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Authors:	H.A. Jackson L.W. Woodhead G.R. Fanjoy CNS/RMEP Staff

ONTARIO HYDRO
CANDU OPERATING EXPERIENCE

ontario hydro

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BY

H.A. JACKSON

L.W. WOODHEAD

G.R. FANJOY

CNS/RMEP STAFF*

ABSTRACT

The CANDU Pressurized Heavy Water (CANDU-PHW) type of nuclear-electric generating station has been developed jointly by Atomic Energy of Canada Limited and Ontario Hydro. This report highlights Ontario Hydro's operating experience using the CANDU-PHW system, with a focus on the operating performance and costs, reliability of system components and nuclear safety considerations for the workers and the public.

* CNS/RMEP staff contact - H.G. Brandford

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SUMMARY

INTRODUCTION

The CANDU-PHW type of nuclear-electric generating station has exceeded the performance of any other type of nuclear station in the world. This outstanding performance depends, in part, on the following:

1. The CANDU-PHW concept was developed into reliable operation in three stages: (1) demonstration, (2) prototype and (3) commercial operation through close cooperation of the two major partners - Atomic Energy of Canada Limited (AECL) and Ontario Hydro.

2. The comprehensive and coordinated nuclear program involves all scientific and engineering disciplines and all life cycle functions (research and development, design, manufacturing, construction and operation).

3. The program is based upon in-depth development of science and technology of heavy water reactors over a period of 42 years, from 1942 to 1984. During this period, Canada was the first country in the world to operate a high flux reactor and the first country in the world to operate fuel in a high flux reactor at high pressure and high temperature conditions.

4. The program is based upon a systematic approach involving establishment of objectives, measurement of results, identification and resolution of problems and continuous feedback of operating experience to researchers, designers and manufacturers.

The first nuclear-electric operating experience of the CANDU type started with the 22 MW e Nuclear Power Demonstration Nuclear Generating Station (NPD NGS) in 1962.

The second stage of operating experience with the CANDU type started in 1968 when the 206 MW e Douglas Point Nuclear Generating Station (NGS) was placed in service.

There were a number of problems which resulted in reduced performance of NPD NGS and Douglas Point NGS in early years. However, the successful solution to these early problems has been reflected in the commercial third stage (Pickering NGS-A and Bruce NGS-A). There has been excellent performance at these 8 commercial units which started up in the 1970s. Since Pickering-5 went into service on May 10, 1983, it has demonstrated excellent performance.

We are extremely proud in Ontario Hydro of this excellent performance and the in-depth technology developed over the past 42 years. The cumulative operating experience measured from first production of electricity of Ontario Hydro nuclear-electric units is 113 reactor years.

Table 1 is a tabulation of the 11 CANDU-PHW nuclear units in service in Ontario Hydro at the end of 1983. Ontario Hydro has 5 764 MW e in operation and 8 072 MW e under construction.

Two other electrical utilities in Canada, the New Brunswick Electric Power Commission and Hydro-Quebec, plus two other countries have CANDU-PHW nuclear units in operation. However, this report deals only with Ontario Hydro CANDU operating experience.

TABLE 1

Ontario Hydro Nuclear Units - In Service

Station	Unit	Net Capacity MW e	Net Capacity MWee*
NPD NGS	2	22	
Douglas Point NGS	1	206	
Pickering NGS-A	1	515	
	2	515	
	3	515	
	4	515	
Pickering NGS-B	5	516	
Bruce NGS-A	1	740	775
	2	740	775
	3	740	775
	4	740	775
TOTAL	11	5 764 MW e	5 904 MWee

* includes the electrical equivalent of steam production

OPERATING RESULTS

From the very beginning of operation of Ontario Hydro nuclear stations, a thorough Management by Objectives system has been utilized.

The five rudimentary objectives are as follows:

- Worker Safety
- Public Safety
- Environmental Protection
- Reliability
- Cost

For each of these objectives, extensive records and evaluations are available.

WORKER SAFETY

The highlights of the Worker Safety performance are as follows:

1. From 1962 to 1983, nuclear operations employees have worked 95 million man-hours.
2. There has never been a fatality of a nuclear operations employee at work for any reason.
3. There has been a very low frequency of temporary disabling injuries. Specifically, the frequency has been 1.9 injuries per one million man-hours for the decade from 1974 to 1983 inclusive.
4. No employee has ever been injured due to radiation.
5. There has never been a serious radiation exposure (greater than 25 rem per annum).
6. The highest whole body exposure which exceeded the regulatory limit of 5 rem per annum was an exposure of 7.3 rem.
7. Overexposures (exceeding whole body regulatory limits) to employees are very infrequent corresponding to 0.17 incidents per million man-hours worked.
8. Nuclear employees have been much safer at work than when not at work.
9. Worker Safety at nuclear plants has been better than at hydro and thermal plants, although the safety at all three types has been good.

PUBLIC SAFETY

Public safety has to do with the protection of the public against acute events, which would result in injury, disability, or death of a member of the public, caused by nuclear generating stations for any reason.

For radioactivity, the risk to members of the public is measured using two separate measuring systems:

1. Actual

   The recorded actual fatalities or injuries arising out of actual events in which significant radioactive release occurs.

2. Predicted

   The computed risk to members of the public based upon recorded or forecast component failures of process and safety systems.

Risk evaluations are required to minimize risk to the most exposed member of the public living near the generating station, and are also required to minimize the total dose to the general population in the event of an accident.

The highlights of Ontario Hydro operating experience are as follows:

1. During 113 reactor years of operation, there has never been a fatality nor has there been an injury to a member of the public involving radioactivity.

2. During 113 reactor years of operation, there has been one fatality to a member of the public. In 1982 a member of the public died in a traffic accident with an Nuclear Generation Division vehicle on a public highway.

3. There has never been a release of radioactivity from any nuclear generating station which resulted in a measurable dose to any member of the public.

4. The radioactivity risk criteria have been fully met at every station for every year.

ENVIRONMENTAL PROTECTION

Environmental protection means the control of chronic emissions from nuclear generating stations which could potentially impair the health and/or well-being of a member of the public, or cause adverse effects to the environment.

Radioactivity emissions are carefully controlled at extremely low levels. Highlights of the performance are as follows:

1. Ontario Hydro has a perfect record. Emissions of radioactivity have been below the annual regulatory limits for all categories of radionuclide, at every station for every year of operation.

2. Radioactivity emissions from Ontario Hydro stations have been maintained at very low fractions of the annual regulatory limits, typically less than 1% of the limits.

RELIABILITY

Reliability of a generating unit refers to the ability of the generating unit to produce electricity (minimum number of outages and deratings).

The highlights are as follows:

1. The lifetime performance of all commercial CANDU-PHW units has exceeded any other type of nuclear-electric stations (Pressurized Water Reactors, Boiling Water Reactors, Gas-Cooled Reactors). Table 2 compares the performance.

TABLE 2

World Comparison of Reactor Types
500 MW e Units and Larger - Lifetime*

(Gross Capacity Factor - %)

CANDU-PHW	80
PWR	58
BWR	57
GCR	49

2. Ontario Hydro's nine CANDU commercial units have extraordinary lifetime reliability. Table 3 is a ranking of the nine CANDU units in the world's 168 large operating reactors, excluding the USSR.

TABLE 3

Ontario Hydro Ranking in World's - Commercial Reactors
500 MW e and Larger - Lifetime*

Unit	Gross Capacity Factor (%)	World Rank
Bruce 3	87	1
Bruce 4	86	2
Pickering 4	82	4
Bruce 1	81	5
Pickering 2	81	6
Pickering 1	79	8
Pickering 3	79	9
Bruce 2	74	21
Pickering 5	71	30

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*Since first production of electricity.

COST

The comparison of CANDU-PHW Costs with other types of nuclear stations and with other types of generating stations such as coal-fired units depends upon numerous variables which are particular to the country and the utility which is making such a comparison.

In the Province of Ontario, the CANDU-PHW is very competitive with the only other practical option for base load application -- coal-fired generating stations.

Table 4 is a cost comparison of Pickering NGS-A, a nuclear station comprised of four 515 MW e units, with Lambton TGS, a four 495 MW e unit, coal-fired station. Both stations are of modern design and were constructed at approximately the same time.

TABLE 4

Cost Comparison Pickering NGS-A and Lambton TGS - 1983
Unit Energy Cost (m$/kW.h e*)

	Pickering NGS-A	Lambton TGS
Interest, Depreciation, and Decommissioning	7.7	2.0
Operation, Maintenance, and Administration	6.1	2.2
Fueling	3.8	21.8
Heavy Water Upkeep	0.8	-
Total Unit Energy Cost	18.4	26.0

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*Milli-dollars per kilowatt-hour electric, 1983 Canadian dollars.

COMPONENT EXPERIENCE

The following are highlights of the performance of some of the components in the commercial CANDU-PHW units at Pickering NGS-A, Pickering NGS-B and Bruce NGS-A.

The on-power fueling feature of CANDU-PHW has contributed to the high Capacity Factor of the commercial stations and to the low Total Unit Energy Costs. The lifetime Incapability Factor caused by on-power fueling problems is less than 1%. Off-power fueling for other reactor types typically results in Incapability Factors between 6% and 20%.

The fuel in CANDU stations can be manufactured in a relatively simple and small shop. The performance of the CANDU-PHW fuel has been excellent with a defect rate of less than 0.1%. Defective fuel has a negligible effect on station incapability.

Following extensive development, the heat transport pumps are working well with proven features allowing good maintainability and low incapability. For example, shaft seals can be replaced without major dismantling of either the motor or the pump. However, nine failures of the pump motor stators have occurred at Bruce NGS-A. A program is in hand to refurbish the Bruce NGS-A motors to obtain acceptable reliability.

The pressure tube development has produced excellent results. The pressure tube life was originally expected to exceed 10 years. This has been achieved. Rupture of one pressure tube is not expected to cause failure in adjacent tubes.

One problem of leaks near the rolled joints was encountered at Pickering NGS-A Units 3 and 4 in 1974. Sixty-nine tubes were replaced and the units were returned to service. At Bruce NGS-A, three pressure tubes in Unit 2 leaked in 1982. These were replaced and the unit returned to full power. The rolling process and joint design have been changed on subsequent units at Bruce NGS-A to eliminate the problem. A pressure tube which had previously been damaged by fuel was replaced at Bruce NGS-A Unit 1 in 1983.

At Pickering NGS-A, a pressure tube in Unit 2 ruptured in August 1983. The reactor was shut down in an orderly, controlled manner without the use of safety systems (shutdown, emergency coolant injection, or containment). The ruptured tube, its calandria tube, and further tubes are being examined by AECL in their hot cells at Chalk River and Whiteshell. The rupturing of this tube suggests that this particular alloy of zirconium (zircoloy-2) may become less ductile during operation. The problem is now being defined. Pickering NGS-A Unit 1, which uses pressure tubes with the same zirconium alloy, has also been shut down for examination of pressure tubes.

Radiation-induced lengthening of pressure tubes will use up original design allowances after a minimum life of 14 years for the first commercial units. Adjustments to the axial location of the pressure tubes are planned which will extend the lifetime beyond 14 years. New pressure tube specifications are seeking a life of 30 years.

The performance of CANDU-PHW steam generators has been excellent with a very low incapability of less than 1.1%. One major problem has been experienced during manufacture which required a change in the steam generator design and stress-relieving procedure.

The CANDU-PHW station at Pickering NGS-A used the first digital computer control system for a nuclear station. Today, all subsequent CANDU-PHW stations utilize dual digital computer controllers with outstanding reliability.

The heavy water management of CANDU-PHW stations is important in order to minimize heavy water losses in systems operating at high pressure and high temperature. The basic methods achieve low cost even though large leaks can occur. Enclosures ensure the effective recovery of both vapour and liquid leakage. The heavy water management costs have been low. The quality control which must be taken to ensure low heavy water cost has contributed to the high Capacity Factors achieved.

GENERAL

Introduction

The purpose of this paper is to discuss the CANDU Operating Experience with particular emphasis on the overall performance.

The three provincial electrical utilities engaged in the CANDU-PHW nuclear program in Canada are Hydro-Quebec (HQ), New Brunswick Electric Power Commission (NBEPC), and Ontario Hydro (OH). Other countries presently engaged in the CANDU-PHW nuclear program include Argentina and Korea.

The CANDU-PHW units Point LePreau (NBEPC), Gentilly 2 (HQ), and Wolsung 1 (Korea) went critical on July 25, 1982, September 11, 1982, and November 21, 1982, respectively. However, this report deals only with Ontario Hydro's CANDU-PHW Operating Experience.

Canadian Experience

Canadian nuclear experience with heavy water reactors goes back 42 years to 1942. The first heavy water reactor, Zero Energy Experimental Pile (ZEEP), went into service in 1945. This reactor advanced the knowledge of physics for this type of reactor.

In 1947, the first high flux reactor in the world (NRX) went into service in Canada. Since the moderator in this reactor was heavy water, there was considerable concern about the design of valves, pumps, and heat exchangers to minimize losses. Although problems with joints and seals did exist, a good technological base was established for the subsequent power program. The dynamic physics behaviour of high flux reactors (dynamic variation of xenon poison between power and time) was established. The elementary dissociation of water under radiation was learned and the chemical engineering requirements to minimize dissociation and to economically recombine the dissociation products were established. Extensive other experience relevant to the CANDU-PHW was also learned in NRX and its higher power successor reactor NRU.

When the USA naval submarine program was developed, Canada possessed the only high flux facility to serve as a reactor test bed. Through this process, the first in-reactor experience with high power fuel in high temperature, high pressure water was established in the late 1940s and early 1950s, some 30 years ago. The NRX and NRU continue to serve as high flux experimental reactors for the CANDU-PHW program.

When Canada decided to proceed with its first heavy water nuclear generating station in 1955, a vertical pressure vessel type was adopted. This demonstration reactor was called NPD-1. In 1958, a decision was made to cancel NPD-1 and a new concept using pressure tubes, a horizontal reactor and on-power fueling was adopted. This reactor was called NPD-2. The NPD-2 reactor (22 MW e) went into service in 1962 and was the first unit of the CANDU-PHW type.

Some of the major concerns when NPD-2 was built were as follows:

1 Would it be practical to build a heat transport system at high pressure and high temperature, or would the loss of heavy water at high cost make it economically impractical?

2. Would the pressure tubes be safe or would they fail?

3. Could pump seals be developed to operate at high pressure and high temperature without high losses of heavy water?

4. Could on-power fueling machines be developed that would work reliably.

5. Could high pressure boilers, transferring heat from heavy water to ordinary water, be built at a reasonable cost with high reliability?

6. Would the fuel yield high burnup and low failure rate?

7. Would the reactor be safe to the public and workers?

8. Would this concept of CANDU-PHW lead to economically competitive electricity cost in large commercial units operating on base load?

These major concerns required thorough research and development, quality controlled manufacturing, quality controlled construction and competent, well-trained operating and maintenance personnel.

Some problems were encountered during the early stages of the NPD-2 reactor (22 MW e) and the prototype reactor, Douglas Point NGS, (206 MW e) which went into service in 1968. The fueling machines were modified as a result of early experience. Better designs and specifications were developed for pumps, seals, pressure tubes, etc.

CANDU-PHW project management and teamwork was established to ensure a mult-disciplined approach of all sciences (chemistry, physics, mechanics, metallurgy, etc) as well as multi-function teamwork (research, design, manufacturing, construction, and operation).

In the above process, all operating experience was carefully documented and fed back to researchers, designers, constructors, and manufacturers.

The thoroughness of research, design, manufacturing, and construction to meet the above concerns, the careful recruitment and training of operators, together with the project management teamwork, has led to the commercial CANDU-PHW concept with excellent operating performance.

Although much of the CANDU design utilizes many ordinary components, a number of specially developed products had to be developed and built by AECL and Canadian manufacturers. Ontario Hydro has worked closely with AECL and Canadian manufacturers to resolve problems and ensure quality control. Through these processes, reliable and reasonably priced CANDU components are available from Canadian manufacturers.

Ontario Hydro Experience

The CANDU-PHW was developed into a reliable commercial generator of electricity through close cooperation of two major partners: the federal agency, AECL, and the provincial electrical utility, Ontario Hydro. Ontario Hydro was generally accountable for the overall project management, the overall construction, the design of the turbine-generator portion of the station, the commissioning, and the operation and maintenance. AECL has been generally responsible for the research, development, and design of the nuclear portion of the station.

Ontario Hydro has operating experience with 11 CANDU-PHW units and has an additional 11 nuclear units under construction. Hydro-Quebec has had operating experience with one CANDU-BLW unit and one CANDU-PHW unit. New Brunswick Electric Power Commission has one CANDU-PHW in operation.

It is not possible in a short presentation to be totally comprehensive in reviewing the operating experience. However, it is important that "bad performance" be presented along with "good performance" in giving an accurate overview of the total experience.

During the 1960s, following the startup of the 22 MW e demonstrator and the startup of the 206 MW e prototype Douglas Point NGS, there were a number of problems which resulted in reduced performance. However, the successful solution to these early problems has been reflected in excellent performance of the 8 commercial units which started up in the 1970s. We are extremely proud in Canada of this excellent performance and the in-depth technology developed in the 42 years between 1942 and 1984. The cumulative Ontario Hydro operating experience is 113 reactor years.

Before proceeding with the detailed experience presentation, the following are some general comments about the Ontario Hydro system. It should be noted that Ontario Hydro's satisfaction with the CANDU-PHW and the favourable relative cost of CANDU-PHW is based upon our in-depth knowledge of CANDU-PHW costs, 80 years of experience with hydraulic generation and 30 years of experience with thermal (ie, fossil: coal, oil, gas) generation.

Ontario Hydro had a total installed electrical capacity of 24 826 MW at the end of 1983. This capacity is comprised of 3 types of generation as in Table 1.

TABLE 1

Ontario Hydro Installed Capacity December 1983 - MW e (Net)

Hydraulic	6 499
Thermal	12 563
Nuclear	5 764
Total	24 826

The operating nuclear units are all of the CANDU-PHW type and are tabulated in Table 2.

TABLE 2

Ontario Hydro - In Service Nuclear Capacity - December 1983

Station	Unit Number	Net Capacity MW e	Net Capacity MWee*	In-Service Date Actual
NPD NGS	2	22		October 1962
Douglas Point NGS	1	206		September 1968
Pickering NGS-A	1	515		July 1971
	2	515		December 1971
	3	515		June 1972
	4	515		June 1973
Pickering NGS-B	5	516		May 1983
Bruce NGS-A	1	740	775	September 1977
	2	740	775	September 1977
	3	740	775	February 1978
	4	740	775	January 1979
Total	5 stations 11 units	5 764	5 904	

*includes the electrical equivalent of steam production.

Bruce NGS-A is also the primary source of thermal energy (steam) for the adjacent Bruce Heavy Water Plant (BHWP). The production reliability and Total Unit Energy Cost information presented in this paper are based on the sum of electrical plus thermal energy production.

Ontario Hydro presently has 11 units under construction as indicated in Table 3.

TABLE 3

Ontario Hydro - Nuclear Capacity Under Construction - December 1983

Station	Unit Number	Net Capacity MW e	Most Probable In-Service Date
Pickering NGS-B	6	516	February 1984
	7	516	December 1984
	8	516	July 1985
Bruce NGS-B	6	750	November 1984
	5	750	February 1985
	7	750	July 1986
	8	750	January 1987
Darlington NGS-A	2	881	May 1988
	1	881	February 1989
	3	881	November 1991
	4	881	August 1992
Total	3 stations 11 units	8 072	

The total nuclear capacity of Ontario Hydro in operation and under construction is indicated in Table 4.

TABLE 4

Ontario Hydro - Nuclear Program Net Capacity

In Operation	5 764
Under Construction	8 072
	13 836

The energy contributions to Ontario Hydro's electrical requirements for the calendar year 1983 were as follows:

	Energy (TW.h)	Contribution (%)
Hydraulic	36.6	34.1
Thermal (coal)	35.8	33.4
Nuclear	39.5	36.8
Purchases and Other	7.2	6.7
Total	119.1	111.1
Export (out of Ontario)	-11.9	-11.1
Net Ontario	107.2	100.0

PART A - RESULTS

A0 INTRODUCTION

From the very beginning of the operation of Canadian nuclear stations a thorough Management by Objectives system has been utilized.

These rudimentary objectives are explained and highlights of performance presented for the following:

A1 - Worker Safety
A2 - Public Safety
A3 - Environmental Protection
A4 - Reliability
A5 - Cost

For each of these objectives, extensive records and evaluations are available for discussion in greater depth.

For example, the overall reliability of commercial generating units is discussed in Section A4. However, detailed reliability data is available for the individual components in the CANDU-PHW system.

A1 WORKER SAFETY

Definition

Worker safety means that electricity can be produced at a generating station with minimum injuries to the employees. Although no injuries is the ideal target, it is recognized that in every industrial process some will occur and standards are defined in order to assess safety performance.

Injuries are classified:

Fatality

An injury which results in death.

Permanent Disability

An injury which results in loss or permanent impairment of any part of the body.

Temporary Disability

An injury which results in a worker being unable to attend his work for one or more days.

The frequency of injury and consequence per injury are measured as follows:

Risk of Disabling Injury

Total number of lost work days per million man-hours worked for all injuries except those that cause death or permanent and total incapability to be gainfully employed.

Standards

The standards which include all types of accidents (nuclear and non-nuclear) defining good performance are as follows:

Fatalities - Two or less fatalities per 100 million man-hours worked.

Permanent Disabilities - Two or less injuries per 10 million man-hours worked.

Temporary Disabilities - Six or less injuries per 1 million man-hours worked.

Risk of Disabling Injury - 150 days lost per 1 million man-hours worked.

These standards of employee safety are intended to meet the following criteria:

1. Employees must be safer at work than not at work.
2. Nuclear employees must be safer at work than non-nuclear employees.
3. Nuclear employees must be safer at work than employees in other industries.

Results and Comparisons

Table A1-1 compares 1983 results with the standards for fatalities.

TABLE A1-1

Worker Safety 1983 Fatalities
Per 100 Million Man-Hours

	Standard	Performance
Hydraulic	3	0
Thermal	2	0
Nuclear	2	0

Table A1-2 compares 1983 results with the standards for permanent disabilities.

TABLE A1-2

Worker Safety 1983 - Permanent
Disabilities Per 10 Million Man-Hours

	Standard	Performance
Hydraulic	1	6.5
Thermal	2	0
Nuclear	2	0

Table A1-3 compares 1983 results with the standards for temporary disabilities.

TABLE A1-3

Worker Safety 1983
Temporary Disabilities
Per 1 Million Man-Hours

	Standard	Performance
Hydraulic	6	8.5
Thermal	6	4.5
Nuclear	6	1.7

Table A1-4 compares 1983 results with the standards for risk of disabling injuries.

TABLE A1-4

Worker Safety 1983
Risk of Disabling Injuries
Days Per 1 Million Man-Hours

	Standard	Performance
Hydraulic	-	161.4
Thermal	150	61.5
Nuclear	150	38.0

Table A1-5 indicates the performance in the last 10 years (1974 to 1983).

TABLE A1-5

Ten-Year Performance
1974 to 1983 Inclusive

	Fatalities Per 100 Million Man-Hours	Permanent Disabilities Per 10 Million Man-Hours	Temporary Disabilities Per 1 Million Man-Hours	Risk of Disabling Injury Days Per 1 Million Man-Hours
Hydraulic	15.6	1.0	4.0	96.3
Thermal	0	0	4.6	86.9
Nuclear	0	1.0	1.9	50.2

Table A1-6 compares off-the-job and on-the-job fatalities for Ontario Hydro and the Nuclear Generation Division.

TABLE A1-6

Worker Safety
1974 to 1983 Inclusive

Fatalities
Per 100 Million Man-Hours

	Off-the-Job	On-the-Job
Ontario Hydro	5.1	6.5
Nuclear	6.0	0

Highlights

From 1962 to the end of 1983, the nuclear operations employees have worked 95 million man-hours. The following are a few of the highlights:

1. There has never been a fatality to a nuclear employee at work.
2. All permanent disabilities were due to non-nuclear causes and all but one were of a minor nature (loss of portion of finger or back limitations). The serious permanent disability (head injury) resulted from a fall at the Bruce Heavy Water Plant.
3. No employees have ever been injured due to radiation.
4. There has never been a serious whole body radiation exposure (greater than 25 rem per annum).
5. The highest whole body exposure to one employee has been 7.3 rem (2.3 above 5 rem per annum regulatory limit).
6. Exposures exceeding the whole body regulatory limit (greater than 5 rem per annum) have averaged 0.17 over exposure per million man-hours worked.
7. The nuclear worker risk has been much lower at work (on-the-job) than not at work (off-the-job).
8. Although worker safety at hydraulic stations and thermal stations has been good, the worker safety at CANDU-PHW stations has been superior.

A2 PUBLIC SAFETY

Definition

Public safety has to do with the protection of members of the public against acute events which would result in injury, disability, or death of a member of the public caused by nuclear generating station facilities or employees.

Classifications

Two basic classifications of public accidents are maintained for nuclear stations:

Conventional Risks	- Where a member of the public is killed or injured from conventional hazards such as electrical apparatus, drowned in water, killed by a transport, etc.
Radioactivity Risks	- Where a member of the public is killed or injured by nuclear accidents involving radioactivity.

Conventional Risk - Standards

Throughout the world, members of the public have been killed or injured as a result of explosions in fossil fuel stations, dams bursting at hydro-electric stations, people being drowned at hydro stations, etc. However, the overall record for thermal and hydro stations has been generally good. The standards which define good performance which have been adopted for Ontario Hydro nuclear stations for conventional public safety are as follows:

Fatality Frequency	- One or less fatality per annum for each 10 000 MW of installed capacity (computed on a moving 10-year basis).
Disability Frequency	- One or less permanent disability per annum for each 1 000 MW of installed capacity (computed on a moving 10-year basis).

Radioactivity Public Risk - Ontario Hydro Standards

A good standard of performance is a risk to an individual member of the public which is negligible compared with the everyday risk to that member of the public.

The average risk to the public in Canada for all accidents is approximately 600 premature deaths per annum for every million persons. If we define negligible to be less than 1%, the standard would be six premature deaths per annum for every million persons. The Ontario Hydro standard has been conservatively set so as to not exceed one chance in a million per annum that the most exposed individual will suffer a premature death.

The standard risk (one chance in a million per annum) must be converted to radiation dose risk (rem/annum). This requires a statistical medical knowledge which correlates units of rem/annum with probability of premature death. Accordingly, the Ontario Hydro impact risk corresponds to an "equivalent whole body" exposure of 0.01 rem per annum.

Equivalent whole body dose is defined as follows:

Equivalent whole body dose = whole body dose + 1/10 thyroid dose
1 rem equivalent whole body dose = 1 rem whole body dose $\doteq 10^{-4}$ fatalities

The evaluation of risk involves two criteria:

1. The frequency of an accident.

2. The consequence of the accident.

$$\text{Risk } \left(\frac{\text{rem}}{\text{annum}}\right) = \text{Frequency } \left(\frac{\text{events}}{\text{annum}}\right) \times \text{Consequence } \left(\frac{\text{rem}}{\text{event}}\right)$$

Thus, reduced risk can be achieved by lowering the chance, (frequency) of an accident occurring (prevention) and/or reducing the consequence (safety systems and/or emergency procedures).

Atomic Energy Control Board (AECB) Criteria

Ontario Hydro and Atomic Energy of Canada Limited (AECL) are also required to satisfy guidelines stipulated by the AECB. As an example, the risk inferred from the AECB criteria, expressed in units of rem/annum for each unit in Pickering NGS-A, is as follows:

Single Failure Accident:

Thyroid:

$$\text{Risk } \left(1\ \frac{\text{rem}}{\text{annum}}\right) = \text{Frequency } \left(0.33\ \frac{\text{events}}{\text{annum}}\right) \times \text{Consequence } \left(3\frac{\text{rem}}{\text{event}}\right)$$

Whole Body

$$\text{Risk } \left(.16\ \frac{\text{rem}}{\text{annum}}\right) = \text{Frequency } \left(0.33\ \frac{\text{events}}{\text{annum}}\right) \times \text{Consequence } \left(0.5\ \frac{\text{rem}}{\text{event}}\right)$$

Dual Failure Accident

Thyroid:

$$\text{Risk } (0.25 \frac{\text{rem}}{\text{annum}}) = \text{Frequency } (10^{-3} \frac{\text{events}}{\text{annum}}) \times \text{Consequence } (250 \frac{\text{rem}}{\text{event}})$$

Whole Body

$$\text{Risk } (.025 \frac{\text{rem}}{\text{annum}}) = \text{Frequency } (10^{-3} \frac{\text{events}}{\text{annum}}) \times \text{Consequence } (25 \frac{\text{rem}}{\text{event}})$$

The risk corresponding to the AECB criteria, expressed in units of rem/annum for each unit in Bruce NGS, is as follows:

Single Failure Accident

Thyroid:

$$\text{Risk } (1 \frac{\text{rem}}{\text{annum}}) = \text{Frequency } (0.33 \frac{\text{events}}{\text{annum}}) \times \text{Consequence } (3 \frac{\text{rem}}{\text{event}})$$

Whole Body:

$$\text{Risk } (.16 \frac{\text{rem}}{\text{annum}}) = \text{Frequency } (0.33 \frac{\text{events}}{\text{annum}}) \times \text{Consequence } (0.5 \frac{\text{rem}}{\text{event}})$$

Dual Failure Accident

Thyroid:

$$\text{Risk } (0.08 \frac{\text{rem}}{\text{annum}}) = \text{Frequency } (3 \times 10^{-4} \frac{\text{events}}{\text{annum}}) \times \text{Consequence } (250 \frac{\text{rem}}{\text{event}})$$

Whole Body:

$$\text{Risk } (0.008 \frac{\text{rem}}{\text{annum}}) = \text{Frequency } (3 \times 10^{-4} \frac{\text{events}}{\text{annum}}) \times \text{Consequence } (25 \frac{\text{rem}}{\text{event}})$$

Thus, the risk corresponding to the AECB guidelines is essentially the same as the Ontario Hydro standard based upon elementary first principles (negligible radioactivity risk compared with other everyday risks).

Radioactivity Public Risk - Measurement

The risk to members of the public is measured using two separate measuring systems:

Actual	- The recorded actual fatalities or injuries arising out of actual events in which significant radioactive release occurs.
Predicted	- The computed risk to members of the public based upon recorded or forecast component failures of process and safety systems for which there may be no release of radioactivity to the public.

Highlights

1. During 113 reactor years of operation in Ontario, there has never been a fatality nor has there been an injury to a member of the public involving radioactivity.

2. During 113 reactor years of operation in Ontario, there has been one fatality to a member of the public. In 1982 a member of the public died in a traffic accident with an Nuclear Generation Division vehicle on a public highway.

3. There has never been a release of radioactivity from any nuclear generating station which resulted in a measurable dose to any member of the public.

4. The radioactivity risk criteria have been fully met at every station for every year.

A3 ENVIRONMENTAL PROTECTION

Definition

Environmental protection means the control of chronic emissions from nuclear generating stations which could potentially impair the health and/or well-being of a member of the public or cause adverse effects to the environment.

Introduction

To ensure protection of the public and environment from adverse effects of emissions, Ontario Hydro's objectives are:

1. To eliminate emissions whenever practical.
2. To minimize emissions by maintaining them within operating target values.
3. To control emissions within applicable regulatory limits.

While controlling emissions within regulatory limits is of the highest importance, it is clear from our performance that ELIMINATION and MINIMIZATION have been given priority in design and operation since radioactivity emissions are always at a small fraction of regulatory limits.

Table A3-1 shows the sources of environmental emissions most significant from nuclear generating stations. Standards are set and emissions are monitored and controlled.

TABLE A3-1

Environmental Emissions

Emission	Medium
Radioactivity	Air
Radioactivity	Water
Heat	Water

Limits and Targets for Radioactive Emissions (Air and Water)

The regulatory requirements for emissions of radioactivity from nuclear generating stations in Canada are the public dose limits set by the AECB of Canada. These dose limits are consistent with the recommendations of the International Commission on Radiological Protection (ICRP).

Emissions of radioactivity from CANDU-PHW reactors are extremely small in everyday operation. To ensure rigorous everyday control, emission rates are measured rather than emission impact. The limits that are used for day-to-day control are called Derived Emission Limits (DELs). The DEL is the quantity of a radionuclide which it is calculated may be safely emitted, while ensuring that no member of the public is likely to receive a radiation dose in excess of the public dose limits. DELs are licensed limits and are used to control the amount of radioactivity released via the plant air exhaust or water effluent channel.

While the regulatory dose limit and the DELs provide a perfectly acceptable level of individual protection to the public, it has long been Canada's policy to maintain public radiation doses at the lowest practical level. Ontario Hydro, since the early 1970s, has adopted a target of maintaining emissions for each major nuclide group at a very small fraction of the DELs. This ensures the conservative standard of 100% DEL will be met.

The radionuclide groups which are continuously monitored in the ventilation exhaust and liquid effluent from nuclear generating stations are given in Table A3-2.

TABLE A3-2

Radioactivity Criteria

Radionuclide Group	Medium
Tritium	Air
Iodine-131	Air
Noble Gases	Air
Particulates	Air
Tritium	Water
Gross Beta-Gamma	Water

The low levels of emission from typical stations (Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A) for the six criteria are presented in Figure A3-1 and A3-2 and A3-3.

Limits and Targets for Thermal Emissions to Water

Heat is emitted to water due to the operation of once-through cooling systems at Ontario Hydro nuclear generating stations. Regulatory guidelines for effluent temperature and temperature rise from intake to discharge have been established by the Ontario Ministry of the Environment. Both the emission of heat and the use of water in the once-through cooling process have potential environmental effects. Thus, Ontario Hydro's thermal discharges are regulated to minimize overall environmental effect by remaining below and as close to the thermal effluent guidelines as possible.

Highlights

The following are highlights of performance during the 22 years (113 reactor years) of experience with CANDU-PHW nuclear generating stations.

1. Ontario has a perfect record - the annual regulatory limit for radioactivity has never been exceeded. That is, all six criteria have been met every year at every station.

2. The frequency, duration, and severity of emissions above thermal effluent guidelines have been very low and no adverse environmental effects have been detected.

FIGURE A3–1
RADIOACTIVE EMISSIONS 1983
PICKERING NGS–A

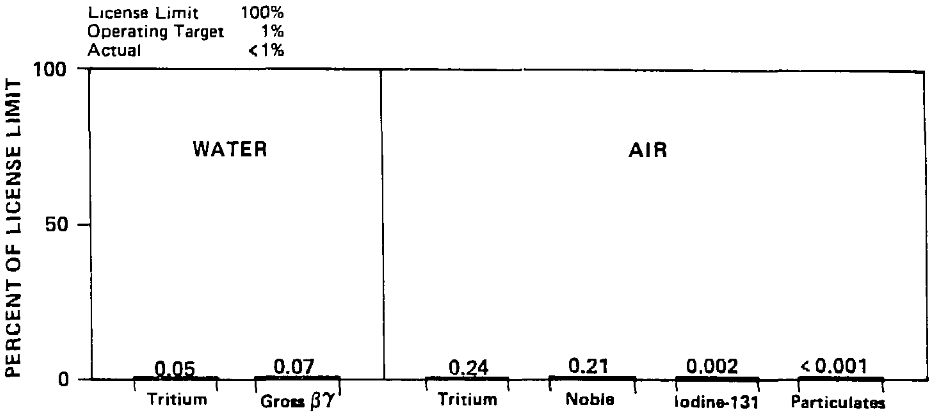


FIGURE A3–2
RADIOACTIVE EMISSIONS 1983
PICKERING NGS–B

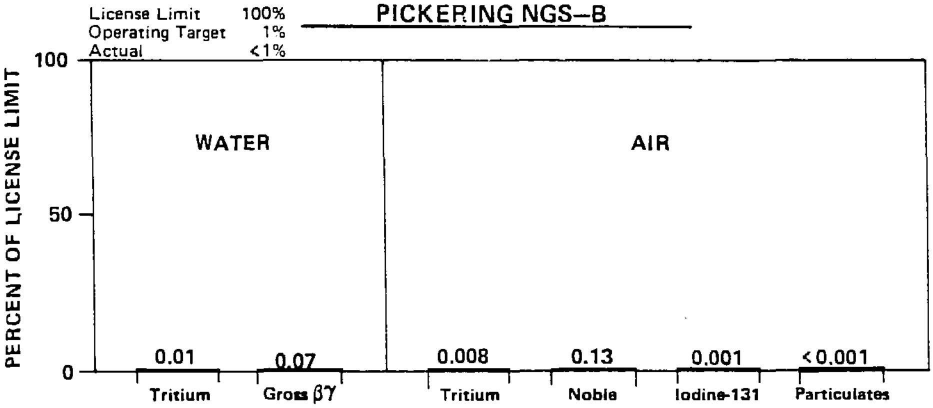
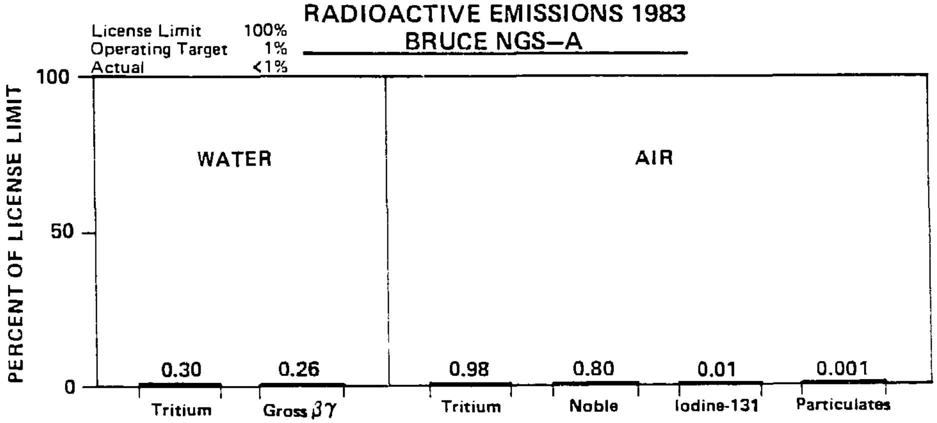


FIGURE A3–3
RADIOACTIVE EMISSIONS 1983
BRUCE NGS–A



A4 RELIABILITY

Reliability of a generating unit refers to the ability of the generating unit to run continuously at the full rated capacity. For a CANDU-PHW, the reliability is important for two reasons:

1. To contribute to the ability of the overall power system to meet customer demands.

2. To minimize the cost of power to the customer. The current fueling costs of CANDU-PHW units in Ontario Hydro are approximately 4 milli-dollars per kilowatt hour (m$/kW.h) as compared with fossil-fueled units in excess of 21 m$/kW.h.

Categories of Reliability

Ontario Hydro measures reliability through three sets of criteria:

1. Do the generating units go into service on schedule? This is called In-Service Date Reliability.

2. Do the generating units cause or magnify stress on the power system? This is called Power System Stability.

3. Do generating units that are in service run continuously at full power? This is called Production Reliability.

Reliability criteria are defined and measured for each of these three categories.

In-Service Date Reliability

It is desirable that the scheduling dates which are planned for a generating unit are met. In-Service Date Reliability is indicative of our ability to design, procure, construct and commission generating units on schedule.

The one criterion we use to measure this performance is In Service Lateness, which may be defined as follows:

In-Service Lateness = MCR x Years Late

Where:

MCR = gross maximum continuous rating for each generating unit

A generating unit declared available for commercial operation early is defined as having a negative in service lateness.

Commercial results in this area are summarized for Ontario Hydro CANDU-PHW generating units in Table A4-1.

TABLE A4-1

In Service Date Reliability

Station/Unit	In-Service Dates Original	 Actual	Lateness Weeks	 MW-Years
Pickering NGS-A				
Unit 1	Nov 1/70	Jul 29/71	+ 39	+ 405
Unit 2	Oct 1/71	Dec 30/71	+ 13	+ 135
Unit 3	Oct 1/72	Jun 1/72	- 17	- 177
Unit 4	Oct 1/73	Jun 17/73	- 15	- 156
Pickering NGS-B				
Unit 5	Apr 1/80	May 10/83	+162	+1 682
Bruce NGS-A				
Unit 1	Jun 1/77	Sep 1/77	+ 13	+ 198
Unit 2	Sep 1/76	Sep 1/77	+ 52	+ 791
Unit 3	Jun 1/78	Feb 1/78	- 17	- 259
Unit 4	Jun 1/79	Jan 18/79	- 19	- 289

The overall performance has been excellent.

Power System Stability

In terms of Power System Stability, two criteria are measured for each generating unit as follows:

1. The generating unit should not cause any power system stresses which would increase the probability of a system collapse. The criterion to measure this characteristic is called Sudden Outage Frequency (SOF).

2. The generating unit should survive and help overcome stresses which the power system was experiencing and,thereby, not contribute through a cascading process to an ultimate system collapse. The criterion to measure this characteristic is called Non-Survival Ratio (NSR).

Sudden Outage Frequency Criterion

The frequency of sudden outages per operating year is a measure of the unit putting a stress on the power system.

$$\text{SOF} = \frac{\text{Number of Sudden Outages}}{\text{Operating Years}}$$

Where a sudden outage is one for which all of the following apply:

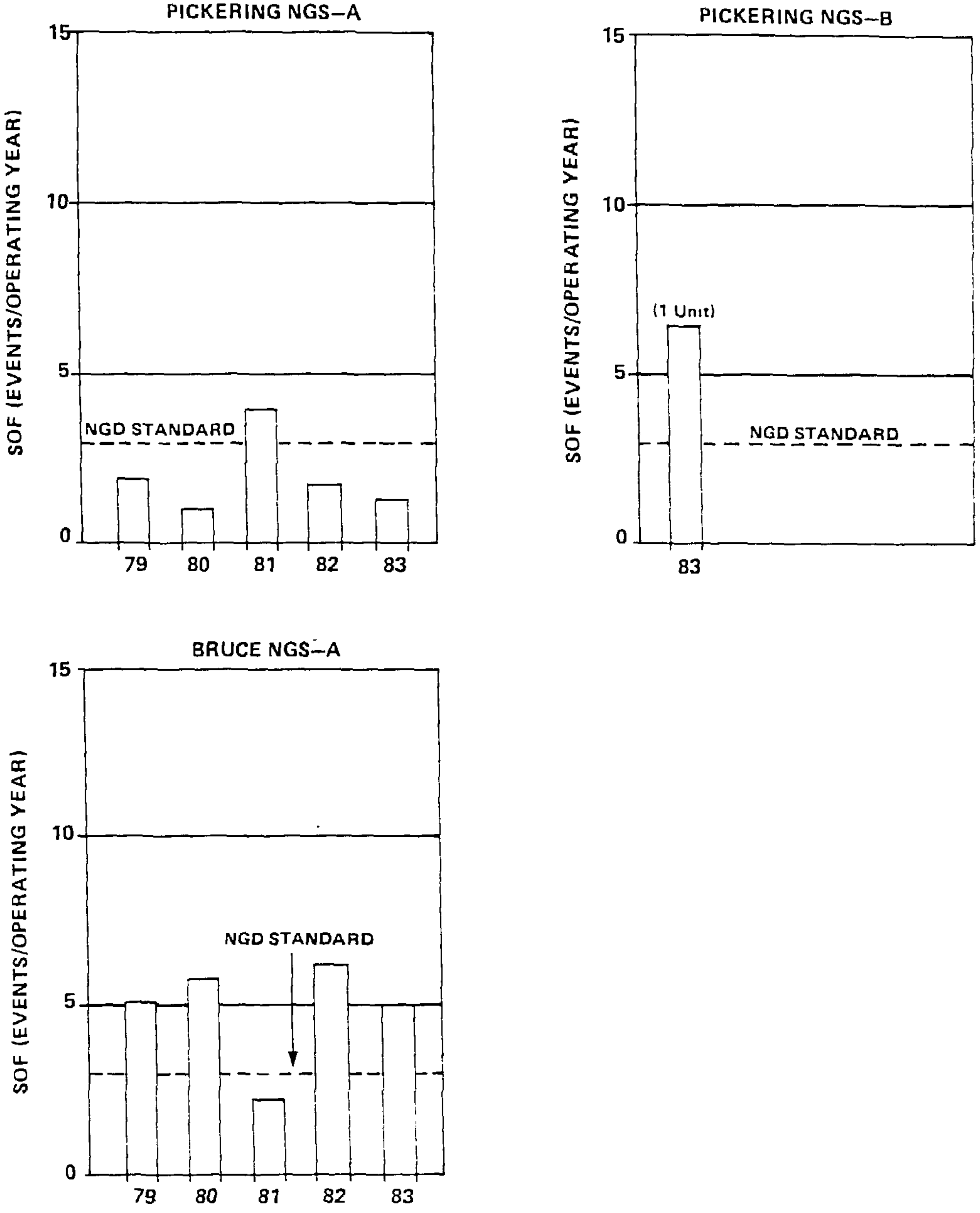
1. No advance notice is possible.

2. Initiation is from within the station boundary.

3. Operation is interrupted from above 25% MCR.

The standard for Ontario Hydro has been established at three or less events per unit per operating year. Our results over the last five years for CANDU-PHW generating units are shown in Figure A4-1.

FIGURE A4–1
SUDDEN OUTAGE FREQUENCIES



The Pickering NGS-A units have been in service for between 10 and 13 years and their performance has been excellent. The early performance at Bruce NGS-A is generally better than the early performance at Pickering NGS-A. The performance at Pickering NGS-B is excellent for a station in the first year of service.

Non-Survival Ratio Criterion

When the system is under stress, the power system frequency fluctuates.

For reasonable frequency deviations, a generating unit should survive the stress and not separate from the power system.

For extreme frequency deviations, a unit will be automatically separated from the power system but should survive the load rejection and be available when required for reloading.

The Non-Survival Ratio is indicative of a unit's performance under power system stress where:

$$\text{Non-Survival Ratio} = \frac{\text{Number of Non-Survivals}}{\text{Number of Stress Events}}$$

Ontario Hydro's results in this area are summarized for CANDU-PHW generating units in Table A4-2.

TABLE A4-2

Non-Survival Ratios

		1979	1980	1981	1982	1983
Pickering NGS-A	Unit 1	0/0	0/0	0/0	0/0	0/0
	Unit 2	0/0	0/0	0/0	0/0	0/0
	Unit 3	0/0	0/0	0/0	0/0	0/0
	Unit 4	0/0	0/0	0/0	1/1	0/0
Pickering NGS-B	Unit 5	-	-	-	-	0/0
Bruce NGS-A	Unit 1	0/0	0/0	0/0	0/0	0/0
	Unit 2	0/0	0/0	0/2	0/0	0/0
	Unit 3	0/0	1/2	0/0	0/1	0/0
	Unit 4	0/2	0/2	0/0	0/1	0/0
Standard		1/4	1/4	1/4	1/4	1/4

It can be seen that Ontario Hydro has an extremely stable power system, but when stress events did occur, our CANDU-PHW generating stations responded very well.

Production Reliability

A large number of criteria are used to measure production performance. For this paper, the three most important criteria are discussed:

1. Derating Adjusted Forced Outage Rate (DAFOR).
2. Gross Incapability Factor (ICbF) or its complement Capability Factor (CbF).
3. Capacity Factor (CF).

Derating Adjusted Forced Outage Rate (DAFOR)

The Derating Adjusted Forced Outage Rate is the random probability of the loss of operating capacity through forced outages, forced deratings, and unscheduled extensions to maintenance and planned outages.

Incapability Factor (ICbF)

The overall probability that energy can be produced by a generating unit is measured by the Capability Factor (CbF):

$$\text{CbF} = \frac{\text{Energy Available (actually produced, plus energy that could have been produced)}}{\text{Perfect Production}}$$

Thus, Incapability Factor indicates the overall reduction of available energy.

Capacity Factor (CF)

$$\text{CF} = \frac{\text{Actual Energy Produced}}{\text{Perfect Production}}$$

For these criteria, Ontario Hydro has established standards for performance based on being equal to or better than the average performance of fossil-fueled units of equivalent size operated throughout North America and reported by the North American Electric Reliability Council in annual reports.

Our results compared to these standards are shown in Figures A4-2 and A4-3.

FIGURE A4–2
DERATING ADJUSTED FORCED OUTAGE RATES

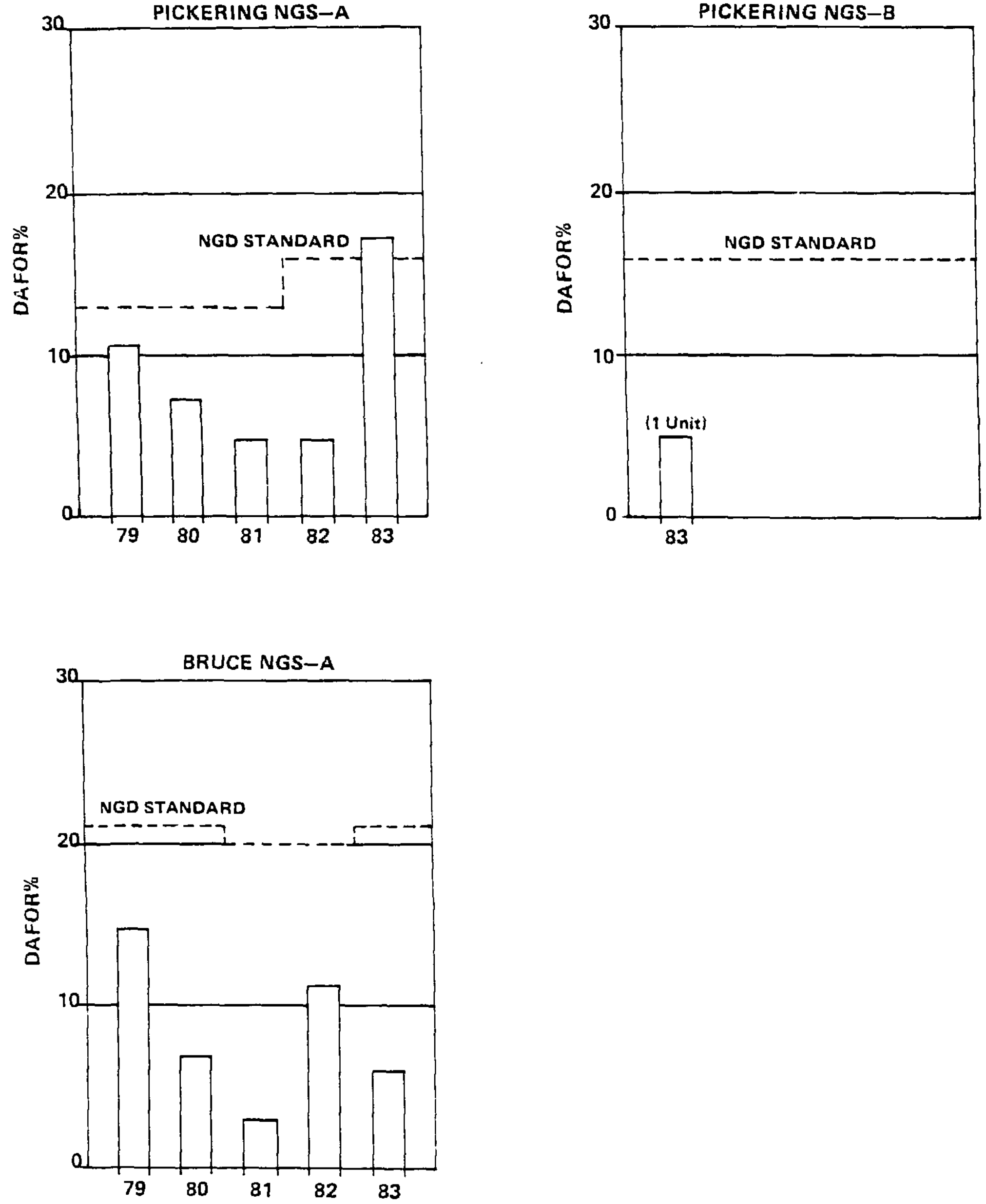
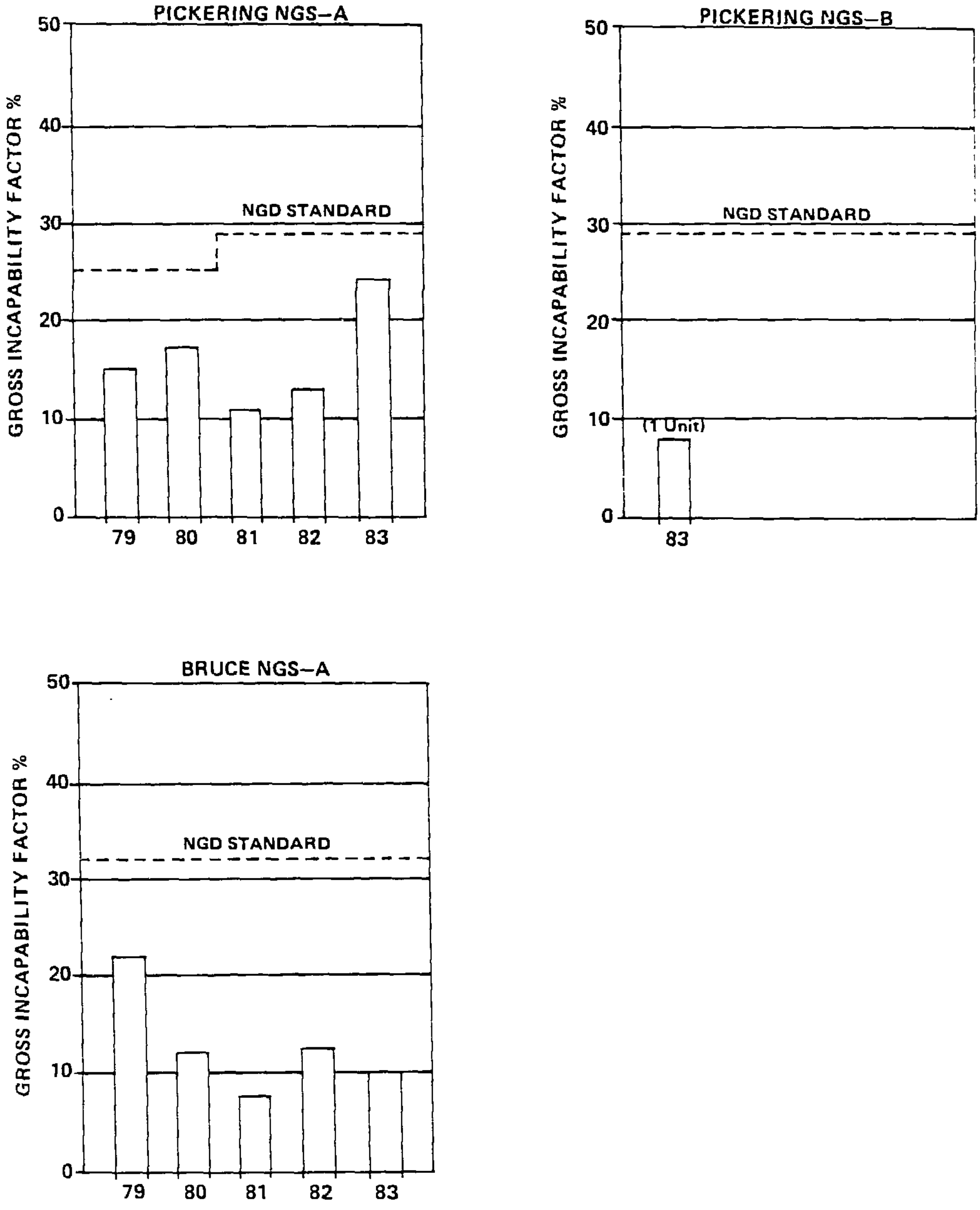


FIGURE A4–3
INCAPABILITY FACTORS



To compare the performance of our CANDU-PHW stations with that of other types throughout the world, Ontario Hydro monitors production data supplied to various international publications and calculates Capacity Factors of the world's 168 commercial reactors larger than 500 MW e. For Bruce NGS-A and Pickering NGS-A, the performance has been as shown in Table A4-3.

TABLE A4-3

Capacity Factor Performance

Gross Capacity Factor

Station	Unit	1983	Lifetime*
Pickering NGS-A	1	69	79
	2	58	81
	3	85	79
	4	93	82
Pickering NGS-B	5**	72	72
Bruce NGS-A	1	86	82
	2	90	74
	3	90	87
	4	95	86

Overall, the performance of CANDU-PHW compared to other commercial reactor types larger than 500 MW e is shown in Figure A4-4.

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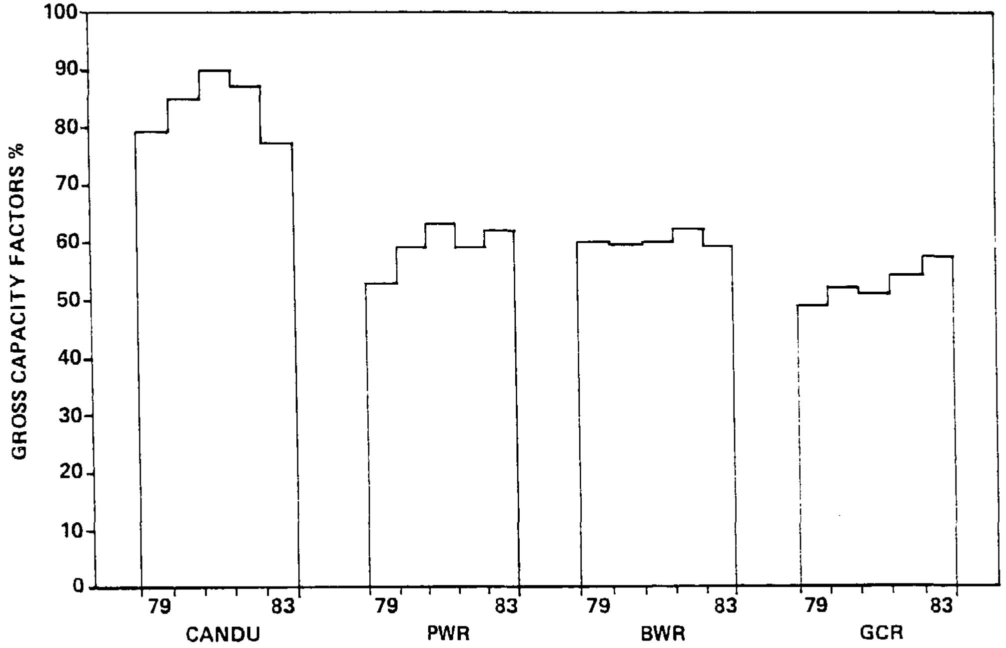
*Since first production of electricity.

**Pickering 5 In-Service May 10, 1983. Pickering Gross Capacity Factor from In-Service to December 1983, 92.0%.

FIGURE A4—4
COMPARISON OF CAPACITY FACTORS WITH OTHER COMMERCIAL REACTOR TYPES LARGER THAN 500 MWe



Detailed reliability data for components within Ontario Hydro CANDU stations is available. Some of this data is presented in Part B.

Highlights

1. Ontario Hydro CANDU units have started up close to schedule reflecting the ability to design, manufacture, construct and commission.

2. CANDU units have performed well in terms of the two criteria to measure Power System Stability.

3. The production performance of CANDU units has been excellent and has exceeded the performance of any other type of nuclear station.

A5 COST

Background

Compared with fossil-fired generating units, CANDU-PHW generating units have a higher Capital Cost and a much lower Fueling Cost.

Therefore, from a cost point of view, the CANDU-PHW units are most attractive for base load application. 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. Thus, it is difficult to generalize in making comparisons between nuclear costs and alternative sources of energy. A literal conversion from Canadian currency to other currencies using present exchange rates may also be misleading.

Coal Versus CANDU-PHW Example

The following data illustrates that the CANDU-PHW is very competitive within Ontario Hydro where hydro-electric resources have been almost fully developed and where coal must be transported a minimum of 800 km. There are other locations in Canada in which coal-fired generation is cheaper than CANDU-PHW where the generating unit is near the mine.

More specifically, the following presentation compares the Ontario Hydro Pickering NGS-A with the Ontario Hydro Lambton TGS. Pickering NGS-A comprises four, 515 MWe nuclear units of the CANDU-PHW type. Lambton TGS comprises four, 495 MWe units which burn coal. Both stations were built at approximately the same time, both are of modern design and both stations are fully operational with good lifetime performance records.

Cost Objective

The cost objective of Ontario Hydro is to produce and deliver electricity at the lowest long-term cost to Ontario customers. In the case of base load stations, the objective is to minimize the Total Unit Energy Cost (TUEC) while being consistent with the achievement of acceptable standards of worker safety, public safety, environmental protection and reliability.

Definition - Total Unit Energy Cost

$$\text{Total Unit Energy Cost} = \frac{\text{Total Annual Cost}}{\text{Total Annual Energy Produced}}$$

Cost Components

For comparison purposes, costs are broken down into four components for a CANDU-PHW station and three components for a coal-fired station.

CANDU-PHW Cost Components

1. Annual Interest, Depreciation, and Decommissioning Cost
2. Annual Operation, Maintenance and Administration Cost
3. Annual Fueling Cost
4. Annual Heavy Water Upkeep Cost

Coal-Fired Thermal Cost Components

1. Annual Interest and Depreciation Cost
2. Annual Operation, Maintenance and Administration Cost
3. Annual Fueling Cost

Annual Interest, Depreciation, and Decommissioning Cost

The computation of the Annual Interest, Depreciation, and Decommissioning Cost depends upon five 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
5. The Provision for Future Decommissioning Cost (Nuclear Only)

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
8. Capitalized Training Cost

Annual Operation, Maintenance, and Administration Cost

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)

Annual Fueling Cost

The Annual Fueling Cost includes:

1. Fuel (purchase cost of fuel consumed)
2. Interest on Inventory
3. Transportation
4. Overheads
5. Provision for Future Irradiated Fuel Transportation, Storage and Disposal

Annual Heavy Water Upkeep Cost

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).

Pickering NGS-A Versus Lambton TGS - 1983

As noted above, the Pickering NGS-A and the Lambton TGS coal-fired station have the same number and size of units and were built at approximately the same time.

TABLE A5-1

Pickering NGS-A/Lambton TGS Cost Comparison - 1983

Net Capacity Factor: 75.9%*

	UEC [m$/kW.he (NET)]	
	Pickering NGS-A	Lambton TGS
Interest, Depreciation and Decommissioning	7.7	2.0
Operation, Maintenance and Administration	6.1	2.2
Fueling	3.8	21.8
Heavy Water Upkeep	0.8	-
Total Unit Energy Cost	18.4	26.0

Bruce NGS-A Versus Nanticoke TGS - 1983

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 Fueling Costs to be driven rapidly upwards.

As a result, new coal-fired generating stations such as Nanticoke TGS (8 x 490 MWe net) and new nuclear stations such as Bruce NGS-A (4 x 775 MWe net) have higher Capital Costs.

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

---

* Assumes Lambton TGS also operated at base load with a Net Capacity Factor the same as Pickering NGS-A.

**Milli-dollars per kilowatt-hour electrical, 1983 Canadian dollars

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$/kWe (net) and Bruce NGS-A was 632.6$/kWee (net).

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

Table A5-2 compares Bruce NGS-A Unit Energy Costs with Nanticoke TGS Unit Energy Costs in 1983.

TABLE A5-2

Bruce NGS-A/Nanticoke TGS Cost Comparison - 1983

Net Capacity Factor: 89.9

	UEC [m$/kW.hee** (NET)]	
	Bruce NGS-A	Nanticoke TGS
Interest, Depreciation, and Decommissioning	9.9	3.4
Operation, Maintenance, and Administration	3.9	1.5
Fueling	4.2	25.8
Heavy Water Upkeep	0.4	-
Total Unit Energy Cost (Net)	18.4	30.7

---

* Assumes Nanticoke TGS also operated at base load with a Net Capacity Factor the same as Bruce NGS-A,

** Milli-dollars per kilowatt-hour electrical equivalent energy, 1983 Canadian dollars.

***Actual capital cost until the station in-service date divided by the station MCR.

Highlights

1. The base load cost (TUEC) of the Pickering NGS-A has been consistently well below the cost of the Lambton TGS (coal-fired) since 1975.

2. The base load cost (TUEC) of the more recent Bruce NGS-A is historically higher than the Pickering NGS-A cost due to capital cost inflation, but it is also very competitive. Due to the exceptional performance at Bruce NGS-A in 1983, however, its TUEC matched that of Pickering NGS-A.

PART B - EXPERIENCE

BO INTRODUCTION

Part A indicates that the Ontario Hydro CANDU-PHW results for the five basic objectives have been excellent for the nine commercial units. However, problems have been encountered and these will be briefly described together with highlights of component and system experience.

An important contributor to successful operation is training of personnel which will also be dealt with together with information on our staffing.

In addition, this part of the presentation will include the important subject of Public Safety Principles developed in the Canadian nuclear program.

One of the most meaningful ways of quantifying the effect of equipment problems is in terms of the Incapability caused by them as a percentage of perfect production in the time period. If a generating unit is perfect, that is, able to operate at full power all of the time, the Capability Factor would be 100%. In practice, the Capability Factor is less than 100% because of outages (full shutdowns) and deratings (less than full power). The Incapability Factor indicates the inability of a unit to operate at full power all of the time.

The equipment which caused Incapability at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A is shown in Tables BO-1, BO-2, and BO-3.

TABLE BO-1

Pickering NGS-A - Lifetime* Incapability to December 31, 1983**

4 Units 45.6 Unit Years

Capability Factor: 80.6 Incapability Factor: 19.4

Cause of Incapability	Incapability (%)
On-Power Fueling	0.7
Fuel	<0.1
Heat Transport Pumps	0.2
Pressure Tubes	5.3
Boilers	0.3
Turbine and Generator	6.8
Instrumentation and Control	0.7
Heat Exchangers	1.1
Valves	0.4
Other	3.9

TABLE BO-2

Pickering NGS-B - Lifetime* Incapability to December 31, 1983

1 Unit 0.6 Unit Years

Capability Factor: 92.0 Incapability Factor: 8.0

Cause of Incapability	Incapability (%)
On-Power Fueling	0.0
Fuel	0.0
Heat Transport Pumps	0.0
Pressure Tubes	0.0
Boilers	0.0
Turbine and Generator	1.5
Instrumentation and Control	4.6
Heat Exchangers	0.2
Valves	1.4
Other	0.3

---

*Lifetime means since in-service date of each unit.

**Figures include a 4 month strike in 1972 (Units 1 to 3 were shut down).

TABLE BO-3

Bruce NGS-A - Lifetime* Incapability to December 31, 1983

4 Units   23.5 Unit Years

Capability Factor: 85.6   Incapability Factor: 14.4

Cause of Incapability	Incapability (%)
On-Power Fueling	0.7
Fuel	0.0
Heat Transport Pumps	0.5
Pressure Tubes	1.4
Boilers	2.0
Turbine and Generator	5.0
Instrumentation and Control	1.5
Heat Exchangers	0.1
Valves	0.2
Other	3.0

---

*Lifetime means since in-service date of each unit.

B1 ON-POWER FUELING

On-power fueling means that the nuclear fuel is replaced while the reactor is producing full power. This produces four major advantages:

1. Enables the unit to have a high Capacity Factor, typically 6% to 20% better than units with off-power fueling. This lowers the TUEC.

2. Permits major outage scheduling independent of fueling.

3. Allows higher fuel burnup and, therefore, lower fueling cost.

4. Allows on-power removal of defective fuel.

Problems were encountered, particularly in the early operation of the demonstrator, NPD NGS and the prototype, Douglas Point NGS.

The on-power fueling machines have required considerable development following the early operating problems. Today's designs, which are operating very reliably at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A, are evidence of the success. Although these machines are complex and require carefully trained staff, they are, nevertheless, based on principles which have eliminated the need for extraordinary manufacturing precision and extraordinary maintenance skills.

Occasional problems do occur when a fueling machine becomes disabled from causes such as damaged seal plugs, seized internal components, or when fuel bundles are damaged by the fueling machine. Special techniques and tooling have been developed to overcome such problems, usually without shutting down the unit.

Results

Table B1-1 shows that Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A have successfully completed 47 030 channel fueling operations at high power, exchanging a total of 280 800 fuel bundles.

Table B1-2 indicates the excellent performance in that the Incapability due to on-power fueling has been typically well below 1% in most years.

TABLE B1-1

Fuel Handling Experience
Lifetime to December 31, 1983

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
Number of Channel Fueling Operations	16 500	430	24 100
Number of Bundles Replaced	153 600	2 200	125 000
Bundles Still in Reactors	18 720	4 560	24 960

TABLE B1-2

Station Incapability Due
to On-Power Fueling Problems (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	1.3	-	-
1972	0.3	-	-
1973	0.9	-	-
1974	4.0	-	-
1975	0.3	-	-
1976	0.5	-	-
1977	0.1	-	0.0
1978	0.2	-	0.6
1979	0.6	-	1.6
1980	0.5	-	0.6
1981	0.3	-	0.6
1982	0.2	-	0.4
1983	0.3	0.0	0.4
Weighted Average	0.7	0.0	0.7

B2 FUEL BEHAVIOUR

CANDU fuel, as for all nuclear fuel, requires rigorous development, testing, design, quality control and manufacture. However, relative to other nuclear fuel, CANDU fuel can be reliably manufactured in simple, small shops.

Figure B2-1 shows a cutaway drawing of a Pickering NGS-A fuel bundle. This bundle is 0.5 m long, 0.1 m in diameter, and has 28 elements. Bruce NGS-A bundles are similar in dimensions with 37 slightly thinner elements.

A total of 330 000 fuel bundles had been irradiated in Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A by the end of 1983. The performance of the fuel at both stations has been very satisfactory. The burnup, when discharged at Pickering NGS is 195 megawatt hours per kilogram of uranium; at Bruce NGS-A it is 196 megawatt hours per kilogram of uranium.

At Pickering NGS-A, the identified defective fuel bundles have been only 0.06% of the total, with 90% of the defects occurring in the first 2 years of operation due to power increases during irradiation. Simple changes in control rod sequencing and fueling schemes to reduce transient local power increases have virtually eliminated this type of defect. More recently, less effort has been devoted to identifying defects at Pickering NGS-A. However, fission product levels in the heat transport system indicate that the defect rate is similar to Bruce NGS-A which has a lifetime defect rate of less than 0.10%. Most of the Bruce NGS-A fuel defects occurred due to early manufacturing faults. Improvements in manufacturing have resulted in a significant decrease in the defect rate to a current value of approximately 0.05%.

Table B2-1 shows the number of fuel bundles irradiated in Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A, the numbers found to be or suspected to be defective and the defect rates.

Defective bundles are removed as soon as they are located to reduce fission products and uranium contamination in the heat transport system. This is done on power. There have been no problems with transferring the defective bundles to the storage bay.

Table B2-2 tabulates the percentage of fuel defects for Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A from 1975 to 1983.

Defective fuel has had a negligible effect on station safety, reliability, the environment and cost. The actual Incapability charged to defective fuel for Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A is less than 0.1% over their lifetimes and more recently has been zero.

TABLE B2-1

Fuel Defect Experience

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
Bundles Irradiated	173 000	6 700	150 000
Bundles Defective	113	6	137
Defect Rate (%)	0.06	0.09	0.09
Station Incapability (%)	0.0	0.0	0.0

FIGURE B2-1

Pickering NGS Fuel Bundle (28-Element)

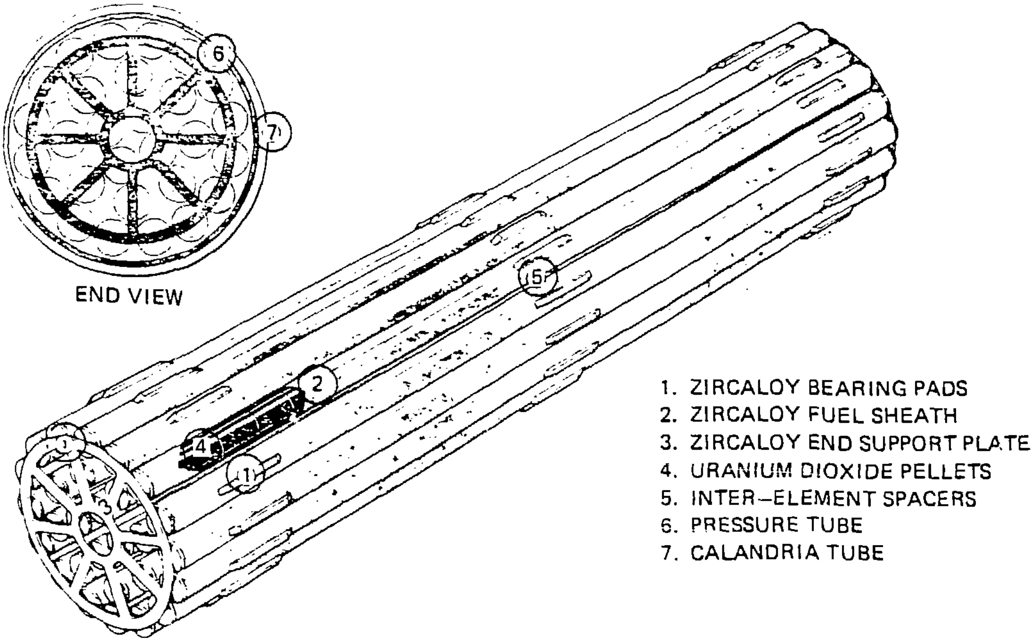


TABLE B2-2

% of Fuel Defects

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	-	-	-
1972	-	-	-
1973	-	-	-
1974	-	-	-
1975	0.031	-	-
1976	0.000	-	-
1977	0.000	-	0.062
1978	0.003	-	0.080
1979	0.000	-	0.255
1980	0.000	-	0.066
1981	0.000	-	0.022
1982	0.007	-	0.053
1983	0.008	0.090	0.052

B3 HEAT TRANSPORT PUMP-MOTOR SETS

The heat transport pump-motor sets in the CANDU-PHW have required extensive development in order to provide high reliability, high maintainability and low heavy water escape, particularly from seals and joints. During this development period, the size of the pump/motor sets was steadily increased.

Today, Canada possesses extensive, in-depth knowledge on a variety of shaft seal concepts. As an example of maintainability, motors do not have to be removed, nor do large pumps have to be dismantled to change a shaft seal. Both long seal life and short repair times have been achieved.

Each of the four Pickering-A units has 16 relatively small (1.4 MW) heavy water circulating pump-motor sets of which 12 are required for full power. These pump-motor sets have performed very well. Only one motor failure has occurred in approximately 443 pump motor operating years. Pump seal failures have occurred, but the loss in energy production has been small. These random seal failures are currently under investigation.

The Bruce-A design uses four large (8.2 MW) heavy water circulating pump-motor sets per unit, all of which are required for full power. The pump performance, including seals, has been very good. The maximum demonstrated seal life has reached 3 1/2 years. However, nine failures of the motor stator windings have occurred. This appears to be due to voids in the conductor insulation specific to the Bruce-A motors.

Since there is no installed spare at Bruce-A, the generating unit must be derated to about 70% of full power when one pump-motor set is removed from service. However, the motors are accessible during operation and can be and have been replaced on power with negligible radiation exposure to the maintenance staff. These factors have minimized the loss of generation during motor failures.

A program is in hand to refurbish the Bruce-A motors to obtain acceptable reliability and to procure additional spares.

The excellent low incapability caused by heat transport pump-motor sets at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A is shown in Table B3-1.

TABLE B3-1

Station Incapability Due to Heat Transport Pump-Motor Sets (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	0.0	-	-
1972	0.0	-	-
1973	0.0	-	-
1974	0.0	-	-
1975	0.1	-	-
1976	0.1	-	-
1977	0.3	-	0.0
1978	0.2	-	0.2
1979	0.6	-	0.3
1980	0.2	-	0.4
1981	0.6	-	0.0
1982	0.0	-	0.3
1983	0.0	0.0	1.8
Weighted Average	0.2	0.0	0.5

B4 PRESSURE TUBES

The CANDU-PHW concept, to be a very practical approach, required that all components be replaceable, with the understanding that certain components which were less proven be replaceable with relative ease. In 1958, when the pressure tube concept was committed at NPD 2, it was decided that all components associated with the fuel channel be relatively easy to inspect and replace. The lifetime of pressure tubes was expected to be at least 10 years and unlikely to achieve 30 years. Accordingly, the design provided for the following replaceable components:

1. Calandria Tubes
2. Pressure Tubes
3. Garter Springs (spacer to separate calandria tube from pressure tube)
4. Pressure Tube End Fittings

In addition, it was required that routine on-power replacements could be made for channel closure plugs which are used in on-power fueling.

The dimensional changes of materials under irradiation were recognized as potentially limiting the life of fuel channel components. Although considerable knowledge existed about materials in general, there was limited knowledge on zirconium alloys. Allowances were made to accommodate dimensional changes in the pressure tubes.

Demonstration

At NPD NGS, programs were established in which pressure tubes were inspected. Although no pressure tubes had failed, two were removed in 1967 to demonstrate replaceability and to acquire knowledge about zirconium performance.

The principle of replaceability with relative ease has since been demonstrated at: the prototype Douglas Point NGS; Pickering NGS-A; and Bruce NGS-A.

Dimensional Changes of Pressure Tubes

The dimensional changes of pressure tubes under neutron irradiation have been monitored for 22 years. Specifically, the pressure tubes lengthen with time. The design provides for such lengthening of the tube material. The current assessment of the tubes at Pickering NGS-A and Bruce NGS-A indicates a minimum life of 14 years before the original design allowances are exceeded. This performance meets the original 1958 criteria.

During 1978 to 1980, minor incapability at Pickering NGS-A resulted from pressure tube inspections and adjustment of pressure tube axial position.

New developments are under way to deal with pressure tube life limits in existing reactors; for example:

1. Procedures are being developed to carry out minor modifications (ie, the Repositioning of End Fittings and Bearings) which may extend the life of existing pressure tubes to a total of 30 years.

2. A Large Scale Fuel Channel Replacement program is being developed to make practical the replacement of all pressure tubes in a reactor.

All future pressure tube installations (in new reactors, as well as, replacements in existing reactors) are being designed to accommodate dimensional changes for 30 years.

Leakage Experience

Rolled Joints

One concern of the pressure tube concept was the question of whether or not the pressure tubes would leak at the rolled joints.

In the 113 reactor years, with each reactor containing several hundred rolled joints, there has never been a rolled joint leak.

Tube Integrity

Other concerns were:

1. Whether zirconium alloy materials would suddenly rupture.

2. Whether a pressure tube rupture could cause rupture of adjacent tubes.

Research and development programs show that rupture of one pressure tube is not expected to cause failure in adjacent tubes.

At Pickering NGS-A in 1974, pressure tube leaks did occur and were promptly detected while very small. The cracked pressure tubes were replaced (a total of 69 out of 780 in Units 3 and 4). No further leaks have occurred in Units 3 and 4.

At Bruce NGS-A, three pressure tubes in Unit 2 (the first unit in-service) leaked in 1982. These were replaced and the unit returned to full power. All the cracks at Pickering NGS-A and Bruce NGS-A were induced by high residual stresses near the rolled joint caused by the rolling process. The rolling process and joint design have been changed on units subsequent to Bruce NGS-A Unit 1 (the second unit in-service) to eliminate this problem. At Bruce NGS-A Unit 1, a pressure tube previously damaged by fuel was replaced in 1983.

At Pickering NGS-A, a pressure tube suddenly ruptured on August 1, 1983 and leaked at a rate of approximately 17 kg/s. A controlled shutdown and cooldown was performed from full power with normal system controls and operator action. None of the safety systems, reactor shutdown, emergency coolant injection nor containment were required or used.

No fuel failures resulted, nor was a significant increase in radiation fields observed throughout the failure except for tritium and the low level of radioactivity normally found in heat transport water.

All heavy water and radioactivity was contained within the reactor building and continued to be so contained throughout the event.

In mid November 1983, Unit 1, a sister unit with the same Zircaloy-2 pressure tubes, was shut down for examination. In 1983, a total of 11 pressure tubes and 1 calandria tube were removed for examination by AECL in their hot cells at Chalk River and Whiteshell. Examinations of pressure tubes in the two reactors were also conducted.

The pressure tube failure was initiated from the outside surface of the pressure tube and was associated with solid zirconium hydride blisters about 4 mm diameter and 1 mm deep. The blisters formed as a result of contact between the pressure tube and calandria tube.

The leak rate was limited by the design of the end fitting and therefore the calandria tube withstood full system pressure.

Further examinations and analyses are underway.

All CANDU-PHW units subsequent to Pickering NGS-A Unit 2 use zirconium-niobium alloy for their pressure tubes. This alloy is felt to be less susceptible to the problem experienced by Pickering NGS-A Units 1 and 2.

Results

Table B4 1 shows Incapability at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A due to pressure tubes.

TABLE B4-1

Station Incapability Due to Pressure Tubes (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	0.1	-	-
1972	0.0	-	-
1973	0.3	-	-
1974	10.5	-	-
1975	21.3	-	-
1976	10.0	-	-
1977	2.3	-	0.0
1978	0.1	-	0.0
1979	1.1	-	0.0
1980	1.4	-	1.2
1981	0.4	-	0.0
1982	0.7	-	6.5
1983	14.2	0.0	3.0
Weighted Average	5.3	0.0	1.4

B5 BOILERS (STEAM GENERATORS)

The two major concerns with regard to boilers are:

1. Will tubes fail causing reduction in capability and loss of heavy water?

2. Will tube heat transfer decrease causing reduction in power levels?

Tube Leaks

Each boiler contains several thousand tubes. To minimize failures, a good design, quality control during manufacturing and chemical control during operation are essential.

From a practical point of view, some tube failures must be expected. This requires three basic provisions:

1. Detection of failure.

2. Location of defective tube(s).

3. Plugging of the defective tube or repair of the defect.

Detection of tube leaks and the defective boiler is relatively easy by detecting the presence of heavy water or tritium in the turbine cycle.

Techniques, such as using fluorescent dye, are used to identify the failed tube.

Canada has developed a remotely controlled eddy current inspection system to inspect the boiler tubes quickly and with low worker radiation dose.

Sufficient tubes are provided so that full power can be maintained with a number of tubes effectively removed from service using explosively actuated plugs.

Ontario Hydro has experienced one major boiler problem at Pickering NGS-B during manufacture. The boiler tubes were distorted during manufacturing due to incompatible design and stress relieving procedure. The tubes have been replaced in accordance with new specifications and stress relieving procedure prior to startup of these units.

Each Pickering NGS-A and Pickering NGS-B unit has approximately 31 000 Monel tubes located in 12 boilers. To date, only one tube has leaked (in Unit 2 in 1974), making Pickering boiler performance an outstanding example of trouble-free operation. This failure was attributed to a random manufacturing defect. Further inspections of the same boiler in 1979 and 1981 did not reveal any significant tube deterioration. However, it was determined that deposits were accumulating in the center of the hot leg tubesheet, in a characteristic "kidney-shape," to a maximum depth of 300 mm.

In 1982, a handhole was machined through the shell of a Unit 1 boiler to gain access to the tubesheet sludge pile. Sludge sampling, visual inspection and eddy current testing confirmed a hard sludge pile having a maximum depth of 275 mm.

A tube removal technique has been developed to recover a tube to determine if damage is occurring in the deposit pile. Both water jet cleaning and chemical cleaning are under development and a demonstration is planned for Pickering NGS-A and Bruce NGS-A 1984.

Each Bruce NGS-A unit contains approximately 34 000 Inconel-600 tubes in 8 boilers. Since 1978, Bruce NGS-A has averaged more than 1 tube failure per annum all on the hot leg side. Tube leaks are located by the fluorescent dye method, confirmed by eddy current inspection, and isolated by explosive plugging of tube ends at the tubesheet. In each of 1978, 1979, and 1980, different Unit 2 boilers experienced failures in the U-bend region of large-radius tubes. The 1980 leaking defect was removed in 1981 for metallurgical examination. Indications were that a stress-corrosion cracking mechanism initiated the failure.

In 1982, single tube leaks in Unit 4 and Unit 3 boilers were identified, inspected, and isolated by plugging. These leaks were located in peripheral tubes in the tubesheet region, suggesting a failure mechanism different from that of the Unit 2 leaks.

In 1983, there were four tube leaks in Units 3 and 4 boilers. These were all in the U-bend region of the large radius tubes at a horizontal support plate, similar to the Unit 2 leaks. All of the failed tubes were removed for metallurgical examination. This indicated a common failure mechanism of high cycle low stress fatigue. The Unit 4 tube also showed considerable fretting wear at a scallop bar support.

Eddy current testing has also revealed that deposits are accumulating in two "kidney-shapes" on both the hot and cold leg sides of the tube sheet. The maximum depth is 175 mm.

Heat Transfer

Any heat exchanger may suffer reduced heat transfer with time if deposits plate out on the heat transfer surfaces.

Good chemical control is vital to minimizing erosion, corrosion and deposits. In general, the experience to date has been excellent. However, by 1979, at NPD NGS after 17 years of operation, the buildup of deposits on the outside surface of the steam generator tubes (ordinary water side) prevented full power operation. The surfaces were cleaned using a mild organic acid sequentially with ammonia treatment to remove deposits and the heat transfer was fully restored.

Results

The Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A steam generator experience is shown in Table B5-1 in the form of Incapability.

Compared with world experience, the performance of the Bruce NGS-A steam generators has been good and the Pickering NGS-A and B steam generators excellent.

TABLE B5-1

Station Incapability Due to Steam Generators (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	0.0	-	-
1972	0.0	-	-
1973	3.2*	-	-
1974	1.1	-	-
1975	0.3	-	-
1976	0.0	-	-
1977	0.0	-	0.0
1978	0.0	-	1.7
1979	0.1	-	5.2
1980	0.0	-	1.5
1981	0.0	-	0.8
1982	0.0	-	0.5
1983	0.0	0.0	2.3
Weighted Average	0.3	0.0	2.0

---

*Due to in service inspection of steam generator welds to confirm no significant defects.

B6 TURBINES AND GENERATORS

The low pressure steam resulted in the adoption of relatively large, low speed (1 800 rpm) turbines for all units after NPD NGS.

One major problem experienced at NPD NGS was the rapid erosion/corrosion caused by wet steam. This problem has been eliminated at Pickering NGS-A and Bruce NGS-A by providing suitable overlays of high alloy steels, changes to material specifications and improved moisture extraction.

In 1980 and 1981, the three low pressure turbine spindles in each of Pickering NGS-A Units 1 and 2 were replaced by spares in order to carry out examination of the LP spindle disks. This examination was recommended by the turbine manufacturer due to the detection of Stress Corrosion Cracking in spindles of similar design in the United States.

Three of the removed spindles have been dismantled and inspected. One cracklike indication was detected. These spindles have been refurbished and are now installed in Unit 8.

The other three removed spindles have been inspected using a nondestructive examination method specially developed for this application. Crack indications have been detected in two of the spindles. As a result, three new LP spindles have been ordered. These spindles will be fitted with blades from the old spindles.

LP spindles inspections are scheduled for Bruce NGS-A Unit 2 in 1985 and for Pickering NGS-A Units 3 and 4 in 1986 and 1987, respectively.

The Incapability at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A due to turbines is shown in Table B6-1. It can be seen that performance has been good.

TABLE B6-1

Station Incapability Due to Turbines (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	7.0	-	-
1972	10.9*	-	-
1973	4.4*	-	-
1974	3.3	-	-
1975	2.3*	-	-
1976	0.0	-	-
1977	0.5	-	0.0
1978	3.2	-	6.2*
1979	1.2	-	4.7*
1980	5.3	-	2.9*
1981	5.1	-	2.7
1982	3.0	-	<0.1
1983	0.0	0.1	1.7
Weighted Average	3.1	0.1	2.8

---

*Includes manufacturer's inspections for warranty purposes.

A number of problems have been experienced with the generators:

1. Vibrations of the stator windings which led to several conductors cracking and causing hydrogen leaks to the stator cooling water.
2. Water boxes cracking causing hydrogen to stator cooling water leaks.
3. Failures of water box gaskets and hydrogen cooler gaskets.
4. Failures of end door sealant material and vent line tubing.
5. Hydrogen seal oil leaks.

Because of concern that the Pickering NGS-A generator stator windings would not have a long life, a complete spare stator was ordered in 1975 and delivered in 1977.

In 1980, a conductor failure (hydrogen leak to stator cooling water) again occurred. The stator was replaced by the spare and was carefully inspected. The cause of the failure was premature aging of the insulation leading to vibration damage to the subconductors. The faulty stator has been modified using a much harder epoxy insulation as part of a planned program to upgrade all of the stators at the station. In addition, the rebuilt stators have been converted from waterbox to hose design.

The incapability at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A due to generators is shown in Table B6-2.

TABLE B6-2

Station Incapability Due to Generators (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	2.0	-	-
1972	0.4*	-	-
1973	3.8*	-	-
1974	4.2	-	-
1975	11.3*	-	-
1976	1.7	-	-
1977	0.8	-	1.7
1978	2.2	-	6.8*
1979	3.7	-	3.0*
1980	3.9	-	0.9*
1981	1.7	-	0.1
1982	5.8	-	0.5
1983	4.0	1.4	3.2
Weighted Average	3.7	1.4	2.2

---

*Includes manufacturer's inspections for warranty purposes.

B7 INSTRUMENTATION AND CONTROL

Reliable instrumentation and control systems are vital to achieving good performance of a nuclear generating station. Complex processes must be controlled and a high degree of automation is required.

Pickering NGS-A was the first nuclear station with substantial portions of the process systems controlled by digital computers. Two digital computers were provided to control several of the most important processes including total reactor power, reactor flux distribution and all process alarm messages. If one computer fails, the other can immediately take over complete control and electricity output is unaffected. The unit cannot be operated with both computers out of service.

The unique Canadian concept of dual digital computer control with support by a number of analogue control circuits has proved excellent and has been further developed and applied at Bruce NGS-A.

The excellent low Incapability caused by the instrumentation and control hardware, including computer control at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A, is shown in Table B7-1.

TABLE B7-1

Station Incapability Due to Instrumentation and Control (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	3.7	-	-
1972	1.7	-	-
1973	0.4	-	-
1974	0.5	-	-
1975	0.4	-	-
1976	0.2	-	-
1977	1.3	-	2.0
1978	1.8	-	2.5
1979	0.9	-	2.7
1980	0.2	-	1.5
1981	0.1	-	0.4
1982	0.5	-	1.9
1983	0.0	4.6	0.0
Weighted Average	0.7	4.6	1.5

B8 HEAT EXCHANGERS

The concerns with regard to heat exchangers in general are the same as were covered for boilers in Section B5. There are two main concerns:

1. Would tubes fail causing reduction in capability and loss of heavy water?

2. Would tube heat transfer reduce, causing reduction in power levels or other problems in the station?

Failure of Pickering NGS-A original moderator heat exchangers, resulted in heavy water leakage to the environment seven times since in service. The first leak occurred in 1978 after approximately seven years in service. Eddy current inspection technique identified the cause of leaks as fretting of the tubes against the baffle plate, in the service water inlet window. A decision was made to replace all eight tube bundles by November 1984. To date, six tube bundles have been replaced.

In November 1982, Eddy Current inspection on Pickering NGS-A, Unit 3 Moderator HX1 revealed severe localized pitting on Incoloy-800 tubes after 4 1/2 years in service. At Pickering NGS-A, this was the only heat exchanger with I-800 tubing. It was replaced in May 1983.

At Pickering NGS-B and Bruce NGS-A all the moderator heat exchangers are tubed with I-800 material. For Pickering NGS-B Moderator heat exchangers new tube bundles are being purchased and the replacement frequency is being determined. At Bruce NGS-A, the moderator heat exchangers are being monitored to determine the condition of the I-800 tubing.

Other heat exchangers, known as bleed coolers, are used to cool heavy water flowing between the heat transport system and its purification system. Two of these coolers have been replaced at Pickering NGS-A due to pitting corrosion on the ordinary water side of the tubes. Modifications have been made to allow better chemical control in the ordinary water circuit. At Bruce NGS-A, the bleed coolers have had problems of severe scaling on the ordinary water side which in turn caused stress corrosion and failure of tubes in two units. New redesigned bleed coolers have been installed on Units 1 to 4, and the secondary side flow has been changed from lake water to a demineralized water system.

Silt deposited from the lake water gradually reduced the capability of the heat exchangers cooling the irradiated fuel storage bay at Pickering NGS-A. The silt was chemically removed in 1979 and heat exchanger performance restored.

Pickering NGS-B Unit 5 F/M return flow HX-7 developed several leaks after less than one year of operation. The heat exchanger is of "heliflow" design. The failure was caused by fatigue from a low energy high frequency vibration (metallurgical flaws were a contributing factor). Acoustic monitoring did not show similar vibration in any of the other "heliflow" heat exchangers remaining in operation. The HX-7 was taken out of service and permanent operation without it is under review.

At Bruce NGS-A, a heat transport pump motor bearing oil cooler failed due to under deposit pitting corrosion of the pure copper tubing. As a result, copper-tubed heat exchangers are being investigated to determine the extent of this corrosion problem.

The Incapability caused by heat exchangers at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A is shown in Table B8-1.

TABLE B8-1

Station Incapability Due to Heat Exchangers (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	0.0	-	-
1972	0.0	-	-
1973	0.0	-	-
1974	0.5	-	-
1975	0.0	-	-
1976	0.1	-	-
1977	0.3	-	3.0
1978	2.7	-	0.0
1979	4.0	-	0.0
1980	0.9	-	0.0
1981	0.0	-	0.0
1982	0.9	-	0.0
1983	3.5	0.2	0.0
Weighted Average	1.1	0.2	0.1

B9 VALVES

In CANDU-PHW units, as for any other reactor concept, valves must open, close, or regulate flow with high reliability and with acceptable leakage to atmosphere.

CANDU-PHW valve requirements for reliable opening, closing, and regulating are similar to other reactor concepts. However, the need to minimize heavy water leakage is unique to CANDU-PHW and has led to significant improvements in design and application of heavy water valves.

In order to minimize heavy water upkeep costs and incapability, the following concepts are applied:

1. The number of heavy water valves is minimized.
2. The number of ordinary water valves in heavy water recovery areas is minimized.
3. Valves specifically designed to minimize leakage such as:
    - (a) Minimum mechanical joints (welded flanges and seal welded bonnets).
    - (b) Zero leakage valves (bellows valves, diaphragm valves).
    - (c) Specially developed spring-loaded stem packings.
    - (d) Double packing with leakage collection at the midpoint.

It should be noted that, where isolation is occasionally required and valves are not provided, temporary ice plugs are used. For example, to isolate and drain a pressure tube for inspection or maintenance, ice plugs are formed in the two feeder pipes using jackets filled with liquid nitrogen.

The good heavy water upkeep experience described in Section B10 and the excellent Capacity Factors achieved by CANDU-PHW units demonstrate the successful application of these concepts.

Table B9-1 shows the low Incapability due to valves at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A.

TABLE B9-1

Station Incapability Due to Valves (%)

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
1971	0.0	-	-
1972	1.2	-	-
1973	0.4	-	-
1974	0.9	-	-
1975	0.2	-	-
1976	0.1	-	-
1977	0.2	-	0.0
1978	0.5	-	0.0
1979	0.3	-	0.0
1980	0.6	-	0.1
1981	0.0	-	0.1
1982	0.0	-	0.0
1983	0.2	1.4	0.9
Weighted Average	0.4	1.4	0.2

B10 HEAVY WATER MANAGEMENT

A CANDU-PHW reactor typically requires a heavy water inventory of one megagram per megawatt of electrical capacity.

The heavy water is contained in two basic systems:

1. The heat transport system contains approximately half of the heavy water inventory and operates at high temperature and high pressure (approximately 9 MPa gauge and 300°C).
2. The moderator system contains the other half and operates close to atmospheric pressure and low temperature (70°C).

Heavy water is expensive and must be carefully managed for two reasons:

1. To minimize Unit Energy Cost
2. To minimize radiation exposure

Minimizing Unit Energy Cost

Heavy water is not consumed, but it can be lost and it can be downgraded by mixing with ordinary water.

Heavy water upkeep is the cost of:

1. Replacing losses.
2. Upgrading any downgraded water to restore its isotopic purity to between 99.8 and 99.9 mass percent heavy water.

These two costs together are called "Upkeep Costs." Downgrading of heavy water occurs in four ways:

1. When heavy water and ordinary water escape into the same air enclosure.
2. When heavy water gets into an ordinary water circuit.
3. When ordinary water gets into a heavy water circuit.
4. When heavy water escapes and is recovered by an in-line recovery system, but is contaminated by materials other than ordinary water, eg, oil.

We desire a practical design and operation with low heavy water upkeep costs, assuming that every day chronic escape will occur and infrequent major spills will occur.

The proven concepts which have led to low cost heavy water upkeep are as follows:

1. High integrity pressure boundary - care in the selection of valve seals, pump seals and mechanical joints - to minimize the escape rate.

2. Provision of a secondary enclosure - leaks go into rooms with a sealed floor, closed circuit ventilation, tight doors, etc.

3. Provision of closed circuit vapour and liquid recovery circuits on the secondary enclosures so that the escaped heavy water does not become a loss.

4. Minimization of the number of ordinary water circuits in the secondary enclosures and leaks from ordinary water circuits within such enclosures.

5. Detection of leaks by use of manual and on-line leak monitors.

Typically, at Pickering NGS-A, Pickering NGS-B, and Bruce NGS-A, the Heavy Water Upkeep Unit Energy Costs are only 2-4% of Total Unit Energy Costs. The 1983 performance is shown in Table B10-1.

TABLE B10-1

1983 Heavy Water Upkeep Costs

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A
Total Unit Energy Cost (m$/kW.h)	18.44	42.18	18.37
Heavy Water Upkeep Unit Energy Cost (m$/kW.h)	0.78	0.97	0.42
% of TUEC	4%	2%	2%

Minimizing Radiation Exposure

Tritium is produced in heavy water mainly through neutron capture in the deuterium. This radioactive tritium requires good management to minimize employee exposure and environmental emissions.

Approximately 90% of the tritium is produced in the moderator which has a low escape rate because of its lower pressure and temperature.

The same principles which minimize heavy water upkeep costs minimize tritium exposures and emissions.

When necessary, work is performed in air-supplied plastic suits which provide a large protection factor.

The tritium dose is typically 25% of total radiation dose to workers.

While not yet being used, tritium removal and storage technology is currently being developed. A tritium removal system, originally to be installed at the Pickering station, has been transferred to the Darlington site. It has been committed to be in service in 1987.

B11 NEGATIVE PRESSURE CONTAINMENT

Ontario Hydro's multi-unit CANDU stations have a unique and very powerful safety containment system which is based on the concept of negative pressure containment. This system consists of:

1. The reactor buildings

2. One vacuum building

3. One pressure relief duct

The vacuum building is separated from the duct and reactor buildings by normally closed pressure relief valves. The pressure within the building is held at about 1/10 atmospheric pressure and leak tightness is constantly monitored. The building also houses an emergency water storage tank which can be used to douse steam or provide emergency cooling water to reactor systems in the event of a loss of coolant accident.

In 1980, the vacuum building at Pickering NGS was extensively inspected after 10 years in service. All components within the building were found to be in generally good condition and working order. No deficiencies were found that would have affected normal operation. Large fibreglass dousing pipes, chosen for expected long life, were confirmed to be in good condition and required only minor repairs to improve long-term strength and reinforcement. Submerged carbon steel metal work sustained minor corrosion damage due to a sulphate-reducing bacteria. Some parts were repaired or replaced and coated with coal tar epoxy. The concrete structure required only superficial repairs. Finally, a successful test of the douse system was performed.

B12 RADIATION DOSE

Atomic Energy Control Board (AECB) regulations require that atomic energy workers receive less than 5 rem per annum.

However, in addition to these regulatory limits, Ontario Hydro is committed to the ALARA principle (As Low As Reasonably Achievable).

Exposures have been reduced through:

1. Canadian developed decontamination techniques such as CANDECON which has been shown to be capable of reducing radiation levels by a factor of 3 to 20.
2. Material specifications such as low cobalt content in feeder pipes and boiler tubes to minimize radiation due to Cobalt-60 (activated corrosion product).
3. Maintainability and reliability which not only reduce costs but reduce exposures.
4. On-power removal of defective fuel bundles.

Table B12-1 shows the results for each year as the ratio of station dose to energy produced for each of the four stations operated by Ontario Hydro.

Note that the commercial stations are considerably better than prototypes and later performance of Douglas Point NGS has considerably improved over its early performance.

In general, staffing levels are not dependent on radiation exposure.

The average radiation dose in 1983 was 1.0 rem per exposed worker at Pickering NGS-A & B and 0.2 rem per exposed worker at Bruce NGS-A.

TABLE B12-1

Radiation Dose Experience
Rem Per Megawatt-Year (Net)

	NPD NGS	DOUGLAS POINT NGS	PICKERING NGS-A	PICKERING NGS-B	BRUCE NGS-A
1970	20.1	13.8	-	-	-
1971	34.6	17.7	1.2	-	-
1972	53.3	39.6	1.6	-	-
1973	30.0	10.3	0.6	-	-
1974	15.5	4.3	1.1	-	-
1975	14.6	5.6	1.6	-	-
1976	7.5	5.5	1.0	-	-
1977	13.4	4.8	0.6	-	0.3
1978	14.6	3.2	0.5	-	0.3
1979	35.5	1.4	0.6	-	0.2
1980	6.2	16.7*	0.5	-	0.2
1981	14.2	2.0	0.4	-	0.2
1982	6.1	3.4	0.5	-	0.2
1983	7.6	4.5	0.9	0.2	0.2

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*During 1980, Douglas Point NGS was shut down for 261 days to effect modifications to the Emergency Core Injection System.

B13 PUBLIC SAFETY PRINCIPLES

Public Safety - Radioactivity

All generating stations present a conventional risk to the public due to the presence of such conditions as fast flowing water streams and high voltage electrical apparatus. Measures, such as erection of high fences, are taken to minimize the frequency and severity of injuries to the public due to these conditions.

Nuclear-electric generating stations use natural uranium fuel to produce heat energy and electrical energy. Radioactivity, which is produced in the fuel, presents a risk to the public of injury or death if there is an acute escape of a significant amount of radioactivity from the fuel to public areas.

Public Safety - Radioactivity has to do with protection of the public against acute releases of radioactivity which would cause immediate death or injury or which would significantly increase the probability of dying in later years as a result of exposure to this radioactivity.

Systematic Approach to Public Safety

Canada was the first country in the world to develop a comprehensive, systematic and quantitative method of measuring, analyzing and maintaining acceptable safety risks during actual operation of generating stations.

Specifically, this systematic method was conceived and introduced by Ontario Hydro Operations at Canada's first nuclear generating station, Nuclear Power Demonstration (NPD) NGS. The method was subsequently adopted and expanded by the AECB. Improvements have been developed through cooperation between AECB, AECL and Ontario Hydro.

During its development, the method has been of major interest to the USA (via the USAEC) and to Europe (via IAEA). There is no other country which uses as comprehensive a method of evaluating the safety performance of its nuclear generating stations.

Public Safety Concepts

Public safety must not depend on perfection of any public safety measures, but must be achieved assuming there will be occasional failures. Thus, the Canadian approach to public safety assumes that:

1. Nuclear station operators will occasionally make mistakes.

2. Nuclear station equipment will occasionally fail.

3. The design of nuclear station equipment will have occasional imperfections.

Our approach to ensuring acceptable public safety has five basic thrusts, each of which contributes to the low probability of an acute escape of radioactivity from the fuel to public areas. These five basic thrusts are:

1. We seek reliable process systems which produce heat and electricity while containing radioactivity within the reactor fuel.

2. We seek reliable safety systems which will compensate for failure of process systems by shutting down the reactor (Reactor Shutdown System), providing additional fuel cooling (Emergency Cooling System), or confining radioactivity which has escaped from the fuel (Containment System).

3. We provide a multiple barrier approach to prevent or impede radioactivity moving from fuel to the public. These multiple barriers are built into the station design and protect against undetected faults or unforeseen events.

4. We seek competent operators who are very knowledgeable about system conditions, alert for any evidence that equipment may be about to fail, and who act promptly to prevent or minimize such failures.

5. We seek to detect and correct failures associated with any of the above and we have developed a systematic approach which achieves that. This systematic method involves procedures which are taken by operating staff for each of the following steps:

   - Detect and Identify Failures

   - Classify Failures

   - Take Short-Term Corrective Action

   - Implement Long-Term Corrective Action

   This systematic method has been a major factor in helping us achieve our public safety record of never having a radioactivity release which resulted in a measurable exposure to any member of the public. Some of the details involved in the systematic method follow.

Detect and Identify Failures

Since we assume that equipment and human failures will occur, we have built into our equipment and operating procedures detection methods which will promptly alert the operator whenever a failure occurs. The detection methods include automatic methods such as instruments which monitor equipment status and send a signal to the operator in the control centre whenever status changes. The detection methods also include operator investigations for evidence of failure such as field patrols, maintenance, periodic tests and study of changes in any plant condition.

Classify Failures

Failures of components, or human or design errors, may cause a process or safety system to be totally inoperative such that it cannot perform any part of its intended function. This is extremely rare. Much more common are failures which only impair the system effectiveness to some degree such that it can perform part of its intended function.

The classification step involves judging whether a failure involves inoperability or impairment and recording this together with the frequency and duration.

Short-Term Corrective Action

All safety system failures, however detected, must be brought to the attention of the Unit Operator and Shift Supervisor.

If the failure represents an inoperative or impaired safety system, the affected system will be placed in a safe state or the generating unit will be shut down unless a prompt repair can be made.

The appropriate corrective action is taken (repair or replace components).

The circumstances are recorded appropriately.

The success of the corrective action is validated by the operators through discussion with maintenance and technical staff, post-repair testing and by inspection. Formal documentation assures that appropriate short-term action has been taken.

The shift records are reviewed daily by station management and supervisory staff to ensure vigilance and quality of the detect and correct process.

Long-Term Corrective Action

The station technical staff systematically review fault data to determine whether or not long-term corrective action is needed. Other Ontario Hydro staff independently audit the performance of safety systems at all operating stations by auditing reviews by station staff, by ensuring consistency of methods, or by doing reviews for the station. Frequently, the design organizations of Ontario Hydro and AECL are utilized to carry out analyses, develop recommendations and redesign when necessary.

As a result of continuing design and research, proposals may be initiated by non-operating personnel to modify an existing station. Modifications may also be initiated as a result of AECB reviews.

These reviews include analyses to determine frequency, duration and cause of failures. System performance is evaluated and compared with targets discussed in the following sections. This process identifies the need, if any, to make long-term improvements and the priorities for these improvements.

Improvements involve such action as component changes or modifications and operating and maintenance procedure changes. Until long-term effectiveness of such corrections is demonstrated, the frequency of tests and inspections is appropriately increased.

Acceptable Public Risk Standard

Risk is the product of the frequency of serious events and the consequences of those events. The consequences include the number of people killed or injured and the severity of injuries both immediate and delayed. This risk can be "actual," if it refers to events that have happened, or, the risk can be "predicted," if it refers to events that might happen in future.

The AECB has developed guidelines which are intended to be a practical definition of acceptable public risk for radioactive releases from an operating nuclear generating station. These AECB guidelines specify a maximum frequency and a maximum consequence for single failures, that is, failure of process systems alone. The guidelines also specify a maximum frequency and a maximum consequence for dual failures, that is, failure of process system coincident with failure of one of the safety systems provided to minimize the process failure.

Since risk is the product of frequency and duration, the equivalent risks inferred in the AECB guidelines are:

1. Single event risk - 1 rem/annum (thyroid)
   or 0.16 rem/annum (whole body)

2. Dual event risk - 0.25 rem/annum. (thyroid)
   or .025 rem/annum (whole body)

The AECB apply the most restrictive of these criteria based on the worst case accident for each nuclear station. This guideline is similar to but less restrictive than NGD's own standard which states, "The most exposed member of the public adjacent to a nuclear station will be subject to an average annual risk not exceeding that which would increase by 1 per 1 000 000 his probability of dying in later years as a result of an acute release of radioactivity."

Process System and Safety System Targets

The important measure of adequate public safety is Risk. However, to ensure an acceptable design and to evaluate and improve operating performance, it is also worthwhile to measure the performance of each process system and each safety system.

Very demanding system targets have been set for process and safety systems to allow this performance measurement and assist in evaluating the benefit of system improvements. Individual system targets may not be met each year. This is acceptable provided the AECB Risk guideline is met.

Since process systems are active while a nuclear generating unit is producing electricity, these targets are set to establish a maximum annual frequency of failures which would lead to escape of radioactivity from the fuel to a public area unless prevented by action of the safety systems.

Safety systems are passive unless called upon to act in the event of process system failure. Comprehensive test programs monitor the status of safety system components during the passive system state and results of these tests are used to calculate the portion of time that a safety system would have been impaired by a fault if the system was called upon to operate. All impairments which would prevent or impede a safety system from fulfilling its specified mission to even a minor extent are included in the calculation of impaired system time. Most safety system faults represent minor impairments rather than complete system inoperability. However, the safety system target was chosen as if all impairments involve inoperability and total safety system impairment time is compared to this extremely high performance standard.

Pickering NGS-A Result Comparison (Lifetime)

Pickering NGS-A is a mature four unit station which represents a typical example of our experience in always meeting Risk criteria by a considerable margin even though some individual process system and safety system targets are not met. The five-thrust multiple approach to public safety has allowed us to achieve this high standard of public safety. The systematic approach that is used to frequently measure and compare performance of process and safety systems with targets has ensured that first priority is always given to maintaining the high quality of these systems.

Process Systems

There have been no process failures which resulted in a release of radioactivity causing a measurable radioactivity dose to a member of the public.

There have been seven regulating system failures which were classed as losses of regulation and which caused these systems to not meet target.

Safety Systems

The Shutdown Systems, which provide rapid reactor shutdown whenever process system limits are not met, have been perfect except for two impairments which existed during a long shutdown of one unit. Despite the impairments, the systems easily meet NGD and AECB targets.

The Emergency Coolant Injection Systems, which provide continued fuel cooling if normal process fuel cooling is disrupted, have had various impairments which caused the systems to not meet impairment targets.

The Containment Systems, which prevent radioactivity released from fuel from escaping to public areas, have not met target over the station lifetime. A single marginal impairment caused by cracks around a penetration in one unit was responsible for the majority of actual impairment time. This fault occurred in the early years of Pickering NGS-A operation.

Public Risk

The actual risk has been zero for both single and dual failures. The predicted potential risks, which are calculated using the best available data from system failure experience, committed changes and design analyses, are within the AECB criteria by considerable margins.

The detailed comparison of process and safety system performance versus target is shown in Table B13-1.

TABLE B13-1

Pickering NGS-A Result Comparison (Lifetime) System Versus Targets

Process Systems	Target	Results Frequency	Results Impairment Time	Results Inoperability
Regulating (LOR)	0.01/a	0.15/a		
Heat Transport (LOC)	0.001/a	0/a		
Safety Systems				
Shutdown	0.3%		0.03%	0%
ECI	0.3%		8.6%	0.08%
Containment	0.3%		3.4%	0%

Public Risk Versus AECB Criteria

		Criteria	Result*
Actual Single Failure	- Thyroid	1.0 rem/a	0 rem/a
	- Whole Body	0.16 rem/a	0 rem/a
Actual Dual Failure	- Thyroid	0.25 rem/a	0 rem/a
	- Whole Body	0.025 rem/a	0 rem/a
Predicted Potential Single Failure			
	- Thyroid	1.0 rem/a	4.85×10^{-3} rem/a
	- Whole Body	0.16 rem/a	4.85×10^{-4} rem/a
Predicted Potential Dual Failure			
	- Thyroid	0.25 rem/a	2.66×10^{-3} rem/a
	- Whole Body	0.025 rem/a	4.56×10^{-4} rem/a

Public Safety Conclusions

1. The Nuclear Industry in Canada is a world leader in establishing a comprehensive systematic approach to measuring and achieving acceptable public risk. This systematic approach achieves acceptable public risk allowing for design, equipment and operator failures.

2. The systematic approach is quantitative and designed to highlight all faults which render systems inoperable or which impair effectiveness. The approach is effective but not perfect and is undergoing continuous improvement.

3. No member of the public has been killed, injured, or exposed to a measurable amount of radiation to date resulting from an accident at an Ontario Hydro operated nuclear station.

4. Every nuclear station in Ontario has met and now meets its basic criteria for public risk set by the AECB.

5. Past achievement cannot be taken for granted and the Canadian Nuclear Industry is committed to a continued program of vigilance and to seek improvement.

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*Includes both short-term and long-term post accident exposures (no credit taken for long-term population control).

B14 STAFFING AND TRAINING

An adequate number of sufficiently motivated and well trained staff is essential for safe and efficient operation of any expensive and complex facility.

Operations Staff

The four major classifications of operations staff are:

1. Management and Professional Staff - Managers, engineers and scientists who solve technical problems, and oversee station operations and maintenance programs. Shift Supervisors are Management and Professional Staff.

2. Operators - Perform tests and isolate equipment, start-up, shut down the units.

3. Mechanical Maintainers - Perform mechanical maintenance work involving such skills as fitting, machining, and welding.

4. Control Maintainers - Perform electrical, control, and instrumentation maintenance.

In addition to these four classifications, there are a number of specialist and support staff such as Planning Technicians, Radiation Control Technicians, Chemical Control Technicians, Security Guards, and clerical staff.

Pickering NGS-A is a typical Four-Unit CANDU station and is presented as an example of the staffing and training requirement. It has a capacity of 2 060 MW e and a staff complement of approximately 600. The organization chart and staff complement for Pickering NGS-A are illustrated in Figure B14-1. Approximately 70% of the station staff are shift workers in the Production Section who operate, maintain and fuel the generating units on a 24-hour per day, 365 days per year basis.

A practical nuclear-electric program must be able to achieve the objectives assuming that station personnel will occasionally make mistakes. Also, a practical station should perform well assuming that station staff are average or somewhat above average persons in terms of their skills, knowledge, and ability. At the same time, it is important that staff be carefully selected, properly trained, and properly managed to ensure that the station operates safely and efficiently.

Specialist Support Staff - Operating

Each CANDU station has available to it the services of three large operating support departments. These departments can supply specialist knowledge in specific areas, assist the stations with long range studies, and interact with Ontario Hydro design and research and outside agencies. The support departments are Central Nuclear Services (CNS), Radioactivity Management and Environmental Protection (RMEP) and the Nuclear Staffing Group (NSG).

These support departments presently serve 5 stations with 11 operating units and will serve 7 stations with 22 operating units by the 1990s.

Training Programs

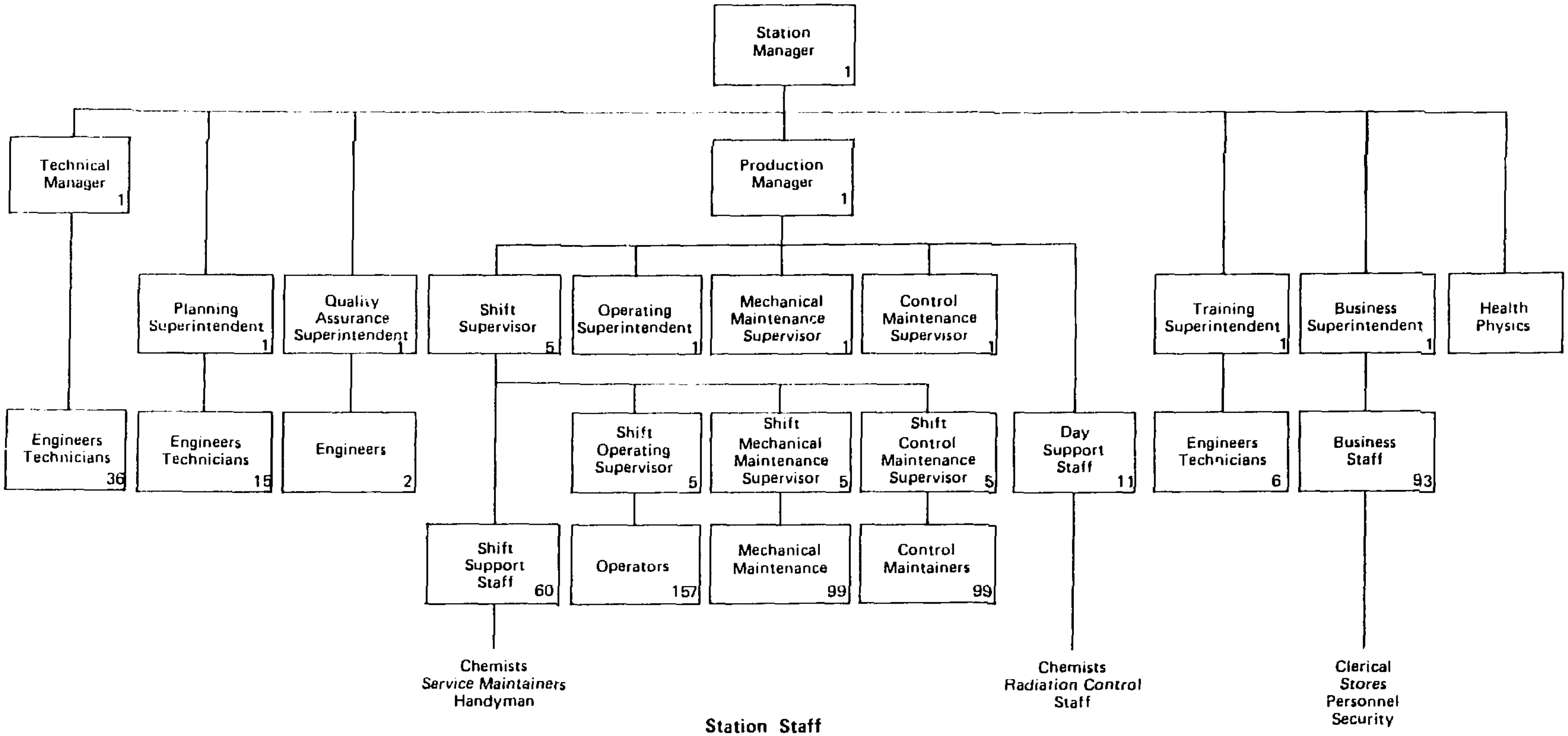
A comprehensive training program has been developed for all the major classifications noted above and for the vital support classifications.

Training Simulators

Ontario Hydro has decided tailored computer simulators are required for each commercial nuclear generating station. The simulators for Pickering NGS-A and Bruce NGS-A are in service and have proven to be extremely useful and vital training tools. Simulators for Pickering NGS-B, Bruce NGS-B, and Darlington NGS-A are under construction.

FIGURE B14–1

PICKERING NGS–A ORGANIZATION



Station Staff

Shift Staff – 5 shifts

By Function	
Management and Professional	77
Operators	157
Control Maintainers	99
Mechanical Maintainers	99
Specialists and Support Staff	176
	608

By Organization	
Station Manager	1
Technical	37
Planning	16
Quality Assurance	3
Production	450
Training	7
Business	94
	608

PART C - OVERALL HIGHLIGHTS

The following are the overall highlights of the Ontario Hydro CANDU-PHW program in Canada:

1. Ontario Hydro has had 113 reactor years of nuclear-electric operating experience with 11 nuclear units in 5 generating stations over a period of 22 years.

2. All objectives have been met with outstanding performance: worker safety, public safety, environmental protection,reliable electricity production and low electricity cost.

3. The achievement has been realized through total teamwork involving all scientific disciplines and all project functions (research, design, manufacturing, construction and operation).

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