PERFORMANCE OF CANADIAN COMMERCIAL NUCLEAR UNITS & HEAVY WATER PLANTS

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INTRODUCTION

This report presents an overview of the lifetime performance of Canada's commercial nuclear-electric units (Pickering Generating Station-A, Units 1-4) and heavy water production plants (Bruce HWP-A and Port Hawkesbury HWP).

These facilities are vital to Canada's rapidly expanding nuclear program. This is the first opportunity to report performance at a major European Conference since all three reached full capacity in 1973.

PICKERING GENERATING STATION-A

When Unit 4 was declared In-Service on June 17, 1973, Pickering GS-A, at 2056 MW net from four identical units, became the largest fully operational nuclear-electric station in the world.

Pickering is owned and operated by Ontario Hydro, and we have been very pleased with its performance since startup of Unit 1 in April, 1971. It is fully competitive, in terms of both economy and reliability, with fossil-fired units of the same size and vintage in Ontario. Pickering, as do all Ontario Hydro's existing and planned nuclear stations, uses a CANDU-PHW (Pressurized Heavy Water) Nuclear Steam Supply System (NSSS) designed by Atomic Energy of Canada Limited (AECL). Pickering was preceded by about three decades of close co-operation between AECL and Ontario Hydro in the design, construction and operation of NPD (Nuclear Power Demonstration) and Douglas Point, Canada's invaluable CANDU-PHW "Knowledge Generators".

	Net Capacity MW	First Electricity	Type
NPD	22.5	1962	CANDU-PHW
Douglas Point	206	1967	CANDU-PHW

Pickering was committed by Ontario Hydro late in 1964, less than two years after startup of NPD and three years before the 200 MW prototype, Douglas Point, produced its first electricity. The initial capital cost of Pickering was $746,000,000. This large financial risk was taken in order to maintain the momentum of Canada's nuclear program. It represented confidence that the CANDU-PHW concept was technically sound, and the proper economic choice for Ontario and Canada. Early experience at Pickering has been excellent and the highlights are briefly described below.

Reliability

IN-SERVICE DATE RELIABILITY

One very important measure of reliability is whether or not a generating unit goes into service on or ahead of schedule. Planned In-Service Dates were originally established in 1964 for Units 1 and 2, and in 1967 for Units 3 and 4. Largely because of a 10-month construction strike in 1967, the actual In-Service Dates of Units 1 and 2 were 9 and 3 months respectively, later than originally planned. However, Units 3 and 4 were declared In-Service 4 and 3½ months, respectively, ahead of schedule.

First critical generally occurs soon after construction is complete. The time taken to go from first critical to first electricity, then to full power and finally to commercial service is a significant measure of reliability.

We were particularly pleased at the short times required to go from first critical to full power:

Unit 1	95 days
Unit 2	53 days
Unit 3	18 days
Unit 4	12 days

This is a dramatic indication of the soundness of the basic design and the total design, construction and commissioning effort.

It also demonstrates one of the many advantages of building multiple identical units at one location.

OPERATING HISTORY

Unit 1 produced first electricity in April, 1971, Unit 2 in October, 1971, Unit 3 in May, 1972 and finally Unit 4 in May, 1973.

We decided to take a four-week planned outage on each unit after its first year of operation, primarily for turbine-generator inspection.

This has been done on Units 1, 2 and 3 but has been deferred until 1975 for Unit 4.

On Unit 2, the planned outage had to be extended by four weeks due to a generator rotor ground fault.

In 1972, Ontario Hydro suffered a four-month strike and during the strike period we did not operate Pickering.

In 1974, Units 1, 2 and 3 again had planned outages of about four weeks each, to modify the Row 7 blading on each of the three low pressure turbines on each unit.

Commencing August 10, 1974, Unit 3 suffered a long forced outage until March 31, 1975 due to leaking pressure tubes.

A highlight of the operating history was an uninterrupted period of full power operation of Unit 2 for 217 days, 3 hours between August 2, 1974 and March 8, 1975. In fact, during the 261 days from July 12, 1974 to March 31, 1975 Unit 2 operation was interrupt for only three brief intervals of 15, 20 and 12 minutes respectivel with the unit still at full power after March 31, 1975.

PRODUCTION RELIABILITY

The following production reliability data <u>excludes</u> the four-month strike shutdown period in 1972.

Over the lifetime of a generating station, production reliability can be measured by many criteria.

However, our CANDU-PHW units, with their unmatched low fuelling costs, are never shutdown or derated for economic reasons. Net Capacity Factor (NCF) is, therefore, the best single production reliability indicator.

NCF subtracts all lost production. During an outage a unit is penalized for electricity that it consumes and, while operating, any energy produced in excess of the declared unit capacity is ignored.

LIFETIME NCF

The average NCF to February 28, 1975, covering 10.2 unit-years is 77.8%. The corresponding average Gross Capacity Factor (GCF) is 78.4%.

	NCF	GCF
Unit 1	79.2%	79.8%
Unit 2	80.7%	81.3%
Unit 3	61.8%	62.5%
Unit 4	92.8%	93.3%
Weighted Average	77.8%	78.4%

WINTER PEAK NCF

In Canada, nuclear unit reliability is particularly important for both system security and customer economics during our winter peak load periods of December, January and February.

For the 1972/73 winter peak period, the three units then in-service had an average NCF of 96%.

For 1973/74 with all four units in-service, the average NCF was 95%.

For 1974/75, the average NCF dropped to 67% because of the Unit 3 pressure tube problem.

	Winter Peak		
	1972/73	1973/74	1974/75
Unit 1	99.4	89.2	72.4
Unit 2	90.2	94.0	100.0
Unit 3	97.6	99.5	-0.9
Unit 4	Not In-Service	95.9	96.1

ANNUAL NCF (1973 and 1974)

In the full calendar year 1973, the four units had an average NCF of 83.4%. Unit 2 was low due to the generator rotor ground fault.

In 1974, the average NCF was 74.3%. Unit 3 was low because of the pressure tube problem.

	1973		1974
Unit 1	92.5%		72.0
Unit 2	69.0		88.4
Unit 3	85.1		42.7
Unit 4	90.1	(6½ months)	93.9

ECONOMICS

For base-loaded units, the valid economic criterion is Total Unit Energy Cost (TUEC ---- m$/kWh). The components of TUEC are:

- Capital UEC
- Operating and Maintenance (O&M) UEC
- Fuelling UEC
- Heavy Water Upkeep UEC

HEAVY WATER UPKEEP UEC

Heavy Water is very expensive and must be conserved. Its cost has been about 66 $/kg, and like most things today, the cost is increasing.

Each Pickering reactor contains about 500 Megagrams, costing 33 million dollars.

Heavy Water is not consumed, but it can be lost, or it can be downgraded by mixing with natural water. If downgraded, it must be upgraded to restore its isotopic purity to the range of 99.7 - 99.8 mass per cent.

Upkeep = Loss + Downgrading Equivalent Loss (DEL)

In 1965 when heavy water was hoped to be less expensive than it is today, Ontario Hydro set a target of 0.2 m$/kWh (corresponds to 1.3 kg/h per unit at 80% NCF and 66 $/kg).

That target has very nearly been met, with an actual lifetime average of 1.8 kg/h per unit. As is the case with other cost factors, inflation has raised the price of heavy water such that the corresponding Heavy Water Upkeep UEC is now approximately 0.5 m$/kWh.

We would consider 2.5 kg/h to be acceptable but we would work hard to reduce it.

Despite the acceptable results to date, we will likely make improvements such as replacing the heavy water recovery equipment which requires excessive maintenance and radiation dose.

As can be seen later in this report, the cost of heavy water upkeep corresponds to about 5% of TUEC.

FUELLING UEC

The unique and exceptionally low fuelling cost of CANDU-PHW units has been previously demonstrated by NPD and Douglas Point. The actual Fuelling UEC at Pickering, without taking any credit for potential recovery of plutonium, has been:

1973	0.91 m$/kWh
1974	0.88 m$/kWh

TOTAL UNIT ENERGY COST (TUEC)

Ontario Hydro is fortunate in having a coal-fired station of similar size and vintage as Pickering. This permits meaningful economic comparisons without having to make adjustments for unit size or capital cost inflation.

As a measure of relative economy, we therefore compare Pickering TUEC with the TUEC of our 4x500 MW Lambton coal-fired station which went into service about two years before Pickering.

The following table is a recent (March 1975) maturity cost estimate for Pickering and Lambton. It is an estimate, since Lambton is not base-loaded and Pickering is not yet mature, but it is based on actual cost experience.

It is based on 80% NCF, low sulphur coal, Ontario Hydro capital depreciation conditions of 30 years life and 8% capital interest rate, and is in 1975 dollars.

	Pickering	Lambton (1)	Lambton (2)
Capital UEC	4.60	1.70	1.70
O&M UEC	1.10	0.96	0.96
Fuelling UEC	0.98	10.60	13.52
Heavy Water Upkeep UEC	0.35	-	-
TUEC (m$/kWh)	7.03	13.26	16.18

O&M UEC is somewhat higher for both Pickering and Lambton than in previous published estimates due to inflation and addition of corporate overheads.

Pickering Fuelling UEC and Heavy Water Upkeep UEC are somewhat higher than in earlier published estimates because of inflation.

Lambton Fuelling UEC is dramatically higher than earlier published estimates due to fossil fuel inflation. Because of the rapid change in coal prices, two values have been shown for Lambton Fuelling UEC.

1. 10.6 m$/kWh corresponding to the average cost of fuel in our current coal inventory.

2. 13.52 m$/kWh corresponding to the current cost of new coal to replenish our coal inventory.

For case 2, which is the most relevant for the near future, Pickering TUEC breaks even with Lambton at about 22% NCF. In May, 1973, before fossil fuel prices escalated so dramatically, the break-even NCF was about 60%.

In 1974, despite the relatively low NCF (74.3%) due to the pressure tube problem, the actual TUEC for Pickering was 8.05 m$/kWh. If Lambton had been required to operate at the same NCF (74.3%), its 1974 TUEC using low sulphur coal would have been at least 9.1 m$/kWh.

We now expect that the original capital cost of Pickering GS will have been repaid, due to coal cost savings, by the end of 1978, when the four Pickering units will be "children" only five to seven years old.

CAUSES OF LOST PRODUCTION

In broad terms and excluding the 1972 strike, the lost production and corresponding effect on NCF, up to February 28, 1975, has been due to:

	% of Total Lost Production	* NCF Reduction (% NCF)
Unit 3 Pressure Tubes	24.4	5.4
Fuel Handling Systems	10.2	2.3
Other NSSS Problems	13.8	3.1
NSSS In-Service Inspection	6.6	1.5
Turbine and Auxiliaries	18.4	4.1
Generator and Auxiliaries	14.6	3.2
First Turbine Inspections	6.8	1.5
Others	5.2	1.1
TOTAL	100%	*22.2%

* The 22.2% NCF Reduction corresponds to 100 - 77.8 = 22.2% where 77.8% is the Lifetime NCF quoted earlier in this report.

EQUIPMENT PERFORMANCE

Some significant equipment performance highlights are:

1. Steam Generator Tubes

   There are approximately 31,000 monel tubes for each reactor. Of these, only one tube has developed a leak. The leaking tube was located and plugged in 120 hours. Eddy current scanning of other selected tubes showed no indications of significant corrosion or fretting. The single leak is believed due to foreign material in the tube.

2. Heat Transport Pumps

   Each reactor has 16 heavy water heat transport pumps, of which 12 are required at full power.

   These pumps and their motors have performed almost flawlessly. No major maintenance has been required, and the occasional seal replacement has had negligible effect on electricity production or heavy water upkeep cost.

3. Pressure Tubes

   Each reactor has 390 Zircaloy-2 (Units 1 and 2) or Zirconium 2-1/2% Niobium (Units 3 and 4) pressure tubes containing the fuel and heat transport heavy water.

   On August 10, 1974, a pressure tube leak was discovered in Unit 3. The faulty tube was identified and replaced by September 3, 1974.

   During startup on September 5, 1974, it was realized that additional tubes were leaking, or about to leak.

   As a result of a remarkable, disciplined, and yet almost spontaneous pooling of effort by AECL, Ontario Hydro, Canadian General Electric Company and Westinghouse Canada Limited, the following were accomplished by December 31, 1974.

(a) A total of 17 leaking tubes were identified and isolated.

(b) The remaining 373 tubes were found not to leak.

(c) An ultrasonic survey of 70 tubes was completed. All were crack-free.

(d) The cause of the 17 leaks was determined, in considerable detail.

(e) A program was established to

  (i) Replace the leaking tubes by March, 1975.

  (ii) Restart Unit 3 by April, 1975.

  (iii) Inspect tubes in other units such as Pickering Unit 4, and Bruce Units 1 and 2 which are under construction.

  (iv) Eliminate the problem in future reactors, including Bruce 1 and 2.

The leaking tubes were all replaced by the end of February, 1975, and Pickering Unit 3 was returned to full power on March 31, 1975.

The leaks were due to tiny axial cracks in regions of high residual stress near the rolled joints which connect the Zirconium-Niobium pressure tubes to the stainless steel end fittings. The stresses are the result of an inadequate rolling procedure. The cracks are produced during long periods of cold shutdown conditions during which zirconium hydrides precipitate in the stressed region causing local weakness. At normal operating conditions of about 250°C the hydrides are in solution, the material is ductile, the cracks do not propagate, and stress relief gradually takes place.

The pressure tube leak problem is described extensively in the attached Appendix.

4. Turbine-Generators and Auxiliaries

In general, the turbines have performed well, with no major damage and negligible wet-steam erosion.

Significant problems include:

(a) Failure of several blades (all in Row 7) in Unit 1 and 3 low pressure (LP) turbines during the first year of operation.

(b) Failures of expansion bellows in steam inlet lines to the LP turbines.

(c) Tube and gasket failures in the live steam reheaters.

(d) Sticking emergency stop valves (an early problem that has been solved).

(e) A generator rotor ground fault.

(f) An unacceptable frequency of hydrogen-to-stator cooling water leaks due to water-box gasket failures, water-box vent line failures and leaking conductors.

ON-POWER REFUELLING

Refuelling at full power, which is a unique advantage of CANDU reactors, has been previously demonstrated at NPD and Douglas Point.

There are two fuelling machines for each reactor. They are complex and must perform difficult tasks in a hostile environment.

At Pickering, computer-controlled on-power refuelling was accomplished on schedule, and has met reactivity needs while causing about 10.2% of the total lost production, corresponding to 2.3% reduction in NCF.

Lost production has generally been due to deratings because of temporary low reactivity, rather than outages for repairs.

To reduce future production loss and to reduce maintenance efforts and radiation dose at Pickering and future CANDU-PHW stations, a vigorous development and improvement effort is being maintained.

FUEL PERFORMANCE

Each reactor contains about 5,000 fuel bundles and by the end of 1974, a total of 48,000 had been irradiated.

Of these, only 101 bundles, or less than 1/4 of 1% have become defective.

All except seven of these defects occurred in Unit 1 between September, 1971 and May, 1972.

The defects occurred as a result of excessive localized power increases experienced by certain fuel bundles, caused by either improper control rod movement or by fuel movement from low flux to high flux conditions during on-power refuelling.

The relation between burnup, initial power, power increase and defect probability has been accurately established.

Simple changes in control rod sequencing and refuelling programs has virtually eliminated fuel defects since May, 1972, the defect rate since then being only 1/60 of 1%.

Defective fuel is removed at full power (an advantage of on-power refuelling) and has had negligible effect on reliability, economy, staff safety and environmental impact.

RADIOACTIVE EMISSIONS TO THE ENVIRONMENT

Our license limits for radioactivity releases to air and to water, established by the Atomic Energy Control Board of Canada, conform to the recommendations of the International Committee on Radiological Protection.

Ontario Hydro and AECL have established design and operating targets of 1% of these license limits for all new CANDU stations.

Although Pickering was designed before these targets were adopted, they have been met. For example, the actual experience at Pickering in 1974 is as follows:

1. Emissions to Air

Emissions to Air	% of Limit
Tritium	0.22
Iodine-131	0.02
Particulates	0.07
Noble Gases	0.20

2. Emissions to Water

Emissions to Water	% of Limit
Tritium	0.09
Gross B-γ	0.29

HEAVY WATER PRODUCTION IN CANADA

Dependable supplies of heavy water at reasonable prices are vital to meet Canada's domestic and export CANDU-PHW needs.

Very roughly, the quantity of heavy water needed is 1 Megagram per Megawatt (1 Mg/MW) of new electrical capacity.

Canadian heavy water plant (HWP) capacity at present is a nominal 150 kg/h consisting of:

- Bruce HWP-A (100 kg/h) owned by Ontario Hydro.
- Port Hawkesbury HWP (50 kg/h) owned originally by Canadian General Electric and now by AECL.

Assuming Net Capacity Factors of 70 - 80% can be achieved, their combined output would be 900 - 1000 Mg/a.

Both plants reached essentially full capacity during 1973.

In 1974, the actual Net Capacity Factors were:

Bruce HWP-A	76%
Port Hawkesbury HWP	69%

In order to approach design capacity, one major problem had to be recognized and overcome. This problem was a phenomenon not uncommon in the chemical and petroleum refining industries, and commonly known as "foaming instability".

The major solution was to modify the enriching unit trays, but in addition, literally hundreds of smaller improvements to components, chemical control and operating procedures were necessary to achieve reliable operation at high capacity (about 97% of design capacity).

These plants, the first in Canada and by far the largest in the world, are reaping the benefits of an intensive research and development effort.

The production from Bruce HWP-A and Port Hawkesbury HWP can satisfy a CANDU-PHW expansion program of about 1000 MW/a.

Within a few years, Ontario Hydro's nuclear expansion will be about 2500 MW/a, with additional expansion in other parts of Canada (Quebec and New Brunswick) and reactor exports to Korea, Argentina, etc.

Accordingly, five additional heavy water plants are under construction or planned, to increase nominal Canadian HWP capacity to 600 kg/h, as follows:

HWP	Owner	Capacity
Glace Bay	AECL	50 kg/h
La Prade	AECL	100 kg/h
Bruce HWP-B	Ontario Hydro	100 kg/h
Bruce HWP-C	Ontario Hydro	100 kg/h
Bruce HWP-D	Ontario Hydro	100 kg/h

CONCLUSION

This report has described some of the events, problems, successes and performance criteria that Ontario Hydro, as the owners and operators of both Pickering GS-A and the Bruce HWP-A, consider most relevant in judging performance.

The most costly single problem encountered so far at Pickering has been the Unit 3 pressure tube leaks. However, the knowledge and experience gained during the investigation and tube replacement programs have simply reconfirmed the inherent safety and maintainability characteristics of the pressure tube concept.

Pickering is the first of a series of CANDU-PHW commercial stations, while Port Hawkesbury HWP and Bruce HWP-A are the first in a series of plants needed to provide the supporting supplies of heavy water.

Table 1 is a list of CANDU-PHW commercial nuclear units operating, under construction, or planned in Canada and for export.

Most are in Ontario, where in 1974 the 2300 MW of CANDU-PHW capacity supplied 17% of the total electrical energy.

By 1990, CANDU-PHW units should provide 60-65% of Ontarios electrical energy --- economically, with minimal negative environmental effects, and using a secure indigenous primary energy resource

Table 1

CANDU-PHW COMMERCIAL UNITS

Status	Station	Location	Net Capacity (MW)	First Electricity
OPERATING	Pickering GS-A	Ontario, Canada	4x514	1971-1973
UNDER CONSTRUCTION	Bruce GS-A	Ontario, Canada	4x745	1976-1978
	Gentilly 2	Quebec, Canada	1x600	1979
	Rio Tercero	Argentina	1x600	1979
	Pickering GS-B	Ontario, Canada	4x514	1980-1982
PLANNED	Pt. Lepreau	New Brunswick, Canada	1x600	1980
	Bruce GS-B	Ontario, Canada	4x750	1981-1983
	Korea	Korea	1x600	1980
	Darlington GS	Ontario, Canada	4x800	1982-1984