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CANDU OPERATING EXPERIENCE

ontario hydro

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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 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 operations).
3. The program is based upon in-depth development of science and technology of heavy water reactors over a period of 38 years, from 1942 to 1980. During this period, Canada was the first country in the world to operate a high flux reactor and the first country 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 (NPD) in 1962.

The second stage of operating experience with the CANDU type started in 1968 when the Douglas Point Nuclear Generating Station was placed in service.

There were a number of problems which resulted in reduced performance of NPD 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) in which there has been excellent performance of eight commercial units which started up in the nineteen seventies.

We are extremely proud in Canada of this excellent performance and the in-depth technology developed in the 38 years between 1942 and 1980. The cumulative operating experience of nuclear-electric units is 72 reactor years.

Table 1 is a tabulation of the 10 CANDU-PHW nuclear units in operation in Ontario Hydro, one of the three electrical utilities in Canada engaged in a nuclear program. Ontario Hydro has 5248 MW e in operation and 8612 MW e under construction.

Two other electrical utilities in Canada, The New Brunswick Electric Power Commission and Hydro Quebec, have nuclear units under construction.

Table 1

Ontario Hydro Nuclear Units

Station	Unit	Net Capacity MW e
NPD NGS	2	22
Douglas Point NGS	1	206
Pickering NGS-A	1	515
	2	515
	3	515
	4	515
Bruce NGS-A	1	740
	2	740
	3	740
	4	740
Total	10	5248 MW e

OPERATING RESULTS

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

The five rudimentary objectives are as follows:

- Worker Safety
- Public Safety
- Environmental Emissions
- 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 1979, nuclear operations employees have worked 54.7 million manhours.
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 2.8 injuries per one million manhours for the decade from 1970 to 1979 inclusive.
4. No employees have 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. Over-exposures to employees are very infrequent corresponding to 0.29 over-exposures per million manhours 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 fossil 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 are as follows:

1. During 72 reactor years of operation in Canada there has never been a fatality nor has there been an injury of any kind for any reason to a member of the public.
2. 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.
3. The radioactivity risk criteria have been fully met at every station for every year.

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 the 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	77
PWR	57
BWR	55
GCR	45

2. The eight CANDU commercial units in Canada have extraordinary lifetime reliability. Table 3 is a ranking of the eight CANDU units in the world's 104 large operating reactors.

Table 3

Canadian Ranking in World's 104 Commercial Reactors
500 MW e and Larger - Lifetime

Unit	Gross Capacity Factor (%)	World Rank
Pickering 2	85	1
Pickering 1	83	3
Bruce 4	79	4
Bruce 3	78	5
Pickering 4	78	6
Pickering 3	78	7
Bruce 1	70	18
Bruce 2	61	43

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 500 MW e units with Lambton TGS, a four 500 MW e units coal-fired station. Both stations are modern design and were constructed at the same time.

Table 4

Cost Comparison Pickering NGS-A and Lambton TGS - 1979

Unit Energy Cost (m$/kW.h e*)

	Pickering NGS-A	Lambton TGS
Interest and Depreciation	5.86	1.87
Operation, Maintenance and Administration	2.84	1.55
Heavy Water Upkeep	0.47	--
Fuelling	1.73	15.95
Total Unit Energy Cost	10.90	19.37

* Milli-dollars per kilowatt hour electric

COMPONENT EXPERIENCE

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

The on-power fuelling 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 fuelling problems is 0.9%. Off-power fuelling 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 0.11%. Defective fuel has had 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.

The pressure tube development has produced excellent results. No ruptures have ever occured. Continued research indicates that the ductile pressure tube will leak long before break. 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. Some tubes were replaced and the problem has now been solved.

The pressure tube life was originally expected to exceed 10 years. This has been achieved. Pressure tube replacements caused by radiation induced growth are expected after a minimum life of 14 years for the first commercial units. New pressure tube specifications are seeking a life of more than 20 years and probably 30 years.

The performance of CANDU-PHW boilers has been excellent with a very low incapability of 1.2%. One major problem has been experienced during manufacture which required a change in the boiler 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 CANDU-PHW stations utilize dual digital computer controllers with outstanding performance.

The heavy water management of CANDU-PHW stations is important 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, New Brunswick Electric Power Commission, and Ontario Hydro. This paper also includes some general remarks about the CANDU-PHW type from the point of view of Ontario Hydro, one of these three utilities, which at the present time has the greatest amount of operating and construction experience.

Canadian Experience

Canadian nuclear experience with heavy water reactors goes back 38 years to 1942. The first heavy water reactor ZEEP (Zero Energy Experimental Pile) 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 fuelling 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 fuelling 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 a prototype reactor Douglas Point NGS (206 MW e) which went into service in 1968. The fuelling 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 multi-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 10 CANDU-PHW units and has an additional 12 nuclear units under construction. Hydro Quebec has had operating experience with one CANDU-BLW unit and has one CANDU-PHW unit under construction. New Brunswick has one CANDU-PHW unit under construction.

As indicated above, all of the operating experience of CANDU-PHW in Canada has been in the one provincial utility - Ontario Hydro.

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 eight 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 38 years between 1942 and 1980. The cumulative operating experience is 72 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 hydro generation, and 30 years of experience with fossil (coal, oil, gas) generation.

Ontario Hydro had a total installed electrical capacity of 23 968 MW at the end of 1979. This capacity is comprised of three types of generation as in Table 1.

Table 1

Ontario Hydro Installed Capacity
December 1979 - MW e (Net)

Hydro	6 460
Thermal	12 260
Nuclear	5 248
Total	23 968

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

Table 2

Ontario Hydro - Operating Nuclear Capacity - December 1979

Station	Unit Number	Net Capacity MW e	In-Service Date Actual
NPD	2	22	September 1962
Douglas Point	1	206	October 1968
Pickering NGS-A	1	515	July 1971
	2	515	December 1971
	3	515	June 1972
	4	515	June 1973
Bruce NGS-A	1	740	September 1977
	2	740	September 1977
	3	740	February 1978
	4	740	January 1979
Total	4 stations 10 units	5 248	

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

Ontario Hydro presently has 12 units under construction as indicated in Table 3.

Table 3

Ontario Hydro - Nuclear Capacity Under Construction - December 1979

Station	Unit Number	Net Capacity MW e	In-Service Date Schedule
Pickering NGS-B	5	516	December 1982
	6	516	June 1983
	7	516	November 1983
	8	516	April 1984
Bruce NGS-B	6	756	October 1983
	5	756	July 1984
	7	756	April 1986
	8	756	January 1987
Darlington NGS-A	1	881	November 1988
	2	881	August 1989
	3	881	November 1990
	4	881	August 1991
Total	3 stations 12 units	8 612	

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

Table 4

Ontario Hydro - Nuclear Program Capacity

In Operation	5 248
Under Construction	8 612
	13 860

The energy contributions to Ontario Hydro's requirements for the calendar year 1979 were as follows:

	Energy (TW.h)	Contribution (%)
Hydro	38.8	39.6%
Thermal (coal, oil, gas)	30.9	31.5%
Nuclear	33.3	33.9%
Purchases	7.6	7.7%
Total	110.6	112.7%
Export	-12.5	-12.7%
Net Ontario	98.1	100.0%

Much publicity has been given to the 1979 problem at the Three Mile Island nuclear generating station in the USA which is a PWR type. The Canadian nuclear program had a major accident at the NRX reactor in 1952. This accident led to the formulation of a comprehensive set of principles for reactor control and safety which has been built into the design and incorporated in the operation procedures. These principles are summarized later in this paper.

PART A - RESULTS

A0 INTRODUCTION

From the very beginning of 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 Emissions
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 CANDU-PHW if such information is desired.

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 of any part of the body 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.

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

These standards of employee safety meet the following specifications:

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

Results and Comparisons

Table A1-1 compares 1979 results with the standards for fatalities.

Table A1-1

Worker Safety 1979
Fatalities Per Hundred Million Man-Hours

	Standard	Performance
Hydro	3	0
Fossil	2	0
Nuclear	2	0

Table A1-2 compares 1979 results with the standards for permanent disabilities.

Table A1-2

Worker Safety 1979
Permanent Disabilities
Per Ten Million Man-Hours

	Standard	Performance
Hydro	1	0
Fossil	2	0
Nuclear	2	0

Table A1-3 compares 1979 results with the standards for temporary disabilities.

Table A1-3

Worker Safety 1979
Temporary Disabilities
Per One Million Man-Hours

	Standard	Performance
Hydro	6	7.4
Fossil	6	6.0
Nuclear	6	1.9

Table A1-4 indicates the performance in the last ten years (1970 to 1979).

Table A1-4

Ten-Year Performance
1970 to 1979 Inclusive

	Fatalities Per Hundred Million Man-Hours	Permanent Disabilities Per Ten Million Man-Hours	Temporary Disabilities Per Million Man-Hours
Hydro	6	0.6	3.7
Fossil	0	0.3	7.0
Nuclear	0	1.4	2.8

Table A1-5 compares off-the-job and on-the-job fatalities for Ontario Hydro and the Nuclear Generation Division.

Table A1-5

Worker Safety 1970 to 1979 Inclusive

Fatalities Per Hundred Million Man-Hours

	Off-the-Job	On-the-Job
Ontario Hydro	5.9	8.9
Nuclear	8.2	0

Highlights

From 1962 to the end of 1979, the nuclear operations employees have worked 54.7 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 were minor in nature (loss of portion of finger).
3. No employees have ever been injured due to radiation.
4. There has never been a serious radiation exposure (greater than 25 rem per annum).
5. The highest whole body exposure to one employee has been 7.3 rem (2.3 rem above 5 rem per annum regulatory limit).
6. Over-exposure (greater than 5 rem per annum) has averaged 0.29 over-exposures 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 hydro stations and fossil stations has been very 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 a whole body exposure of 0.01 rem/annum or an infant thyroid dose of 0.1 rem/annum.

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 Criteria

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

Single Failure Accident (thyroid):

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

Dual Failure Accident (thyroid):

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

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

Single Failure Accident (thyroid):

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

Dual Failure Accident (thyroid):

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

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 72 reactor years of operations in Canada, there has never been a fatality nor has there been an injury of any kind for any reason to a member of the public.

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

3. The predicted radioactivity risk has met the Ontario Hydro standard and the risk corresponding to the AECB guidelines for every station for every year.

A3 ENVIRONMENTAL EMISSIONS

Definition

Environmental emissions mean 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. As a result, emissions are very low and the regulatory limits are consistently met.

Table A3-1 shows the more important sources of environmental impact from nuclear generating stations. Standards are set for the emissions and the emissions are monitored and controlled. Only radioactivity will be discussed here.

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 1% or less of DELs. This ensures the conservative standard of 100% DEL will be met.

Environmental Criteria

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

Highlights

During the 17 years (72 reactor years) of experience with the CANDU-PHW nuclear generating station, the following are highlights of performance:

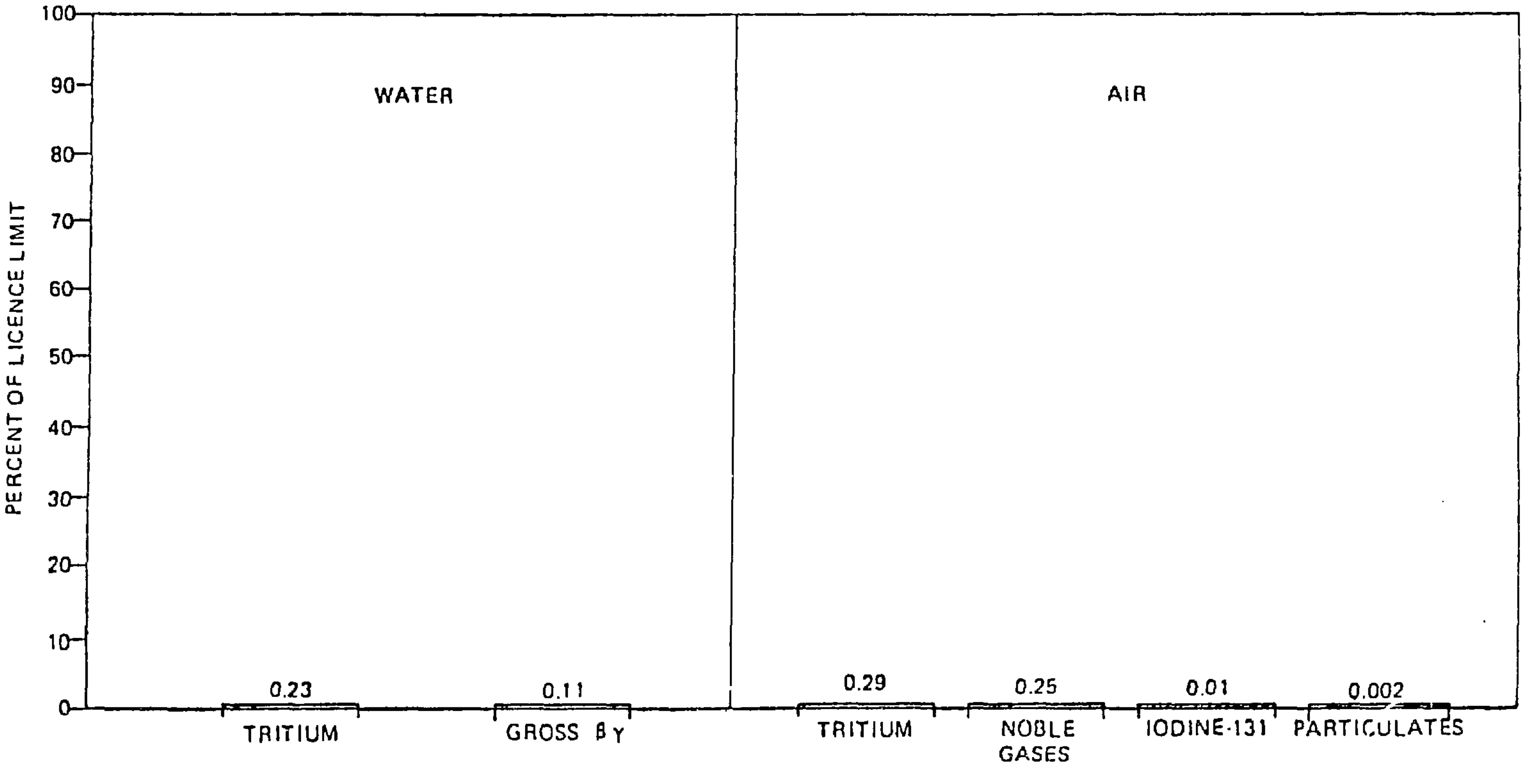
1. Canada has a perfect record - the annual regulatory limit has never been exceeded. That is, all six criteria have been met every year at every station.

2. The low levels of emission from a typical station (Pickering NGS-A) for the six criteria are presented in Figure A3-1.

FIGURE A3–1

RADIOACTIVE EMISSIONS 1979
PICKERING NGS–A

LICENCE LIMIT	100%
OPERATING TARGET	1%
ACTUAL	< 1%



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 fuelling costs of CANDU-PHW units in Ontario Hydro are approximately 2 milli-dollars per kilowatt hour (m$/kW.h) as compared with fossil-fuelled units in excess of 16 m$/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 dates which are planned for a generating unit are met. In-service lateness is indicative of our ability to design, procure, construct, and commission generating units on schedule.

The one criterion we use to measure the 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.

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

Table A4-1

In-Service Date Reliability

	In-Service Dates		Lateness	
Station/Unit	Original	Actual	Weeks	MW-Year
Pickering NGS				
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 17/72	- 15	- 156
Bruce NGS				
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 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 probability that a unit could cause 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.

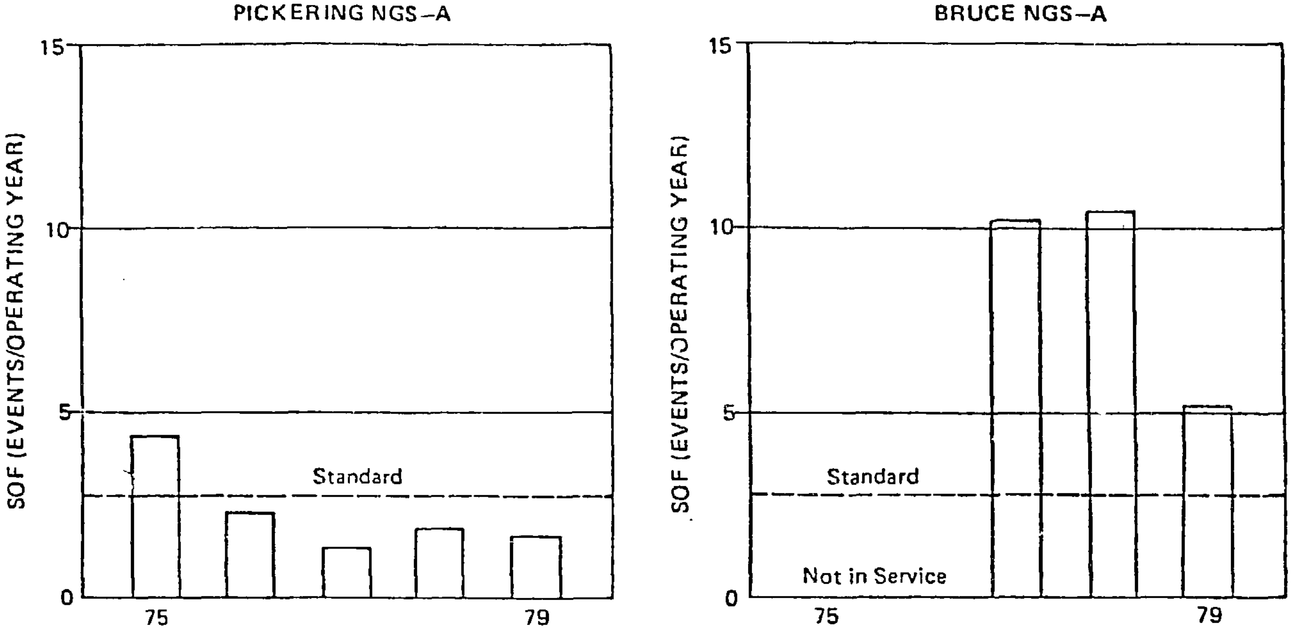
2. Initiation is from within the station boundary.

3. Operation is interrupted from above 25% MCR.

The standard for Ontario Hydro has been established at 3 or less events/operating year. Our results over the last 5 years for CANDU-PHW generating units are shown in Figure A4-1.

Figure A4-1

Sudden Outage Frequencies



It should be noted that the Bruce units are in their first few years of operation and consequently still suffering run-in failures. The performance of the more mature Pickering units is exceptional.

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 deviation, 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

		1975	1976	1977	1978	1979
Pickering	Unit 1	0/1	0/0	0/0	0/0	0/0
	Unit 2	0/1	0/0	0/0	0/0	0/0
	Unit 3	0/1	0/0	0/0	0/0	0/0
	Unit 4	0/0	0/0	0/0	0/0	0/0
Bruce	Unit 1			0/0	0/6	0/0
	Unit 2			0/0	1/1	0/0
	Unit 3				0/1	0/0
	Unit 4					0/2
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).

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

Incapability Factor = 1 - CbF

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 fuelled units of equivalent size operated throughout North America and reported by the National 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

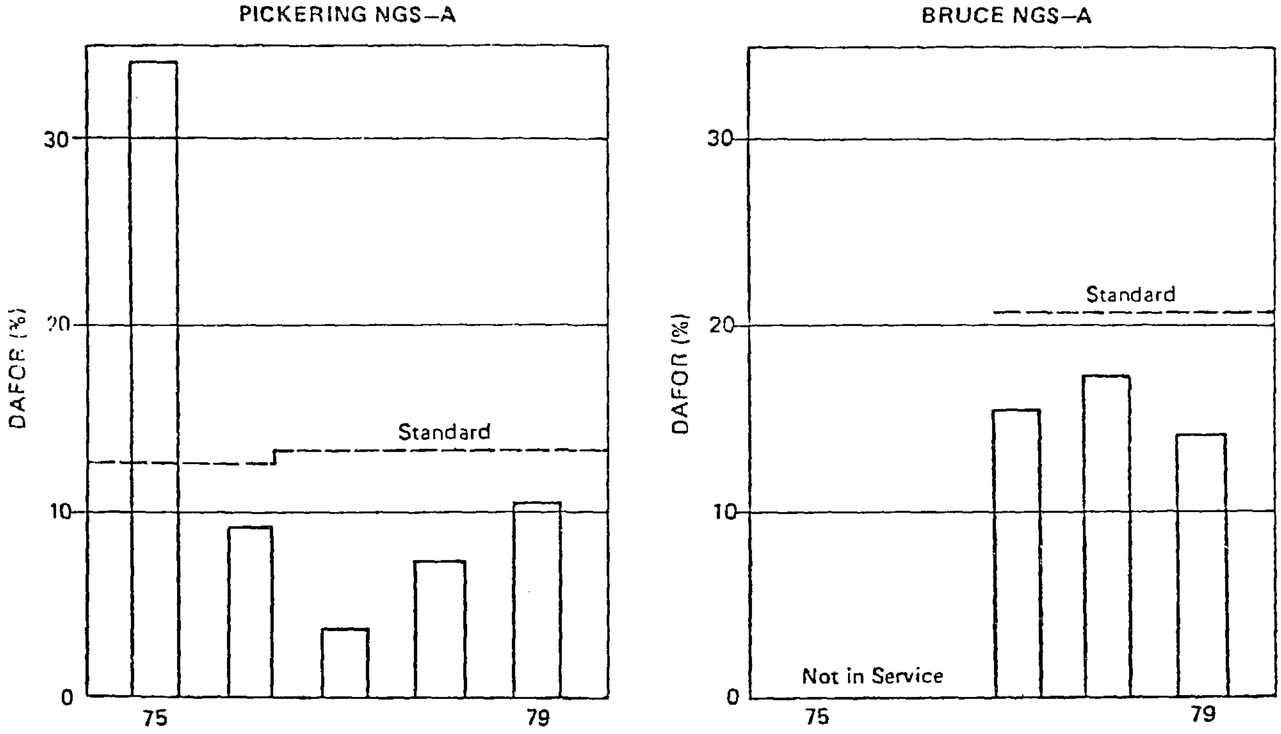
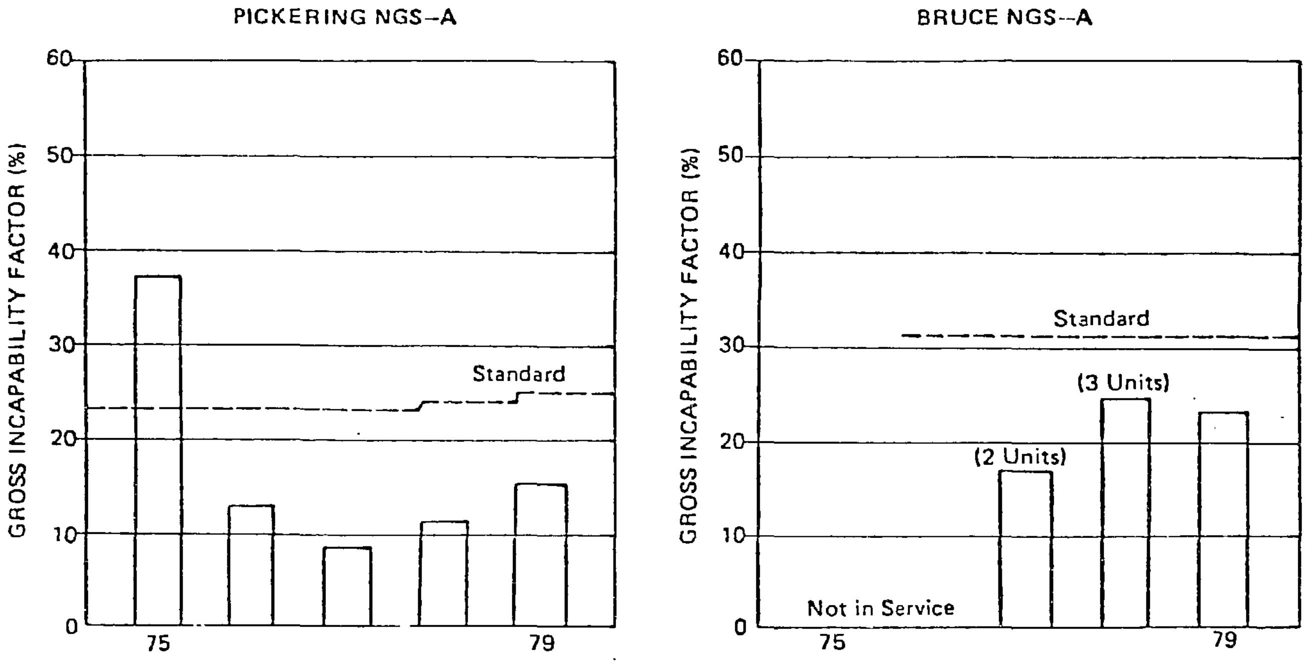


Figure A4-3

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 104 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

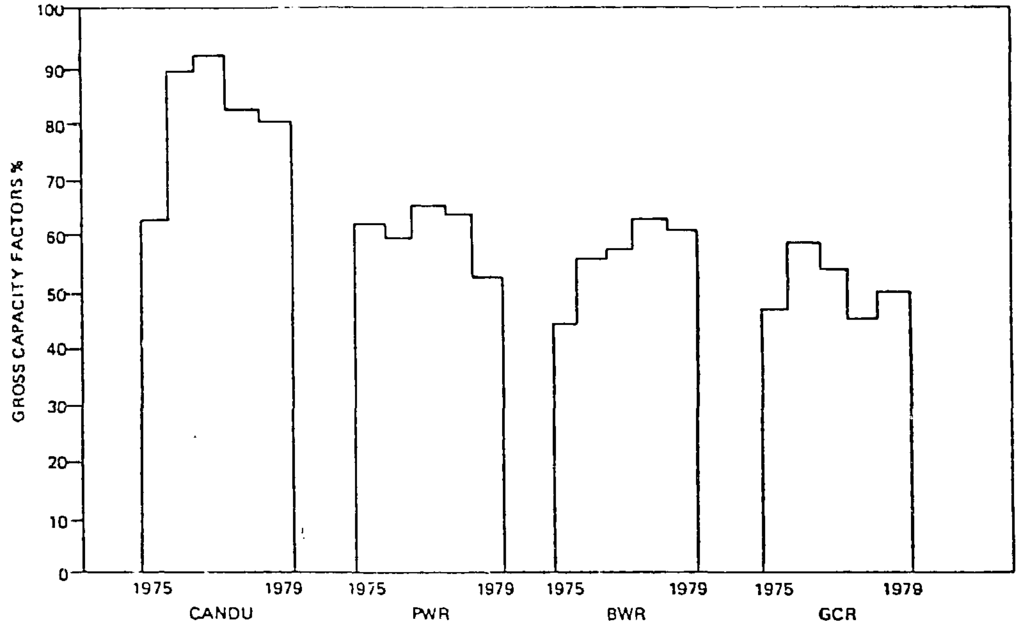
Capacity Factor Performance

	Gross Capacity Factor		
Station	Unit	1979	Lifetime
Pickering	1	84	83
	2	85	85
	3	80	78
	4	90	78
Bruce	1	77	70
	2	68	61
	3	74	78
	4	81	79

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

Figure A4-4

Comparison of Capacity Factors With Other
Commercial Reactor Types Larger Than 500 MW e



1975–77 Includes Pickering
1978–79 Includes Pickering and Bruce

The reliability of components within the Ontario Hydro CANDU stations are available. Some data for components is presented in Part B of this presentation.

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 fuelling 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 in the context of Ontario Hydro for which hydro-electric resources have been almost fully developed and for which coal must be transported a minimum of 800 kilometres. There are other locations in Canada in which coal-fired generation is cheaper than CANDU-PHW where the generating unit is near the mine.

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

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) consistent with achievement of acceptable standards of worker safety, public safety, environmental emissions, and reliability.

Definition - Total Unit Energy Cost

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

Cost Components

There are four cost components for a CANDU-PHW station and three cost components for a coal-fired station.

CANDU-PHW Cost Components

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

Coal-Fired Thermal Cost Components

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

Annual Interest and Depreciation Cost

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

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

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

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 Inventories
5. Overheads (including taxes)

Annual Fuelling Cost

The Annual Fuelling Cost includes:

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

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 - 1979

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

For the year 1979, Pickering NGS-A had a Gross Capacity Factor of 84.6%. Table A5-1 illustrates the Unit Energy Cost (UEC) of these two stations.

Table A5-1

Pickering/Lambton Cost Comparison - 1979

Gross Capacity Factor: 84.6%*

	UEC m$/kW.h	
	Pickering NGS	Lambton TGS
Interest and Depreciation	5.86	1.87
Operation, Maintenance, and Administration	2.84	1.55
Fuelling	1.73	15.95
Heavy Water Upkeep	0.47	-
Total Unit Energy Cost	10.90	19.37

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).
2. The base load cost (TUEC) of the more recent Bruce NGS-A (17.1 m$/kW.h) is higher than the Pickering NGS-A due to capital cost inflation. However, due to rapid inflation of coal fuelling cost, it is also very competitive.

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*Assumes Lambton also operated at base load with capacity factor of 84.6%.

PART B - EXPERIENCE

B0 INTRODUCTION

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

Another 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 and Bruce NGS-A is shown in Tables B0-1 and B0-2.

The Lifetime Capability and Incapability data given for Pickering NGS-A excludes the Incapability due to a four-month labour dispute in 1972 during which the three units then in service were not operated.

Table BO-1

Pickering NGS-A - Lifetime Incapability to December 31, 1979

Four Units
29.6 Unit Years

Capability Factor: 82%
Incapability Factor: 18%

Cause of Incapability	Incapability (%)
On-Power Fuelling	0.9
Fuel	0.1
Heat Transport Pumps	0.2
Pressure Tubes	6.2
Boilers	0.6
Turbine and Generators	6.5
Instrumentation and Control	0.8
Heat Exchangers	1.0
Valves	0.4
Other	1.8

Table BO-2

Bruce NGS-A - Lifetime Incapability to December 31, 1979

Four Units
7.5 Unit Years

Capability Factor: 77%
Incapability Factor: 23%

Cause of Incapability	Incapability (%)
On-Power Fuelling	1.0
Fuel	0.0
Heat Transport Pumps	0.2
Pressure Tubes	0.0
Boilers	3.5
Turbine and Generators	9.2
Instrumentation and Control	2.5
Heat Exchangers	0.0
Valves	0.0
Other	6.4

B1 ON-POWER FUELLING

On-power fuelling means that the nuclear fuel is replaced with the reactor producing full power. This has produced four major advantages:

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

2. Permits major outage scheduling independent of fuelling.

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

4. Allows on-power removal of defective fuel.

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

The on-power fuelling machines have required considerable development following the early operating problems. Today's designs, which are operating very reliably at Pickering and Bruce, 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 in which a fuelling machine becomes disabled, such as damaged seal plugs and seized internal components. The techniques and tooling have been demonstrated to overcome such problems, usually without shutting down the unit.

Results

Table B1-1 shows that Pickering and Bruce have successfully completed 17 500 channel fuelling operations at high power, exchanging a total of 133 100 fuel bundles.

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

Table B1-1

	Pickering NGS-A	Bruce NGS-A
Number of Channel Fuelling Operations	10 700	6 800
Number of Bundles Replaced	99 800	38 300
Bundles Still in Reactors	18 720	24 960

Table B1-2

Incapability Due to On-Power Fuelling Problems (%)

	Pickering NGS-A	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
Weighted Average	0.9	1.0

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 fuel bundle. This bundle is 0.5 metres long, 0.1 metres in diameter, and has 28 elements. Bruce NGS bundles are similar in dimensions with 37 slightly thinner elements.

A total of 182 000 fuel bundles had been irradiated in the Pickering and Bruce stations by the end of 1979. The performance of the fuel at both stations has been very satisfactory. The burnup when discharged at Pickering is 183 megawatt hours per kilogram of uranium; at Bruce it is 178 megawatt hours per kilogram of uranium.

At Pickering, the identified defective fuel bundles have been only 0.09% of the total, with 90% of the defects occurring in the first two years due to power increases during irradiation. Simple changes in control rod sequencing and fuelling schemes to reduce transient local power increases have virtually eliminated all of these defects.

Bruce has a lifetime defect rate of 0.15%, with most defects occurring due to early fuel manufacturing faults. However, improvements in manufacturing have resulted in a significant decrease in defect rate.

Table B2-1 shows the number of fuel bundles irradiated in Pickering NGS-A 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.

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

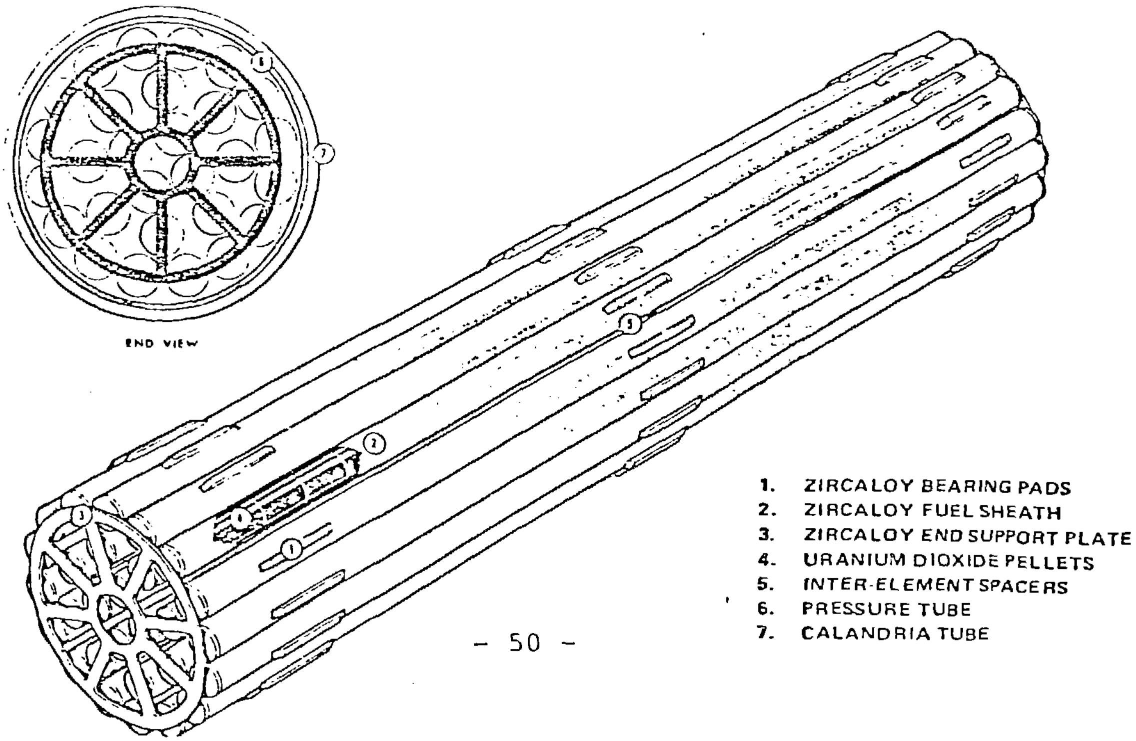
Table B2-1

Fuel Defect Experience

	Pickering NGS-A	Bruce NGS-A
Bundles Irradiated	118 520	63 260
Bundles Defective	111	95
Defect Rate (%)	0.09	0.15
Station Incapability (%)	0.1	0.0

Figure B2-1

Pickering Fuel Bundle (28-Element)



B3 HEAT TRANSPORT PUMPS

The heat transport pumps 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 units has 16 relatively small (1.4 MW) heavy water circulating pumps of which 12 are required for full power. These pumps have performed very well. Only one motor failure has occurred in approximately 390 pump motor operating years. Pump seal failures have occurred but the loss in energy production has been negligible. The random nature of these seal failures is currently under investigation.

The Bruce design uses four large (8.2 MW) heavy water circulating pumps per unit, all of which are required for full power. The pump performance, including seals, has been very good. However, four failures of the motor stator windings have occurred. This appears to be due to vibration caused by inadequate support of the end windings.

Approximately 50% of the motors are now equipped with improved end winding supports and heavier subconductor insulation. The remaining motors will be upgraded with the same improvements. Since there is no installed spare, the generating unit must be derated to about 65% of full power when one pump 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.

The excellent low Incapability caused by heat transport pumps at Pickering NGS-A and Bruce NGS-A is shown in Table B3-1.

Table B3-1

Incapability Due to Heat Transport Pumps (%)

	Pickering NGS-A	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
Weighted Average	0.2	0.2

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 1957, 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 fuelling.

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, programs were established in which pressure tubes were inspected. Although no pressure tubes had failed, two were removed 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 and at Pickering NGS-A.

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 72 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.

There has never been a rupture. Continued research indicates that the ductile pressure tube will leak long before break. Leaks are readily detectable.

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). The cracks were induced by high residual stresses near the rolled joint caused by the rolling process. The rolling process and joint design have been changed to eliminate the problem. No further leaks have occurred.

Dimensional Changes of Pressure Tubes

The dimensional changes of pressure tubes under neutron irradiation have been monitored for 18 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 design allowances are exceeded. Although this performance meets the original 1958 criteria, new development and design for tubes and reactors will increase their life to at least 20 years and probably 30 years.

Results

Table B4-1 shows Incapability at Pickering NGS-A and Bruce NGS-A.

Table B4-1

Incapability Due to Pressure Tubes (%)

	Pickering NGS-A	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
Weighted Average	6.2	0.0

B5 BOILERS (STEAM GENERATORS)

The two major concerns with regard to boilers are:

1. Would tubes fail causing reduction in capability and loss of heavy water?
2. Would tube heat transfer reduce 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.
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.

Simple techniques using fluorescent dye are used to identify the failed tube.

Canada has developed a remotely controlled eddy current device 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 isolated with explosively actuated plugs.

Although this presentation is dedicated to operating experience at the in-service stations (Pickering NGS-A and Bruce NGS-A), 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 are being replaced in accordance with new specifications and stress relieving procedure.

Each Pickering unit has approximately 31 000 Monel tubes located in 12 boilers. Only one tube on one unit has leaked, in 1974, which gives an outstanding example of trouble-free operation. This failure was due to a random manufacturing defect. Further inspection in 1979 of 77 tubes in the same boiler did not reveal any significant deterioration or defects.

There are approximately 34 000 Inconel-600 tubes in eight boilers at each Bruce unit.

In 1978, during the first year of operation of Unit 2, a tube leak was detected. The leak was so small that early positive location was difficult, but three tubes had defects which had started from the inside (heavy water side).

A total of 9 suspect tubes were isolated with explosive plugs. About 60 tubes were inspected with no indication of a chronic problem.

In the following year, a tube leak was detected in another boiler of the same unit. Eddy current inspection was performed which detected both the leaking tube and a defect in the adjacent tube. There were no indications of growing or similar defects in any of the surrounding or other tubes tested. This is believed to be an isolated failure. Both tubes were plugged using explosive plugs in the tubesheet.

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. One problem did occur in 1979 at NPD after 17 years of operation when the buildup of deposits on the outside surface of the boiler 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 and Bruce NGS-A boiler experience is shown in Table B5-1 in the form of Incapability.

Compared with world experience, the performance of the Bruce boilers has been good and the Pickering boilers excellent.

Table B5-1

Incapability Due to Boilers (%)

	Pickering NGS-A	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
Weighted Average	0.6	3.5

---

*Due to in-service inspection of boiler 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.

One major problem experienced at NPD 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.

The Incapability at Pickering NGS-A 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

Incapability Due to Turbines (%)

	Pickering NGS-A	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*
1989	1.2	4.7*
Weighted Average	2.7	4.8

---

*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.

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

Table B6-2

Incapability Due to Generators (%)

	Pickering NGS-A	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*
Weighted Average	3.8	4.4

---

*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 and Bruce, is shown in Table B7-1.

Table B7-1

Incapability Due to Instrumentation and Control (%)

	Pickering NGS-A	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
Weighted Average	0.8	2.5

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?

Pickering has experienced leaks in the heavy water moderator heat exchangers on three of its four units after approximately seven years of operation. These were indicated by an increase of tritium level in the lake water coolant, but the small sizes of the leaks made actual location difficult until improved location techniques were developed. These techniques (special eddy current probes) were used to identify leaks or wall thinning in several tubes of the moderator heat exchangers.

The damage was caused by fretting between the tubes and baffles where the lake water coolant enters the heat exchanger. Several tubes have been plugged and brass rods fitted between the rows of tubes in that region to reduce fretting.

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 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, 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. The short-term solution has included tube plugging and some changes in internal shrouding to limit hot spots. A modification to the ordinary water circuit is also proceeding which will use demineralized water to prevent scaling.

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.

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

Table B8-1

Incapability Due to Heat Exchangers (%)

	Pickering NGS-A	Bruce NGS-A
1971	0.0	
1972	0.0	
1973	0.0	
1974	0.5	
1975	0.0	
1976	0.1	
1977	0.3	0.0
1978	2.7	0.0
1979	4.0	0.0
Weighted Average	1.0	0.0

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, and
    - (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 and maintained 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 and Bruce NGS-A.

Table B9-1

Incapability Due to Valves (%)

	Pickering NGS-A	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
Weighted Average	0.4	0.0

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 (9.2 mega Pascals 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 about 99.7 mass percent heavy water.

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

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. Provide a secondary enclosure - leaks go into rooms with a sealed floor, closed circuit ventilation, tight doors, etc.
3. Provide closed circuit vapour and liquid recovery circuits on the secondary enclosures so that the escaped heavy water does not become a loss.
4. Minimize the number of ordinary water circuits in the secondary enclosures and minimize the 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 and Bruce NGS-A, the Heavy Water Upkeep Unit Energy Costs are only about 4% of Total Unit Energy Costs. The 1979 performance is shown in Table B10-1.

Table B10-1

1979 Heavy Water Upkeep Costs

	Pickering NGS-A	Bruce NGS-A
Total Unit Energy Cost (m$ per kW.h)	10.9	17.1
Heavy Water Upkeep Unit Energy Cost (m$ per kW.h)	0.47	0.67
% of TUEC	4.3%	3.9%

Minimizing Radiation Exposure

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

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.

B11 RADIATION DOSE

Atomic Energy Control Board 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 B11-1 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 has considerably improved over its early performance.

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

The average radiation dose in 1979 was 0.9 rem per worker at Pickering NGS-A and 0.5 rem per worker at Bruce NGS-A.

Table B11-1

Radiation Dose Experience
(Rem Per Megawatt-Year)

	NPD NGS	Douglas Point NGS	Pickering NGS-A	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

B12 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 <u>operation</u> of generating stations.

Specifically, this systematic method was conceived and introduced by Ontario Hydro Operations at Canada's first nuclear generating station, the Nuclear Power Demonstration Station, NPD. The method was subsequently adopted and expanded by the Atomic Energy Control Board (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 or be impaired.

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:

   (a) Detect and Identify Failures

   (b) Classify Failures

   (c) Take Short-Term Corrective Action

   (d) 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, 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 Atomic Energy Control Board 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:

Single Event Risk - 1 rem/annum

Dual Event Risk - 0.25 rem/annum

The Dual Event Risk is the most restrictive and is equivalent to the standard which we have adopted that 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 one 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)

The 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 given always to maintaining 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 were six 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 if process system limits are not always met, have been perfect except for two impairments which existed during a long shutdown of one unit; however, these systems easily met impairment 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 during the station lifetime due to a single marginal impairment.

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 detail comparison of process and safety system performance versus target is shown in Table B12-1.

Table B12-1

Pickering NGS-A Result Comparison (Lifetime)

System Versus Targets

	Target	Results Frequency	Results Impairment Time	Results Inoperability
Process Systems				
Regulating (LOR)	0.01/a	0.2/a		
Heat Transport (LOC)	0.001/a	0/a		
Safety Systems				
Shutdown	0.3%		0.05%	0%
ECI	0.3%		15.0%	0.2%
Containment	0.3%		6.0%	0%

Risk Versus AECB Criteria

	Criteria	Result
Actual Single Failure	1.0 rem/a	0 rem/a
Actual Dual Failure	0.25 rem/a	0 rem/a
Predicted Potential Single Failure	1.0 rem/a	0.0002 rem/a
Predicted Potential Dual Failure	0.25 rem/a	0.026 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 serious 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.

B13 STAFFING AND TRAINING

Major Classifications

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

The four major classifications of staff at the CANDU-PHW generating stations are as follows:

1. Management and Professional Staff
2. Operators
3. Mechanical Maintainers
4. Control Maintainers

The Management and Professional Staff (managers, engineers, scientists, etc) oversee and supervise the overall station programs as well as the work on each shift.

The Operators are general practitioners who perform:

1. The hands on operations (startup, shutdown, change power, etc).
2. The tests to determine that the systems and equipment conform to specifications.
3. Isolations to prepare equipment for maintenance.
4. Return to service of repaired equipment.

The Mechanical Maintainers perform mechanical maintenance work using fitting, machining, and welding skills.

The Control Maintainers perform electrical, control, and instrumentation maintenance.

In addition to the four major classifications noted above, there are a number of specialist and support categories of workers such as planning technicians, radiation control technicians, chemical control technicians, security guards, handymen, clerks, typists, etc.

Staffing Requirements

As a typical example, the four-unit Pickering NGS-A with a capacity of 2 060 MW e has a staff of approximately 600 persons. The organization chart and staff complement for Pickering NGS-A are illustrated in Figure B13-1.

Approximately 72% of the station staff are shift workers in the Production Section who operate, maintain, and fuel the generating units on a 24 hours 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 the 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 the staff be carefully selected, properly trained, and properly managed to ensure that the station operates safely and efficiently.

Training Programs

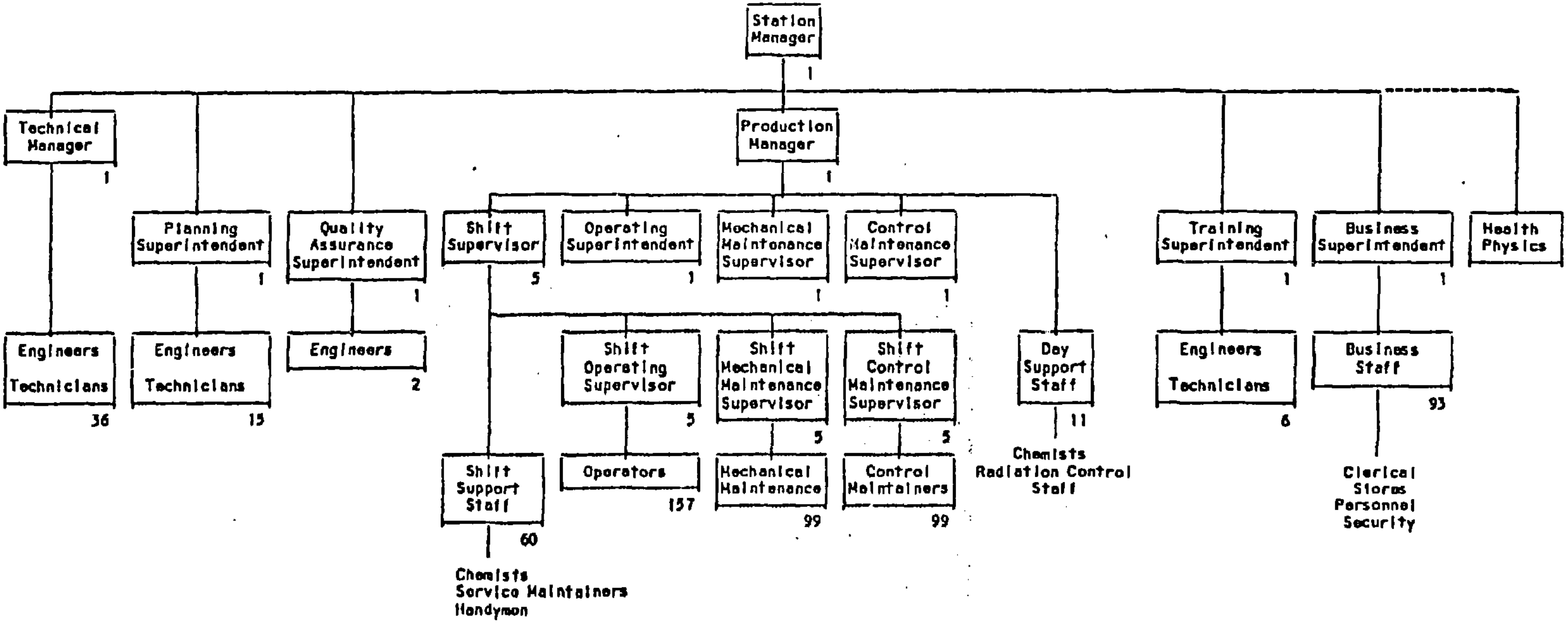
A comprehensive training program has been developed for all the major classifications noted above and for the vital support classifications.

Training Simulators

Ontario Hydro has had one training simulator in operation for Pickering NGS-A since 1976. Training simulators for Pickering NGS-B, Bruce NGS-A, Bruce NGS-B, and Darlington are being obtained.

FIGURE B13–1

PICKERING NGS–A ORGANIZATION



Station Staff

	By Function		By Organization	
	Management and Professional	77	Station Manager	1
Shift Staff - 5 shifts	Operators	157	Technical	37
	Control Maintainers	99	Planning	16
	Mechanical Maintainers	99	Quality Assurance	3
	Specialists and Support Staff	176	Production	450
			Training	7
		608	Business	94
				608

PART C - OVERALL HIGHLIGHTS

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

1. The CANDU-PHW program is based upon 38 years of heavy water reactor experience with 35 years of operating experience.
2. Canada has had 72 reactor years of nuclear-electric operations experience with 10 nuclear units in 4 generating stations during a period of 18 years.
3. All objectives have been met with outstanding performance: worker safety, public safety, environmental emissions, reliable electricity production, and low electricity cost.
4. 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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