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ECONOMICS OF CANDU

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ONTARIO HYDRO

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0. Introduction

The purpose of this paper is to:

- discuss the cost of producing electricity from CANDU-Pressurized Heavy Water (PHW) nuclear generating units,
- present actual cost experience of CANDU units in Ontario Hydro,
- compare CANDU cost experience with fossil (coal) experience in Ontario Hydro,
- present projected CANDU and fossil cost data in Ontario Hydro, and
- present cost estimate comparisons of CANDU and Light Water Reactors (LWR) in Ontario Hydro.

1. Cost Criteria

The Cost Objective of Ontario Hydro is to produce and deliver electricity at the lowest long-term cost to Ontario customers, while satisfying the other rudimentary objectives:

- Worker Safety
- Public Safety
- Environmental Protection
- Reliability.

If a comparison is made between two alternative types of generation, the degree to which all of those objectives are satisfied should be considered.

A comprehensive discussion of the CANDU-PHW type nuclear unit, including Worker Safety Experience, Public Safety Experience, Environmental Protection Experience, and Reliability Experience, has been reported by the authors in a companion paper, CANDU OPERATING EXPERIENCE (NGD-9-1980).

The load of Ontario Hydro (as with most electrical utilities) varies with time. Loads peak in the daytime Monday to Friday when factories are busy and society is active. In Ontario, the loads are higher during the winter when temperatures are low.

The most economical generating system for Ontario Hydro is a mix of hydraulic generation, fossil generation, and nuclear generation.

The majority of available economic hydraulic resources in Ontario has been developed. New loads must be met by alternative resources of which nuclear and coal are the primary options for the balance of this century.

The Ontario Hydro system Load Factor is typically 68% (the ratio of average annual power to peak annual power). Fossil-fired generation is most economical for peak load requirements because of its lower capital and OM&A costs*. Nuclear generation is most economical for base-load application because its higher capital and OM&A costs are more than offset by the very low fuelling costs.

This paper is limited to a cost discussion for base-load generation in Ontario Hydro.

Cost evaluations for generation commitment decisions of Ontario Hydro are very complex, utilizing present value techniques, uncertainty analyses, load forecasts, reliability assessments, environmental impacts, etc, that are beyond the scope of this paper.

The Total Unit Energy Cost (TUEC) method is a simple and accurate indicator of the relative economics for base-load application, and is used in this paper.

Total Unit Energy Cost (TUEC)

The cost of producing electricity from generating stations involves the following cost classifications:

- the research and development of generation concepts,
- the cost of building the stations,
- the cost of operating and maintaining the stations,
- the cost of fuelling the stations,
- the cost of in-service modifications,
- the cost and benefits associated with disposal of the stations at the end of their useful life, and
- overhead costs to support the above cost classifications.

*OM&A: Operating, Maintenance, and Administrative Costs.

In addition, the cost of producing electricity must also consider:

- the method employed for financing and amortizing the investments,
- the interest rates applicable to the above classifications,
- the lifetime assumed for the facilities,
- the reliability of the stations to produce electricity, and
- the policies that are adopted concerning source of supply, taxes, regulations, etc.

The Total Unit Energy Cost (TUEC) is defined as the total annual cost of producing electricity (dollars) divided by the total annual electricity energy produced (kilowatt-hours).

$$\text{TUEC} = \frac{\text{Total Annual Cost}}{\text{Total Annual Electricity Produced}}$$

In this paper, the research required to develop the generation concepts is excluded and the costs and benefits of station disposal have been excluded. In the opinion of the authors, these exclusions do not have a serious effect on the absolute costs and relative costs of the generation alternatives, in the long-term for a major program.

The four cost components for the CANDU-PHW concept are:

1. Annual Interest and Depreciation on the Capital Cost
2. Annual Operation, Maintenance, and Administration Cost
3. Annual Fuelling Cost
4. Annual Heavy Water Upkeep Cost

The three cost components for the Light Water Reactor (LWR) concept and coal-fired stations are:

1. Annual Interest and Depreciation on the Capital Cost
2. Annual Operation, Maintenance, and Administration Cost
3. Annual Fuelling Cost

The computation of the Annual Interest and Depreciation Cost depends upon four factors:

1. The Initial Capital Cost and the Capital Modifications Cost
2. The Interest Rate
3. The Lifetime of the Station
4. The Method of Amortization of the Initial Capital Cost and the Capital Modifications Cost

The Initial Capital Cost includes:

1. The Design and Engineering Cost
2. The Construction Cost
3. The Commissioning Cost
4. The Permanent In-Reactor Fuel Charge
5. The Heavy Water Inventory
6. Overheads
7. Accumulated Compound Interest During Construction

The Initial Capital Cost includes the Permanent In-Reactor Fuel Charge (one-half of the Initial Fuel Charge) and the Heavy Water Inventory. The Initial "Dry" Capital Cost is identical to the Initial Capital Cost except that the Permanent In-Reactor Fuel Charge, the Heavy Water Inventory and Commissioning are included.

The Annual Operation, Maintenance, and Administration Cost includes:

1. Labour
2. Materials
3. Purchased Services
4. Interest on Operating and Maintenance Inventories
5. Overheads (including taxes)

The Annual Fuelling Cost includes:

1. Fuel (quantity and price)
2. Interest on Inventory
3. Transportation
4. Overheads

The Annual Heavy Water Upkeep Cost is comprised of two basic factors:

1. The cost of replacing any heavy water lost during operation.
2. The cost of upgrading any heavy water which becomes downgraded during operation (diluted with ordinary water).

The Total Unit Energy Cost (TUEC) is the sum of the Unit Energy Cost (UEC) for each of the cost components. As an example, the Fuelling Unit Energy Cost is as follows:

Fuelling Unit Energy Cost =

$$\frac{\text{Fuelling Annual Cost}}{\text{Total Annual Electricity Energy Produced}}$$

The Total Unit Energy Cost is very dependent on the Capacity Factor* achieved.

The Total Annual Electricity Energy used to determine TUEC may be either the gross or net electricity produced. Ontario Hydro prefers to use net energy - TUEC (net). However, for some utilities only the gross production is published and TUEC (gross) is determined.

The Specific Capital Cost is the Total Initial Capital Cost (\$) divided by the Net Capacity (kW) and is expressed in dollars per kilowatt.

All costs expressed in this paper are in Canadian dollars.

2. Ontario Hydro Cost Comparison -- CANDU-PHW Versus Fossil (Coal)

The cost comparison between CANDU-PHW units and alternative sources of generation will depend upon many factors which are particular to the electrical utility making the comparison.

Nuclear fuel cost tends to be independent of the distance between the uranium source and the generating station because transport cost of nuclear fuel is small. In the case of coal, the transport cost is low if the generating unit is near the coal mine, but can be very high if the coal has to be transported a great distance.

$$\text{*Capacity Factor} = \frac{\text{Actual Energy Produced}}{\text{Perfect Production}}$$

for any specified period.

The following data illustrates that the CANDU-PHW is very competitive within Ontario Hydro where economic hydroelectric resources have been almost fully developed and where coal must be transported a minimum of 800 kilometres. There are other locations in Canada in which coal-fired generation is cheaper than CANDU-PHW where the generating unit is near the mine. The high current and projected cost of oil and gas makes their use uneconomical for base-load generation in Ontario Hydro.

More specifically, the following presentation compares the Ontario Hydro Pickering Nuclear Generating Station-A (NGS-A) with the Ontario Hydro Lambton Thermal Generating Station (TGS). The Pickering NGS-A comprises four 515 MW (net) nuclear units of the CANDU-PHW type. The Lambton TGS comprises four 495 MW (net) units which burn coal. Both stations were built at the same time, both are of modern design, and both stations are fully operational with good performance records.

For the year 1980, Pickering NGS-A had a Net Capacity Factor of 82.6%. Table 1 illustrates the Unit Energy Costs (UEC) of these two stations.

The following should be noted from Table 1:

- the coal-fired capital cost is much lower than the nuclear capital cost,
- the coal-fired OM&A cost is lower than the nuclear OM&A cost,
- the nuclear fuelling cost is very much lower than the coal-fired fuelling cost,
- the heavy water upkeep cost, which applies only to the nuclear, is only a small percentage (about 4%) of the Total Unit Energy Cost, and
- for base-load application, Pickering NGS-A had approximately one-half the Total Unit Energy Cost of Lambton in 1980.

During the period up to 1980, in-service capital modifications have been made to both Pickering NGS-A and Lambton TGS. These modifications are amortized on a remaining lifetime basis and are included in the comparison.

It is expected that further capital modifications will be required from time to time to replace major components and meet new requirements.

TABLE 1

PICKERING/LAMBTON COST COMPARISON - 1980

Pickering and Lambton Net Capacity Factor: 82.6%*

| | UEC m\$/kW·h (net) | |
|--|------------------------|--------------------|
| | <u>Pickering NGS-A</u> | <u>Lambton TGS</u> |
| Interest and Depreciation Operation, Maintenance, and Administration | 6.06 | 1.94 |
| Fuelling | 3.95 | 1.78 |
| Heavy Water Upkeep | 2.33 | 17.46 |
| | <u>0.43</u> | <u>-</u> |
| Total Unit Energy Cost (Net) | 12.77 | 21.18 |

Station Data

| | <u>Pickering</u> | <u>Lambton</u> |
|--|------------------|----------------|
| Capacity (Maximum Continuous Rating) MWe net | 4 x 515 | 4 x 495 |
| In Service | 1971 - 1973 | 1969 - 1970 |
| Initial Capital Cost (M\$ Canadian escalated) | 746.5 | 257.0 |
| Specific Capital Cost (\$/kW) | 362.4 | 129.8 |
| Economic Lifetime (years) | 30 | 30 |
| Depreciation Method | Straight Line | Straight Line |
| Interest Rate (%) | 9.7 | 9.7 |

Assumes Lambton also operated at base load with net capacity factor of 82.6%. Lambton actual 1980 net capacity factor was 8.0%.

For example, the pressure tubes at Pickering NGS-A may have to be replaced and Lambton may have to be retro-fitted with SO₂ scrubbers to meet acid rain requirements.

Figure 1 presents the Pickering versus Lambton Unit Energy Costs (assuming Lambton operated at the same high capacity factors as Pickering) for each year 1975 to 1980 inclusive.

This graph clearly shows the steadily increasing cost advantage of the nuclear plant due to the continuing inflation of coal costs. This is an example of the "inflation-proof" characteristics of the CANDU-PHW.

This graph also shows that the cost of Heavy Water Upkeep is only a small component (about 4%) of the Total Unit Energy Cost.

Highlight

The base load cost (TUEC) of the Pickering NGS-A has been consistently well below the cost of the Lambton TGS (coal-fired).

This cost advantage is expected to increase as fossil fuels become more expensive.

3. CANDU Costs Versus Time

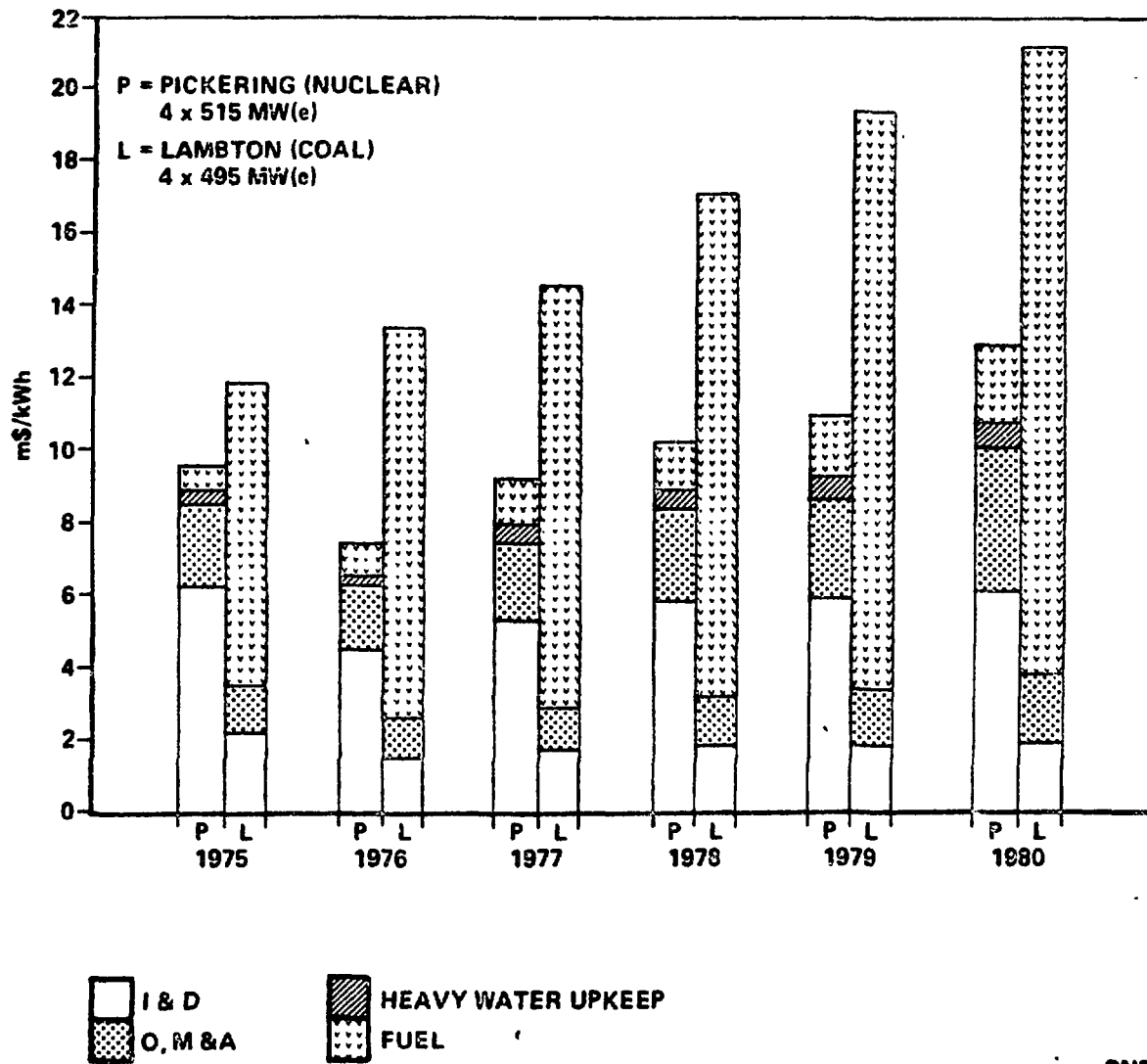
The actual or estimated TUEC for in-service stations and stations under construction will vary with time due to a variety of reasons including:

- escalation of labour and material costs,
- changes in interest rates,
- escalation of fuel costs,
- changes in design and operating requirements,
- changes in operating performance, and
- competence and maturity of workforces (design, manufacturing, construction, operation).

The Pickering NGS-A and the Lambton TGS were built in the late 1960s and placed in-service in the early 1970s.

During the 1970s, high inflation caused Capital, OM&A, and Fuelling Costs to be driven rapidly upwards.

FIGURE 1
TOTAL UNIT ENERGY COST COMPONENTS
THERMAL VERSUS NUCLEAR (1975-1980)



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As a result, new coal-fired generating stations such as Nanticoke TGS (8 x 490 MW net) and new nuclear stations such as Bruce NGS-A (4 x 740 MW net) have higher capital costs.

In addition, the TUEC of the in-service coal-fired station, Lambton TGS (4 x 495 MW) and the in-service nuclear station, Pickering NGS-A (4 x 515 MW), are rising due to inflation in OM&A and fuelling costs.

The Specific Capital Cost of Bruce NGS-A compared with the Specific Capital Cost of Pickering NGS-A is affected by three major factors:

- Bruce NGS-A has lower costs due to larger unit size,
- Bruce NGS-A has higher costs due to new regulatory requirements,
- Bruce NGS-A has much higher costs due to inflation of labour and materials.

The result is that the Pickering NGS-A Specific Capital Cost was 362.4\$/kW (net) and Bruce NGS-A was 662.5 \$/kW (net).

Pickering NGS-A came into service between 1971 and 1973, while Bruce NGS-A came into service between 1977 and 1979.

Table 2 shows Bruce NGS-A Unit Energy Costs in 1980, while Figure 2 shows the lifetime trends (1977 to 1980).

Table 2

Bruce NGS-A 1980 Costs

Net Capacity Factor = 86.7%

| | <u>UEC m\$/kW·h</u> |
|---|---------------------|
| Interest and Depreciation | 9.67 |
| Operation, Maintenance and Administration | 3.06 |
| Fuelling | 2.67 |
| Heavy Water Upkeep | 0.45 |
| Total Unit Energy Cost (Net) | <u>15.85</u> |

Station Data

| | |
|--|---------------|
| Capacity (Maximum Continuous Rating) MWe net | 4 x 740 |
| In Service | 1977 - 1979 |
| Original Capital Cost (M\$ Canadian escalated) | 1 961.1 |
| Specific Capital Cost (\$/kW) | 662.5 |
| Economic Lifetime (years) | 30 |
| Depreciation Method | Straight Line |
| Interest Rate (%) | 9.7 |

FIGURE 2
BRUCE NGS-A - LIFETIME TRENDS

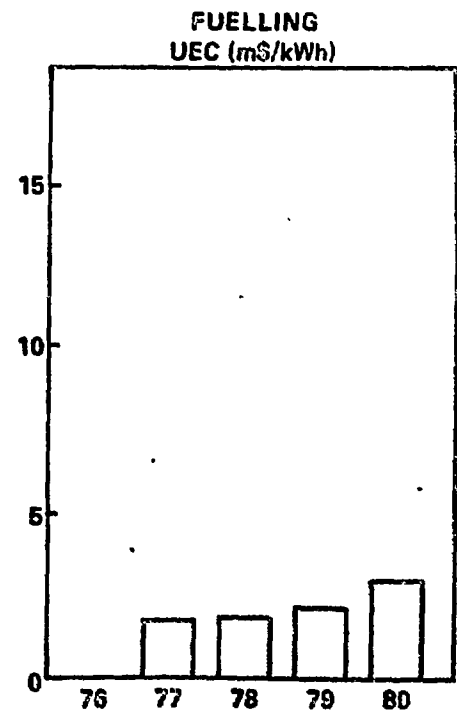
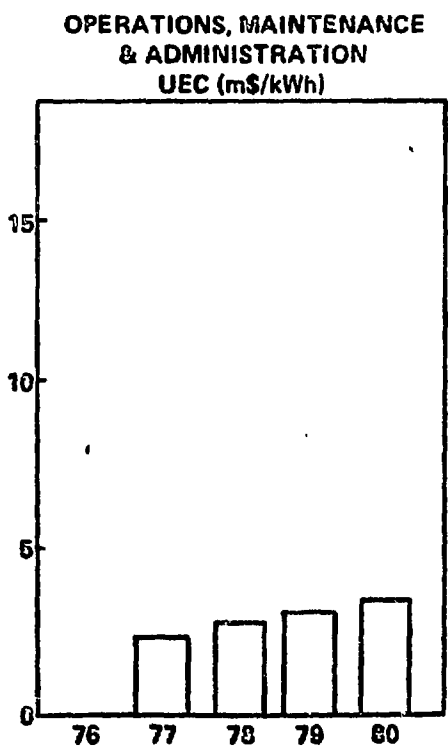
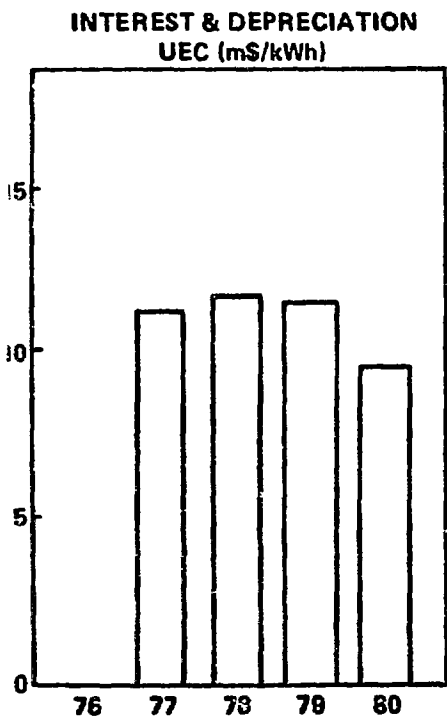
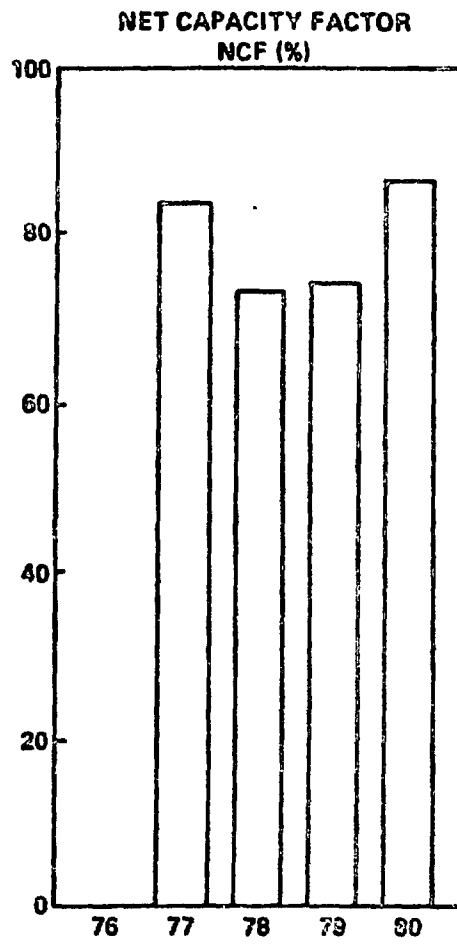
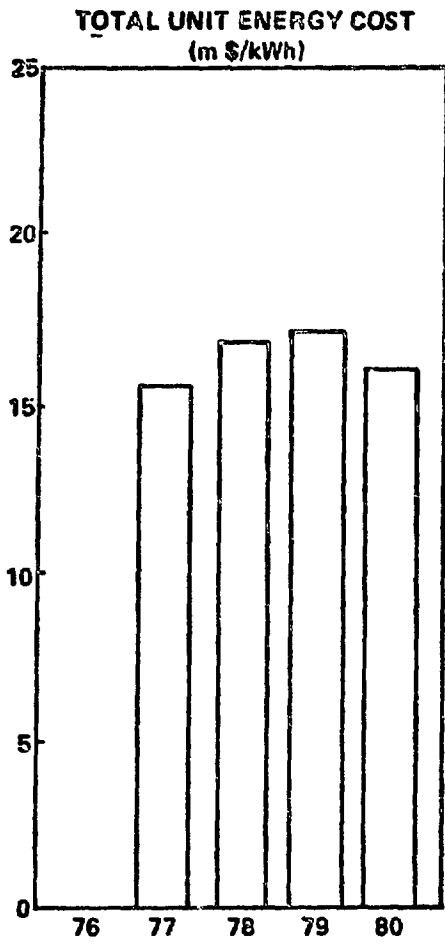


Table 3 presents the actual Initial Capital Cost of Pickering NGS-A and Bruce NGS-A together with the estimated costs of three nuclear stations under construction -- Pickering NGS-B, Bruce NGS-B, and Darlington NGS-A.

4. Ontario Hydro Cost Projections

The CANDU-PHW at Pickering NGS-A has demonstrated major cost advantage for base-loaded application in Ontario Hydro in the 1970s. The TUEC has been projected for CANDU-PHW and coal-fired stations for the period from 1980 to 2000. These projections exclude the possible retrofit of SO₂ scrubbers in coal-fired stations and exclude possible major retrofits in nuclear stations to meet new requirements.

Figure 3 compares actual TUEC for Pickering NGS-A with Lambton TGS (assuming base-load application) for the period up to 1980. It also compares the forecast TUEC for these stations for the period from 1980 to 2000, assuming Ontario Hydro escalation forecasts of labour, materials, and fuels.

Figure 4 displays forecast TUEC for base-load application of five stations currently in service:

- Coal-Fired - Lambton TGS (4 x 495 MW)
- Nanticoke TGS (8 x 490 MW)

- CANDU-PHW - Pickering NGS-A (4 x 515 MW)
- Bruce NGS-A (4 x 740 MW)

- Oil-Fired - Lennox TGS (4 x 495 MW)

These projections indicate:

- that the base-load advantage of CANDU-PHW is expected to continue,
- that the base-load advantage of CANDU-PHW is expected to increase with time, and
- the "inflation-proof" characteristic of CANDU-PHW.

5. Factors to be Considered for Inter-Utility and Concept Cost Comparisons

Relevant and meaningful comparisons of cost experience using data from two or more utilities demand a very objective and rigorous analysis.

TABLE 3

Nuclear Capital Cost Data (Net)

Actual

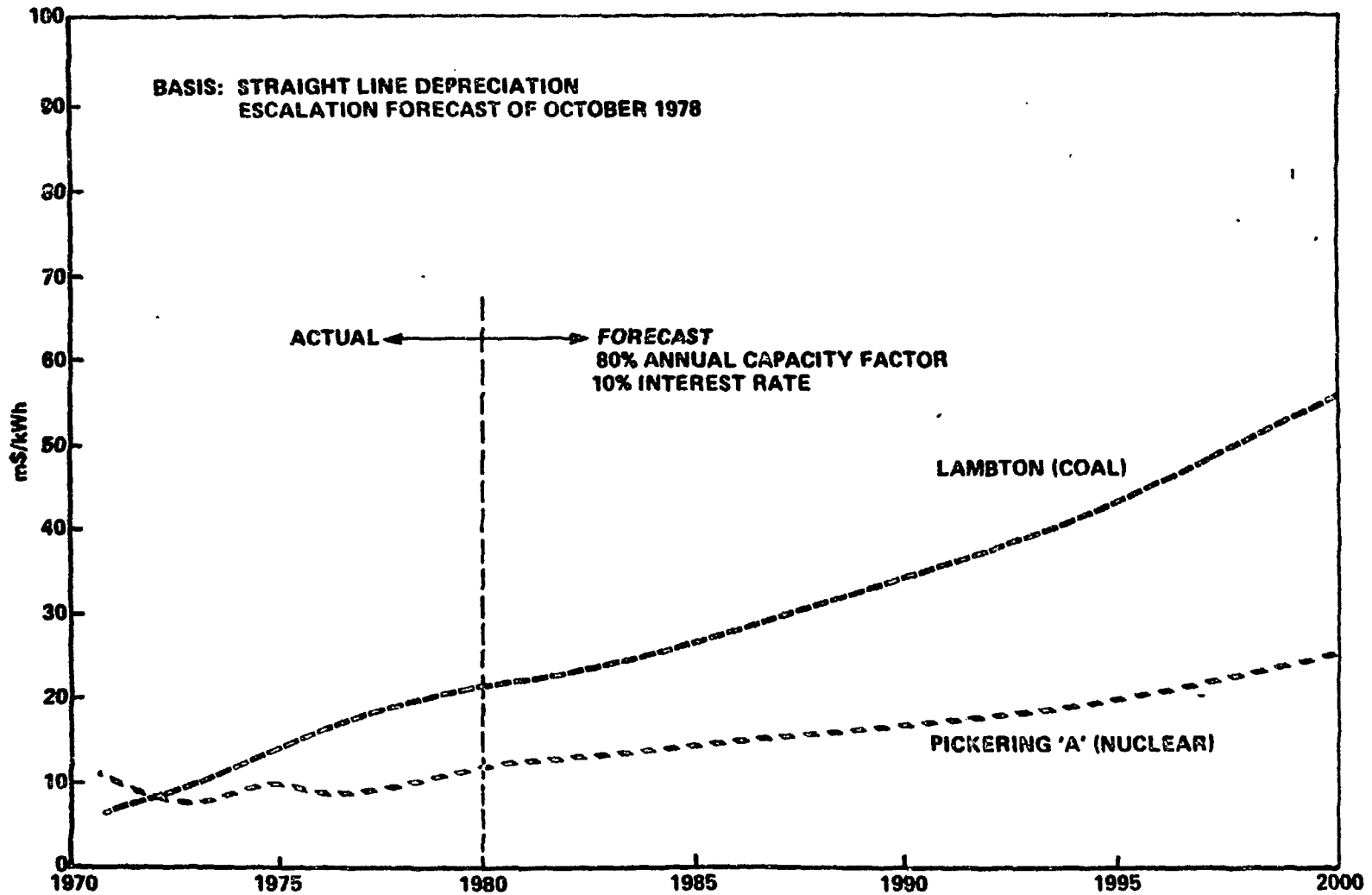
| <u>Station</u> | <u>Net Capacity MW e</u> | <u>Initial Capital Cost M\$</u> | <u>Specific Cost \$/kW</u> | <u>Dry* Capital Cost M\$</u> | <u>Specific Dry* Capital Cost \$/kW</u> | <u>Year In Service</u> |
|-----------------|------------------------------|---|------------------------------------|--------------------------------------|---|----------------------------|
| Pickering NGS-A | 2 060 | 746.5 | 362.4 | 565.7 | 274.6 | 1971-1973 |
| Bruce NGS-A | 2 960 | 1 961.1 | 662.5 | 1 498.9 | 506.4 | 1977-1979 |

Estimated

| <u>Station</u> | <u>Net Capacity MW e</u> | <u>Initial Capital Cost M\$</u> | <u>Specific Cost \$/kW</u> | <u>Dry* Capital Cost M\$</u> | <u>Specific Dry* Capital Cost \$/kW</u> | <u>Year In Service</u> |
|-----------------|------------------------------|---|------------------------------------|--------------------------------------|---|----------------------------|
| Pickering NGS-B | 2 064 | 3 097.3 | 1 500.6 | 2 325.6 | 1 126.7 | 1983-1984 |
| Bruce NGS-B | 3 024 | 4 579.0 | 1 514.2 | 3 400.0 | 1 124.3 | 1983-1987 |
| Darlington NGS | 3 524 | 6 639.5 | 1 884.1 | 5 490.5 | 1 558.0 | 1988-1991 |

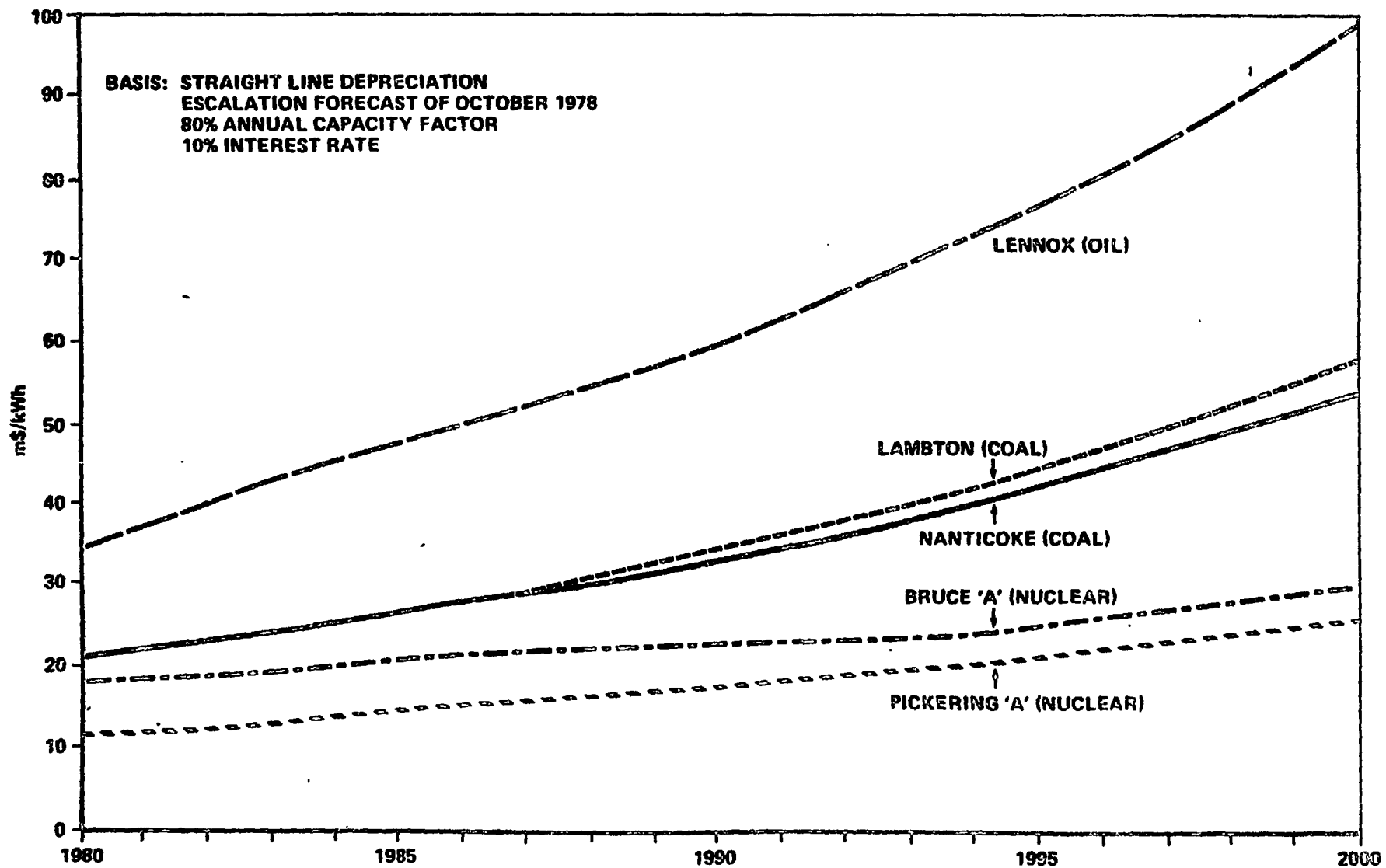
*Dry capital costs exclude heavy water, fuel, and commissioning.

**FIGURE 3
TOTAL UNIT ENERGY COST
FOR PICKERING AND LAMBTON**



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**FIGURE 4
PROJECTED TOTAL UNIT ENERGY COST
FOR MAJOR OPERATING THERMAL STATIONS**



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The following are some of the factors which should be considered:

- Unit Size
- Larger units will tend to have lower Specific Capital Costs (\$/kW) and lower Specific OM&A Costs (\$/kW).
 - Larger units will tend to have lower capacity factor performance for the same vintage and technology.
- Units Per Station
- Increased number of identical units will tend to have lower Specific Capital Costs and lower Specific OM&A Costs.
 - Increased number of identical units will tend to have higher Capacity Factor Performance.
- Schedule Upsets
- Generating stations that suffer schedule delay because of program changes or because of major problems in executing the project, will tend to have higher Specific Capital Costs due to higher interest during construction and re-scheduling costs.
- Concept Maturity
- A well-developed and proven concept will tend to enjoy lower costs and higher performance. Promising new concepts will require tolerance while maturing.
- Utility Maturity
- Independent of concept maturity, each utility adopting the concept must go through a learning process during which costs and performance will suffer.
- Designer Maturity
- Independent of concept maturity and utility maturity, the cost and performance will depend upon the maturity of the designers.
- Supply Industry Maturity
- The cost and performance will depend, in part, on the composite capability of the many suppliers of station components.

Supply Industry Volume

- The cost of a station will depend, in part, on the throughput volume of supply industries.

Project Management Efficiency

- Nuclear station costs depend not only on the maturity of the individual project members, but also on the overall efficiency of the project members working as a team. New teams will tend to have higher costs.

Industry Management Efficiency

- The cost of designing and manufacturing components in a given nation will depend, in part, on the general industrial capability and labour stability of that nation.

Labour Costs

- Nations with lower labour costs will tend to have lower costs assuming similar industrial efficiency.

Operating Staff Maturity

- A rapidly expanding nuclear program increases costs and reduces performance due to less than optimum operating experience.

Operations Management Efficiency

- Some utilities will enjoy better management systems to reduce problems and respond to problems more effectively.

Research and Development Efficiency

- The ready availability of research and development capability will enhance design and facilitate problem solving during design and operation.

Regulatory Efficiency

- A regulatory authority with good judgment and ability will enhance the achievement of objectives including schedule and cost. Immature or incompetent regulatory authorities will cause schedule delays with attendant cost penalties.

General Society Behaviour

- Where a concept has been generally endorsed by society, the cost of building and operating a nuclear station will tend to be reduced.

Foreign Exchange Rates

- Comparisons between utilities in different countries require conversion from one currency to another. The relationship between currencies can change dramatically over a period of a few years.

Supply Policies

- Costs and performance will depend, in part, on supply policies. For example, a policy to utilize domestic sources may increase cost.

In view of the above factors, precise conclusions from comparisons between nuclear concepts are difficult, if not impossible, to make. Nevertheless, the authors have attempted to recognize these factors in the following comparison applicable to Ontario. The conclusions could be quite different for alternative assumptions and conditions in another location in Canada or a different country.

6. Ontario Hydro Cost Comparison -- CANDU-PHW Versus Light Water Reactors (LWR)

The Ontario Hydro nuclear program to date has been limited to experience with CANDU-PHW units. Ontario Hydro has exchanged cost information and operating performance with other utilities in the USA, Europe, and Asia. In particular, this information applied to alternative nuclear types -- Light Water Reactors (LWR) and Gas-Cooled Reactors (GCR).

Ontario Hydro is continuing to observe the world progress on fast breeder reactors (FBR).

At the present time, the LWR is the only viable nuclear alternative to CANDU-PHW in Ontario Hydro.

The LWR has two basic options -- the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR).

Inasmuch as Ontario Hydro has had no design and operating experience with LWR, the cost comparisons between CANDU-PHW and LWR must be based upon the following:

- comparison of costs reported by other utilities for LWR with Ontario Hydro costs for CANDU-PHW, and
- estimates of CANDU-PHW and LWR assumed to be built in Ontario under Canadian licensing requirements.

The judgments expressed below are those of the authors and are based upon the following:

- the detailed insight Ontario Hydro possesses on CANDU-PHW with regard to cost,
- the detailed insight Ontario Hydro possesses on CANDU-PHW with regard to performance,
- capital cost information on LWR units built in the USA, and extensive discussions with sister utilities in the USA,
- detailed performance information on LWR units throughout the world,
- interpolative judgment of the authors regarding expected LWR costs and performance of LWR in Ontario.

CANDU-PHW Costs -- Ontario Hydro

The actual cost data and projected cost data for CANDU-PHW units in Ontario have been presented above.

CANDU-PHW Operating Performance -- Ontario Hydro

The CANDU operating performance has been documented by the authors and published in a companion paper, CANDU OPERATING EXPERIENCE (NGD-9-1980).

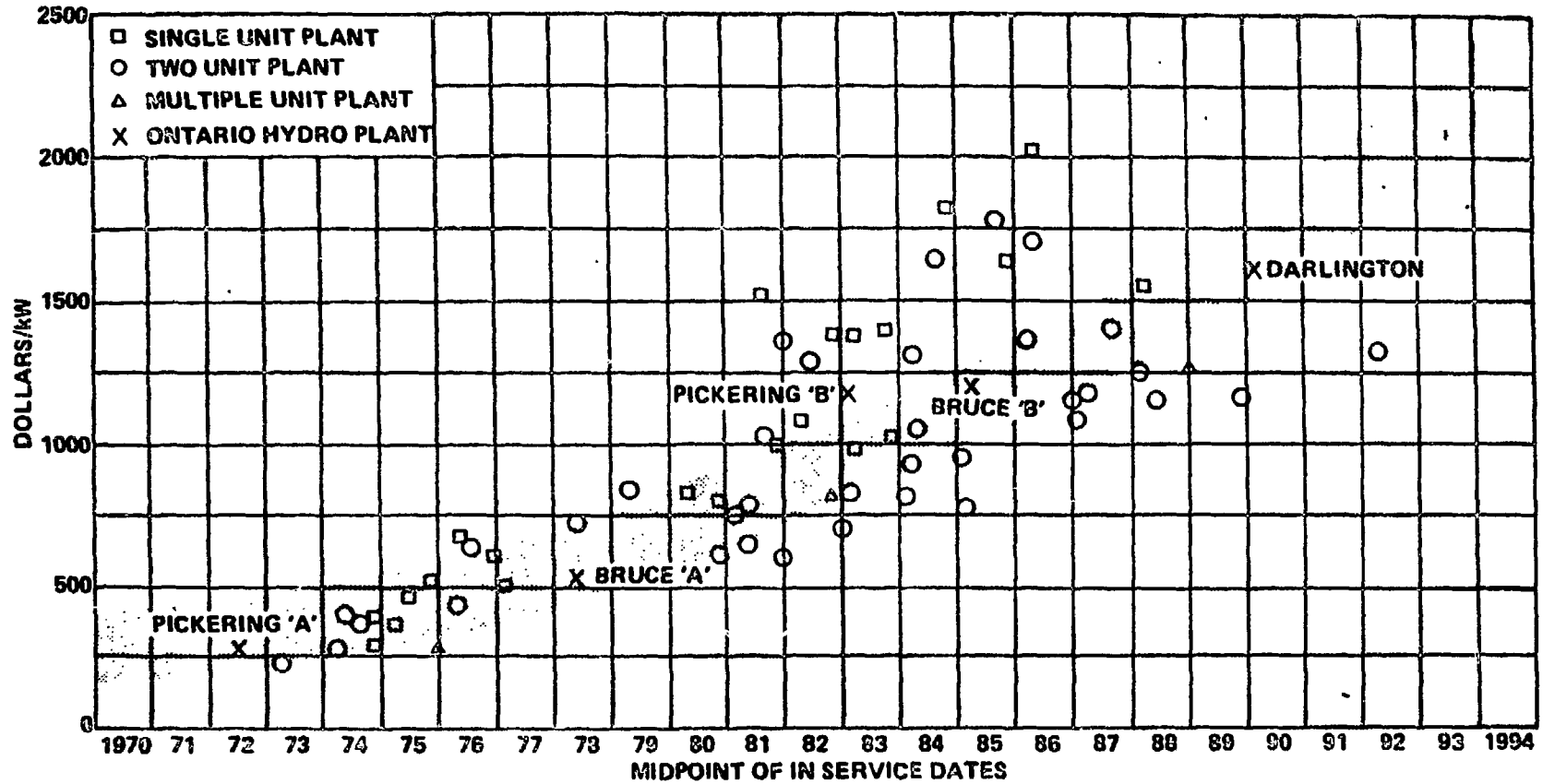
The eight commercial CANDU units have demonstrated a net Capability Factor of 77% (from first electricity production) and 79% from the In-Service Dates.

The authors use demonstrated capability for CANDU/LWR comparisons.

Capital Cost Information - LWR - USA

The actual or estimated initial Specific Dry Capital Costs for LWR units of 500 MW and greater built in the USA are shown in Figure 5 based on information provided by a number of USA utilities, in USA dollars.

**FIGURE 5
INTERUTILITY COMPARISON - NUCLEAR PROJECTS
SPECIFIC DRY CAPITAL COSTS**



CANADIAN STATIONS IN CANADIAN DOLLARS
OTHER STATIONS IN US DOLLARS

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The actual or estimated initial Specific Dry Capital Costs for CANDU-PHW units in Ontario Hydro are also shown in Figure 5 in Canadian dollars.

The following observations may be made:

- (a) There is a wide scatter in the Specific Capital Cost data.
- (b) The CANDU-PHW units have a similar cost and cost trend compared to the average LWR.

LWR Performance - Actual

The actual LWR lifetime performance has been reviewed and documented by Ontario Hydro and published in a document "Comparison of Ontario Hydro with World Power Reactors 1979."

The lifetime average Gross Capacity Factor of PWR and BWR has been 57% and 55% respectively. In the following comparisons, we have used the PWR performance of 57%.

Authors' Judgment

Through examination, discussion, and study of available data, the following judgments have been made by the authors:

(a) Performance

There is a wide range of PWR performance (Capacity Factor) with a world average of 57%. The PWR Capacity Factor performance is expected to further improve.

The available data is based upon stations which usually have only one or two units per station. Four-unit stations (Ontario Hydro practice) are expected to have better performance due to improved diversity (spare parts, technical support, etc).

The authors also feel that Ontario Hydro enjoys better than average project management and operator training.

The authors judge that if Ontario Hydro had an extensive PWR program (same number of units in service, same number of units per station and in-service dates similar to the actual CANDU-PHW program) that the expected PWR performance in Ontario Hydro would be 67%.

This is to be compared with a typical coal-fired capability of 74% in the USA and a demonstrated CANDU-PHW performance of 77% (since first electricity production).

Both coal-fired and CANDU-PHW stations enjoy the advantages of on-power fuelling.

The judged 10% capability factor superiority of CANDU-PHW assumes a judged 6% capability factor credit for on-power fuelling and a 4% capability factor credit for other concept advantages.

Ontario Hydro's performance for coal-fired stations is similar to USA experience at 74% for 500 MW units.

The authors judge that Ontario Hydro could achieve 77% in coal-fired stations if staffing levels and spare part diversity were increased. However, this is not economically justified for peak load application.

(b) Capital Cost

The above comparison of Ontario Hydro and US utility data (Figure 5) indicates no major Specific Dry Capital Cost difference between CANDU-PHW units built in Ontario and LWR units built in the USA.

Examination of the design requirements of the two concepts suggests there should be no major Dry Capital Cost differences for most facilities such as site, turbine-generator, cooling systems, instrumentation and controls, buildings and containment.

In the opinion of the authors, assuming identical supply capability and manufacturing volume, the CANDU reactor with on-power fuelling should be less expensive due to the absence of enriched fuel, very demanding pressure vessel specifications as compared with pressure tubes, the need for in-core high pressure regulating and shut-down devices and the like.

However, in this paper the cost comparisons which follow assume the Dry Capital Cost for CANDU-PHW and LWR in Ontario Hydro to be identical.

(c) OM&A Costs

The Capacity Factor achieved by Ontario Hydro has depended, in part, on maintaining around-the-clock maintenance staff at four-unit stations. This high staff level is economically warranted because of the high cost of burning coal whenever a CANDU unit is shut down. Example -- in the Bruce NGS-A, one-percent Capacity Factor is equivalent to the wages of about 100 people.

Since PWR units also have a low fuelling cost compared with coal, around-the-clock maintenance would also be justified. In the opinion of the authors, there is no significant difference in optimum staff levels for four-unit CANDU-PHW and four-unit PWR in Ontario Hydro.

Similarly, the total OM&A cost is expected to be the same.

(d) Fuel

Examination of available USA data suggests that, for a large PWR program in Ontario, the Fuelling Unit Energy Cost for PWR would be 5.46 m\$/kWh or higher in 1980.

This evaluation assumes the mining and refining costs of natural uranium are identical for CANDU and PWR. Enrichment cost is peculiar to the PWR units. Fabrication costs are particular to each design.

Comparison - CANDU-PHW Versus PWR - Ontario Hydro

Table 4 is a cost comparison of CANDU-PHW and PWR in Ontario Hydro.

It is based on actual cost and performance experience of CANDU units in Ontario and the estimated performance and cost of PWR as outlined above.

Two sets of estimates are given for the PWR, corresponding to the world average capacity factor of 57% and the authors' judgment of 67% for a major PWR program in Ontario Hydro.

This comparison indicates that:

- the TUEC for PWR operating in Ontario at the world average Capacity Factor (57%) would be approximately 37% higher than the TUEC of CANDU-PHW actually experienced.
- the TUEC for PWR operating in Ontario at the author's judgment of 67% capacity factor would be approximately 26% higher than the TUEC of CANDU-PHW actually experienced.
- the costs of Capital Heavy Water plus Heavy Water Upkeep for CANDU are more than offset by the higher Fuelling UEC of the enriched PWR fuel.

Table 4

ONTARIO HYDRO 1980 CANDU-PHW VERSUS PWR COSTS

| | <u>CANDU-PHW</u> | <u>PWR</u> | |
|--------------------------------|------------------|-----------------|--------------------|
| | <u>PNGS-A</u> | <u>High NCF</u> | <u>Average NCF</u> |
| Station Size (MW e net) | 2 060 | 2 060 | 2 060 |
| Net Capacity Factor (NCF %) | 77 | 67 | 57 |
| Capital UEC | | | |
| Dry Capital | 4.93 | 5.67 | 6.66 |
| Commissioning | 0.17 | 0.20 | 0.23 |
| Fuel | 0.07 | 0.35 | 0.41 |
| Heavy Water | <u>1.33</u> | <u>-</u> | <u>-</u> |
| Capital UEC | 6.50 | 6.22 | 7.30 |
| OM&A UEC | 4.24 | 4.87 | 5.73 |
| Fuelling UEC | 2.33 | 5.46 | 5.46 |
| Heavy Water Upkeep UEC | <u>0.46</u> | <u>-</u> | <u>-</u> |
| Total UEC | 13.53 | 16.55 | 18.49 |

Note:

All UEC data in m\$/kW·h 1980\$.

7. Summary

1. Nuclear-Electric and Coal-Electric Generating Stations are the primary options in Ontario for new generating requirements for the period from 1980 to 2000.
2. Coal-Electric Generating Stations are the best choice to meet peaking requirements.
3. Nuclear-Electric Generating Stations are the best choice to meet base-load requirements.
4. For base-load applications, the CANDU-PHW has a proven lower cost than Coal-Electric. In 1980, the Total Unit Energy Cost for Pickering NGS-A was 12.77 m\$/kWh compared with the same size, same vintage Lambton coal-fired station with a corresponding cost of 21.18 m\$/kWh.
5. CANDU-PHW has inflation-proof characteristics due to its very low fuelling costs.
6. CANDU-PHW with on-power fuelling is expected to continue to enjoy high Capacity Factor performance.
7. The actual performance of CANDU-PHW units in Ontario is 77% Capacity Factor since first electricity production and 79% since the In-Service Dates.

The actual average lifetime performance of PWR in the world is 57% since first electricity production.

The authors judge that 67% PWR Capacity Factor would be achievable in Ontario for a mature PWR program.

8. For Ontario conditions and requirements, the estimated Total Unit Energy Cost of PWR units as compared to CANDU-PHW experienced costs indicates the PWR to be 26% higher, assuming a 67% PWR performance and a 77% CANDU performance.

