak-before-break"), and

(2) a leak of a pressure tube can be detected quickly (by means of the surveillance system analyzing the gas flowing in the annular space between pressure tubes and calandria tubes), thus allowing ample time for corrective action. It is furthermore noted that the pressure tubes in a CANDU-type reactor can be replaced with relative ease, whereas the pressure vessels of LWRs are intended for the entire life time of the plant. Regular inspection of the pressure tubes in the core region appears to be another important means to guarantee safety operation for CANDU reactors.

The subdivision of the CANDU core region into separate power channels has a number of further implications, some of which are listed in Table I.B.1 under items (2) through (4). One of the primary objectives of the current U.S. LWR-safety program is to prove timely reestablishment of cooling for all core regions by the ECCS following a LOCA. In the LWR, penetration of emergency coolant into the core is made difficult by generation of large volumes of steam (which tend to expel the coolant from the core region as soon as it enters), as well as by ECCS coolant bypassing. Similar problems may exist to some extent for CANDU reactors; however, the following considerations tend to make the emergency cooling issue less critical for CANDU reactors:

TABLE I.B.1. Some Important Safety-Related Intrinsic Characteristics of Heavy-Water-Moderated Pressure-Tube Reactors

Characteristics	Safety Implications
1. The pressure tubes (which are part of the primary coolant pressure boundary), traverse the active core region.	- Stress-bearing components of the primary coolant pressure boundary are subjected to the full neutron flux. - Rupture of a pressure tube in the core region has to be analyzed as part of the safety evaluation. - Probability for tube-to-tube failure propagation in core region must be proven to be very low and self-limiting. - Limited in-service inspectability of pressure tubes in core region must be shown to be acceptable.
2. The pressure tubes (having a relatively small wall thickness) have leak-before-break characteristic.	- The probability of catastrophic failure of a pressure tube is very small, because the tube will first develop a leak.
3. The pressure tubes are surrounded by calandria tubes, creating a gas-filled annular space between the tubes.	- A crack in a pressure tube, resulting in primary coolant leakage, is easily detected by means of the surveillance system analyzing the gas flowing between pressure tubes and calandria tubes.
4. The core is subdivided in separate fuel channels having individual coolant supply.	- The primary cooling system can be subdivided into a number of completely separate subsystems, thus allowing limitation of a loss-of-coolant accident (LOCA) to only a part of the core. - LOCA is mitigated by hydraulic resistance in piping. - The ECCS is capable of delivering emergency coolant to all core locations with low probability of performance failure. - The simple configuration of the power channels (pressure tube + fuel) allows relatively easy testing of ECCS performance (no scaling problems). - Faulty fuel can be easily detected, and located.

TABLE I.B.1 (Contd.)

Characteristics	Safety Implications
5. Relatively small inventory of high-enthalpic primary coolant.	- Relatively small energy release in case of LOCA. - Relatively low pressurization of containment.
6. Large inventory of cold moderator.	- Large heat sink in core region. - Decay heat removal by moderator cooling system prevents core meltdown in case of ECCS failure. - Large calandria tank for moderator may require special attention for seismic protection (this appears to be primarily an economic issue).
7. Total excess reactivity is small for natural uranium versions.	- Relatively mild power excursions due to accidental reactivity insertions.
8. Power-reactivity coefficient is negative.	- Transient-over-power (TOP) accident tends to be self-limiting.
9. Void-reactivity coefficient is positive.	- LOCA leads to a reactivity increase. - Transient-under-cooling (TUC) accidents lead to reactivity increase due to boiling in power channels.
10. The control rods and safety-shutdown rods are installed in the low pressure moderator region.	- There is no pressure-assisted reactivity accident associated with the control or shutdown rods (compare with rod-ejection accident in LWRs).
11. On-load refueling.	- Faulty fuel can be easily replaced without necessitating reactor shutdown. - Refueling malfunctions may result in small-scale LOCA. - Jamming of fuel subassembly during refueling operation could result in under-cooling incident, affecting a single channel. - Seismic event during refueling operation could cause mechanical interaction between refueling machines and feeder lines and calandria, resulting in a LOCA.

TABLE I.B.1 (Contd.)

Characteristics	Safety Implications
12. Burnup of fuel is low (< 10,000 MWD/ton).	- Fission product inventory is relatively small. - Fission gas pressure inside fuel pins is relatively small, allowing higher cladding temperatures before ballooning occurs following LOCA. This has as consequence that emergency coolant is not required in the early phase of the blowndown, so that a high pressure ECCS is not needed.
13. Inventory of tritium is relatively large.	- May require special attention.

(1) The time available for establishing emergency core cooling prior to the occurrence of substantial fuel damage (cladding ballooning and rupture, etc.) is longer for CANDU reactors than for LWRs in view of the lower fission gas pressure for the former;

(2) The simple configuration of the individual fuel channels tends to facilitate coolant delivery to all core locations (no downcomer region, etc.);

(3) Experiments aimed at verifying ECCS performance for CANDU reactors appear to be simpler and more conclusive in that the results are less scale-dependent;

(4) The correct performance of the ECCS does not constitute for CANDU reactors the final defense against core meltdown for a LOCA, as is the case for LWRs. Canadian analyses, supported by experiments, indicate that a LOCA combined with ECCS failure, though resulting in substantial fuel damage (including partial clad melting and loss of fuel bundle configuration) and deformation of the pressure and calandria tubes, does not result in fuel melting. The decay heat (up to 5% of nominal power) can be removed by conduction through the walls of the pressure and calandria tubes into the moderator, and rejected by the moderator cooling system.

For small breaks in the primary cooling system, long-term cooling in CANDU reactors can be provided by natural circulation. However, for a large-break LOCA, long-term cooling has to be provided by forced convection, in view of the horizontal orientation of the fuel channels.

CANDU reactors have a positive void-reactivity coefficient. However, the total excess reactivity available in a natural uranium system is rather limited, and it is possible to limit the total reactivity inserted by a LOCA by subdividing the primary cooling system into separate subsystems. This latter approach was followed for the Pickering nuclear power station, which has a primary cooling system consisting of two completely separate subsystems. However, for the Bruce nuclear power station, this option was not followed. The total reactivity introduced by completely voiding all pressure tubes in the core region at nominal operating conditions is $\sim$1% for the Bruce nuclear power station.

It is of interest to mention here that the CANDU reactors are not alone in having a pressure-assisted reactivity effect, capable of rapid positive reactivity insertion under accident conditions. LWRs also have pressure dependent positive reactivity effects: (1) Pressure increase in BWRs results in void collapse and reactivity insertion, and (2) Control rod ejection in PWRs and BWRs results in reactivity insertion.

The on-load refueling capability, listed in Table I.B.1 under point (11) has a number of safety-related implications; one is the possibility of mechanical interaction between the refueling machine and the feeder lines in case of a seismic event during the refueling operation, possibly resulting in a small-scale LOCA.

B.3. Safety-Related Non-Intrinsic Characteristics of the NSSS and the Balance of Plant

Table I.B.2 gives a list of some safety-related non-intrinsic characteristics of the NSSS and the balance of plant. It should be kept in mind that design changes have been, and are being, introduced from plant to plant so that some of the characteristics listed may apply to only one unit and not to another. As an example, the Pickering nuclear power station has four separate containment buildings which can separately be connected to the vacuum building, whereas the Bruce station has four permanently interconnected containment buildings, which can be connected to the vacuum building only as a group.

The use of computers for certain control functions may not conform to current U.S. licensing regulations and criteria. In CANDU plants, redundancy has been provided. Two nearly identical computers, linked only by a data channel, are operated in a main and standby configuration, and a strict separation between control and protective functions is maintained. Accommodation to current U.S. licensing regulations and criteria regarding redundancy (e.g., single failure criterion, etc.) of the various auxiliary systems and engineered safeguards could probably be accomplished without a major redesign of the NSSS.

B.4. Safety Approach and Accident Analysis

The Canadian safety approach, from its early inception, has displayed a tendency towards probabilistic risk assessments. The basic idea is that accidents with low frequency should be allowed to carry larger consequences than accidents with higher frequency. In order to formalize this approach, all systems pertaining to a CANDU reactor are subdivided into two classes, namely (1) the process systems, and (2) the safety systems. The first class (process systems) comprises all systems necessary

TABLE I.B.2. Some Safety-Related Non-Intrinsic Characteristics of Current CANDU-PHW Reactors

	Characteristics	Safety Implications
1.	Use of computers for:	
	- power control (both overall power and zonal power).	- Malfunction of zonal power control could possibly lead to localized burnout and fuel damage. This, however, would have only economic implications, unless the fuel damage were to be large enough to affect off-site doses.
	- control of on-line refueling operation.	- Malfunction of refueling machine could possibly result in small-scale LOCA.
	- annunciation and event recording.	- Results in improved plant surveillance.
	- recording of selected process variables.	- Results in improved plant surveillance.
2.	Protective functions are kept strictly separated from control functions and are performed by means of hard-wired circuitry.	- This limits considerably the safety implications of malfunction of the control system.
3.	Use of separate vacuum building for containment system.	- Provides subatmospheric conditions in the containment following a LOCA.
		- Makes it possible to keep containment spray function away from NSSS.
		- May increase sensitivity to seismic events (e.g., by rupture of connecting duct, etc.).
4.	Use of active components for vacuum building (valves, vacuum pumps, etc.)	- Valves could in many cases be replaced by rupture diaphragms.
		- Reliance on vacuum pumps could be reduced (e.g., by use of steel liner).
5.	Redundancy of various auxiliary systems and engineered safeguards systems, such as: - auxiliary feedwater supply - ECCS - containment cooling system - moderator cooling system - emergency power supplies, etc.	- Could be modified for construction in the U.S., if found in discrepancy with current U.S. licensing regulations and requirements.

for the normal operation of the plant (cooling systems, control systems, electrical systems, etc.), whereas the second class is made up of all safety systems, including the safety-shutdown system(s) (also moderator dump, if available), the ECCS, the containment system, etc. A design requirement is that there be absolute separation among safety systems, and between safety systems and process systems.

Accidents are categorized on the basis of whether they are of the single-failure type, i.e., caused by a single failure in any one of the process systems, or whether they are of the dual-failure type, i.e., caused by a single failure in any one of the process systems combined with a simultaneous and independent failure of any of the safety systems. The Atomic Energy Control Board (AECB) has established allowable irradiation doses for individuals and for the total population for the two accident categories. The plant designer has to show, for all postulated single- and dual-failure accidents, and for the particular plant in the particular site, that the calculated irradiation doses do not exceed the allowable values.

Up to and including the Pickering station, failure of the (fast-acting) plant protection system was considered in the accident analysis in combination with failures in the process system. However, starting with the Bruce station, this approach was modified because the reliability of the protection system was considerably improved by the addition of a diverse and fully redundant second scram system.* It appears that the combined failure rate of the two scram systems is now considered to be $<10^{-6}$ failures per demand, so that total failure of the plant protection system (i.e., failure of both reactor scram systems) is now excluded from accident analysis considerations.

Among the Design Basis Accidents (DBAs) considered is the double-ended rupture of a header, analogous to that considered in the U.S. for LWRs. This accident would result in blowdown of part of (Pickering), or the entire (Bruce), primary coolant system, and would require correct performance of the ECCS in order to avoid extensive damage to the fuel and core structure. However, as mentioned earlier, failure of the ECCS does not result in core meltdown. Emergency coolant is either D_2O (for Pickering), or H_2O (for Bruce), and is injected simultaneously into all headers.

B.5. Summary

The regulatory issues, that may have to be considered if CANDU reactors are to be constructed in the U.S., derive primarily from the fact that most of the U.S. Licensing Regulations and Regulatory Guides have evolved predominantly around the current generation of Light Water Reactor (LWR) power plants. The primary issue then appears to be not whether CANDU reactors meet adequate safety standards, but rather how much effort is required to introduce the CANDU technology into the U.S. regulatory environment.

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*The primary reactor scram system is based on gravity-driven shut-off rods (16 per unit for Pickering, 30 per unit for Bruce), whereas the second system for Bruce is based on injection of helium-pressurized gadolinium-nitrate into the moderator through perforated tubes traversing the entire calandria.

In the evaluation of the licensability in the U.S. of current as-built-in-Canada CANDU-PHW reactors, it is desirable to focus primary attention on the safety-related intrinsic characteristics of the NSSS, since most of the safety-related nonintrinsic characteristics of the NSSS and the balance of plant could be modified without changing the essential characteristics of the NSSS to meet U.S. licensing regulations and criteria.

Some of the principal safety-related intrinsic characteristics of CANDU-PHW reactors that may require further consideration are the following: (1) pressure tubes in the core-region may need evaluation of the probability of tube-to-tube failure propagation, the change of material properties due to irradiation (embrittlement, etc.), the nature, frequency, and limitations of pressure tube surveillance, and the applicability and possible discrepancies with U.S. codes and standards currently in force for the primary coolant pressure boundary of LWRs; (2) positive void-reactivity coefficients require consideration of the possible need for subdividing primary coolant system into independent separate subsystems; (3) on-load refueling capacity requires consideration of the possibility for small-scale LOCA due to malfunction during refueling operation, and the possible increased sensitivity to seismic events during the refueling operation.

Other areas that may require evaluation are the overall safety approach, the assumptions made with respect to hypothetical accidents, the redundancy of auxiliary systems and engineered safeguard systems, the reliability of the plant protection systems, and the safety implications of computer control (if any).

C. Miscellaneous Issues

The CANDU-PHW reactor does represent a different base of experience, and aside from economic and safety considerations, there are issues concerning plant performance and engineering that may become important in the implementation of a different technology. A few such issues are:

C.1. Plant Performance

The importance of plant performance and resulting capacity factors in the analysis of power generation costs has been discussed above. CANDU-PHW reactors currently demonstrate a better capacity factor than LWRs in the U.S. But the information regarding CANDU performance is limited to the operations of the single Pickering plant. The issue is whether or not a high capacity factor is a general characteristic of CANDU reactors.

The total lost production time at Pickering is reported to be split about evenly between problems associated with the NSSS and the conventional portion of the plant. The NSSS problems included failure of pressure tubes in two units, malfunction of the fuel handling system during refueling, and in-service inspection. Non-NSSS problems included malfunctions or defective parts in turbines and auxiliary equipment.

The average unit plant capacity factor for the fifty-four U.S. licensed power reactors was 62.7% from January to August 1975, and has been 64.2% for twenty nuclear units reporting for the period of 1964-1973. A recent survey[8] of seven LWR units provides the following information:

		% Capacity Factor Reduction
NSSS:	Refueling	-- 7.7
	Defective fuel	-- 3.0
	Steam generators	-- 4.6
	Reactor internals	-- 3.0
	Regulatory restrictions	-- 4.5
	Testing	-- 0.9
	Miscellaneous	-- 4.5
		28.2%
Conventional:	Turbine	-- 2.8
	Condenser	-- 1.6
	System Load	-- 0.8
	Miscellaneous	-- 3.9
		9.1%
	TOTAL	37.3%

Factors unrelated to the reliability of the system (refueling, testing, regulatory restrictions, etc.) contribute 14.4% of the total 37.3% reduction. Except for refueling and possibly defective fuel, these factors probably apply in somewhat the same manner to CANDU reactors operated in the U.S. The contribution due to the conventional portion of the plant appears to be about the same as for CANDU reactors.

The on-line refueling capability of the CANDU reactor might have contributed significantly to the high capacity factors achieved by the Pickering Generating Station. However, it is difficult to quantify this contribution because in LWRs other necessary routine inspection and preventive maintenance are also performed during the scheduled refueling outage. Other factors should also be considered, such as; the plant size (500 MWe for CANDU versus ∿1000 MWe for current LWRs) which could affect the equipment size and its reliability, the system load requirement, the technical specifications and quality control of manufacturing processes, the regulatory requirements, and the effect of design evolutions. All of these factors should be analyzed in detail to evaluate the intrinsic characteristics of the CANDU plant performance as compared to that of LWRs.

C.2. Heavy Water Systems

Since heavy water is expensive, the CANDU system has been engineered to minimize the loss rate of heavy water in the reactor system. Special valves and pump seals, air driers, sealed rooms, etc., are all items related to the use of heavy water that are necessary and these items probably show up in power generation costs as part of the larger capital costs of CANDU reactors. The fact that heavy water loss rates have been held to acceptable low levels (∿1.6 kg/hr in Pickering) indicates that the engineering problems associated with a heavy water system may not be an issue. However, as with any heavy water reactor system, there is the additional hazard associated with the release of tritium. The maintenance of certain CANDU systems (pumps, valves, refueling machine, etc.) represent the greatest source of tritium dose and special measures must be taken to protect plant personnel.

C.3. Large Components

Some problems may arise with introduction of a different reactor technology in the manufacture and use of certain large components in the steam generation plant. Data concerning boilers and coolant pumps is compared for the CANDU Pickering plant and a U.S. LWR plant in Table I.C.1. The size of the Pickering CANDU steam generators and main coolant pumps are generally smaller than in U.S. pressurized water reactors and it appears that the U.S. manufacturing and operating experience regarding these two large components scopes the CANDU requirements in most important aspects.

TABLE I.C.1. Large Plant Components

	Pickering	LWR[a]
Boiler Data		
Performance		
Total number of boilers	12	2
Rate of heat load/boiler, MWt	171	642
Steam output, lb/hr	6.5×10^6	5.6×10^6
Steam pressure, psia	593	1050
Steam temperature, °F	485	570
Feedwater temperature, °F	340	455
Primary fluid	Heavy water	Light water
Water flow, lb/hr	5.8×10^6	6.5×10^6
Water inlet temperature, °F	560	604
Recirculation ratio (minimum)	8.0	Once through
Moisture in steam, wt %	0.20	Superheated
Steam superheat, °F	-	35
Physical		
Height (overall including steam head)	∿46 ft	68 ft
Outer diameter - heat exchanger	∿6 ft	13 ft
Number of tubes per boiler	2600	15,530
Tube material	Monel	Inconel alloy 600
Outer diameter of tubes, in.	0.50	0.625
Wall thickness of tubes, in.	0.049	0.034
Main Coolant Pumps		
Total	16	4
Operating	12	4
Standby	4	0
Arrangement, pumps/boiler	4	2
Type	Vertical Single Stage	Vertical Single Stage
Power, hp	1570	9000
Flow, gal/min	12,100	88,000
Pressure, psig	1600	2500
Head, ft	480	350
Seals	Mechanical	Mechanical

[a]LWR data pertains to the Oconee Unit 1 plant.

II. LONGER-TERM ISSUES

A. Economics

A.1. Projected Power Generation Costs

Because of the lead times involved, the present version of CANDU is likely to be the only one of commercial interest for the 1980's. Some projections of future CANDU and LWR costs are available, but these estimates must be regarded as highly uncertain. However, the sensitivity of power costs to important factors may be demonstrated and future power costs may be compared for possible ranges of these factors.

A.1.1. Capital Costs

The difficulty and uncertainty associated with any attempt to estimate capital costs has been pointed out in Section A.1. Some recent estimates of power plant capital costs for plants coming on-line during the next ten years are available and they are summarized here. These capital cost estimates are displayed in Fig. 1.

CANDU capital cost estimates are available for two CANDU stations being built in Canada, the BRUCE A and BRUCE B plants. Each plant will include four 750 MW(e) units. The BRUCE A plant will be brought on-line beginning in 1977 with the last unit on-line in mid 1979. The cost of the BRUCE A plant is estimated to be \$586/kW(e) with the initial inventory of heavy water contributing \$128/kW(e).[2] The BRUCE B plant will be brought on-line over the period 1983 to 1985. The cost of the BRUCE B plant is estimated to be \$1320/kW(e) with the cost of heavy water contributing \$249/kW(e).[2] The cost estimates are based upon a predictive economic model where costs are inflated at rates ranging $\sim$7.5% in the 1970's, up to 10.5% in the early 1980's.

For LWRs in the U.S., an estimate computed with the CONCEPT code gives \$815/kW(e) for a 1140 MW(e) plant located in the Northeast and coming on-line in 1982.[17] This estimate is updated for the most recent changes in regulatory requirements and is based on assumed inflation rates of 10% for labor, 6% for equipment, and 5% for material. For a LWR coming on-line in 1986, a survey of three architect engineering firms yielded the following estimates:[18] (1) \$1150/kW(e) for 1100 MW(e) plant located in the midwest, (2) \$1100/kW(e) for plant with twin 1000 MW(e) units located in "Middletown," (3) \$1050/kW(e) for a 1150 MW(e) plant located in "Middletown." These three estimates used constant cost inflation rates ranging 7-9% for equipment, materials and labor and 8-9% for the cost of capital.

These estimated capital costs are compared in Fig. 1. While the BRUCE A cost appears to be comparable to LWR costs in the period around 1980, it must be noted that a cost estimate for a CANDU plant built in the U.S. would have to include estimates of possible design modifications and equipment changes needed to satisfy U.S. standards and regulatory requirements. Estimates of factors such as these are very subjective and it may be more useful for present purposes to treat capital costs as a variable and to examine the range of possible CANDU capital costs that yield power costs comparable to LWR estimates.

In Fig. 4, the fixed charge costs, mills/kWhr, for LWRs are displayed as a function of capital costs at a fixed charge rate of 15%. The fixed charge costs are shown for ranges of capacity factors. If capacity factors remain at the level achieved today (average CF $\gtrsim$ 63%) fixed charge costs may range 25-35 mills/kWhr for capital costs around \$1100/kW(e) for LWRs. If current capacity factors achieved by CANDU reactors were assumed for reactors operating in the U.S. in the mid 1980's, capital costs 20% greater than LWR costs (i.e., \$1300/kW(e)) would offer the same fixed charge costs.

If all conventional plant problems were solved by 1985, such that only factors unrelated to plant reliability limit plant availability, capacity factors for both CANDU and LWRs will improve, and the differential in capacity factors becomes less important. The maximum capacity factor for an LWR would be $\sim$85% and in this case, the fixed charge costs would be $\sim$20 mills/kW(e). Because of on-line refueling, the CANDU reactor may have the potential to achieve a capacity factor that is a few percent greater than LWRs, and capital costs only a few percent greater than LWR costs would then offer the same fixed charge costs.

The uncertainty in the estimates of future capital costs and plant capacity factors allow no definite conclusions regarding relative fixed charge costs for LWRs and CANDUs operating in the U.S.

A.1.2. Heavy Water

The current (1975) price of heavy water is \$110-120/kg, with the cost of coal the prime factor affecting the price of heavy water. About two-thirds of the production capabilities of the Savannah River facilities have been shut down over the years. Otherwise, heavy water is not a scarce commodity. The production is standard; coal may be replaced by nuclear power for steam generation, and the cost of heavy water has not and should not rise as rapidly as other factors such as U_3O_8 prices and construction costs. Heavy water costs currently make up 20% of the total capital costs of a CANDU-PHW plant and this fraction is not expected to increase in the future.

The current capacity of the remaining heavy water production facilities at Savannah River is about 175 MT/yr. The plant is old and is not optimized for the high cost of coal. The current stockpile of heavy water is about 380 MT and is projected to remain so until about 1980 when the reserve is projected to be about 600 MT. The heavy water inventory requirement for the current CANDU-PHW design is about 1 MT/MW(t), and if CANDU plants of this type are to be built in the 1980's or later, additional heavy water production capacity would be required. The capital invetment for such a plant would be large. For a Canadian plant capable of producing $\sim$800 MT/yr, beginning late in 1977, the cost was estimated to be \$550,000,000.[6] Such a plant along with the present Savannah River plant, could produce enough heavy water to bring one 1000 MW(e) CANDU plant on-line each year and also supply heavy water for upkeep.

There are CANDU designs that require less heavy water inventory. Designs of large (1250 MW(e)) CANDU-PHW reactors anticipated (by Ontario Hydro) for the 1980's require about 0.75 MT/MW(e) and CANDU reactors employing enriched fuel would require less than this amount.

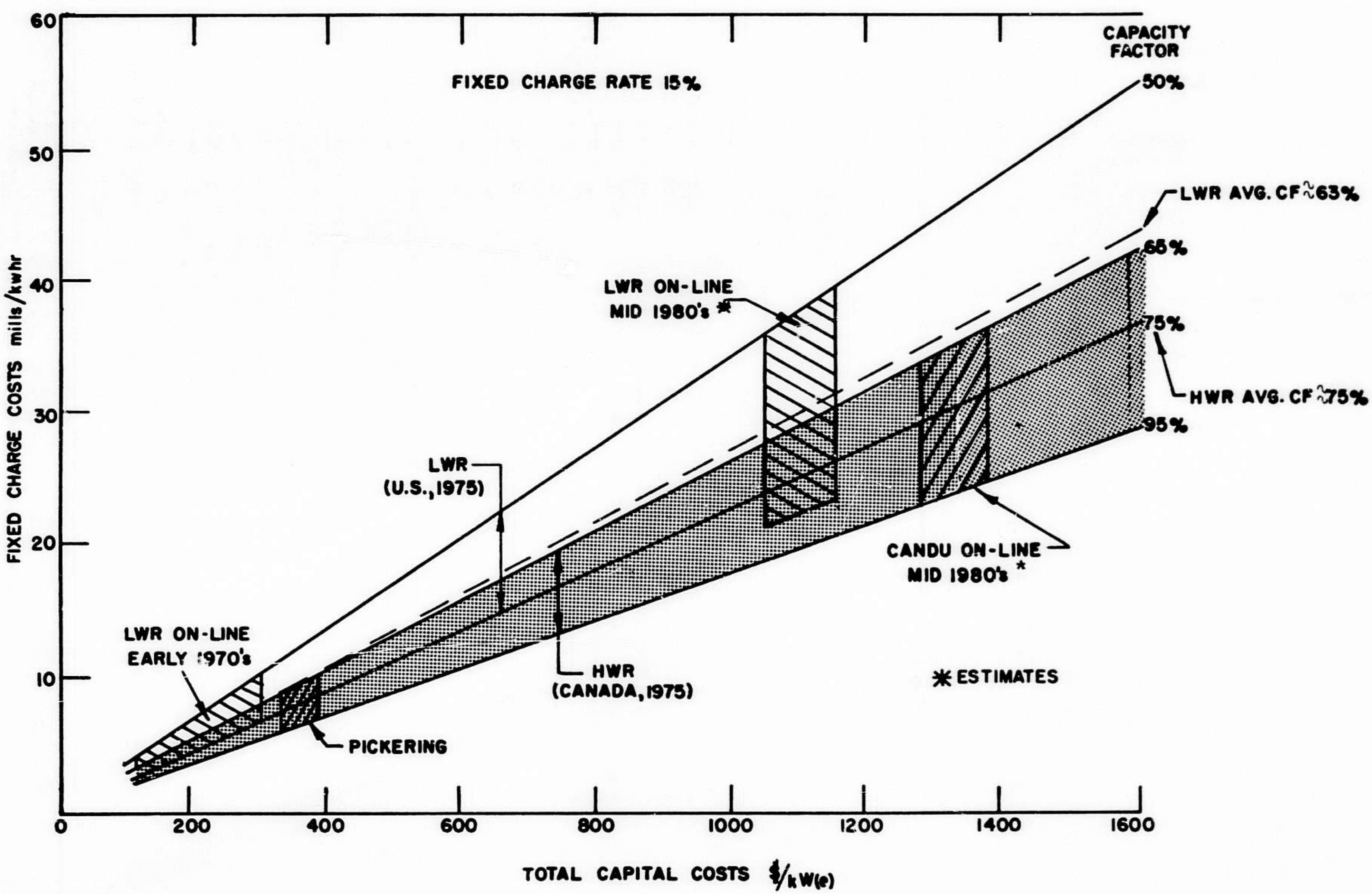

Fig. 4. Power Generation Costs due to Fixed Charges as a Function of Total Capital Costs and Capacity Factor. ANL Neg. No. 116-77-61.

A.1.3. Fuel Cycle Costs

Fuel cycle cost estimates for light water reactors and for CANDU-PHW reactors operating in the 1980's are presented in Table II.A.1. These estimates were calculated for the equilibrium fuel cycles characterized in Table I.A.3. The costs (1975 dollars) and other pertinent parameters used to arrive at these estimates are summarized in Tables II.A.2-.3. The costs assumed (Table II.A.2) correspond closely to costs being used now by U.S. utilities to estimate fuel costs in the 1980's. Note that the uranium price assumed is \$30/lb U_3O_8 the enrichment cost is \$75/kg SWU, and the reprocessing cost for both the LWR and CANDU is taken to be \$120/kg HM.

TABLE II.A.1. Fuel Cycle Cost Estimates for 1980's (mills/kWhr 1975 \$)

	LWR			CANDU	
	No Recycle	U Recycle	U + Pu Recycle	No Recycle	Pu Recycle
U_3O_8	2.50	1.95	1.54	1.70	0.86
UF_6	0.08	0.06	0.05	-	-
Enrichment	1.82	1.74	1.31	-	-
Fabrication	0.54	0.54	0.64	0.84	0.76
Reprocessing	(a)	0.32	0.32	(a)	0.79
Shipping	0.04	0.04	0.04	0.18	0.09
TOTAL	4.98	4.65	3.90	2.72	2.50

[a]For no-recycle cases the reprocessing or discharged fuel permanent disposal costs are not estimated.

TABLE II.A.2. Fuel Cycle Cost Parameters for the 1980's (1975 \$)

1.	Uranium	\$30/lb U_3O_8
	Thorium	\$10/lb Th
	UF_6 conversion	\$2.5/kgU
	Enriching	\$75/kgSWU
	Fabrication	
	LWR-U	\$100/kgHM
	CANDU-U	\$40/kgHM
	Pu penalty	+80%
	^{233}U penalty	+150%
	Reprocessing	\$120/kgHM
	Shipping	\$10/kgHM
2.	Annual carrying charge rate	15%
3.	Tails assay	0.2%
4.	Pu and ^{233}U value	Zero for self-generated recycle

TABLE II.A.3. Loss Factors and Lead Times

1. Loss Factors		
U_3O_8-UF_6	0.5%	
Fabrication	1.0%	
Reprocessing-U	1.0%	
Reprocessing-Pu	1.5%	
2. Lead Times (months)	LWR	CANDU
U_3O_8-Loading	12	9
UF_6-Loading	10	-
Enrichment-Loading	8	-
Fabrication-Loading	4	6
Discharge-Reprocessing	9	6

The CANDU fuel cycle costs are estimated to remain 1-2 mills/kWhr less than for light water reactors in the 1980's. But considering reasonable uncertainties associated with the fuel cycle cost parameters and the fact that the capital costs are characterized by large uncertainties, this fuel cycle cost differential is not very significant. The results in Table II.A.1 do demonstrate that the LWR fuel cycle costs will be dominated by U_3O_8 and enrichment costs, and in the case of CANDU, the reprocessing cost will be as high as the U_3O_8 cost (due to the large annual discharge quantity in the CANDU fuel cycle).

The sensitivity of the LWR uranium-recycle and CANDU once-through fuel cycles to selected parameters is summarized in Table II.A.4. These estimates are based on the sensitivity coefficients listed in Table II.A.5. The most important parameter is the price of U_3O_8, but, as the results indicate, both CANDU and LWR fuel cycle costs display about the same sensitivity to this cost parameter. The net effect (LWR-CANDU) is only a small differential in fuel cycle costs, even for large changes ($100/lb) in the price of U_3O_8. An enrichment price increase of $50/kgSWU gives a cost differential of 1.2 mills/kWhr in favor of CANDU. Price increases in fabrication and reprocessing favor light water reactors due to the lower discharge burnup, and hence the larger quantities of fuel handled in the CANDU reactors.

In Table II.A.4, only the LWR uranium recycle case is tabulated. The sensitivity coefficients associated with the other possible fuel cycles indicate that the LWR no-recycle case would show a slightly larger sensitivity to the price of U_3O_8 but the differential effect (LWR-CANDU) is still small. The same result holds for the case of plutonium recycle.

TABLE II.A.4. Sensitivity of Fuel Cycle Cost to Selected Parameter Changes (Δ mills/kWhr)

	LWR U Recycle	CANDU No Recycle	LWR-CANDU Differential
1. U_3O_8, Δ$/lb U_3O_8			
10	0.65	0.57	0.08
50	3.25	2.84	0.41
100	6.50	5.68	0.82
2. Enrichment, Δ$/kgSWU			
10	0.23	0	0.23
50	1.16	0	1.16
3. Fabrication, Δ$/kgHM			
10	0.05	0.21	-0.16
50	0.27	1.05	-0.78
4. Reprocessing or Disposal, Δ$/kgHM			
10	0.03	0.16	-0.13
50	0.14	0.78	-0.64
5. Carrying Charge Rate, Δ%			
1	0.07	0.03	0.04
5	0.32	0.13	0.19

TABLE II.A.5. Fuel Cycle Cost Sensitivity Coefficients, Δmills/kWhr/Δ Unit Cost

	LWR			CANDU	
Unit Cost	No Recycle	U Recycle	U & Pu Recycle	No Recycle	Pu Recycle
Uranium, $/lb U_3O_8	0.0834	0.0650	0.0512	0.0568	0.0288
Enrichment, $/kgSWU	0.0242	0.0232	0.0175	-	-
Fabrication					
U fuel, $/kgHM	0.0054	0.0054	0.0040	0.0209	-
Pu fuel, $/kgHM	-	-	0.0013	-	0.0105
Reprocessing, $/kgHM	0.0027	0.0027	0.0027	0.0155	0.0065
Annual carrying charge, %	0.0877[a]	0.0638	0.0501	0.0251[a]	0.0059

[a]Carrying charge not included for reprocessing.

Thus, the results of the sensitivity analysis indicate that even for large uncertainties that may exist in fuel cycle cost estimates, the differential between CANDU and LWR fuel cycle costs is expected to remain relatively small. Small differentials in operational costs from the fuel cycle are offset to some degree by the D_2O upkeep costs, and hence, operational cost differentials between CANDU reactors and LWRs are expected to remain small.

A.2. Fuel Utilization

A.2.1. Current Reactor Types

The lifetime U_3O_8 requirements (initial core plus 30-year refueling) and cumulative net fissile production for a 1000 MW(e) plant are compared below for LWRs, CANDU reactors and HTGRs based on an 80% capacity factor and 0.2% tails assay. (These results are based on the data in Table I.A.3.)

	Uranium Requirement (ST U_3O_8)	Fissile Production (Net kg)
1. LWR - no recycle	6800	5230
2. Basic uranium cycle		
LWR - U Recycle	5410	5230
CANDU - no recycle	5190	10180
HTGR - no recycle	4820	6110
3. Self-generated recycle		
LWR - U+Pu recycle	4370	1500
CANDU - Pu recycle	2540	560
HTGR - ^{233}U recycle	2960	760

For the basic uranium cycle the difference in uranium consumption between LWR and CANDU is insignificant and uranium conservation offers little incentive for introduction of CANDU reactors based on the throwaway cycle.

The fissile plutonium production in CANDU reactors is greater than in LWRs and the fuel utilization can be improved significantly in CANDU reactors by using self-generated plutonium recycle. However, the economic incentive to recycle plutonium in CANDU remains questionable. As shown in Table II.A.1, significant savings in U_3O_8 and enrichment costs could be realized for the case of plutonium recycle in LWRs. In CANDU, however, the savings in U_3O_8 cost are almost offset by the high reprocessing cost. Thus, while plutonium recycle in CANDU does result in a significant reduction in U_3O_8 requirements, the amount of uranium resource conservation for the near future may not be of practical significance in the light of overall fuel cycle costs. If ultimate resource utilization is the important issue, the relevant fuel cycles to examine are thorium-based.

A.2.2. Thorium Cycle in CANDU

a. Design Considerations

The $Th/^{233}U$ cycle is intrinsically a better thermal reactor fuel cycle than the $^{238}U/^{235}U$-Pu cycle because of the high thermal η for ^{233}U. The use of thorium can substantially improve the conversion in any thermal reactor type, but the neutron economy of D_2O allows more potential for flexibility in the design of CANDU reactors for high conversion ratios than is possible for H_2O moderated systems. Some of the trade-offs associated with high fuel utilization in CANDU reactors are discussed below and summarized in Table II.A.6.

A higher specific power reduces the size of the core and hence the D_2O inventory. However, the conversion ratio is also reduced and a higher fissile makeup is required to obtain the same burnup. Thus if the capital cost is the dominant component of power costs, a high specific power would be favored at the expense of fuel utilization. Very high U_3O_8 costs would tend to lower specific powers. The range 16-38 kWth/kgHM is currently being considered in the CANDU-thorium cycle.[19-21] This range represents approximately a 20% differential in capital costs.

Reducing the lattice pitch also reduces the capital cost by reducing the D_2O inventory. A reduction of the lattice pitch from the current value 28.6 cm to the 22.9 cm used for some of the advanced designs gives a capital cost reduction of 5-7%. The conversion also suffers, however, and high fuel costs would tend to hold the lattice pitch at the current value.

The burnup capability is directly related to the fissile makeup for a given specific power and lattice pitch. Typical CANDU thorium-cycle performance characteristics are listed in Table II.A.7, illustrating the dependence of burnup on plutonium makeup required. As the burnup is increased from 10 to 33 MWD/kgHM the conversion ratio is reduced from 1.0 to 0.9. If fabrication and reprocessing costs are high, relatively high burnup would probably be favored over improved fuel utilization.

Boiling light water or organic coolants substantially reduce the D_2O inventory ($\sim$10% savings in capital cost), and have other advantages as well. Increased neutron absorption in the coolant, however, again decreases conversion.

In Table II.A.7 a wide range of CANDU thorium-cycle performance characteristics are illustrated.[19] If a design with a small lattice pitch (22.9 cm) and a high specific power (38 kW/kgHM) is chosen to reduce the capital cost, then the U_3O_8 requirement at a burnup of 30 MWD/kg is about 80 ST U_3O_8/GWe-yr, and this is $\sim$50% of the natural uranium fueled CANDU-PHW or about the same as the plutonium recycle case in standard CANDU-PHW. On the other hand, for a lattice pitch of 28.6 cm and specific power of 29 kW/kgHM, a conversion ratio of 1.0 is feasible at 10 MWD/kgHM provided that the fabrication and reprocessing losses can be kept below 1% and neutron economy is emphasized.[19]

TABLE II.A.6. CANDU Th Cycle Optimization

	Pickering Station Data	Standard PHW-NU[a] Data	Ranges Considered for Th Cycle	Major Effect on Capital Cost and Fuel Utilization	Optimum Trend for: Capital Intensive	Optimum Trend for: U_3O_8 Cost Intensive	Optimum Trend for: Fab-Rep Cost Intensive
Specific Power (kWth/kgHM)	19 (28 pins)	26 (37 pins)	16-38	Increased specific power: 1. Reduced D_2O Inventory 2. Poor fuel utilization - increased fissile makeup or reduced burnup	High[b]	Low	Med
Lattice Pitch (cm)	28.6	28.6	28.6-22.9	Reduced lattice pitch: 1. Reduced D_2O inventory 2. Poor fuel utilization - increased fissile makeup or reduced burnup	Low	High	High
Burnup (MWD/kgHM)	7.5	7.5	10.0 up	Increased burnup: 1. Poor conversion ratio 2. Increased fissile makeup	-	Low	Med
Coolant	PHW	PHW	PHW BLW OCR	BLW & OCR: Reduced D_2O inventory OCR: Higher thermal efficiency and higher specific power limit	BLW or OCR	-	-

[a]CANDU-PHW, natural uranium fueled.

[b]For example, a "High" specific power is the optimum trend if capital costs are dominant.

TABLE II.A.7. CANDU-PHW Th Cycle Characteristics

	Fixed Lattice Pitch and Specific Power							Fixed Burnup				
Lattice pitch, cm				28.6				28.6	28.6	28.6	22.9	22.9
Specific power, kWth/kgHM				29				22	29	38	29	38
Burnup, MWD/kgHM	10	20	25	33	40	44	47			30		
Conversion ratio	1.0	0.96	0.93	0.90	0.87	0.85	0.84					
Reactor ratio, Th/NU[a]	-	5.79	4.21	2.73	2.14	1.80	1.66	4.78	3.01	2.14	1.38	1.13
Th-fuel residence time, yrs	1.2	2.4	3.0	3.9	4.7	5.2	5.6	4.7	3.5	2.7	3.5	2.7
Pu makeup, gm/kgHM[b]	0	1	2	4	6	8	9.3	2.0	3.4	4.9	7.6	9.3
Equilibrium loading,[c] MTHM/GWe-hr												
Natural uranium	0	18.8	24.5	34.2	40.7	45.6	48.0	22.1	31.8	40.7	53.6	59.9
Th + ^{233}U	95.7	40.8	30.9	21.2	16.3	14.0	12.7	26.4	24.0	21.8	18.5	16.9
U_3O_8 requirement,[c] ST/GWe-yr	0	24.7	32.2	44.9	53.4	59.9	63.0	29.0	41.8	53.4	70.4	78.7

[a]Ratio of CANDU reactors operating on the Th-U cycle to CANDU reactors operating in natural uranium cycle.

[b]Pu makeup is supplied by natural fueled CANDU reactors.

[c]At 80% capacity factor.

b. Fuel Cycle Cost Characteristics

Both the choice of concept and the design of a commercial reactor utilizing the thorium cycle will evolve from economic optimizations. Cost sensitivities to U_3O_8, fabrication and reprocessing prices for thorium-cycle CANDU reactors are given in Figs. 5 and 6. The fuel cycle costs for various thorium cycles presented in Table II.A.7 are illustrated in Fig. 5 as a function of the conversion ratio. The base case in Fig. 5 is based on the assumptions and cost parameters presented in Table II.A.2-3 (U_3O_8 = $30/lb, fabrication = $100/kgHM, reprocessing = $120/kgHM). For a wide range of conversion ratios (0.85-0.95) in the base case the fuel cycle cost is almost constant and as the conversion ratio approaches 1.0 the fuel cycle cost is increased by 75%. As the uranium price is increased to $100/lb U_3O_8 (other parameters held constant) the low conversion ratio is penalized, and as the fabrication price is increased to $200/kgHM the high conversion ratio is penalized more, as expected. The impact of an increase in the reprocessing cost is similar to a fabrication price increase. If conversion ratios of 1.0 and 0.9 are compared, the breakeven fuel cycle cost occurs at a uranium price of $125/lb U_3O_8, for the fixed fabrication price of $100/kgHM. On the other hand, if the uranium price is less than $50/lb the fuel cycle cost for CR = 1.0 is greater than for CR = 0.9 even at zero fabrication cost. In Fig. 6 the relationship between the fabrication cost and the uranium price which gives the same fuel cycle costs for CR = 1.0 and 0.9 is illustrated

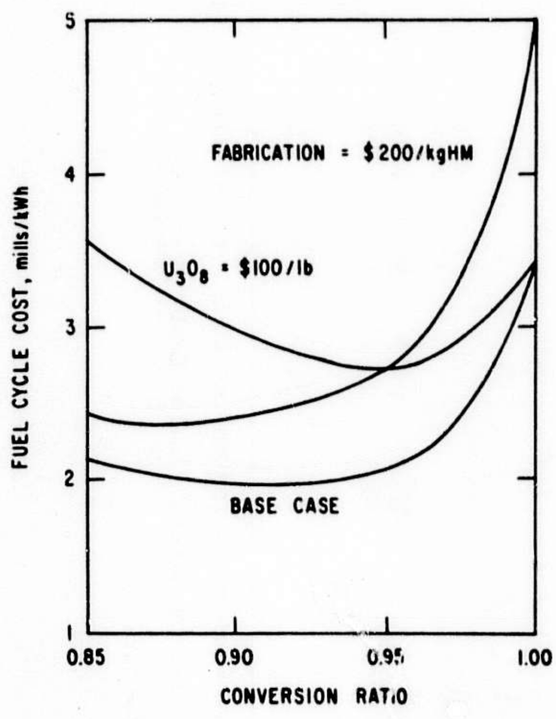

Fig. 5. Effect of Conversion Ratio of Fuel Cycle Cost. ANL Neg. No. 116-77-63.

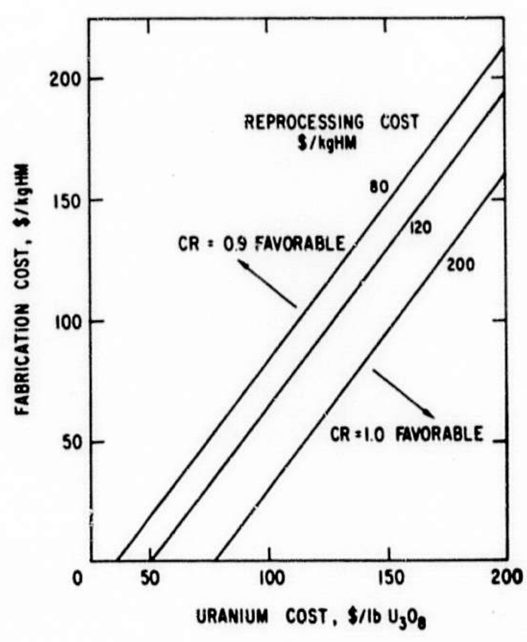

Fig. 6. Influence of Fabrication, Reprocessing and U_3O_8 Cost on Economic Choice of Conversion Ratio, CANDU Thorium Cycle. ANL Neg. No. 116-77-54.

for various reprocessing costs. Figure 6 illustrates that unless the uranium price is very high (~\$150/lb U_3O_8) and the fabrication cost of ^{233}U bearing fuel is low (<\$100/kgHM) the self-sufficient thorium cycle (CR = 1.0) cannot compete economically with designs with a lower conversion ratio.

A.2.3. Long-Term Fuel Utilization of Thermal Near-Breeders Using Thorium Fuel

a. Fuel Utilization Characteristics

Thermal reactors designed to operate on self-sufficient Th/^{233}U fuel cycles at best have a marginal breeding gain and thermal breeders (except possibly the MSBR) cannot produce appreciable excess fissile material. Self-sufficiency is only possible with ^{233}U as the fissile material, and if self-sufficiency is required from the beginning the core must be externally supplied with ^{233}U. If other fissile materials (^{235}U or ^{239}Pu) are used for the initial core, a few transition cycles are required to reach an equilibrium. The fuel utilization characteristics of thermal converters and near-breeders are summarized in Table II.A.8. The initial core fissile inventory requirement is about 2000 kg for a 1000 MWe CANDU near-breeder and 2000-4000 kg for a LWBR depending upon fuel type (highly enriched uranium, slightly enriched uranium, or plutonium), specific power, and design burnup.

TABLE II.A.8. Fuel Utilization Characteristics of Thermal Converters and Near-Breeders (1000 MWe)

	CANDU	LWBR	HTGR	MSBR
CR or BR	1.0	1.0	0.9	1.07
Initial core fissile Inventory (kg)[a]	2000	2000-4000	4800	1500
Annual uranium requirement (ST U_3O_8/yr)	0	0	35	0
Lifetime uranium requirement[b] (ST U_3O_8)	1100	1800-4000	2300	~0[c]

[a]Indicated data are estimated based on fissile Pu for CANDU, ^{235}U or fissile Pu for LWBR, ^{235}U for HTGR, and ^{233}U for MSBR.

[b]U_3O_8 required to achieve equilibrium cycle plus annual feed (if required) for 30 years.

[c]Excess fissile production of 50 kg/yr is assumed to compensate the initial core inventory.

The lifetime uranium requirement for a CANDU near-breeder is about 1100 short tons of U_3O_8 if enriched uranium feed is used. This requirement will be doubled if the CANDU near-breeder is fueled by plutonium produced in the natural uranium fueled CANDU because about 0.5 gm of fissile plutonium is produced per gm of ^{235}U consumed. The lifetime uranium requirement for the LWBR ranges from about 1300 to 3000 short tons of U_3O_8 depending on the fuel type, specific power and design burnup.[22] Also shown in Table II.A.8 for comparison are the characteristics of a high conversion HTGR, and a MSBR.

The CANDU near breeder has a smaller uranium requirement than the LWBR but other considerations may influence the utilization of these advanced reactors; e.g., LWBRs have an advantage if they can be accommodated in existing LWR facilities.

b. Implications on Uranium Resource and Power Growth

The most basic question associated with the thermal near-breeder is whether it could remove the need for the fast breeder. As shown in Table II.A.8, the thermal breeders are at best self-sufficient, and then only in their equilibrium condition. The total power capacity that can be installed will be limited if the uranium supply is limited and the final power capacity achieved will depend upon system characteristics. For example, in the LWR uranium recycle case (Table I.A.2), 180 kg of fissile plutonium per GW(e)/yr are produced in each LWR consuming 163 ST of U_3O_8 per GW(e)/yr and thus $\sim$1.1 kg of plutonium are available per short ton of uranium consumed to start up a thermal converter. In a system made up of CANDU natural uranium reactors, $\sim$2.0 kg of plutonium are produced per short ton of uranium consumed. Thus, in power systems limited to just these reactor types and assuming equivalent inventories required for startup and transition to equilibrium cycle in the converter reactors, a system made up of natural uranium and thorium cycle CANDU reactors could establish an equilibrium power generation capacity nearly twice that of the LWR-LWBR system. For a non-growth power system with a fixed equilibrium nuclear power capacity, thermal near-breeder reactors could conceivably replace the fast breeder reactors. For a growing power system, however, the need for fast breeder reactors with sufficient breeding capability is inevitable if the uranium supply at economically affordable recovery cost is limited in the long-term.

A separate question is whether the thermal breeder could stretch out the limited uranium supply and thus allow a useful delay in FBR introduction. If thermal breeders are introduced into the power economy, then a full commitment to these reactors at least for the order of a few decades would be required to capitalize the RDD efforts required to introduce a new fuel cycle. This issue is sensitive to estimates both of uranium resources and power growth rates in the intermediate future.

We have taken a brief look at the possible impact of thermal near-breeders in a growing power system -- a simplified model of the U.S. nuclear power economy. The nuclear power growth rate assumed was that given in the Final Environmental Statement for LMFBR Program,[23] (590 GWe in 2000 and 1830 GWe in 2030). We used ALPS,[24] an LP optimization code, to compare the cumulative uranium requirements for the following five scenarios.

Case 1: LWR only

Case 2: LWR + Near-Breeder (1995 introduction)

Case 3: LWR + LMFBR (1995 introduction)

Case 4: LWR + Near-Breeder (1995 introduction) + LMFBR (2015 introduction)

Case 5: LWR + LMFBR (2015 introduction)

The advanced reactor types are introduced starting 1995 with constraints on introduction rate and the plutonium availability. Both the near-breeder and the LMFBR were assumed to be fueled initially with fissile plutonium produced in LWRs. Plutonium was recycled in the LWR when the storage costs (assumed to be $500/kg-yr) exceeded the savings possible from reduced uranium requirements that would result from the introduction of additional near-breeders or LMFBRs at a later date. The U_3O_8 price was assumed to be the function of the cumulative consumption shown in Fig. 7.

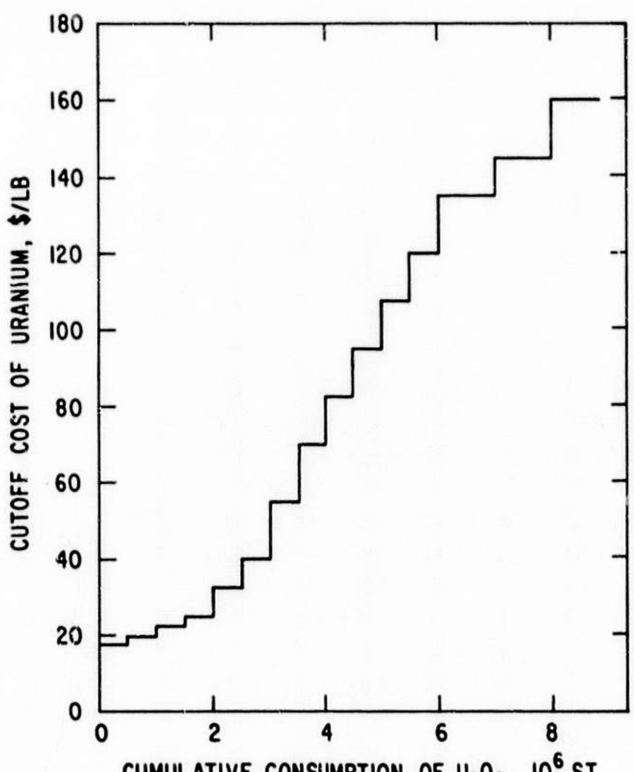

Fig. 7

Assumption on Uranium Price vs. Cumulative Consumption (data source Ref. 22). ANL Neg. No. 116-77-57.

The near-breeder characteristics were those of a CANDU on a thorium-cycle with CR = 1.0 at equilibrium. (Initial core inventory is 2000 kg/GWe and additional fissile makeup and external inventory requirements until the equilibrium is reached were estimated to be 2300 kg/GWe.) The LMFBR was assumed to have an initial core inventory of 3000 kg/GWe and an external inventory of 1600 kg/GWe. (The corresponding compound doubling time was 15 years.)

The cumulative uranium requirements for the five scenarios listed above are presented in Fig. 8, and the LWR capacity installed are presented in Fig. 9. Comparison of Cases 1 and 2 indicates a reduction in uranium requirements of the order of 20% from the LWR plutonium recycle base case for near-breeder introduction in 1995, with uranium requirements continuing to increase as long as demand increases. In contrast, Case 3, fast breeder introduction in 1995, limits consumption to levels consistent with current estimates of economic U.S. uranium resources.

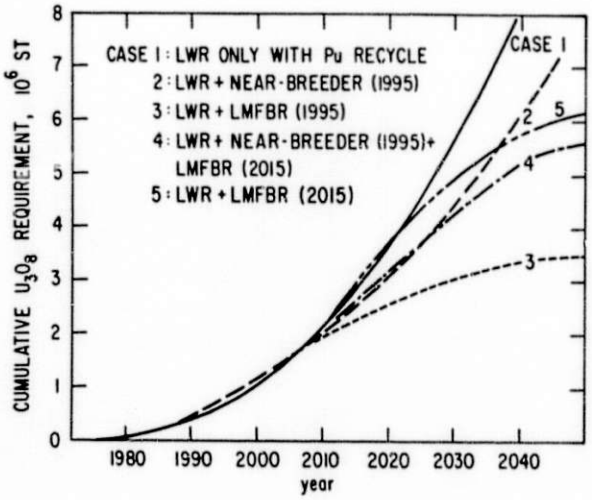

Fig. 8. Cumulative Uranium Requirements for LWR-Based Scenarios. ANL Neg. No. 116-77-38 Rev. 1.

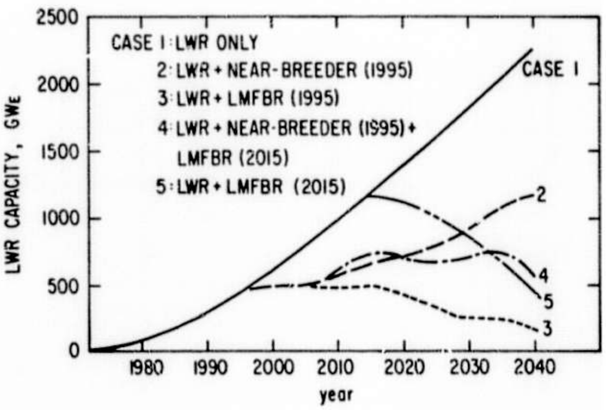

Fig. 9. Installed LWR Capacity for LWR-Based Scenarios. ANL Neg. No. 116-77-56.

Cases 4 and 5 give a measure of the effect of significantly delayed LMFBR introduction, and the relatively small ameliorating effect on uranium consumption of a near-breeder intermediate period.

Other cases, for still smaller nuclear demand (400 GWe in 2000, 1250 GWe in 2030) and further delay in LMFBR introduction (to 2025) show similar results. For this smaller demand case, 1995 LMFBR introduction gives a cumulative consumption of 2.5 million ST U_3O_8, 2015 LMFBR introduction 4.5 million ST, and the saving from 1995 near-breeder introduction in the latter case is less than 10%. Delaying LMFBR introduction to 2025 increases U_3O_8 consumption to over 6 million ST, and 1995 near-breeder introduction in this case reduces consumption less than 15%.

For a CANDU-based power economy, qualitatively the same results are obtained (see Figs. 10 and 11) except that the uranium requirements for all scenarios are scaled down from the LWR-based power economy because of the increased plutonium availability from CANDUs.

The key point remains, however, that in the U.S. only through the early introduction of a good breeder (such as the LMFBR) can a ceiling be put on uranium requirements that is consistent with current estimates of nuclear growth rates and uranium reserves.

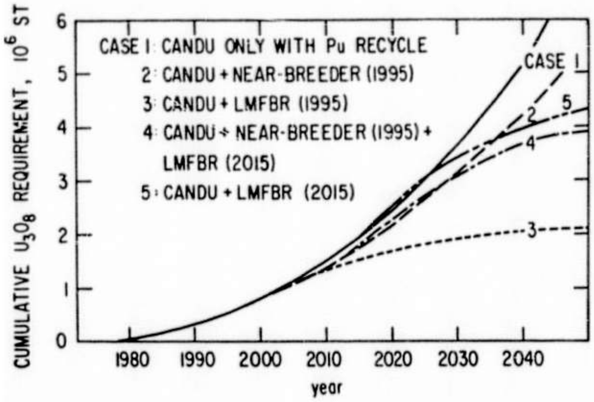

Fig. 10. Cumulative Uranium Requirements for LWR-Based Scenarios. ANL Neg. No. 116-77-60.

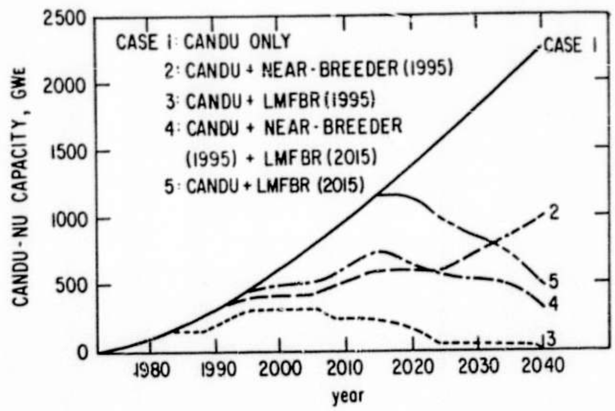

Fig. 11. Installed Capacity of Natural Uranium Fueled PHW for CANDU-Based Scenarios. ANL Neg. No. 116-77-59.

It is of interest, however, that other system studies[19] (reproduced here in Figs. 12 and 13) have indicated a quite different impact for thermal near-breeders in an expanding power economy than we found in our studies. The reference studies indicated that the uranium resource conservation realized by the introduction of the thermal near-breeder is about the same magnitude as it is for LMFBR introduction or even better. The two studies apparently directly contradict each other. The contradiction is simply explained by differences in the growth patterns assumed in the two studies. To see this it is useful to examine the relationship between the doubling time of the energy demand and the doubling capability of the breeder system.

Consider a growing power economy, where the total nuclear capacity growth rate is given by the energy doubling time, EDT, and the breeder reactor is characterized by the reactor doubling time, RDT, and the reactor specific inventory SI. For breeders introduced at time t_0, when the total nuclear capacity is GW_0, the cumulative requirement for the externally supplied fissile inventory of breeder reactors is given by:

$$SI \cdot GW_0 \cdot \left[\left(1 - \frac{EDT}{RDT}\right)\left(e^{0.693\, t_e} - 1\right) + 0.693\,\frac{EDT}{RDT} \cdot t_e\right] \qquad (1)$$

where

$$t_e = \frac{t - t_0}{EDT} \quad \text{(time in units of EDT).}$$

As the fissile inventory for the breeder reactors is provided by plutonium produced in the converter reactors, Eq. (1) is proportional to the uranium requirements. Hence, the uranium requirements is a

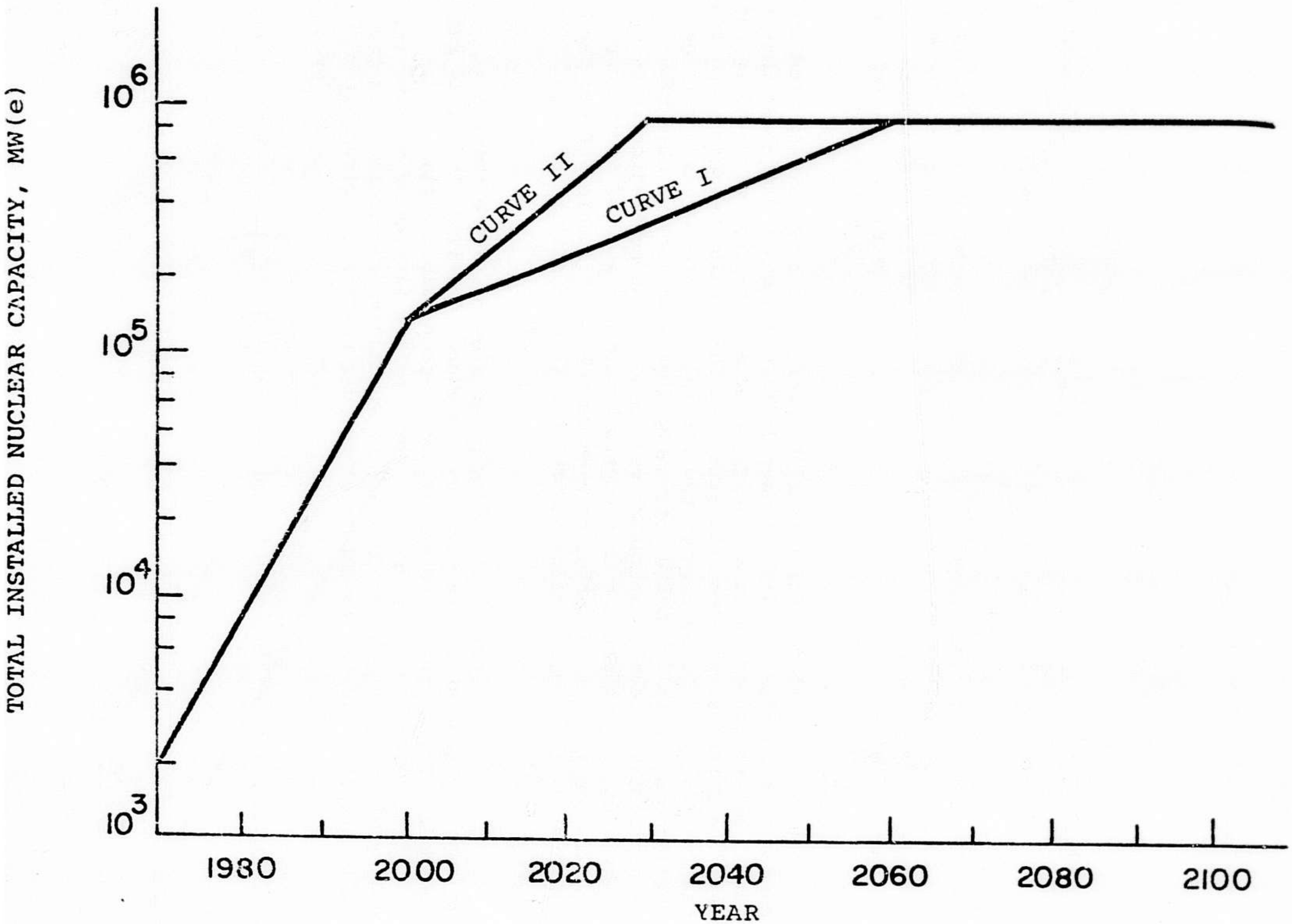

Fig. 12. Assumed Installed Nuclear Power Capacity to 2100.
ANL Neg. No. 116-77-65.

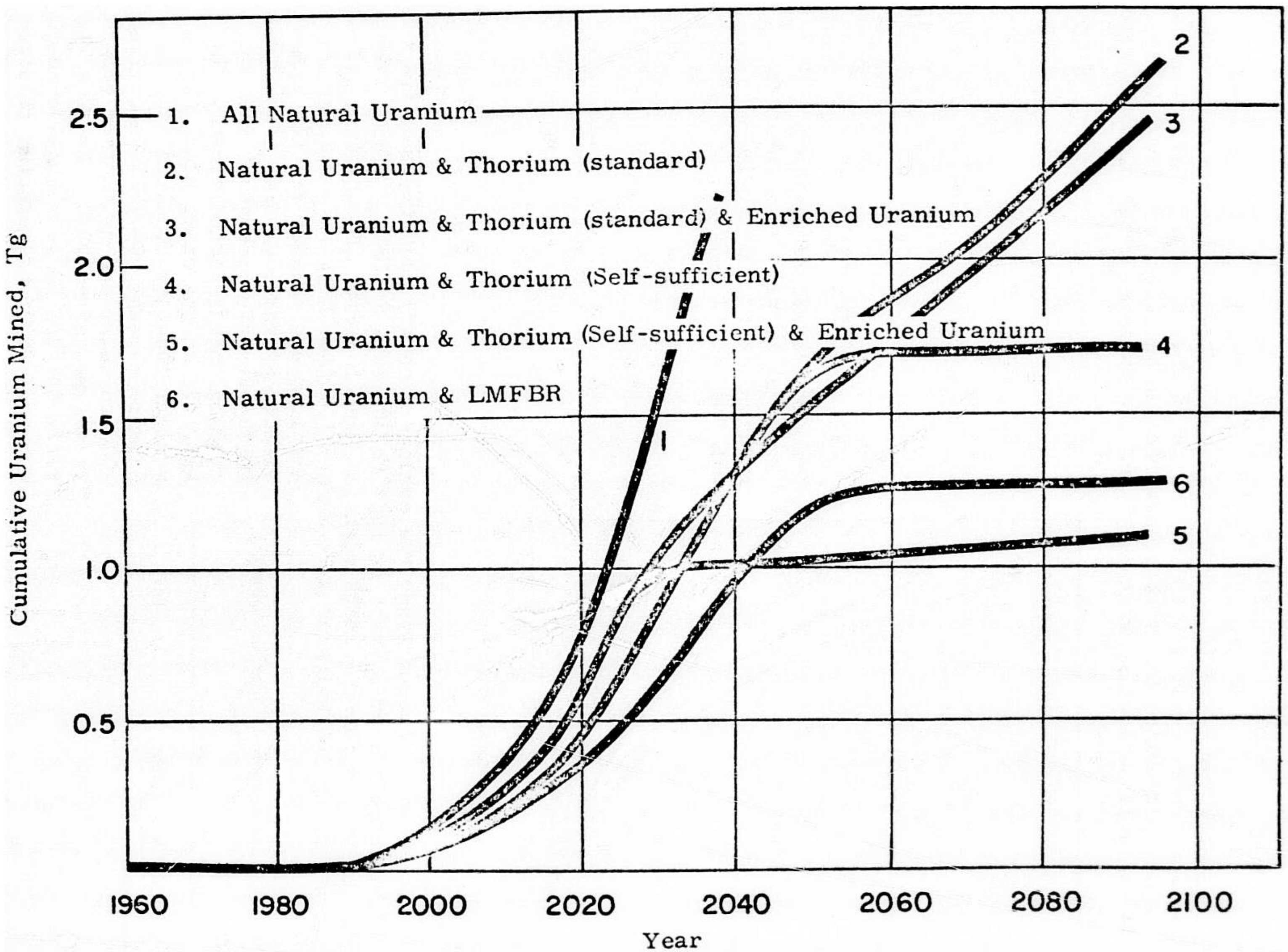

Fig. 13. Cumulative Uranium Consumption for Systems 1 to 6 (Growth Curve II). ANL Neg. No. 116-77-58.

function of the ratio EDT/RDT. Figure 14 shows this relationship. For a very fast energy growth rate EDT/RDT is small, and the uranium requirements are almost independent of the breeder reactor doubling time. At the other extreme also, the case of no energy growth, EDT/RDT is large and the uranium requirements again are independent of the breeder reactor doubling capacility. Realistic cases in the U.S. are expected to lie in between, however, and over the range from zero to slightly greater than unity uranium requirements are very sensitive to the precise magnitude of EDT/RDT. The nuclear capacity doubling times (EDT) assumed for our study and for Ref. 19 are compared in Table II.A.9, which explains the opposite conclusions indicated.

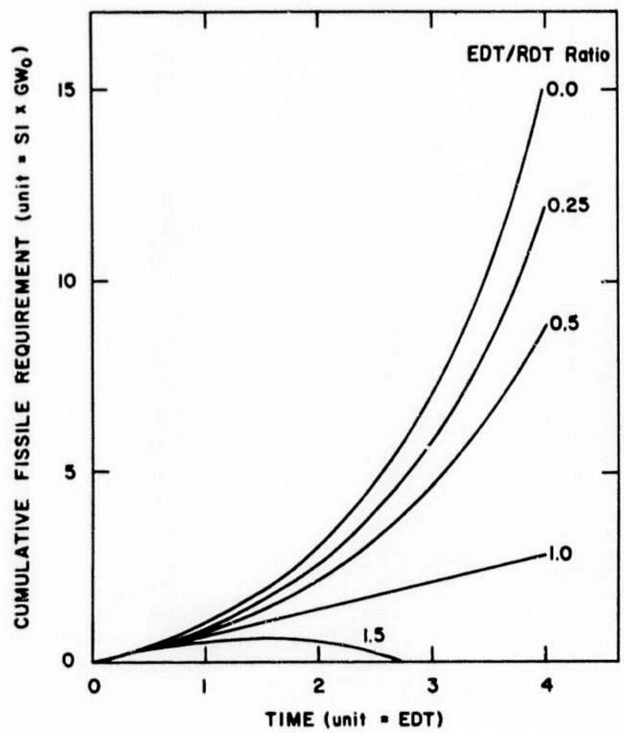

Fig. 14

Breeder Fissile Requirement (External Supply) as a Function of Time and EDT/RDT Ratio. ANL Neg. No. 116-77-37.

In our study the nuclear capacity doubling time increases continuously from 5 years in 1985 to 30 years in 2030. Hence, the uranium requirements for the LMFBR scenario tend to level off starting around 2020 when the ratio EDT/RDT starts to exceed 1.0 (see Fig. 14), whereas the uranium requirements for the near-breeder scenario diverge from the LMFBR scenario because of the continuing energy demand growth. In Ref. 19, on the other hand, the nuclear capacity doubling time is 5 years through 2000, 11 years from 2000 to 2030, and no further growth is assumed after 2030. Because the ratio EDT/RDT is very small through the year 2000, the uranium requirements are about the same for both near-breeder and LMFBR scenarios. The uranium requirements for the

TABLE II.A.9. Comparison of Nuclear Capacity Doubling Time

Year	This Study	Ref. 3
1985	5	5
2000	12	5
2025	26	11
2030	30	No Growth

two scenarios diverge somewhat during the period 2000-2030 as EDT/RDT becomes larger, but after 2030 they level off quickly because of the assumption of no further energy growth. The ceiling on uranium requirements under these assumptions is therefore mainly sensitive to initial core inventories rather than any doubling time properties of a breeder reactor.

These studies illustrate two points. First they highlight one of the problems that arises in quoting results from system studies. Plausible differences in input assumptions can lead to drastically different conclusions. Second, they underline the fact that under certain specific assumptions for nuclear electric power growth, thermal near-breeders can be shown to be equivalent in resource utilization to fast breeder systems. The answer to the question of whether thermal near-breeders do, in fact, provide a realistic alternative to fast breeders hinges on the realism of such assumptions.

The introduction of thermal breeders over the next several decades, however, appears unlikely to significantly affect the rate of uranium usage during that period in either an LWR-based or a CANDU-based power economy. Thus under continuing load-growth conditions, which require fast breeder introduction, the concept of a thermal breeder providing a stretchout of the time before fast breeder introduction is required does not seem well-founded.

A.3. Summary

Definite conclusions regarding relative power generation costs in the 1980's for CANDU-PHW reactors and LWRs are not possible, but the important factors influencing these costs can be identified. Capital costs will remain the dominant costs and the factors that must be examined include costs associated with modifying CANDU reactors to meet U.S. standards and regulations, use of enriched fuel cycles to reduce the heavy water inventory, and the potential plant performance of a CANDU reactor operating in the U.S. environment. The portion of capital costs attributed to heavy water is not expected to increase, but heavy water production capacity would have to be installed to support CANDU type reactors operating in the U.S. and a large capital expenditure would be required. Relative fuel cycle cost estimates for CANDU reactors and LWRs indicate that a small differential of 1-2 mills/kWhr in favor of CANDU reactors is likely to continue in the 1980's. This differential is relatively insensitive to large U_3O_8 price changes and it is partially offset by heavy water upkeep costs.

The potential for uranium resource conservation in the current CANDU-PHW reactors, by themselves, is little different than current reactors in the U.S. and it is the thorium fuel cycle that is to be considered for possible long term fuel utilization benefits.

The thorium cycle in CANDU reactors can be designed for high conversion ratios. In fact, a conversion ratio of 1.0 appears feasible at a low burnup with the same fuel design as the natural uranium CANDU. However, unless the uranium price rises much higher than \$100/lb U_3O_8, there is no economic incentive to push the conversion ratio above 0.9, and if reprocessing and refabrication costs turn out to be very high, the optimum will be even less than this. If thermal converters or near-breeders are introduced into the power economy, the technological and economic considerations probably favor backfit application to the existing industry base, so the LWBR would probably be favored in the LWR based power economy and the CANDU near-breeder in the CANDU natural uranium based economy.

Since thermal breeders are at best self-sufficient and then only on their equilibrium cycle they cannot replace the need for FBRs with high breeding capability unless the power economy reaches an equilibrium capacity with no further growth. Even if uranium conservation becomes the dominant issue, the role of thermal breeders in an expanding power economy is not clear. The uranium requirements for the initial core and transition cycles of thermal breeders are equivalent to about 15-year U_3O_8 requirements for uranium cycle reactors. Hence, in a growing power economy, the benefit from thermal breeders cannot be realized in the intermediate future, in which period the currently estimated reserves of high grade uranium would all be consumed.

B. Safety Considerations for Advanced CANDU Reactors

Several variations of the heavy-water-moderated pressure-tube reactor have been considered in the past or are now under development. These alternate concepts are summarized in Table II.B.1. Following are some specific comments:

TABLE II.B.1. Heavy-Water-Moderated Pressure-Tube Reactors

Name	Coolant	Flow-Regime	Fuel Enrichment	Void-Reactivity Effect	Developing Country or Organization
CANDU-PHW[a]	D_2O	Single-Phase	Natural	Slightly Positive	Canada
CANDU-BLW[b]	H_2O	Two-Phase $T_i < T_{sat}$	Natural	Positive	Canada
CANDU-OCR[c]	Organic	Single-Phase	Natural	Positive	Canada
SGHWR[d]	H_2O	Two-Phase $T_i < T_{sat}$	Slightly Enriched	∿Zero (undermoderated)	UK
CIRENE[e]	H_2O	Two-Phase $T_i > T_{sat}$	Natural or Slightly Enriched	Positive	Italy
EL-4[f]	CO_2	Single-Phase	Natural	-	France
FUGEN	H_2O	Two-Phase $T_i < T_{sat}$	Slightly Positive	Zero or Slightly	Japan
ORGEL[g]	Organic	Single-Phase	Natural or Slightly Enriched	Positive	Euratom

[a]CANDU-PHW: CANDU-Pressurized Heavy Water.
[b]CANDU-BLW: CANDU-Boiling Light Water.
[c]CANDU-OCR: CANDU-Organic Cooled Reactor.
[d]SGHWR: Steam Generating Heavy Water Reactor.
[e]CIRENE: CISE Reattore a Nebbia.
[f]EL-4: Eau Lourde-4.
[g]ORGEL: Organique-Eau Lourde (discontinued program).

Advanced CANDU-PHW

The present commercial CANDU-PHW can be further developed. One important objective is a higher thermal efficiency and this requires higher primary system pressures. The main safety-related difference from current CANDU-PHW reactors might possibly be an increased potential for pressure tube-to-tube failure propagation.

CANDU-BLW

A prototype of the boiling light water CANDU reactor, using natural uranium fuel, was built and operated at Gentilly, Quebec. Because of the strongly positive void-reactivity coefficient, the system is inherently unstable and requires continuous and rapid-acting zonal power control. In under-moderated systems using enriched fuel, these instability problems can be overcome. However, this enhanced stability would be obtained by sacrificing the simple natural-uranium fuel cycle and the high conversion ratio.

CANDU-OCR

Some of the attractive features of organic cooled reactors include: (1) low primary coolant pressure, and (2) high primary coolant temperatures (400-450°C). Some of the operational problems such as fouling and polymerization appear to have been satisfactorily solved. The principal potential safety-related problem areas are: (1) pressure tube-to-tube failure propagation as caused by steam explosions (due to a pressure-tube failure followed by injection of hot organic coolant into the moderator), (2) severe pressure pulses in the primary coolant system due to leakage (in the steam generator) of water into the primary coolant, (3) positive void-reactivity effect. Of these potential problem areas, the first two appar to be the most important, possibly requiring considerable experimental evaluation. Substantial experimental work has already been performed in these areas, among others, at Ispra, Italy, where a heavy water-moderated organic-liquid cooled test reactor (ESSOR) has been in operation since 1969.

Steam Generating Heavy Water Reactor (SGHWR)

A prototype of this reactor type has been in operation at Winfrith, UK, since 1970. The performance appears to have been satisfactory. The pressure-tubes are vertically oriented, and the reactor has no on-load refueling capability. Undermoderation, made possible by the use of enriched fuel, results in a void-reactivity coefficient close to zero.

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REFERENCES

1. L. W. Woodhead, *"Performance of Canadian Commercial Nuclear Units and Heavy Water Plants,"* A Report Adapted from a Paper presented at the European Nuclear Conf., Paris (1975); also, *"Performance Review of CANDU-PHW Nuclear Electric Units and the Bruce Heavy Water Plant,"* AECL, pp. 31 (1976).

2. H. E. Thexton, AECL, private communication (1976).

3. *"Central Station Nuclear Plants,"* Industry Relations, ISL-USERDA (March 1976); also *"Significant Milestones, U.S. Central Station Nuclear Electric Generating Units,"* ERDA-30 (1976).

4. *"Operating Status Report,"* U.S. NRC (1976).

5. A. D. Rossin et al., *"Reliability and Economics of Light-Water Reactors,"* Trans. Am. Nucl. Soc. *22*, 833-835 (Nov. 1975).

6. R. G. Garvin, Savannah River Plant, private communication (1975).

7. D. L. S. Bate et al., *"Costing of Canadian Nuclear Power Plants,"* A/Conf. 49/P/149, Fourth Geneva Conf. (1971).

8. G. H. Applegreen et al., *"Appraisal of Nuclear Power Plant Reliability,"* Power Engineering, *79* (May 1975).

9. J. O'Toole, Consolidated Edison, Co., private communication (1975).

10. C. L. Moon, *"Pickering Generating Station;)"* P. C. Loken, *"Core Physics;"* C. A. Simmonds, *"Mechanical Design of the Pickering Core;"* G. R. Fanjoy and A. S. Bain, *"Fuel and Fuel Cycle,"* Nucl. Eng. Int. p. 501-515 (June 1970).

11. J. S. Foster and E. Critoph, *"The Status of the Canadian Power Program and Possible Future Strategies,"* Presented at Wingspread Conf. on Advanced Nuclear Converters and Near Breeders (May 14-16, 1975).

12. A. J. Mooradian and O. J. C. Runnals, *"CANDU - Economic Alternative to the Fast Breeders,"* AECL-4916 (Sept. 1974).

13. D. A. Meneley, *"CANDU Systems,"* Presented at ASME-ANS Int. Conf. on Advanced Nuclear Energy Systems (March 15-17, 1976).

14. L. J. Colby et al., *"HTGR Fuel and Fuel Cycle Summary Description,"* GA-10233 (May 1971).

15. R. H. Brogli et al., *"The High Conversion HTGR for Resource Conservation,"* GA-A13606 (Oct. 1975); also Trans. Am. Nucl. Soc. *22*, 707 (1975).

16. R. L. Witzke, E. E. Smith and J. H. Bach, *"Enriched Uranium Supply and Demand Economic Factors,"* Proc. Am. Power Conf. *30*, 211 (1968).

17. R. Hudson, ORNL, private communication (1976).

18. N. F. True (Sargent & Lundy), R. Sears (Bechtel) and E. Ziegler (United Engineers and Constructors), private communications (1976).

19. S. R. Hatcher et al., "*Thorium Cycle in Heavy Water Moderated Pressure Tube (CANDU) Reactors*," Invited paper presented at ANS Winter Meeting (Nov. 16-21, 1975).

20. E. Critoph et al., *Prospects for Self-Sufficient Equilibrium Thorium Cycle*," Invited paper presented at ANS Winter Meeting (Nov. 16-21, 1975).

21. S. Banergee et al., *Thorium as a Nuclear Fuel for CANDU Reactors*," Can. J. Chem. Eng. *53*, 291 (1975).

22. *Environmental Statement LWBR*, draft, ERDA-1541 (July 1975).

23. *Final Environmental Statement: Liquid Metal Fast Reactor Program*, WASH-1535 (Dec. 1975).

24. R. W. Hardie, W. E. Black and W. W. Little, "*ALPS, A Linear Programming System for Forecasting Optimum Power Growth Patterns*," HEDL-TME 72-31 (April 1972).