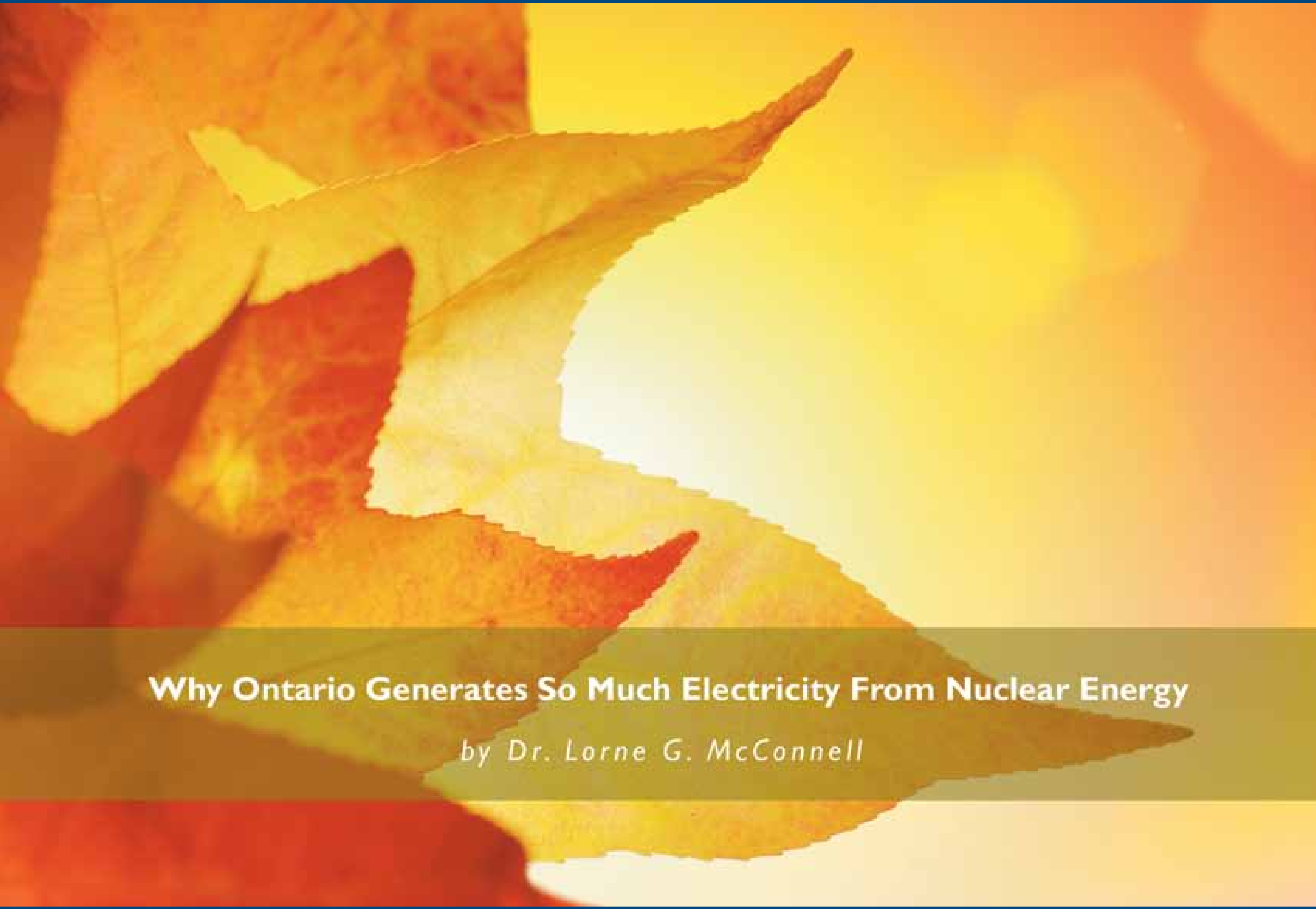

Why Ontario Generates So Much Electricity From Nuclear Energy

by Dr. Lorne G. McConnell

Former employee of: Defence Industries Limited (1945 to 1948) • National Research Council (1948 to 1952) • Atomic Energy of Canada (1952 to 1955) • Ontario Hydro (1955 to 1989)

Acknowledgements

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Why Ontario Generates So Much Electricity From Nuclear Energy

By Lorne McConnell

Purpose of this Paper

From 1906 to 1952, most of Ontario's electricity requirements were met by converting hydro energy into electricity. From 1952 to 2010, the amount of hydro energy converted into electricity continued to grow slowly because additional sources of hydro energy were limited. However, from 1906 until today there has been a huge increase in demand for electricity coinciding with population growth and increasing uses for electricity in Ontario's domestic, commercial, industrial and transportation sectors.

In 2009, electricity generation by type in Ontario was: 55.2% from nuclear energy; 25.5% from hydro energy; 6.6% from coal; 10.3% from oil and gas; and 2.4% from other sources.

Nuclear energy provides about 16% of the world's electricity supply. This paper reviews highlights of why Ontario now generates so much electricity (55%) from nuclear energy as compared with the world (16%).

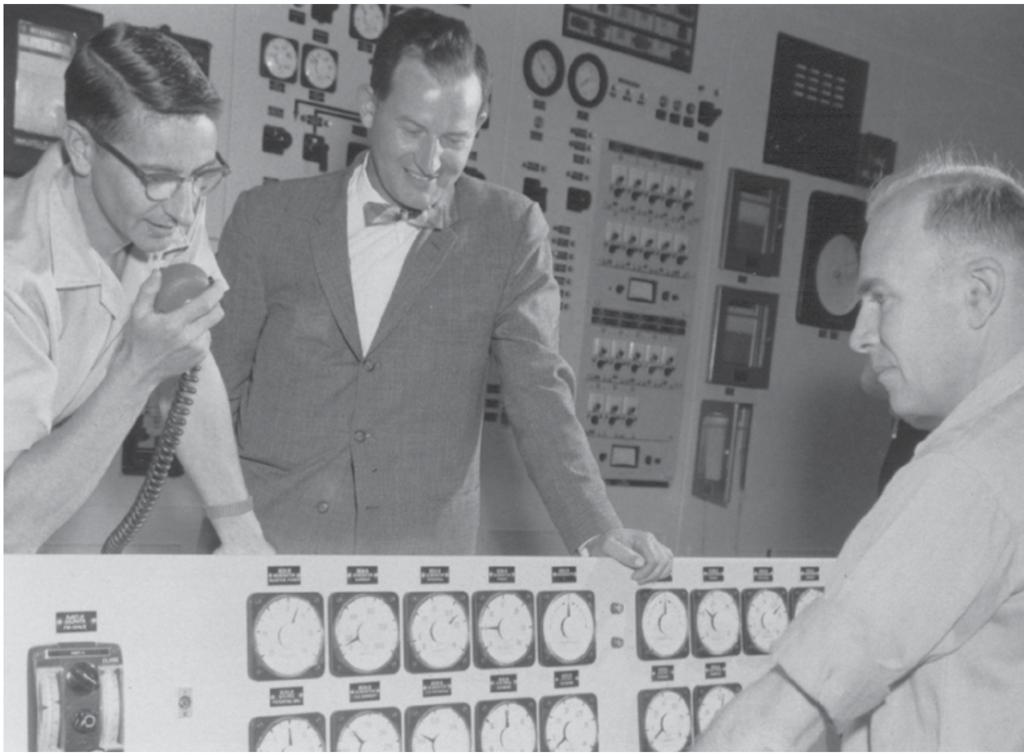
This paper first presents:

(A) Some Energy Basics;
(B) Ontario Hydro Overview.

This paper then looks at nuclear development in Canada during three time periods:

(C) The Nuclear Technology Foundation Period from 1942 to 1952;
(D) The Three-Step Development of Nuclear-Electric Generating Units in Ontario from 1952 to 1977; and
(E) Ontario Hydro Commercial Nuclear-Electric Generating Stations in Ontario after the First Commercial Pickering A Nuclear-Electric Generating Station.
(F) Conclusions — Hindsight View from 1989;

Important Canadian development and commercial nuclear activities in Quebec, New Brunswick, Manitoba and overseas between 1952 and today are not presented in this paper.



First Electricity In Canada from Nuclear Energy – NPD2 at Rolphton, Ontario – June 4, 1962 – Left to right: Bill Lawson (Shift Supervisor), Lorne McConnell (Station Superintendent) and Allan McCarthy (First Operator).

(A) Some Energy Basics

Introduction

Before discussing the early development of nuclear-electric generation in Canada with emphasis on Ontario, I propose to briefly review the following energy basics:

- the uses of energy;
- factors influencing energy consumption;
- energy forms: primary and secondary;
- primary energy resources;
- every energy option has advantages and disadvantages;
- electricity resources;
- energy objectives; and
- energy decisions.

The uses of energy

People use energy to help meet their needs and wants. Examples of people's needs are home heating in winter, water, food, clothing and health.

In addition to needs, people also want energy for comfort, education and enjoyment. Examples of people's wants are keeping homes cool in the summer, providing heat and light in schools and universities, and transporting families in cars to and from their cottages on weekends.

People use a large amount of energy directly to heat their homes, cool their homes, heat water and power their personal cars. However, people typically use a much greater amount to meet their needs and wants through commerce, industry and transportation such as mining, manufacturing, agriculture, fishing, forestry, garbage disposal, transportation, recycling of material, banks, stores, hotels, summer resorts, roads and parks. Assembly lines in manufacturing plants use electricity-powered devices extensively to provide maximum flexibility and minimize cost as designs change.

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World energy consumption is often divided into four end-use energy sectors: residential (about 15% of world energy consumption in 2006), commercial, industrial and transportation (moving people and goods: cars, trucks, buses, subways, trains, ships, airplanes).

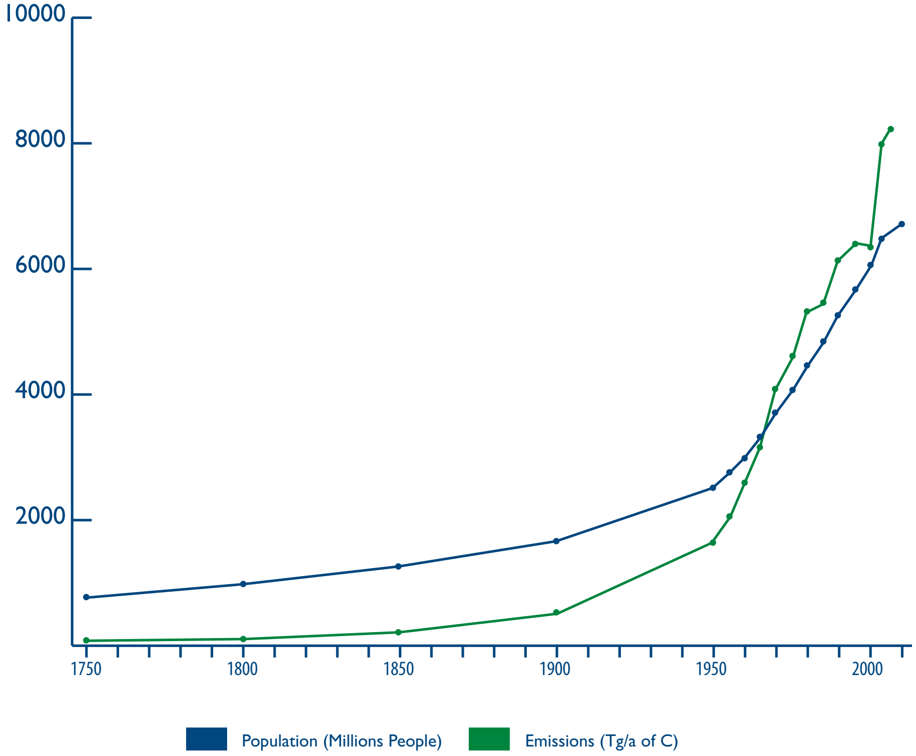
Factors influencing energy consumption

The following are major factors that have caused the actual total amount of energy consumed in any country or region and in the whole world to increase or decrease:

- Since the beginning of the Industrial Revolution there has been a dramatic increase in the population of the world. For example, the world population has increased from 0.79 billion people in 1750 to 6.71 billion people in 2008, corresponding to an increase by a factor of 8.5.
- Since the beginning of the Industrial Revolution there has also been a dramatic increase in the amount of energy consumed per person as people have struggled to increase their standard of living through education, research, creativity, high productivity, high employment, etc. The average annual fossil fuel consumption is now typically 1.05 Mg per person per annum of carbon and has not changed dramatically in the past 10 years. However, the total carbon dioxide emissions continued to rise as the world population increased. In the year 2008, the world consumed about 474 exajoules of energy for which about 80% to 90% was derived from fossil fuels. Figure G3 compares the global emissions of carbon and the world population from the beginning of the industrial revelation until now.
- The amount of energy required (needs plus wants) by people can be reduced by using energy more wisely, such as by: improving efficiency; innovation; cutting waste; and doing without.

Figure G3

The Growth of World Population and the Growth of Annual Emission of Carbon Between 1750 and 2008



World Emissions of Carbon Dioxide into the atmosphere is normally measured as Teragrams per Annum of C (Tg/a)

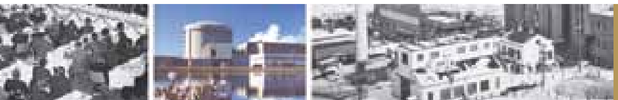
Source: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, and United Nations Population Division.

Dramatic improvements were made in improving energy efficiency between 1900 and 1950. In the case of electricity use, industry and commerce motors exceeded 90% efficiency and fluorescent lighting was developed before 1950. Important improvements in energy efficiency continued after 1950 and future efficiency improvements can be expected. Competition, education and cost reduction have been the three primary methods for motivating the four end-use energy sectors to implement and sustain efficiency improvements. Government regulations and subsidies have also contributed to efficiency improvements. Voluntary cutting of energy waste and doing without energy has also been achieved through research, competition, education and cost reduction.

In many cases, waste versus want depends upon the eye of the beholder. Consider the following three examples: Throughout the world, sports events occur daily in which 10,000 to 100,000 people go to a stadium or arena, often in their personal cars. In Ontario, many families use gasoline to drive their cars to and from their cottage or ski chalet on weekends. Many people in Ontario take vacations to other parts of the world in jet-propelled airplanes. Are these three examples of unjustified energy waste or justified people enjoyment?

Energy forms: primary and secondary

Down through the centuries, people have used wood, oil, gas, coal, wind, hydro (water), etc. to meet their energy needs. These forms of energy



Darlington NGS

are called primary forms of energy. Primary forms of energy may be used directly by people. But these forms of energy may also be converted into other forms of energy before they are used by people. For example, during the 1800s people used water (hydro) to produce mechanical energy, which in turn was used to grind wheat to make flour. This mechanical energy is called a secondary form of energy. Similarly windmills were used to convert wind energy into mechanical energy, which in turn was used to pump water to meet people's needs.

Electricity is not a primary energy. All electrical energy is produced by converting various forms of primary energy into electricity.

Electricity has a low environmental impact at the point it is utilized. When electricity is consumed, the impact on the environment primarily depends upon the emissions into the environment at the point where the electricity was produced from primary energy.

Electricity is a highly versatile form of secondary energy. When electricity was first developed, electric lighting accounted for a major part of the energy consumed. Today there are so many uses for electricity that lighting no longer accounts for the majority of the energy consumed.

The fossil fuels (coal, oil, natural gas) are a chemical form of energy. They are considered to be a primary form of energy because they exist in nature on this planet. These fossil fuels can be burned to produce heat energy. In this case, the carbon and hydrogen in the fossil fuels combine with the oxygen in the atmosphere to produce carbon dioxide, water and heat. The heat produced is considered a secondary form of energy. Heat can in turn be converted into electrical energy.

The production of hydrogen is another example of secondary energy. Although a great deal of research and development has taken place, this option has not yet emerged as a major contributor to meeting people's needs and wants.

Although major progress has been made in technology associated with energy, the only major new primary energy option that has emerged commercially during the past 1,000 years is the option of nuclear fission. Although most energy used in the world today comes from nuclear fusion on our sun, the commercial availability of primary energy from nuclear fusion on our planet will probably take two or more decades to achieve.

Why Ontario Generates So Much Electricity From Nuclear Energy

Continued from page 5

Pickering A and B complete

Primary energy resources

The following are the world's current most important primary energy resources. They are the most important because they are the current major contributors plus promising future contributors. They are divided into three categories. The current six major energy resources are marked with an asterisk (*). The energy usage is for 2008.

- Fossil energy resources (85%): coal* (25%); oil* (37%); gas* (23%)
- Nuclear energy resources (6%): nuclear fission (uranium)* (6%); nuclear fusion (hydrogen) (0%)
- Renewable energy resources (7.5%): solar (radiant energy from the sun) (0.04%); wind (kinetic energy) (0.3%); wave and tidal (kinetic energy) (0%); geothermal (0.2%); biomass (wood, waste)* (4%); hydro* (3%)

The fossil energy resources (coal, oil and gas) were created and stored by nature millions of years ago, using solar radiation from the sun. Solar radiation from the sun is derived from the nuclear fusion of hydrogen and helium in the sun.

The nuclear energy resources (fission and fusion) exist in nature. Nuclear fission using uranium fuel is a recent commercial technology used to produce electricity. Nuclear fusion using hydrogen isotopes is not yet commercially available. Although not renewable, it is available without limits.

The renewable energy resources are attractive because of their long-term sustainability. Renewable energy (excluding geothermal and tidal) is direct radiation from the sun (solar) or radiation energy from the sun converted into other forms (wind, wave, biomass and hydro). Tidal energy derives from the mass attraction between the Earth and the moon and sun.

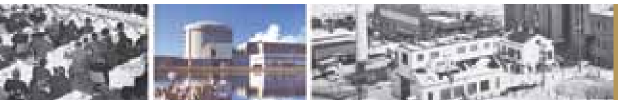
Every energy option has advantages and disadvantages

Each of the above resources has advantages and disadvantages. For example, the high energy density of oil and oil derivatives, such as gasoline and diesel fuel, at normal temperatures and pressure makes oil very attractive for the transportation sector (cars, trucks, trains, ships, airplanes). The major disadvantage of oil is the negative environmental impact of emissions of carbon dioxide and nitrous oxides when it is burned to produce energy. Also, for example, renewable wind energy has the major advantage of being sustainable, but has the disadvantages of low energy density and low dependability (low capacity factor), which limits its cost competitiveness.

Electricity resources

In 2010, most of the electricity energy in the world, including North America, is produced from chemical energy utilizing coal, oil and natural gas. If electricity used to power public transportation such as subways or streetcars, or private automobiles, is produced by burning coal or oil or gas, the atmosphere is still being polluted with carbon dioxide and other combustion products such as sulphur dioxides and nitrous oxides. However, in Canada and Ontario about 75% of the electricity is produced in hydro-electric and nuclear-electric generating stations with no emissions of carbon dioxide or nitrous oxides.

Hydro energy includes (a) potential energy in the form of elevated water (dams); and (b) kinetic energy in the form of running water (run of the river). When the water in dams falls, the potential energy is converted into kinetic energy. The kinetic energy of running or falling water can be converted into electricity using a hydro turbine-generator. If we then use this electricity to power subways, streetcars or automobiles, we will not be polluting our atmosphere with carbon dioxide and other combustion products. However, some people do oppose the use of hydro energy because they believe the negative effects are too great, such as the flooding of agricultural land, the loss of beautiful waterfalls, interference with fishing or other similar objections. Although most energy used in North America is from fossil fuels (coal, oil and gas), hydro energy is an important contributor to energy needs in both the United States and Canada. In Canada, hydro energy is particularly important in Quebec,



Ontario, British Columbia, Manitoba and Newfoundland and Labrador.

Fossil energy (coal, oil and gas) was originally derived from radiant energy from the sun and hydro energy is today derived from the radiant energy from the sun (evaporation of water followed by rain). This radiant energy was in turn produced from nuclear fusion energy on the sun. Other forms of primary energy produced by the radiant energy from the sun are: the kinetic energy in ocean waves, the kinetic energy of wind and the direct use of the radiant energy from the sun (solar energy). In the past, the wind energy was extensively used by people for transportation (sailing ships) and water pumps (windmills). Solar energy, wind energy and tidal energy are often referred to as forms of "renewable energy." However, the production of economic, competitive electricity from solar energy, wind energy and tidal energy is very challenging because of the inherent low-energy density that tends to result in high initial capital cost and high land use. The variability of the wind (calm to storm) is also a challenging characteristic. At present only hydro energy is a major renewable contributor to electricity supply. Nevertheless, renewable energy other than hydro energy, such as wind energy, is expected to make important contributions to future energy requirements. In spite of major technology advances during the past 250 years, very few advances have been made in respect to new resources of primary energy. One exception is the development of nuclear energy during the last century (1900 to 2000). As with all other forms of energy, nuclear energy (fission), which burns uranium, has its pros and cons. Many people have concerns relating to the radioactivity produced from nuclear fission.

Energy objectives

During the past 250 years there has been tremendous progress in advancing the technology of all of the energy options, which in turn has advanced the use of energy to meet the needs and wants of people.

Douglas Point was the full scale prototype of the CANDU reactor system

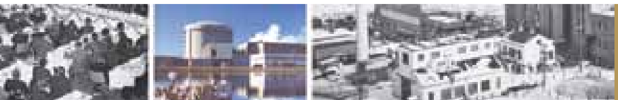
Why Ontario Generates So Much Electricity From Nuclear Energy

Continued from page 7

Pickering A and Rouge River Park

The five most fundamental criteria in evaluating and choosing energy options are:

- **Cost:** What is the delivered energy cost to the energy consumer for each energy option? In the case of electricity, two cost units are important in Canada. The energy cost is measured in cents per kilowatt hour and the capacity cost is measured in dollars per kilowatt. For each energy option, the cost is not a single fixed number, but depends on many factors. For example, the intensity of renewable solar energy is much greater and is more economic near the Equator than in Canada. On the other hand, Canada has enjoyed extensive renewable hydro energy. The province of Ontario has very little economic indigenous fossil fuels (coal, oil and gas). Coal burned in Ontario that is transported from the Maritime provinces or Western Canada is expensive because of the high transportation cost. Coal burned in Ontario from the United States has a much lower cost, but all of the economic benefits (jobs) are gained in the U.S. rather than Canada. Canada has extensive amounts of low-cost uranium. However, in Ontario the capital cost (dollars per kilowatt) of renewable hydro energy and nuclear energy is high, which requires large initial investments.
- **Reliability:** People depend on energy. Is the energy available most of the time with the quality expected? The key measures are capacity factor, capability factor and forced outage rates.
- **Employee safety:** Are the people engaged in the production and utilization of energy acceptably safe (minimum adverse effects such as death, injury, deterioration of health)? Although an annual rate of zero injuries is ideal, an industry may be considered good when the risk of injury at work is 10 times safer than when not at work.



- **Public safety:** Are the members of the public near the production of the energy or utilizing of the energy acceptably safe (minimum adverse effects such as death, injury)?
- **Environmental protection:** Does the energy have an acceptable impact on the general public and biosphere regarding (a) adverse health effects, (b) excessive use of valuable land, (c) adverse degradation of appearance, (d) adverse effect on climate, and (e) increased flooding of land, etc.

Every one of these is a vital objective. For example, the global, regional and local consequences of adverse environmental effects are extremely serious. Similarly, any country that ignores cost will suffer the consequences of increased poverty, increased unemployment, reduced health services and a reduced standard of living.

The following is suggested as a good overall energy objective: Achieve the lowest cost consistent with acceptable reliability, employee safety, public safety and environmental protection; meet all regulatory requirements; and maximize Canadian benefits.

If minimizing consumer cost is in conflict with maximizing Canadian benefit, the authorities will have to make the compromise decision.

Energy decisions

The above five objectives are very important in making energy decisions. There are other important considerations (both rational and irrational) that influence energy decisions. A few examples of social and other considerations that may influence decisions are:

- If a country or region is well endowed with a resource such as coal, oil, gas or hydro, the people in that region may favour the use of the indigenous resource. Whether or not it is the lowest cost or has serious adverse consequences, it will create jobs and enhance the economy of the local community, region or country.

MDS Nordion

Continued from page 9

Wolsong 1 under construction

- The geography of the resource may influence the costs of an energy option. For example, solar energy will be more competitive if close to the Equator because the energy intensity is higher. Fuel such as coal will be cheaper if close to the point of use because of high transportation costs. Fuels may be cheaper if water transport is available. Wind energy will be more competitive in windy locations. A resource such as hydro will be less competitive if located a long distance from consumers because of the capital cost of the transmission lines and the cost of transmission energy loss.
- Public opinion, whether or not the opinion is well founded, will continue to influence energy decisions.
- Political ambitions, the vested interest of corporations (often to obtain or oppose project approvals) and special interest groups, or SIGs (often to oppose or support proposed projects), may contribute to rational or irrational energy decisions or contribute to costly delays.
- Energy independence is a powerful factor for many countries because energy is so vital to every country. Energy independence enhances job security and military strength. Canada has been, and continues to be, one of the most energy independent countries in the world.

(B) Ontario Hydro Overview

Purpose

Sir Adam Beck, an Ontario politician, was of the view that politicians knew little about managing energy and therefore energy should be managed by dedicated professional staff. However, he also felt strongly that the water resources in Ontario should be free and developed for the public good. In 1906, under the leadership of Sir Adam Beck the Ontario government created the Hydro-Electric Power Commission of Ontario to manage and provide the province's electricity supply, assuming the extensive hydro resources such as Niagara Falls would be developed to meet the electrical needs of Ontario at low cost. This organization was commonly called "Ontario Hydro." Although Ontario Hydro was a public organization and subject to policy direction from the Ontario government, it was constituted to minimize political interference in its operations. Proposals to meet future needs were carefully reviewed by the commission, which included a chairman and experienced commissioners. Distribution of electricity was through a large number of municipal utilities not managed by Ontario Hydro. Major installations in Ontario Hydro did require the approval of the Ontario government.

Ontario Hydro met most of the electrical needs in Ontario during the period from 1906 to 1999.

Ontario Hydro was essentially taken over by the Ontario Government in 1990. In 1993, the design and construction capability of Ontario Hydro was dismantled. In 1999, Ontario Hydro was terminated by the Ontario Government and replaced by successor organizations.

Financing

Some key highlights of Ontario Hydro between 1906 and 1996 were:

- It was not subsidized by Ontario taxpayers. In fact, Ontario Hydro was required to subsidize Ontario taxpayers through water rentals.
- Electricity was delivered to Ontario municipalities at a price equal to cost.
- Ontario Hydro paid grants in lieu of taxes to municipalities for Ontario Hydro facilities located in each municipality.
- Ontario Hydro did not have "deficits." The electricity rates each year were set to recover all costs. Deficits occur when the revenues are lower than costs. The federal government and the Ontario government ran "cumulative deficits," but Ontario Hydro did not have "cumulative deficits." Debt financing of new assets is common to most public utilities throughout the world.
- Ontario Hydro was regularly audited to ensure it was being managed financially in accordance with its constitution, established by the Ontario government.
- Rainfall each year was variable, which affected the amount of hydro-electric energy available. A rate stabilization fund was created to smooth customer rates from year to year.
- Ontario Hydro was always financially sound and it maintained a financially sound debt ratio of about 80% (total debt divided by total assets). This debt ratio was better than most of the public electrical utilities in other provinces of Canada.
- Ontario was required by law to finance new installations by bonds (debt). After each new installation was placed in service, the debt was retired (interest and depreciation) as part of the consumer cost.
- Ontario Hydro was a key manager of electricity supply in Ontario. Not commonly understood by the media or the public, most of the expenditures (typically over 70%) were spent through competitive private enterprise. With no exceptions, all of the fuel (oil, gas, coal, uranium) was provided by private enterprise. With few exceptions, all of the manufacturing of components required for electricity generation, transmission and distribution of electricity was

Qinshan under construction

Continued from page 11

CEGB – test collision with transport cask

provided by competitive private enterprise. The main public enterprise expenditures were operations and maintenance staff (not material), energy research, project management, construction management and part of the design requirements.

Note: Technological progress (wireless cell phones, microwave, satellites, etc.) has permitted increased communications competition (telephones, radio, television, Internet, etc.). In the case of electricity supply to consumers, no technology exists and it is doubtful that any technology will become available in the next few decades that will allow the consumer to receive alternative competing electricity supplies (all electricity transmission and distribution remains hard wired). With respect to electricity generation, the people of Ontario benefited from the low-cost electricity achieved through having few generating stations, which contained large generating units.

- Ontario Hydro was responsible for the main high-voltage transmission while most (but not all) retail distribution was the responsibility of local municipal utilities.

Research
Ontario Hydro had a research division with three purposes: to seek long-term improvement in electrical demand and supply; to support design and construction for new installations; and to support operations and maintenance in problem solving.

The costs of research were included in Ontario Hydro rates. Profits arising from research performed for other utilities (primarily U.S.) reduced Ontario Hydro research costs. Ontario research expenditures typically constituted about 2% to 3% of the total customer electricity cost. However, the net cost of the research division was negative because the problem-solving service lowered the cost of operations and maintenance, and the capital cost of new facilities.

Major electricity cost components
The three major consumer cost components were interest and depreciation on capital (bond debt); operations and maintenance; and fuel costs (coal, oil, gas, uranium, water rental, etc.).

For planning and decision purposes, costs include the full life cycle costs for all options such as (a) capital modifications (b) retubing of fossil and nuclear plants (c) decommissioning of old plants; (d) transportation and disposal of ashes from coal fired stations; (e) transportation, temporary storage, and final repository for spent nuclear fuel; and (f) corporate overheads such as accounting, legal costs, and power system planning.

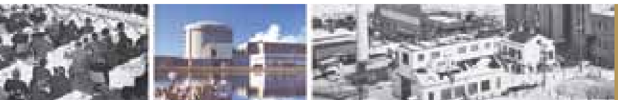
Dedicated power system operations ensured that generating stations were operated to minimize total costs and ensure reliable supply; electricity was purchased from other electrical utilities to minimize total costs; and electricity was sold to other electrical utilities to minimize costs.

Emissions from fossil-electric generation
Ontario Hydro shut down fossil plants when required because of adverse meteorological conditions to ensure that Ontario Hydro fossil stations had a low impact on the environment at ground level. In Ontario, Ontario Hydro made a very low contribution to emissions of particulates, sulphur dioxide and nitrous oxides at ground level. For example, in Toronto the major ground-level contributions of these emissions are caused by cars, trucks, trains, homes and some industries.

Since 1980, Ontario Hydro was aware of growing concerns about carbon dioxide emissions. Also in 1980, Ontario Hydro was a low emitter of carbon dioxide due to the zero emissions from the hydro and nuclear generation of electricity.

The 25-year plan for the period 1990 to 2015 specifically outlined plans to further reduce carbon dioxide emissions through additional renewable and nuclear generation. Due to the 1990 major recession, the takeover of Ontario Hydro by the Province of Ontario in1990, and the subsequent termination of Ontario Hydro in 1999, this 25 year plan was never implemented.

Ontario Hydro: 1906 to 1952
During the period from 1906 to 1952, most of the Ontario electricity needs were met by hydro-electric generation. The cost of electricity from hydro-electric generation in Ontario was lower than the average cost of electricity in the United States. Although the U.S. also had major hydro-electric generation,



American needs were primarily met through thermal-electric generation by burning coal, oil and gas. Low-cost hydro-electric generation was of vital importance in helping the expansion of commerce and industry in Ontario. During the Second World War, the expansion of electric generation was limited and so at the end of the war there was a need to build more generation. Although, more economic hydro-generation was available, it became clear that Ontario would have to turn to other sources to meet its future needs. At that time, the carbon dioxide emissions (global greenhouse gas emissions) were not an issue.

After the war, Richard L. Hearn was the Chief Engineer at Ontario Hydro. Hearn knew that the only major commercially available option to hydro-electric generation was to build thermal generating stations using coal, oil or gas fuels. However, Ontario did not possess any major low-cost, indigenous coal, oil or gas. The prospects for finding such resources in Ontario were very low. Low-cost coal was available elsewhere in Canada, but the transportation cost was very high. The best economic choice for Ontario was to build coal-electric generating stations and buy coal from the U.S., which could be transported cheaply across Lake Ontario.

Hearn was very concerned about this situation because:
- Ontario might lose its electricity low-cost advantage;
- jobs associated with supply fuel would go to the U.S.;
- Canada had a complete infrastructure to plan, design, manufacture and construct hydro-electric generating stations. Although hydro-electric generating stations are capital intensive (high bond debt), they are not vulnerable to high cost escalation; and
- most of the cost for coal-electric generating stations is the cost of the coal, which would make Ontario Hydro vulnerable to uncontrollable escalation in U.S. coal prices.

Of course, it was also desirable to continue to expand all remaining available, economical hydro-electric generation. The development of the St. Lawrence Seaway, with further hydro-electric generation, was undertaken during the 1950s.

Ontario Hydro's Director of Research, Percy Dobson, had visited the Chalk River National Laboratories in Chalk River, Ontario, and he advised Hearn of the possibility of using indigenous Ontario uranium to power nuclear-electric generating stations in Ontario. Hearn and Dobson recognized that such an option would have to be developed commercially. Hearn strongly desired to continue generating electricity in Ontario below the U.S. average cost. Also at the end of Second World War, Ontario Hydro recognized the need to change from a 25 Hertz electrical system to a 60 Hertz system, which had become the North American standard. One of the key engineers whom Hearn assigned to this frequency standardization program was Harold Smith. This mammoth frequency standardization program posed many major problems, but it was carried out promptly and efficiently. Hearn subsequently arranged to attach Smith to the Chalk River National Laboratories to participate in the plans of Atomic Energy Canada Limited (AECL) to develop nuclear-electric generation in Canada.

Increased demand expected: 1952

During the Second World War, wartime priorities had prevented or reduced the production of many consumer goods. For example, you couldn't buy a new car in Ontario during the war. But after the war, Ontario Hydro planners foresaw a major increase in demand for more electricity. Most of the electricity generated in Ontario in 1952 was from hydro-electric units. The average electricity cost in Ontario was much lower than in the United States. More electricity generation was expected from new hydro-electric generating stations, but this new generation would be small compared with the expected increased demand. For example, additional hydro-electricity would be provided by the hydro-electric Saunders Generating Station to be built in conjunction with the St. Lawrence Seaway and the Des Joachims hydro station built on the Ottawa River. Nevertheless, Ontario Hydro knew that the only other major economic alternative to meet most of the future requirements at that time was by burning fossil fuels (coal, oil and gas).


CANDU 6 interlock to reactor

Continued from page 13

Wolsong construction by night

Ontario Hydro challenges

The only low-cost coal available to Ontario Hydro was from the United States. Accordingly, after the war, Ontario Hydro decided to get experience with fossil-generating plants, and the J. Clark Keith and R.L. Hearn Generating Station were built. Prior to the war, most of the generating units in North America were 30 Megawatt units or smaller. Ontario Hydro knew that major cost reductions could be achieved using larger units and multi-unit generating stations. Also, Ontario Hydro hired several managers with extensive thermal-generation experience to ensure the plants were acquired and operated efficiently.

Hearn worried that if Ontario Hydro lost its low-cost advantage, Ontario would be less attractive for establishing and maintaining industry. Ontario Hydro's planning and research organizations advised Hearn that there was little promise of finding extensive low-cost coal, oil or gas in Ontario. He knew that most of the components in hydro-generating stations could be manufactured competitively in Canada, but that many of the major components for fossil stations would have to be procured outside Canada. Coal from Western Canada would be expensive because of the high transportation cost. On the advice of Dobson, Hearn decided to cooperate with Atomic Energy of Canada Limited (AECL) in exploring the possibility of developing economical nuclear-electric generation and hopefully maintaining Ontario Hydro electricity costs below the U.S. average cost. Subsequently Hearn moved from his position as Chief Engineer to become the Chairman of Ontario Hydro.

(C) The Nuclear Technology Foundation Period From 1942 to 1952

Introduction

The following is a quotation from a paper by John Foster, who played a key role in the development of nuclear power in Canada from 1953 to 1977:

"The potential to produce useful energy was recognized from the outset. The Second World War intervened and the fission reaction was first applied in the manufacture of bombs. This was the First Stage, the stage of development of the use of nuclear fission, which uncovered many of the fundamentals relative to the process and demonstrated the feasibility of building and operating nuclear fission reactions. To develop any use of fission it was necessary to have comprehensive knowledge of the fission products and their properties in order for a chain reaction to be sustainable."[1]

U.S. atomic bomb program: 1942 to 1945

In 1942, the United States undertook the rapid development of atomic bombs using two different processes:

- a nuclear fission bomb using plutonium produced in low flux graphite moderated reactors, fuelled with natural uranium; and
- a nuclear fission bomb using enriched uranium 235 produced in enrichment plants.

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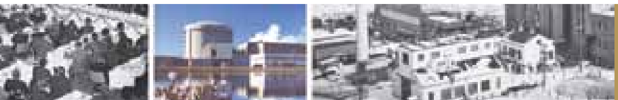
[1] First Stage of Nuclear Development, The Development of Nuclear Power – John Foster – Special Symposium 29th Annual Conference of CNA, Ottawa, Ontario, June 5, 1989.



This U.S. bomb development was known as the Manhattan Project and was carried out by the U.S. Army Corps of Engineers, headed by General Leslie Groves. European scientists and engineers were employed in this U.S. program. Canada cooperated with the U.S., for example, by supplying natural uranium.

Key Canadian nuclear organizations: 1942 to 1952

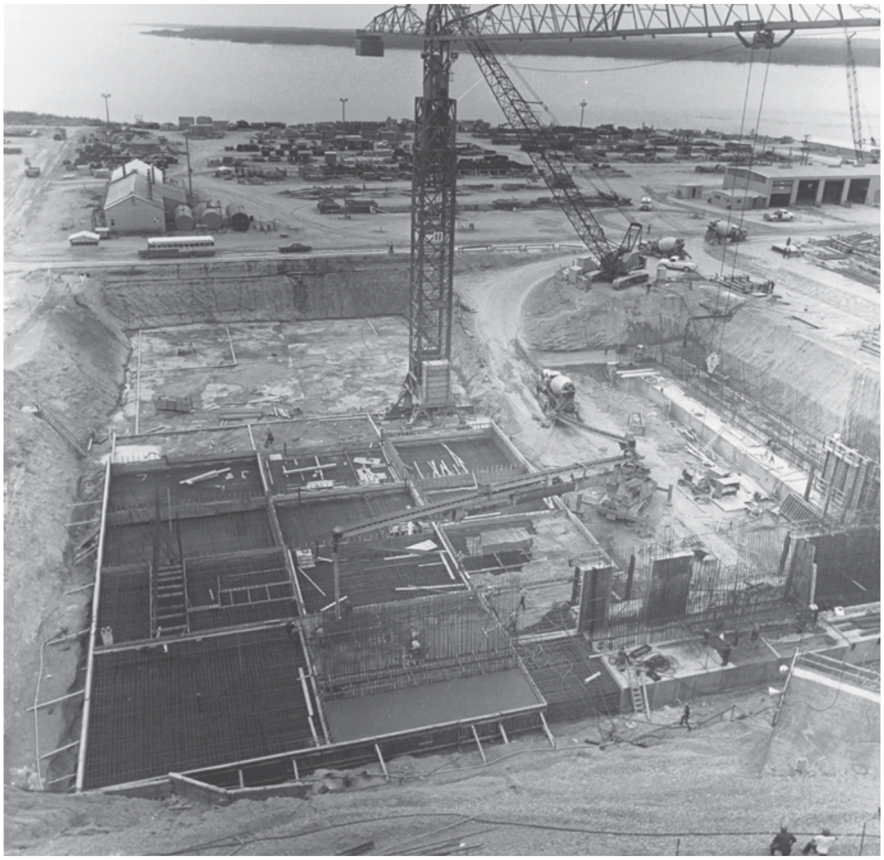
Two of the key Canadian decision makers who oversaw the Canadian program were C.D. Howe, a professional engineer and a Cabinet Minister in the Canadian government, and C.J. Mackenzie, a professional engineer and Head of the National Research Council of Canada. The two key Canadian organizations during the war were:

- the Defence Industries Limited (DIL), responsible for design and operation; and
- the National Research Council (NRC), responsible for the underlying research and development to support project activities for which there was no prior world experience.

Many Canadian organizations were deployed to construct the committed Canadian facilities and to manufacture the required components. Defence Industries Limited had been created during the war by the Canadian government to support the Canadian military program. DIL used management from Canadian Industries Limited, a competent Canadian company.

Early Anglo-Canadian nuclear program: 1942 to 1947

In 1988, Professor Robert Bothwell, a prominent Canadian historian, published a book called "Nucleus," which presents the history of AECL. The following quotation is from his book: "In December 1940, two European scientists, (Hans von) Halban and (Lew) Kowarski, produced experimental proof that a combination of uranium oxide and heavy water could produce a divergent chain reaction — where output of neutrons is greater than any input from a neutron source. The conception of a heavy-water reactor was no small accomplishment and as far as Canada was concerned, it was a lasting one. Every subsequent Canadian or Canadian-designed reactor is properly a descendant of Halban's original conception and experiments. The Canadian government agreed in August 1942 to accept and support a laboratory of British scientists. They were to work on atomic research. The Canadian government for its part — through the agency of Howe and Mackenzie — expected to pay many if not most of the lab's expenses, and to send Canadian staff, both scientific and support, to join Halban's team."[2]


Preparing a reactor's foundation

This laboratory was established in Montreal at the Université de Montréal.

Britain, Canada and the U.S. recognized that Halban was not a good leader and he was replaced by Sir John Cockcroft of Britain in April 1944. This Anglo-Canadian laboratory also included important scientists from other countries, including France and Italy.

Because the Allies were concerned that Germany might already be developing an atomic bomb, the United States and Canada gave high priority to these wartime nuclear programs. Under peacetime conditions, such developments would be expected to take much longer.

Canadian nuclear facilities: 1942 to 1952

In 1944, the staff of DIL and NRC were located in Montreal where the DIL staff performed the design with the theoretical support of the Anglo-Canadian laboratory, also in Montreal.

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[2] Early Anglo/Canadian Nuclear Program – Robert Bothwell – Nucleus – The History of Atomic Energy of Canada Limited – University of Toronto Press 1988 – ISBN 0-8020-2670-2.

Continued from page 15

Qinshan construction

At this time a Canadian national nuclear laboratory was established on the Ottawa River, near the town of Chalk River, Ontario. It was called the Chalk River National Laboratories (CRNL). A new town called Deep River was established near CRNL, which provided residences for the DIL and NRC and overseas support staff.

The following facilities were built and installed at the Chalk River National Laboratories:

- a low flux heavy water reactor called Zero Energy Experimental Pile (ZEEP);
- a high flux heavy water reactor to produce bomb grade plutonium. This reactor, called NRX (National Research Experimental), also featured excellent facilities for research, applied development, production of radioisotopes and testing of prototypes;
- a chemical processing plant to recover the plutonium produced in the NRX reactor; and
- a number of research laboratories, development laboratories, service buildings and an administrative building to facilitate ongoing research and development.

Wartime successes

New concepts produced by pure research often require major expenditures for applied research, development, demonstrators and prototypes. The establishment of design, construction, manufacturing and operating capability can take decades, and in some cases the implementation of an idea can require an extensive infrastructure. The American and Canadian wartime ventures included many challenges and problems, differences of opinion and conflicts amongst the leaders and doers. However, with wartime priorities, success was achieved in a few years rather than decades.

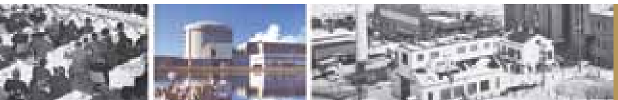
All of these U.S. and Canadian wartime ventures were successful:

- uranium 235 was extracted from natural uranium using U.S. enrichment plants;
- plutonium 239 was produced in U.S. graphite moderated reactors; and
- atomic bombs (nuclear bombs) were developed by the U.S. and dropped on Japan, which contributed to the early termination of the war with Japan.

In 1947, Canada brought the world's first high flux nuclear reactor, called NRX, into service.

During the 10-year period from 1942 to 1952, Canada acquired extensive nuclear technology, particularly at its Chalk River National Laboratories (CRNL), which contributed to the knowledge foundation for Canada and other countries to proceed with the peaceful uses of nuclear energy. In addition, universities in Canada participated in the advancement of this nuclear technology. Valuable commissioning and operating experience was acquired between 1947 and 1952. The operating staff learned how to manage radioactive contamination of buildings, equipment and the atmosphere both during normal operation and during maintenance. The operating staff learned how to control radiation exposure within specified limits utilizing personal self monitors. Procedures were developed to minimize the chance of a nuclear accident and to manage such accidents.

In addition, important testing and experiments were performed for other countries, particularly the U.S. and Britain. Nuclear fuel tests were done for nuclear submarines. Experience was gained in the operation of installations operating at high temperature and high pressure. For example, chemical control was established to minimize corrosion in high temperature water circuits and minimize the precipitation



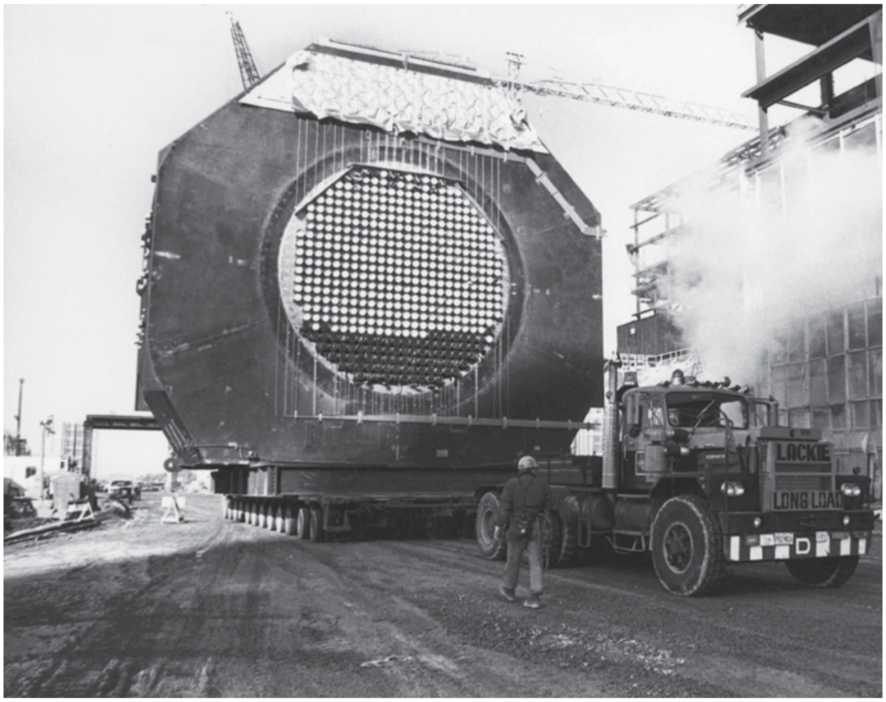
of corrosion products on nuclear fuel operating at high temperature. Detailed knowledge was acquired about fission products such as iodine, xenon, and samarium, which sometimes prevented reactor restart after a shutdown. Most important, methods were developed to increase the operating reliability while maintaining a high safety standard. Another important product of NRX was the production of radioisotopes, which contributed to medical research; sterilization of medical supplies; improved shelf life of foods; and cancer therapy.

NRX central thimble

The NRX reactor featured a vertical central thimble, which permitted large-scale experiments and tests to be performed in the high neutron flux of this reactor. In cooperation with the Westinghouse Atomic Power Division (WAPD) in the United States, a high-pressure, high-temperature water loop was installed to test nuclear submarine fuel. A major problem occurred, resulting in excessive corrosion products precipitating on the test fuel. WAPD proposed changes to the water chemistry to solve this problem. The operating staff at CRNL made these modifications and achieved excellent performance of the loop. As a result, there was high confidence in the operation of a future pressurized water reactor (PWR) application or a future pressurized heavy water reactor (PHWR) application under high flux conditions.

NRX nuclear accident

In 1952, there was an accident at the NRX reactor at the Chalk River National Laboratories. Radioactivity was released from the NRX reactor into the NRX building. However, the radioactivity was contained acceptably inside the building. In hindsight, this accident was a blessing in disguise. A set of safety principles was established to prevent a recurrence, the design of NRX was modified and the reactor was restored to service. The safety principles were subsequently modified from time to time but were essentially adopted and applied to all nuclear-electric units in Canada, and similar principles were adopted throughout the world. The DIL operating staff supported by DIL design staff made major changes to improve the operating reliability of the reactor while maintaining a high level of protection. Similar measures became vital features of all future nuclear-electric generating stations. An electrolysis-based heavy water upgrader was placed in service at CRNL to restore recovered downgraded heavy water.



Delivery of a calandria at the Bruce A nuclear power station

Learning from others

This paper has been written to focus on the development of the Ontario Hydro nuclear-electric program in cooperation with Atomic Energy of Canada Limited. Although many countries benefited from Canadian nuclear technology, it must be emphasized that Canada acquired important nuclear technology from other countries. For example, the very low fuelling cost of the pressure tube Canadian reactors was vitally dependent on the development of zirconium alloys used for both pressure tubes and fuel manufacture. Canadian researchers, designers and operators benefited from the experiences of nuclear programs in other countries. For nuclear generating units that AECL supplied to other countries, Ontario Hydro operating staff often trained the operating staff of other countries and/or oversaw the commissioning of such units, for which Ontario Hydro was reimbursed for its costs.

The technical choices

Again I would like to quote John Foster:

“When countries turned their attention back to using nuclear fission to produce energy for constructive uses, the first question was what kind of reactor to build. The potential scope for choice was very great indeed. The reactor might be moderated or not and, if moderated, graphite, beryllium, water, heavy water or an organic liquid might be the moderating material. The fuel might be uranium metal or an alloy, oxide or carbide of uranium. Heat might be removed from the reactor by water, heavy water, carbon dioxide, helium, organic liquids, molten salts or liquid metals. If water, it might be boiling or not. The fuel might be

Continued from page 17

Pickering opening 1971 – Premier Bill Davis

sheathed in stainless steel, zirconium alloys, graphite or other ceramics. Fortunately, not all the permutations and combinations are possible. Nevertheless, there are probably a few hundred conceivably feasible combinations and a surprising number were attempted. Many more were proposed. I am sure that a hundred years from now, when nuclear power is as normal as apple pie was before Meryl Streep, enterprising young engineers will find that latest bright ideas were anticipated by someone in the 1950s."[3]

Amalgamation into one NRC organization

During the Second World War, Defence Industries Limited, known as DIL, was created by the Canadian government to oversee the development and improvement of supplies and equipment to support the Canadian Armed Forces. This organization was managed by people borrowed from Canadian Industries Limited (CIL). DIL was not created through an Act of Canada's Parliament, but was created using wartime authority of the Canadian government. However, NRC was created by an Act of Parliament. As a result, after the war, the DIL staff and the NRC staff at the Chalk River National Laboratories were integrated into one NRC organization. Some of the borrowed CIL managers returned to CIL. Most of the DIL staff responsible for design, applied development and operations remained at CRNL, and their experience was used for the subsequent development of nuclear-electric generating stations.

The NRU Reactor

Shortly after the NRX reactor was started in 1947, a CRNL development group, which included both engineers and scientists, undertook to build a higher flux combined plutonium production/research reactor called National Research Universal, or NRU. This reactor also was to include excellent facilities to advance research and produce radioisotopes. The reactor featured a heavy water moderator, heavy water coolant natural uranium fuel, a vertical reactor and on-power fuelling. NRC placed a contract with the C.D. Howe Company, located in Montreal, to design and oversee the construction of NRU. The C.D. Howe Company had been established by C.D. Howe in 1935. However, at the time the contract was placed, C.D. Howe had severed all connections with this company.

No NRU operating experience was obtained before the launch of the Canadian nuclear-electric program. However, Canada acquired considerable experience in designing the on-power fuelling system, which became an important feature of the Canadian nuclear-electric units called the CANDU design. In 1948, it was expected that NRU would have a lifetime of perhaps only 15 years. But NRU has been operating for more than 50 years and is still in operation in 2010. NRU went into service in 1957 and contributed to the development of the Canadian nuclear-electric generation program.

(D) 1952 to 1977: The Three-Step Development of Economic Nuclear-Electric Generating Stations in Ontario

Atomic Energy of Canada created

After the Second World War ended, Canada made a major decision that it would pursue nuclear programs for peaceful purposes of nuclear energy. The Act of Parliament that created the National Research Council did not permit NRC to establish commercial organizations. For this reason, in 1952 the Canadian government created Atomic Energy of Canada Limited (AECL), which took over the Chalk River National Laboratories (CRNL) and became directly responsible for advancing the uses of nuclear energy in Canada. In essence, all NRC staff at the CRNL became employees of AECL. AECL was initially a part of the Atomic Energy Control Board headed by C.J. Mackenzie, and later reported directly to a federal Minister. In 1953, the AECL President, Bill Bennett, issued a mission statement: "The development of nuclear energy for power purposes is the prime objective of AECL."

Nuclear Power Group: 1954 to 1957

In early 1954, a team called the Nuclear Power Group was created. This AECL

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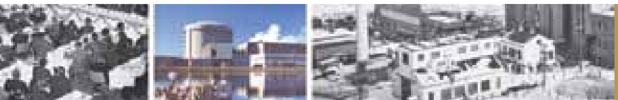
[3] The Technical Choices, The Development of Nuclear Power – John Foster. Special Symposium 29th Annual Conference of Canadian Nuclear Association, Ottawa, Ontario, June 5, 1989.



study team was intended to establish "a potential Canadian nuclear power system." The team, operating under the auspices of AECL, included "a cross section of Canadian industry, both electric supply utilities and manufacturers."

Harold Smith, the leader of the team, was from Ontario Hydro. Other organizations represented were Montreal Engineering, Babcock & Wilcox, Shawinigan Engineering, Brazilian Traction, BC Hydro and Ontario Hydro.

John Foster (of Montreal Engineering) recorded the following: "In these early stages of the program, a number of important givens were assumed: vertical reactor core geometry contained in a steel pressure vessel; the adoption of heavy water cooling; on-power refuelling; and control and shutdown by mechanical control rods."

In effect then, the concept represented a direct evolution of NRU with the pressure vessel allowing operation of the heavy water coolant at high pressure and, hence, temperature — essential if a usefully high thermodynamic efficiency was to be achieved for electricity production.

In terms of neutron economy and high burn-up, heavy water is a superior neutron moderator compared with other moderators such as graphite and light water. This meant that heavy water moderated reactors promised to have a lower fuelling cost. However, heavy water was expensive and there was a worry that during operation too much leakage might occur under conditions of high pressure and high temperature. Preventing the loss and downgrading of heavy water became one of the major design and operating challenges.

Key authorities

The development of nuclear-electric generating stations in Ontario between 1952 and 1977 depended on funding and program approvals by the key authorities, including Canada's prime minister, Ontario's, federal and provincial government ministers, Ontario Hydro's chair, AECL's president, AECL's board of directors and the Ontario Hydro commissioner. Any progress depended on these people to approve or obtain approval of the required funding for research, applied development and nuclear projects. Five notable key authorities in the 1950s were C.D Howe, an engineer and a federal Cabinet Minister; C.J. Mackenzie, an engineer and Head of the Atomic Energy Control Board; David Keys, a physicist and Head of NRC Chalk River National Laboratories; Bill Bennett, President of AECL; and R.L. Hearn, chief engineer and later Chairman of Ontario Hydro.

Doers

The ideas that shaped the Canada/Ontario Hydro nuclear-electric program between 1952 and 1977 came from hundreds of competent doers throughout the participating organizations (research, development, design, construction and operations). A complete nuclear infrastructure required the competitive private enterprise in Canada with the ability to design and manufacture the equipment and components needed to build the nuclear-electric generating stations, and the ability to manufacture the nuclear fuel required to operate the stations.

Key leaders

In between the doers and the key authorities were outstanding key leaders who:

- assimilated the knowledge and recommendations of the doers;
- endorsed, rejected or modified recommendations of doers and/or formulated recommendations (projects, organizations, staffing, etc.);
- obtained the approvals of the key authorities;
- oversaw, nurtured and monitored the progress of the committed programs, and made changes as necessary. As might be expected, different people had different opinions in 1952 as to how the future electricity needs in Ontario should be met.

The four major key leaders shaping the joint Canadian/Ontario Hydro nuclear program between 1947 and 1977 were:

- W.B. Lewis of AECL, who oversaw research at CRNL; he was a powerful brilliant highly respected scientist and a dedicated promoter of the CANDU concept.

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Why Ontario Generates So Much Electricity From Nuclear Energy

Continued from page 19

- Harold A. Smith of Ontario Hydro, who was the key team leader in formulating the CANDU concept at CRNL; he proposed AECL/ Ontario Hydro agreements; and promoted teamwork between all project functions. Subsequently, Smith became the Chief Engineer at Ontario Hydro from 1958 to 1974 and was in charge of all Ontario Hydro planning, research, development, design, construction and operations. He was widely recognized as one of the most brilliant engineers in Canada during the last century.
- Lorne Gray of Atomic Energy of Canada was an engineer, a powerful decision maker and negotiator as well as a good organizer, who formulated sound policies. He also was very effective in obtaining funding approvals from key authorities in the Canadian government.
- John S. Foster was a power plant engineer formerly with Montreal Engineering. He was a dedicated and highly respected engineer, key deputy leader in the design of the Nuclear Power Demonstration (NPD) and head of the Nuclear Power Plant design team, which designed nuclear stations in Canada and overseas. He succeeded Lorne Gray as President of AECL.

Step 1: Nuclear Power Demonstration 1–20 MWe: 1955 to 1957

Atomic Energy of Canada Limited was the lead organization in the beginning of the nuclear-electric development program in Canada. The electric utilities in Canada and industrial organizations were contacted and invited to contribute proposals, staff and funding to get the program under way. AECL initially concluded that Canada needed to establish competing private companies that could design and/ or supply nuclear-electric generating units to meet Canada's requirements (domestic or overseas).

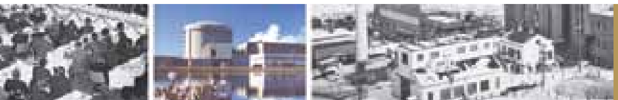
Most fossil-fired units in the world were 30 MWe or smaller before the war. However, Ontario Hydro had already proceeded to build 100 MWe coal-fired generating units in Ontario. The United States, Britain and France were already designing and building nuclear-electric generating units. These countries intended to establish competing organizations to design and supply nuclear-electric generating units.

Delivery of calandria to a CANDU 6

Based on the recommendations of the Nuclear Power Group, a decision emerged that Canada's first nuclear-electric demonstration should be a small unit. Measurements at NRX indicated that low fuelling cost could be achieved with natural uranium, and Canada had extensive deposits of it. Ontario Hydro knew that extensive deposits of uranium had already been established in Ontario. There was no uranium enrichment plant in Canada. This design would permit Canadian nuclear fuel supply with no requirement to build an enrichment plant in Canada or depend upon a foreign source.

Proposals received from Canadian organizations led to an agreement as follows:

- Canada would first build a single unit 20 MWe nuclear-electric generating station, which would be located in Ontario close to the Ontario Hydro Des Joachims Hydro-Electric Generating Station on the Ottawa River and also close to the Chalk River National Laboratories;
- This station would be called NPD, which stood for Nuclear Power Demonstration;
- This unit would feature a heavy water moderator, natural uranium fuel, a vertical pressure vessel, heavy water heat transport system and off-power refuelling;
- The site and conventional part of the station (turbine-generator, step-up transformer, etc.) would be designed, supplied and funded by Ontario Hydro;
- The nuclear part of the station (reactor, steam generators, etc.) would be designed by the Canadian General Electric Company (CGE) in Peterborough, Ontario;
- The nuclear part of the station would be funded by AECL (federal funding) with a $2 million contribution from CGE;

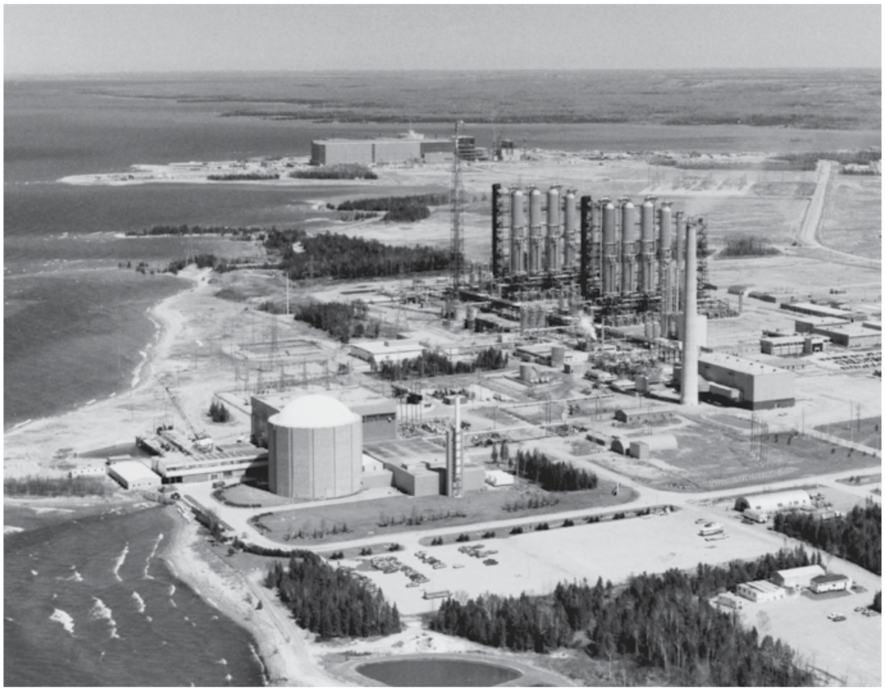


- Ontario Hydro would buy the steam at an agreed rate based upon the cost of an Ontario Hydro coal-fired generating station and would own the electricity produced by NPD; and
- NPD would be operated by Ontario Hydro.

The Canadian General Electric Company created a department called the Civilian Atomic Power Department (CAPD) to design and build the nuclear part of NPD. A number of capable engineers and scientists from CRNL became part of the CAPD staff. The team was headed by Ian MacKay and John Foster. The Ontario Hydro staff who designed the conventional part of the station (electrical generators, steam turbines, civil structures, etc.) were qualified experienced people, located in Toronto.

CAPD recommended that the fuel be uranium oxide and agreement finally was reached with CRNL. The fuel development proceeded at CAPD with support from CRNL. The pressure vessel contract was placed with a firm in Scotland. The turbine-generator contract was placed with a firm in England and the NPD site was selected by Ontario Hydro. Detailed designs were developed between 1955 and 1957, and the construction of NPD got under way.

Ontario Hydro recruited and trained operating staff with thermal-electric experience, hydro-electric experience and NRX nuclear experience to operate the NPD station. The Ontario Hydro operations staff were sent to CRNL to get nuclear experience and the staff with nuclear experience received training at Ontario Hydro's coal-fired stations. Manufacturing organizations in Canada developed capability to design and/or supply NPD equipment and components. The development of a Canadian nuclear-electric infrastructure was under way. The expected cost to complete NPD became better defined by 1957 and the cost was much higher than originally estimated.



The Bruce heavy water plant, shown next to the Douglas Point reactor

Further developments

Part of the Nuclear Power Group joined the CGE team designing NPD1. Harold Smith remained Head of this Nuclear Power Group and new members became part of this group. Ontario Hydro and AECL did not expect NPD to be commercially competitive with coal-fired generating stations in Ontario or elsewhere in Canada. Concurrently with the design and construction of NPD1, this group had the task of studying and proposing a heavy water moderated concept, which would hold promise of being economically competitive.

Harold Smith originally hoped to develop a 200 MWe concept that would be competitive in Ontario with coal-fired generation. However, Tod MacKenzie, the Head of the Planning Division at Ontario Hydro, persuaded Smith that nuclear units in Ontario Hydro would have to compete with 500 MWe or larger coal-fired units in Ontario Hydro.

It also became clear that Ontario Hydro could buy coal from the United States and produce electricity more cheaply than the U.S. average by building large multi-unit stations. Ontario Hydro was a larger utility than most of the U.S. utilities. The focus for economical nuclear competition in Ontario Hydro became clear.

Many concepts and concept variations were considered by the Nuclear Power Group. By 1957 Harold Smith and his team had formulated a proposed concept called CANDU, which promised to be commercially competitive with fossil-electric generation (coal, oil and gas). The main features of this concept were:

- a heavy water moderated reactor;
- a zirconium alloy pressure tube reactor (not a pressure vessel reactor);
- natural uranium fuel in the form of uranium oxide (not uranium metal);
- a horizontal calandria to hold the low temperature moderator;
- the zirconium-clad uranium oxide fuel would be in the form of short fuel bundles;
- bi-directional fuelling with short fuel bundles rather than long rods; and
- on-power fuelling.

Why Ontario Generates So Much Electricity From Nuclear Energy

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The technology for zirconium alloy pressure tubes came to Canada from the U.S. This concept promised to be competitive for large generating units, for example, 500 MWe. Zirconium alloy pressure tubes do not absorb neutrons as much as stainless steel. Heavy water moderated pressure vessels are much larger than light water moderated pressure vessels because the neutron migration length of heavy water is longer than light water.

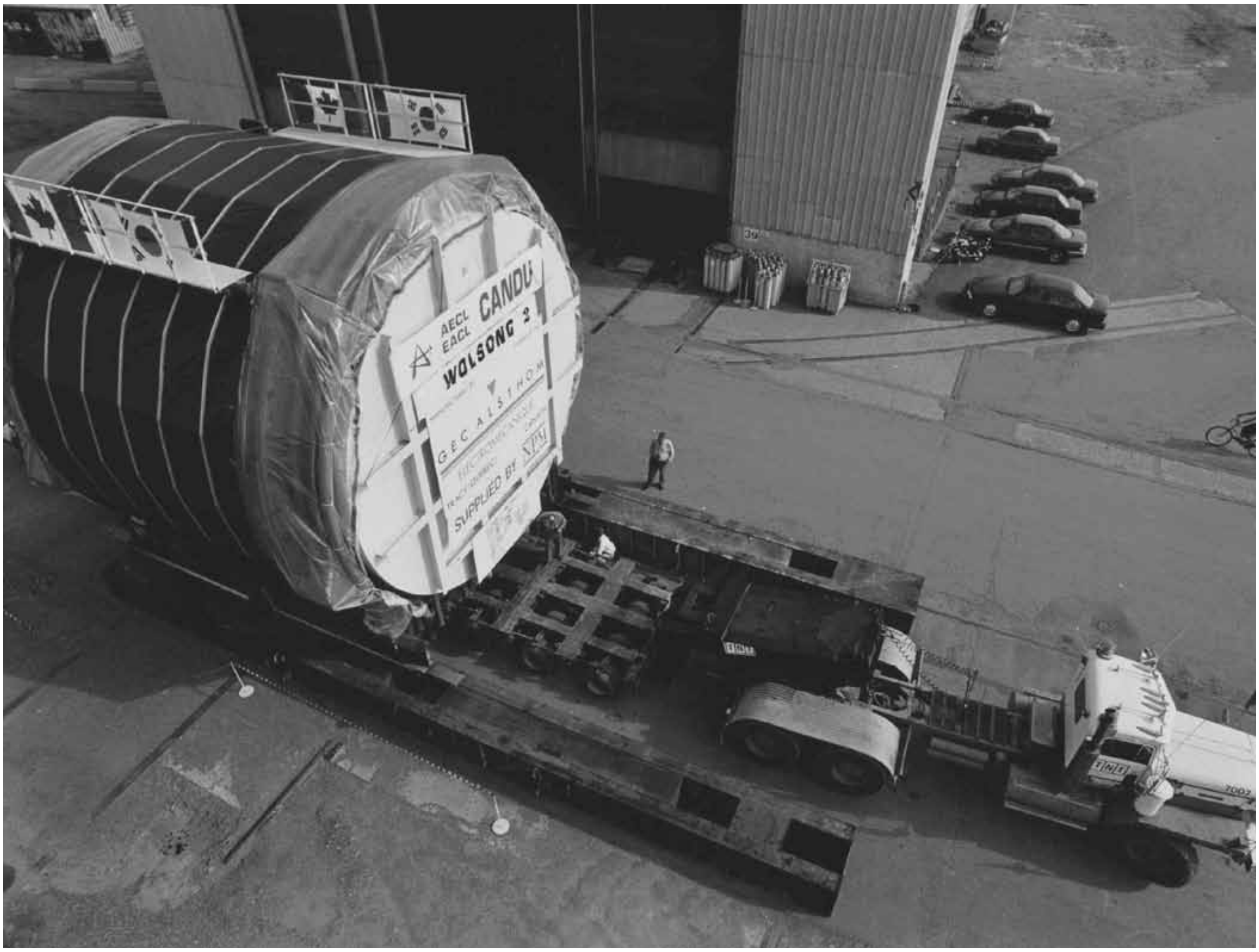
This new concept by Harold Smith and his team was given the acronym “CANDU,” which stands for CANadian Deuterium Uranium. Heavy water is deuterium oxide. Ordinary water is mostly protium oxide.

It was Harold Smith’s opinion that this concept held promise of being competitive after the following were put in service: one demonstration station, one prototype station and one commercial station. In other words, Harold Smith was of the view that the second commercial station held promise of being competitive in Ontario Hydro.

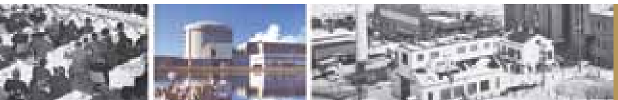
CANDU: major concerns

When the CANDU concept was created some of the concerns were:

- Would it be practical to build a heat transport system to operate at high pressure and temperature, or would the loss of high-cost heavy water make it economically impractical?
- Would the pressure tubes be reliable? Would they meet the original 15-year target life before replacement would be necessary?
- Could pump seals be developed to operate at high pressure and temperature without significant heavy water losses?
- Could reliable on-power fuelling machines be developed?
- Could high-pressure boilers transferring heat from heavy water to ordinary water with high reliability be built at reasonable cost?
- Would the fuel yield the expected high burn-up and low failure rate?
- Would the reactor be safe to the public and workers?



Delivery of the Calandria to Wolsong 2 in South Korea



- Would the concept of CANDU-PHW lead to economically competitive electricity cost in large commercial units operating at base load?

One concept—one design

Based on the advice received from the Ontario Hydro Planning Division, Harold Smith concluded that Canada was too small to develop two or more design concepts and support two or more competing design and supply organizations. Smith convinced Lorne Gray of AECL that:

- Canada needed to make a single good concept choice;
- Canada needed to have one efficient nuclear design organization;
- Canada needed to have competitive supply of all or most components made in Canada; and
- one design organization meant a monopoly and therefore it should be a Canadian public organization.

Obviously, such a proposal was a terrible blow to CGE and the very competent CAPD team that was working on the design and construction of NPD1.

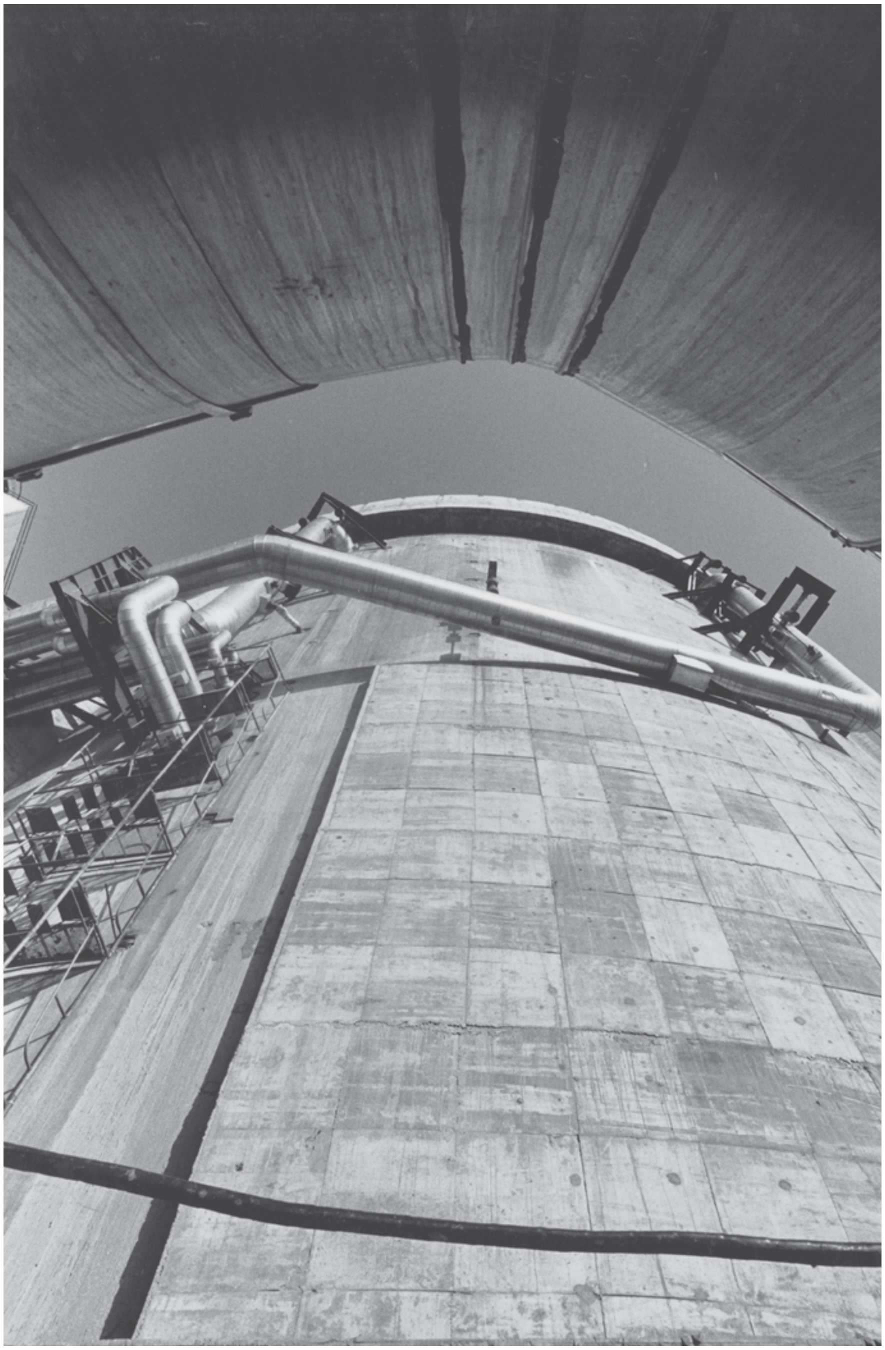
Note: Later Britain and France copied Canada (one design organization with competing suppliers). Even the U.S., with a population 10 times that of Canada, can afford only a few competing nuclear design organizations.

NPD moratorium: 1957 to 1958

With this new CANDU promise and the expectation that completing NPD would be a higher cost than originally expected, the question was asked: "Should NPD1 be cancelled or switched to the new CANDU concept?" AECL proposed and Ontario Hydro agreed that the construction of NPD1 should be suspended. This was called the "NPD1 Moratorium." The estimated cost to complete NPD1 would be about $34 million, about double the original estimate.

AECL and Ontario Hydro proposed and obtained approval for the following:

- NPD would be redesigned by CGE (CAPD) to the new CANDU concept. This would be called NPD2.
- AECL would create a new Canadian design team in Toronto called "Nuclear Power Plant Division." This team would design and build a prototype 200 MWe Generating Station, called Douglas Point, also based on the new CANDU concept.



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CGE staff members were initially extremely disappointed. However, the staff proceeded with enthusiasm to redesign NPD to the new concept. In the longer term, CGE became an excellent Canadian competitive provider of nuclear products, including

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KANUPP Pakistan

nuclear fuel and on-power fuelling machines. The later commercial stations of Ontario Hydro used the best design features of both the NPD2 demonstrator and the Douglas Point prototype.

The Atomic Energy Control Board

Canada created a regulatory agency initially called the Atomic Energy Control Board, or AECB. It is beyond the scope of this paper to review the development of this part of the Canadian nuclear infrastructure. However, this agency reviewed and licensed Canadian nuclear projects, which in some cases required changes to meet AECB requirements. Also, nuclear operators had to pass AECB examinations to become qualified to operate nuclear stations.

NPD2 placed in service: 1958 to 1962

The sudden change-over to the new CANDU concept was very challenging. Major decisions relating to the new short bundle fuel design, zirconium alloy pressure tubes and bi-directional on-power fuelling were an extraordinary challenge. However, by 1957, CAPD was already a smoothly functioning design team and NPD2 proved to be an excellent demonstration of the CANDU concept.

The hiring of Ontario Hydro operations staff was completed, and all staff received appropriate training corresponding to their jobs. All staff had to pass Ontario Hydro examinations. Some had to pass AECB examinations. NPD2 was constructed by Bechtel under the project supervision of CGE. NPD2 was commissioned and placed in service on October 1, 1962, by Ontario Hydro.

The first electricity in Canada from nuclear fuel was produced at NPD2 on June 4, 1962. It was a product of the agreement between three Canadian organizations: Atomic Energy of Canada Limited, Canadian General Electric and Ontario Hydro. NPD2 was operated from 1962 until 1986. Its 24-year operation demonstrated that the CANDU nuclear concept was sound. Numerous small problems emerged, which Ontario Hydro identified and solved in cooperation with CGE designers, CRNL research, Ontario Hydro research and manufacturers. Some major problems were also encountered. For example, CGE later redesigned and built new on-power fuelling machines that performed with excellence.

Heavy water loss and heavy water upgrading

In the early operation of NPD, a major heavy water leak occurred during a fuelling machine operation on the end of a pressure tube. This again raised the concern about heavy water loss and downgrading cost. In hindsight, this incident was a blessing in disguise. Ontario Hydro operations conceived and implemented a heavy water vapour recovery concept.

CGE designed and installed the system, which served three purposes:

- if small unseen leaks of heavy water were taking place in the vicinity of the reactor, the heavy water would be recovered in everyday operation without a nuclear generating unit shutdown;
- if a major leak or spill occurred, most of the heavy water would be quickly recovered and the generating unit promptly restored to service; and
- the heavy water recovery would lower the tritium level in the reactor rooms in which heavy water equipment is located, and improve the working conditions.

Today all operating commercial nuclear-electric stations have this vapour recovery system, and heavy water losses and downgrading costs have been low.

Nuclear training centre

Nuclear operating staff must include qualified managers, supervisors, operators and maintenance staff to effectively operate, maintain and solve problems at nuclear stations.

Shortly after the startup of NPD2, Ontario Hydro built a nuclear training centre alongside it. This nuclear training centre recruited hundreds of new staff and gave them initial training. NPD was used to provide the completion of training. The nuclear training centre also provided training for other Canadian and overseas staff in nuclear operations.

AECL Nuclear Power Plant Division created: 1958

AECL created the Nuclear Power Plant Division in 1958. This division was the

Research activity at the NRU

new publicly owned nuclear design organization intended to design and manage future nuclear steam supply systems to meet the needs of nuclear-electric generating stations in Canada and overseas. The first assignment was the design and management of the prototype 200 MWe Douglas Point Nuclear Generating Station.

In 1958, Harold Smith (of Ontario Hydro), who led the Nuclear Power Group that formulated the CANDU concept, was appointed Head of this new division. John Foster, who previously worked on the design of NPD, became Deputy Head of this new division. Only one year later, Harold Smith was appointed Chief Engineer of Ontario Hydro. Subsequently, John Foster managed the Nuclear Power Plant Division.

The first location for the new NPPD division of AECL was at the Manby Service Centre in Toronto, which was owned by Ontario Hydro. Later, NPPD moved to new facilities at Sheridan Park in Mississauga, Ontario. As with CGE, many staff moved from the Chalk River National Laboratories to become part of the new team. Also a number of Ontario Hydro staff members were attached to this new design division. Staff members were competent, enthusiastic, hard-working people with applied experience. However, very few of the new staff at NPPD had any experience designing a power station

Step 2: Douglas Point Prototype 200 MWe: 1958 to 1968

The first major task of the Nuclear Power Plant Division was to proceed with the design and construction of the 200 MWe Douglas Point Nuclear-Electric Prototype Generating Station, based on the heavy water moderated, natural uranium fuelled, horizontal pressure tube reactor, bi-directional on-power fuelling CANDU concept. Independent of size, there were design differences between the Douglas Point prototype and the NPD2 demonstration regarding

Continued from page 25

Shipment of a calandria from Tracy, Quebec

fuelling machines, containment, safety systems and control.

The agreement between Ontario Hydro and AECL was also different than with NPD:

- With the exception of the site, Douglas Point was entirely owned by AECL;
- AECL retained Ontario Hydro to design the conventional part of the station, manage the construction and operate the station; and
- Ontario Hydro would pay AECL for all electricity produced at a price equal to the cost of producing electricity in an Ontario Hydro coal-fired generating station.

The original schedule was an in-service date of 1964, but the actual in-service date was 1968. The delay had a combination of reasons, such as: the new design staff was maturing as a working team; there were significant problems with equipment during commissioning that required redesign and reconstruction; and after startup there were many additional problems and a high capacity factor was not achieved.

In a nutshell, the performance of Douglas Point was disappointing and Ontario Hydro was not motivated to buy the station from AECL. Although Douglas Point suffered many problems unrelated to the concept, it reinforced the soundness of the CANDU reactor concept. The majority of the components and material were procured on a competitive basis and the Canadian content for the station was about 71%.

In hindsight, the Douglas Point experience motivated the competent, creative staff of NPPD to mature rapidly and to be very careful and thorough in the design of the first commercial nuclear-electric generating station. The experience and confidence in the basic CANDU concept was reinforced.

Step 3: Commercial Pickering Nuclear-Electric Generating Station A, Units 1 and 2

The third step in the development of nuclear-electric stations in Ontario Hydro was the construction of a large commercial, multi-unit nuclear-electric generating station. The early experience with NPD2 was encouraging. However, the problems that had occurred made Ontario Hydro very cautious about the financial risks associated with committing to a commercial station. Harold Smith did not wish to proceed further unless he could get the political endorsement of the Ontario government. Lorne Gray of AECL did not want to commit unless he got a political endorsement of the federal government.

To obtain the required commitment of the federal and Ontario governments, Harold Smith proposed to Lorne Gray the following:

- proceed with the design and construction of two 500 MWe nuclear-generating units known as Pickering 1 and 2 at a site on Lake Ontario near Toronto;
- Ontario Hydro would fund an amount equal to a coal-fired generating station built by Ontario Hydro;
- the federal and Ontario governments would share the additional capital funding required for the station;
- when the two units were placed in service, the three parties would receive revenue in proportion to their funding contribution. The total revenue would equal the amount of electricity produced at Pickering times a price determined by the actual cost of the Ontario Hydro coal-fired Lambton Generating Station.

Harold Smith felt that such a commitment would ensure the genuine support of the governments, knowing that major risk existed with this proposed venture. The agreement was drawn up and signed by the federal and Ontario governments and by Ontario Hydro.

Pressure Tubes

This paper is not intended to review the technical problems and solutions associated with the CANDU concept. However, because the CANDU concept depends on pressure tubes, a few comments about the pressure tubes follow.

In 1957, the lifetime of each unit in a future commercial nuclear-electric station was assumed to be 30 years. The lifetime of the pressure tubes was assumed to be 15 years because of the limited technology and experience with zirconium alloys at that time. It was assumed that one retubing would have to be performed during the lifetime of each unit. It was also assumed in 1957 that the lifetime capability factor for nuclear stations would be 80%. If one pressure retubing is performed during the lifetime of each unit and it takes two years to retube a reactor, then the average capacity factor for the other 28 years would have to average 86%.

To meet the requirement for retubing, the CANDU concept provided for all fuel channel components to be replaceable with relative ease. There are five basic fuel channel components: pressure tubes, end fittings, calandria tubes, spacers between the pressure tubes and calandria tubes, and fuel bundles. Today, without exception, every CANDU unit has this replaceability feature. Under operating pressure and temperature, it was expected the pressure tubes would undergo (a) changes in dimensions; (b) oxidation; (c) hydriding; and (d) mechanical property changes. For this reason, the program arranged for periodic removal and inspection of pressure tubes. It was expected that pressure, temperature, neutron flux and time would result in diametral creep (a few mm), lengthening (several cm) and sagging. To prevent sag causing the pressure tubes to touch the calandria tubes, spacers were placed between the pressure tubes and the calandria tubes. Furthermore, the operations staff had to assume that infrequent failures of a pressure tube would occur. For the first four units (NPD, Douglas Point, Pickering 1 and 2), the pressure tubes were made of zircalloy (an alloy of zirconium and tin). In all generating units after 1967, the pressure tubes were made of a superior alloy of zirconium and niobium.

In the period from 1962 (when NPD started) to 1983, the performance of pressure tubes was very good. However, on August 1, 1983, one pressure tube at Pickering Unit 2 failed. This failure was a zircalloy tube failure caused by two factors: (a) zirconium hydrides and (b) an improperly located spacer. Design changes have also been made to accommodate greater length growth than originally provided and design changes have also been made to overcome a deficiency in the rolling procedure where pressure tubes were connected to end fittings. On the negative side, capacity factors have

Open pit uranium mining

Why Ontario Generates So Much Electricity From Nuclear Energy

Continued from page 27

suffered because of the need to replace pressure tubes. On the positive side, we now expect units with one retubing to exceed a 30-year lifetime and we may, with the current knowledge, be able to install new units in which the pressure tube lifetime may exceed 30 years. After some problems were solved, the performance of nuclear fuel and on-power fuelling has been excellent.

Yes, problems with nuclear components have occurred. However, the majority of the problems experienced were ordinary problems with pumps, valves, tubes, wiring, instruments, etc., which are characteristic of many non-nuclear generating units.

Commercial Pickering Nuclear-Electric Generating Station A, Units 3 and 4

By 1967, Ontario Hydro had gained five years of experience with NPD2 and confidence with the design of Pickering Units 1 and 2. Also the NPPD designers had matured as a result of the experience with Douglas Point. With the expected demand for electricity, Ontario Hydro assumed 100% of the economic risk and costs, and committed to Pickering 3 and 4. Ontario Hydro wanted to have four standardized units but did approve the change in the pressure tube to zirconium-niobium alloy. The vacuum containment concept provided for Pickering 1 and 2 was simply extended to Units 3 and 4. As a result of installing Units 3 and 4, Ontario obtained precise capital cost knowledge of extending units on the same site as compared with the cost for a new site.

Canadian heavy water supply — Bruce heavy water plant

Ontario Hydro and AECL wanted all components and supplies needed for CANDU to be obtained on a competitive basis, and strongly supported competing Canadian suppliers. AECL was expected to establish the heavy water supply and did take action to establish it. However, reliability compromises were made to accommodate Canadian regional development.

Research activity at the NRU in Chalk River National Laboratories

Ontario Hydro came to the conclusion that the heavy water arrangements through the federal government were not reliable and decided to establish its own heavy water supply at the Douglas Point site. This arrangement proceeded in cooperation with AECL. Four Bruce heavy water units were built and their performance was highly successful. Ontario Hydro also received excellent cooperation from the United States where Ontario Hydro operating staff received training, which contributed to this high performance and low cost.

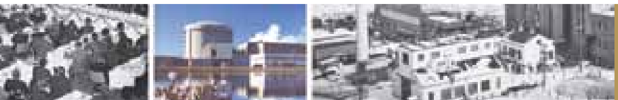
Pickering A Nuclear-Electric Generating Station startup: 2000 MWe

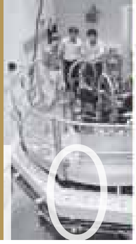
The four 500 MWe Units in the Pickering A Nuclear-Electric Generating Station went into service as follows: Unit 1 in July 1971; Unit 2 in December 1971; Unit 3 in June 1972; and Unit 4 in June 1973. The commissioning of all four units at Pickering A proceeded with outstanding success.

To put this major nuclear achievement into perspective, Pickering A was generating more power than Ontario Hydro was generating at Niagara Falls. During the six-year period from 1971 to 1977, the four commercial units at Pickering A continued to operate at high capacity. The total cost of producing electricity in this first CANDU commercial station was lower than the total cost of the largest coal-fired stations in Ontario Hydro.

In 1952, nuclear-electric generation was an unproven promise. In 1957, the CANDU concept was developed. In 1977, the economic commercial achievement of CANDU was realized.

When Harold Smith and his team first developed the CANDU concept in 1957, Smith suggested economic success would be achieved by the second commercial nuclear station. However, economic nuclear-electric generation was achieved in this first





commercial nuclear-electric generating station. During the six-year period, from Pickering A's first unit startup in 1971 to 1977, the station's performance was excellent in terms of the five fundamental objectives: cost, reliability, employee safety, public safety and environmental protection.

Some members of the general public may view 25 years (1952 to 1977) as a long time to develop the nuclear option from a promise to an economic commercial reality. However, from an engineering point of view, 25 years is a short time to achieve economic nuclear-electric generation. Most other energy options had been developed over a period of centuries.

Problem-solving at nuclear generating stations

Utilities throughout the world have all experienced major problems with generating units. Many problems occurred when the units were being commissioned. Many problems occurred during the first few years of service (infant mortality) and some problems occurred as a result of aging components (erosion, corrosion, stress cracking, etc.).

Certainly, the NPD2 (20 MWe demonstration) and the Douglas Point (200 MWe prototype) had many problems. This was not a surprise. After all, we expected to learn by identifying and solving problems. Most of the early problems were resolved by the operations staff and the manufacturers who had designed and supplied the plant components. In other cases, the operators had to engage the designers and research support to resolve problems. Certainly there were healthy debates and differences of opinion between functions (design versus research) and within functions (different designers in the same organization). Most, but not all, of these differences were constructive and led to better solutions. For major suppliers, the operating staff conducted annual reviews. For example, the operating staff had annual performance reviews with the turbine-generator suppliers (both British and U.S.). The operators also held annual performance reviews with major steam generator suppliers (Canadian).

(E) Ontario Hydro Commercial Nuclear Stations

Introduction

Figure E1[4] shows the delivery of electrical energy to industrial, commercial and residential consumers in Ontario during the period from 1958 to 2004, expressed in GWh. From the end of the Second World War in 1945 to 1990, there was a very large increase in the demand for electrical energy in Ontario. In 1990, a large economic depression took place. From 1990 to 1996, the demand for electrical energy dropped a small amount. From 1996 to 2004, a slow growth in electrical energy demand resumed. During the period from 1958 to 1990, there was a steady growth in all three end-use energy sectors (residential, industrial and commercial). From 1990 to 2004 the demand for the industrial sector and

Figure E1

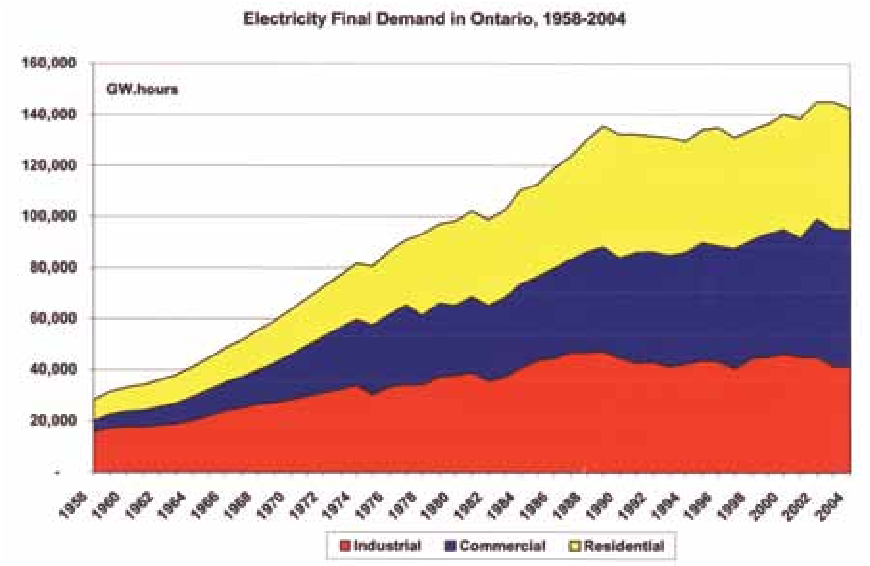
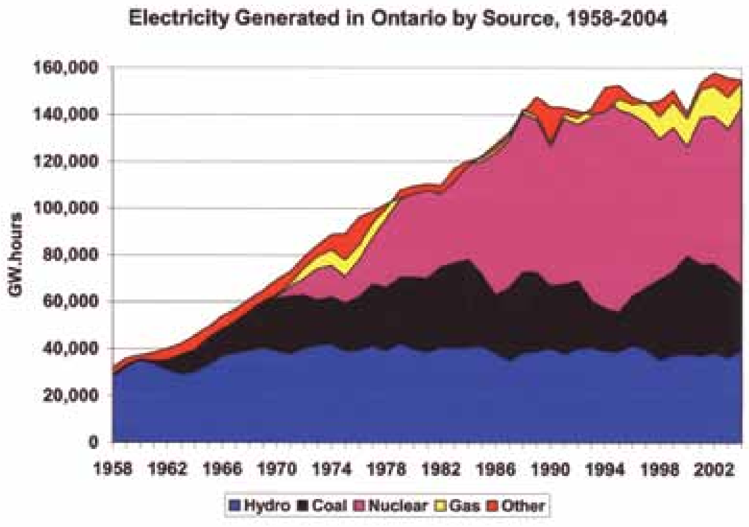


Figure E2



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[4] Figure E1 – Electricity Demand in Ontario – A Retrospective Analysis – Prepared for Ontario Power Authority – ICF Consulting, Toronto, Ontario.

Continued from page 29

for the residential sector changed very little, but the energy demand for the commercial sector continued to grow.

Figure E2[5] shows the source of electrical energy generated from 1958 to 2004 in GWh. Figure E2 shows that the limited supply of available economic hydro-energy generation met a small part of this large increase in demand. The development of economical nuclear-electric energy generation for base load application met most of the base load growth. Figure E3[6] shows the percentage contribution of each type of generation from 2004 to 2008. For the period from 1970 to 2010 , Ontario was a significant exporter of electricity which is not reflected in these Figures. It should be noted though that in the period 1997 to-2003, while some units were in lay up, imports of up to 7% per annum were necessary to meet domestic demand.

Figure E3:
Ontario Electric Generation: Percentage Electrical Energy Contribution — Resources

Year	Nuclear	Hydro	Coal	Oil & Gas	Other
2004	40	25	25	9	< 1
2005	51	23	19	7	<1
2006	54.1	22.3	16	6.5	1.1
2007	51	21	18	8	2
2008	53	24.1	14.5	6.9	1.5

Figure E4A
Ontario Hydro Nuclear-Electric Generating Stations — 1964 to 1993
Sites, Units, Nominal Capacity and In-Service Dates

Design Series	Site	Station	Unit	Net Capacity MWe	In-Service Date
1	Lake Ontario (Pickering)	Pickering A	1	515	1971 Jul 29
1			2	515	1971 Dec 30
1			3	515	1972 Jun 1
1			4	515	1973 Jun 17
2	Lake Huron (Bruce)	Bruce A	1	848	1977 Sep 1
2			2	848	1977 Sep 1
2			3	848	1978 Feb 1
2			4	848	1979 Jan 18
1	Lake Ontario (Pickering)	Pickering B	5	516	1983 May 10
1			6	516	1984 Feb 1
1			7	516	1985 Jan 1
1			8	516	1986 Feb 28
2	Lake Huron (Bruce)	Bruce B	6	860	1984 Sep 14
2			5	860	1985 Mar 1
2			7	860	1986 Apr 10
2			8	860	1987 May 82
2	Lake Ontario (Darlington)	Darlington	2	881	1990 Oct 9
2			1	881	1992 Nov 14
2			3	881	1993 Feb 14
2			4	881	1993 Jun 14
	Total			14,480	

The peak electrical load, expressed as capacity in GigaWatts (GWe), in Ontario grew from about 2 GWe in 1945 to about 23 GWe in 1990. In other words, the Ontario demand capacity in 1990 was about 10 times larger than in 1945. The Ontario Hydro generating capacity grew to meet this large growth in load. The Canadian nuclear infrastructure established between 1952 and 1977 continued to be utilized and expanded to achieve the desired results. Ontario Hydro and AECL expected that some problems would occur due to erosion, corrosion and wear as a result of the aging of the nuclear-electric generating units.

Nuclear program steady except for economic upsets

The expansion of nuclear generation in Ontario was generally orderly. However, there were some economic upsets during the 1970s and the 1980s with some economic consequences.

The assumed 15-year lifetime of pressure tubes suggested pressure tube replacement might occur about 1986. Accordingly, Ontario Hydro initiated a program to develop a large-scale pressure tube replacement process in the early 1970s. However, the extreme inflation during the 1970s imposed a knee-jerk pressure on Ontario Hydro and further development of pressure tube replacement was suspended in 1976. Another knee-jerk pressure developed in the early 1980s as the result of a mild Canadian economic recession. The recruitment of nuclear operations staff by Ontario Hydro operations branch to meet the needs for commissioning and operations of nuclear projects under construction was temporarily suspended and the construction of

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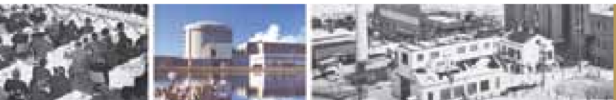
[5] Figure E2 – Electricity Demand in Ontario – A Retrospective Analysis – Prepared for Ontario Power Authority – ICF Consulting, Toronto, Ontario.

[6] Figure E3 – Pierre Charlebois, e-mail to Lorne McConnell, January 27, 2010.



Darlington A was delayed. In 1983, the pressure tube replacement program resumed after a pressure tube failed in Pickering 2. In the mid-1980s the Ontario electric load growth resumed and reached an all-time high growth rate expressed in Megawatts per annum. In 1990, a more serious economic recession occurred.

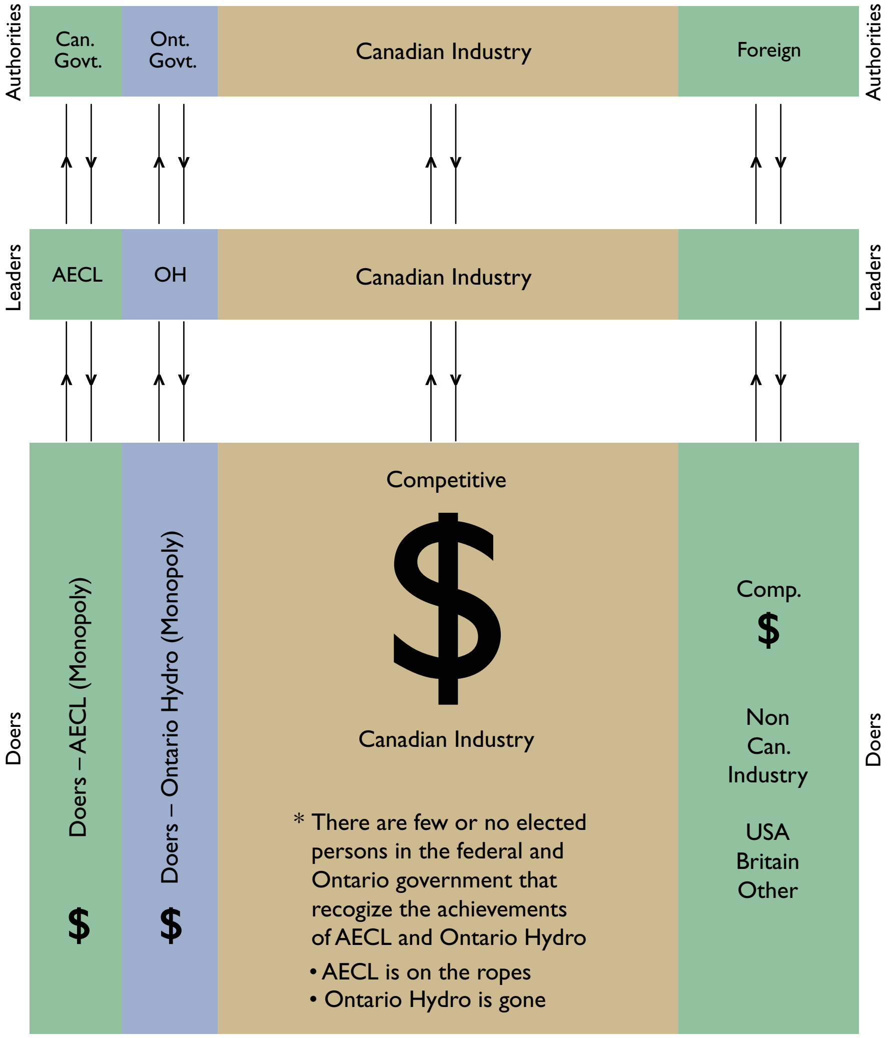
The purposes of this section are:

- to list the five Ontario Hydro commercial nuclear-electric generating stations that contain 20 large nuclear-electric generating units, which were committed and brought into service in the 29-year period between 1964 and 1993. (Note: After the Ontario government terminated Ontario Hydro in 1999 and replaced it with successor organizations, no additional nuclear-generating units were committed or built);
- to review the organizations and responsibilities for the acquisition and operation of the five Ontario Hydro nuclear-electric generating stations;
- to present a description of all the nuclear generation cost components; and
- to present the total 1988 Levelized Unit Energy Cost estimate for electricity for a nuclear generating station.

In section F of this paper, the actual costs and estimated costs of Ontario Hydro electricity up to 1988 are discussed and compared with other countries.

Figure E4B

CANDU Acquisition



Canadian Nuclear Infrastructure

Five commercial nuclear generating stations

Figure E4A[7] lists the five Ontario Hydro commercial generating stations, which contain 20 large nuclear-electric generating units. The in-service date of each unit is shown.

During the period from 1900 to 1950, Canada had brought a very large number of electricity generating units into service. They were typically 30 MWe or smaller. In 1952, AECL and Ontario Hydro assumed that a nuclear-electric program would require the establishment of competing organizations to design and/or supply nuclear steam supply systems and/or nuclear-generating stations.

Acquisition of the five stations

By 1957, the System Planning Division of Ontario Hydro had convinced Harold Smith that for nuclear-electric generating units in Ontario to be competitive, units of 500 MWe or larger would be required. System Planning also emphasized the cost savings that could be achieved in building multi-unit generating stations. It became clear that very few such generating stations would be required in Canada. Harold Smith concluded that Canada was too small to support two or more competing organizations to design and/or supply nuclear steam supply systems and/or nuclear generating stations. Figure E4B illustrates the Canadian Nuclear Infrastructure (1957 to 1990).

During the 1950s, Sir Christopher Hinton played a major role in establishing competing nuclear power plant suppliers in Britain. In 1968, Hinton

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[7] Figure E4A – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.

Continued from page 31

Figure E5

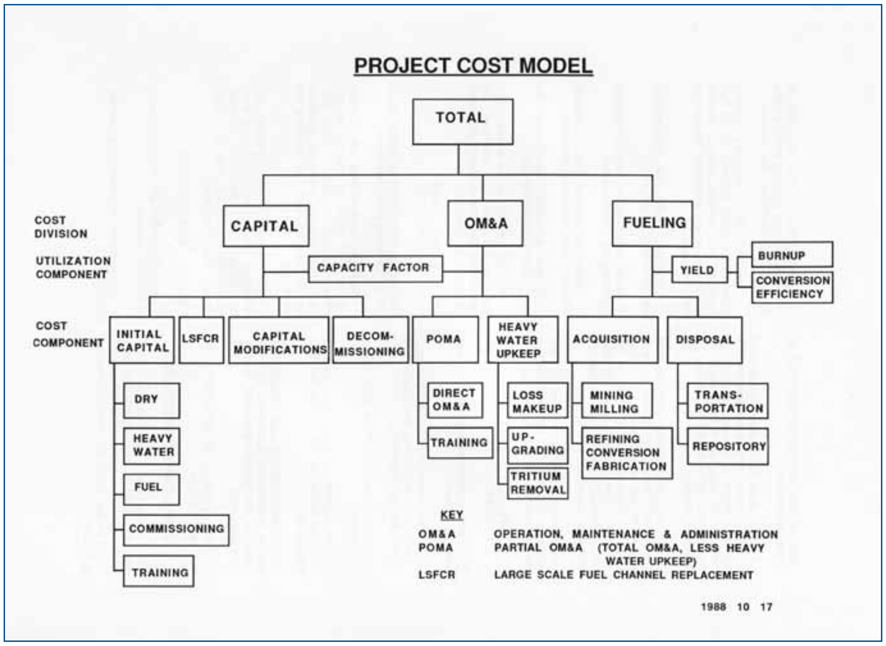
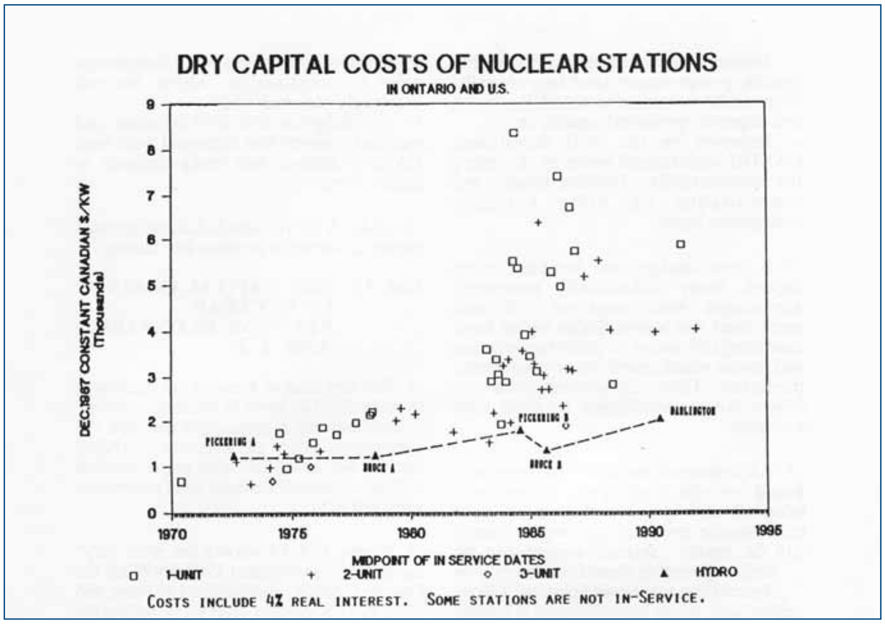


Figure E6



COSTS INCLUDE 4% REAL INTEREST. SOME STATIONS ARE NOT IN-SERVICE.

expressed his view to Ontario Hydro that Canada had adopted the best approach for the design and supply of nuclear power plants in Canada. Also, France changed its approach to a single nuclear power plant supplier (Framatome) and EDF (France's Electrical Utility) became the largest generator of economic electricity in the world, utilizing nuclear energy. Even one single supplier in France (Framatome) and one single supplier in Canada (AECL) have faced problems during the past 20 years because of the few new nuclear generating stations required.

In 1957, the Canadian nuclear program assumed there would be one publicly owned nuclear supply system organization called the Nuclear Power Plant Division (NPPD) of Atomic Energy of Canada. However, to minimize capital cost, Ontario Hydro and AECL agreed that all or most of the components and supplies needed to build nuclear stations would be acquired through competing private enterprise. Thus, the cost of nuclear stations is primarily from competing private enterprise managed through public enterprise.
For Ontario Hydro's five commercial nuclear electric generating stations, Ontario Hydro managed the acquisition and construction, and retained AECL to design the nuclear steam supply. With few exceptions, most of the required components and materials were obtained through competitive supply. Furthermore, as a matter of policy, competing Canadian suppliers were developed to supply the CANDU components and nuclear fuel. The same team managed major modifications and retubing. Ontario Hydro Operations managed and performed the commissioning and operations of all the Ontario Hydro nuclear stations.

By 1990, Ontario Hydro and France had the lowest nuclear-generated electricity costs in the world. Information to support this claim is presented in Section F of this paper.

The Bruce Generating Station A was committed before the startup of Pickering A. The Bruce A units came into service in the late 1970s. Pickering A's Units 1 and 2 were funded by Ontario Hydro, the federal and Ontario governments.

During the period from 1964 to 1993, Ontario Hydro funded the other 18 large nuclear units:

- Pickering Generating Station A: two additional 500 MWe units on Lake Ontario;

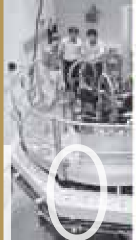
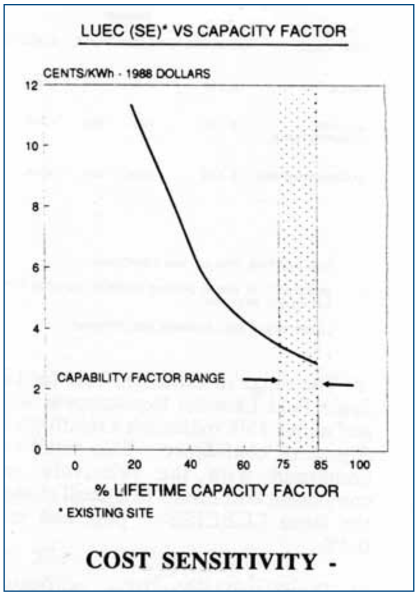


Figure E7:
FUTURE 4 X 881 MWe CANDU Station
Levelized Unit Energy Cost (LUEC) — 1988 Cents per kWh (C/kWh)

		Existing Site (SE)		**New Site (SE)**		**Existing Site (D&A)**		**New Site (D&A)**	
Cost Components		**C/kWh**	**%**	**C/kWh**	**%**	**C/kWh**	**%**	**C/kWh**	**%**
Capital	Initial Capital								
	Dry Capital	1.443	49.8	1.582	49.4	1.453	41.5	1.574	42.6
	Heavy Water	0.050	1.7	0.050	1.6	0.261	7.4	0.262	7.1
	Fuel	0.003	0.2	0.007	0.2	0.011	0.3	0.011	0.3
	Commissioning	0.071	2.4	0.073	2.3	0.074	2.1	0.076	2.1
	Capitalized Training	0.030	1.0	0.034	1.1	0.060	1.7	0.065	1.9
	Subtotal	1.601	54.2	1.746	54.6	1.859	53.0	1.988	53.8
	LSFCR	0.078	2.6	0.078	2.4	0.078	2.2	1.988	2.1
	Capital Modification	0.239	8.1	0.239	7.5	0.240	6.8	0.240	6.5
	Decommissioning	0.035	0.8	0.025	0.8	0.025	0.7	0.025	0.7
	TOTAL CAPITAL	1.943	65.7	2.088	65.3	2.202	62.8	2.331	63.0
OM&A	Partial OM&A								
	Direct OM&A	0.571	19.3	0.632	19.9	0.678	19.3	0.717	19.4
	Training	0.075	2.5	0.088	2.8	0.084	2.4	0.091	2.5
	Subtotal	0.646	21.9	0.725	22.7	0.762	21.7	0.808	21.8
	Heavy Water Upkeep								
	Loss Makeup	0.004	0.1	0.004	0.1	0.025	0.7	0.025	0.7
	Upgrading	0.008	0.3	0.008	0.3	0.009	0.3	0.009	0.2
	Tritium Removal	0.000	0.0	0.021	0.7	0.005	0.1	0.023	0..6
	Subtotal	0.012	0.4	0.033	1.0	0.039	1.1	0.057	1.5
	TOTAL OM&A	0.658	22.1	0.758	23.7	0.801	22.9	0.965	23.4
Fuelling	Fuel Acquisition								
	Mining/Milling	0.101	3.4	0.101	3.2	0.158	4.5	0.158	4.3
	Conv/Refin/Fab	0.101	3.4	0.101	3.2	0.103	2.3	0.103	2.8
	Subtotal	0.202	6.8	0.202	6.3	0.261	7.4	0.261	7.1
	Used Fuel Disposal								
	Transportation	0.021	0.7	0.021	0.7	0.029	0.0	0.029	0.8
	Repository	0.131	4.4	0.131	4.1	0.212	6.0	0.212	5.7
	Subtotal	0.152	5.1	0.152	4.8	0.241	6.9	0.241	6.5
	TOTAL FUELLING	0.354	12.0	0.354	11.1	0.502	14.3	0.502	13.6
TOTAL	cents per kWh	2.955	100 %	3.200	100 %	3.505	100 %	3.698	100 %

Continued from page 33

Figure E8



- Bruce Generating Station A: four 850 MWe units on Lake Huron;
- Pickering Generating Station B: four 500 MWe units on Lake Ontario;
- Bruce Generating Station B: four 850 MWe units on Lake Huron;
- Darlington Generating Station A: four 850 MWe units on Lake Ontario.

In summary, the Ontario Hydro nuclear-electric program included a total of 20 large nuclear-electric generating units in five generating stations located at three sites.

The installed nominal nuclear capacity of 14,480 MWe was approximately equivalent to eight times the Ontario Hydro capacity of Niagara Falls.

Nuclear-generated electricity cost components

The cost components of electricity generated from nuclear energy are shown in Figure E5[8].

To fairly compare the electricity costs of available options requires that the life-cycle costs of each option be estimated. The accuracy of such estimates depends upon the availability of actual costs, if any, for the option being considered.

The full life-cycle costs of the CANDU option include all costs attributable to the facility from its initial design and construction through its lifetime to its decommissioning and dismantlement. These life-cycle costs include all the direct costs associated with the engineering, construction and operation of the plant as well as all the indirect costs such as overheads that are associated with carrying out these activities. For example, where you see the capital cost component called LSFCR, this means Large Scale Fuel Channel Replacement. Some cost component information is presented in Section F of this paper.

Another important cost component is the capital cost of a nuclear station (measured in Canadian dollars per kilowatt). Figure E6[9] shows capital cost of the 5 Ontario Hydro nuclear stations versus all USA nuclear generating stations. The data shown beyond 1989 is forecast and not actual data.

Estimated total unit energy cost for new stations (1988 dollars)

The following estimates were based upon Ontario Hydro's cost experience with four previous commercial nuclear-electric generating stations already built and placed in service.

The Levelized Unit Energy Cost, expressed in 1988 cents per kWh for planning purposes, was:

- The Levelized Unit Energy Cost for System Expansion (SE) at an existing site LUEC(SE) was 2.96 cents per kWh;
- The Levelized Unit Energy Cost for System Expansion at a new site LUEC(SE) was 3.29 cents per kWh;
- The Levelized Unit Energy Cost using Direct and Allocated (D&A) costs for a station at an existing site LUEC(D&A) was 3.51 cents per kWh; and
- The Levelized Unit Energy Cost using Direct and Allocated costs for a station at a new site LUEC(D&A) was 3.70 cents per kWh.

Figure E7[10] is a table showing the Levelized Unit Energy Cost components for a future 4x881 MWe CANDU station in Ontario expressed in 1988 dollars.

It should be emphasized that the capacity factor is the single largest factor that influences electricity cost. Figure E8[11] shows a sensitivity analysis of how Levelized Unit Energy Cost varies with Capacity Factor. This sensitivity analysis does not include the large additional costs required to back up a low-capacity generating unit.

(F) Conclusions — Hindsight View from 1989

Introduction

In this section, evidence is presented that in 1988 the cost of electricity generated in Ontario Hydro nuclear-generating stations was amongst the lowest in the world.

Ontario Nuclear Cost Inquiry (ONCI): 1988

In 1988, the Ontario government created an independent panel of both Canadian and international experts to conduct a review process called the "Ontario Nuclear Cost Inquiry." The ONCI review panel included a chairman, two members, two advisors and two support staff.

Ontario Hydro created a six-member ONCI Task Force to prepare and present (a) actual cost experience and (b) planning costs. This Ontario Hydro Task Force had seven support staff, 11 major contributors and 34 noteworthy contributors. All of the presentations made by the Ontario Hydro ONCI Task Force are documented in a report called "Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry — November 1988."

ONCI Report: January 1989

The ONCI panel submitted its report to the Ontario Minister of Energy in January 1989. In essence the ONCI panel endorsed the cost data they reviewed and made valid observations about the accuracy. The ONCI panel also made a comparison of

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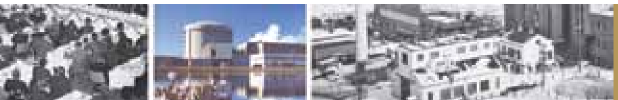
[8] Figure E5 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.
[9] Figure E6 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.
[10] Figure E7 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.
[11] Figure E8 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.



Ontario Hydro costs with reported data from other countries (UNIPEDE). This comparison was for the Levelized Unit Energy Cost (LUEC) for base load. All costs were converted to cents per kWh (Canadian). All costs were adjusted to costs corresponding to a new site.[12]

Ontario Hydro	2.31
Federal Republic of Germany	3.71
Belgium	2.72
Spain	3.99
France	2.53
Italy	3.79
Japan	4.03
Netherlands	3.36
United Kingdom	3.47
Switzerland	3.83

In this table it should be noted that Ontario Hydro had the lowest cost. However, the report emphasized "that cross comparison between countries is sensitive to uncertainties about exchange rates." The ONCI panel went on to say: "It is clear that Ontario Hydro cost is in the lower range of international costs with an order of magnitude similar to French and Belgium ones."

The ONCI panel made a further comparison between Ontario Hydro and France in respect to the siting of nuclear-generating stations.

France	Separated Units	2 units/ site	Cooling Tower
Ontario	Multi-units	4 units/ site	Direct Cooling

The panel reported that if corrections were made for the superior siting in Ontario, the comparison of costs would be the same; France would be 2.33 cents/kWh and Ontario would be 2.31 cents/kWh.

Reasons for low cost of nuclear-generated electricity: 1989

The delivered cost of electricity to consumers in Ontario has typically been below the average cost of electricity delivered to consumers in the U.S. Also, Ontario Hydro costs have been typically equal or lower than other utilities in Canada regarding (a) hydro generation and (b) fossil generation. This naturally begs the question: "Why have Ontario Hydro costs been the lowest or among the lowest in the world?"

The following refers only to the nuclear option although similar reasons exist for hydro and fossil fuel options. (This author is not qualified to speak about nuclear costs in Ontario from 1990 to 2010.) In the opinion of this author (based upon selected views of other people), the low cost of electricity produced in Ontario Hydro nuclear-electric generating stations up to 1989 can be attributed to the following factors:

- soundness of the CANDU concept;
- within limits, large nuclear-electric units are more economic than small units;
- high level of standardization of design and operation;
- very large Ontario Hydro commercial nuclear program;
- acquisition process for new nuclear plants tailored to Canada's ability;
- high Canadian competitive acquisition of components and fuel for nuclear-generating stations;
- effective Ontario Hydro funding process;
- excellence in operator recruitment and training; and
- high utility performance in design, construction, research and operations.

Soundness of the CANDU concept

Ontario Hydro committed and placed into service five commercial generating stations containing 20 nuclear-electric units located on three sites in the 29-year period from 1964 to 1993.

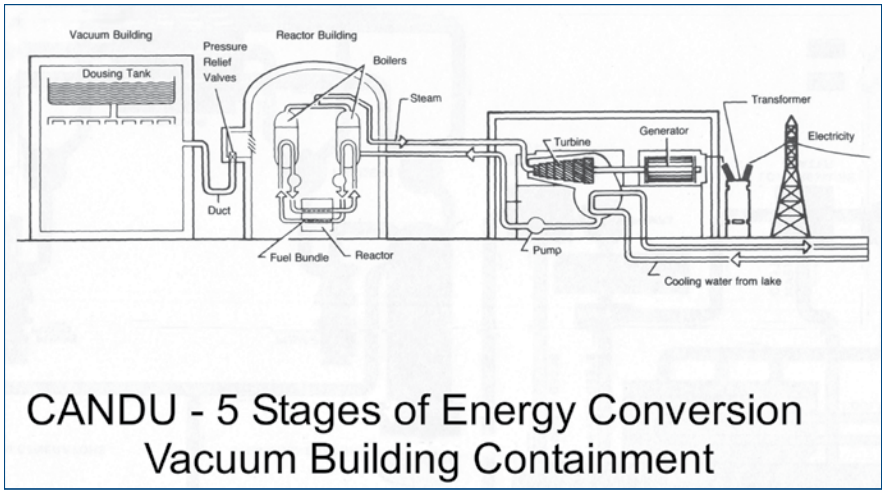
The basic concept of CANDU in 1957 did not radically change in subsequent years to 1993.

As of 1993, the 20 commercial units of Ontario Hydro had two design series: Series 1 was eight units with a nominal capacity of 500 MWe each; and Series 2 was 12 units with a nominal capacity of 850 MWe each.

Series 1 includes eight standardized units on one Pickering site. The two stations are Pickering A (four units) and Pickering B (four units). The eight 500 MWe units are contiguous and occupy one continuous building. These eight units share one vacuum containment system. However, Units 1 and 2 originally had zirconium alloy (zirconium and tin) pressure tubes and the other six units had zirconium niobium pressure tubes.

Series 2 includes 12 850 MWe standardized units in three four-unit stations located on two sites — Bruce A and Bruce B are on one site, and Darlington A on the other site. Each

Figure F1



CANDU - 5 Stages of Energy Conversion
Vacuum Building Containment

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[12] Ontario Nuclear Cost Inquiry – Report to Minister of Energy (Ontario), January 1989. Ralph Brooks and Howard Bowers.

Why Ontario Generates So Much Electricity From Nuclear Energy

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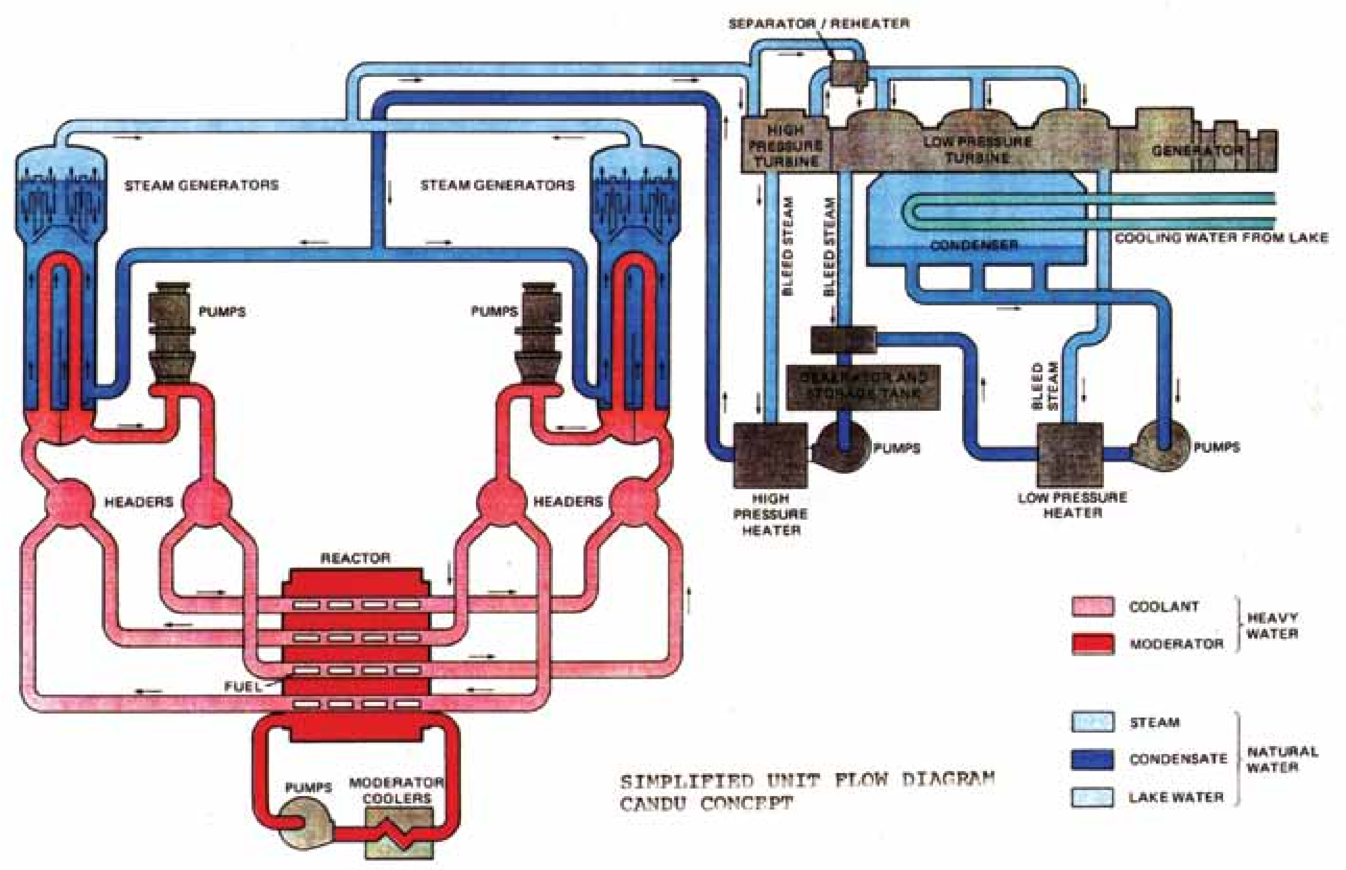
Figure F2



of these three generating stations has one vacuum containment system. The reactors all have zirconium niobium pressure tubes.

The following is an update of the CANDU-PHW concept corresponding to Series 2 of Ontario Hydro.

The CANDU concept features five stages of energy conversion (See Figure F1):[13]

- the REACTOR is the first stage of energy conversion. The nuclear energy in the nuclear fuel is converted into heat energy;
- the BOILER, or Steam Generator, is the second stage of energy conversion in which the heat energy is converted into ordinary steam energy;
- the TURBINE is the third stage of energy conversion in which the steam energy is converted into mechanical energy;
- the GENERATOR is the fourth stage of energy conversion in which the mechanical energy is converted into electrical energy at relatively low voltage; and
- the TRANSFORMER is the fifth stage, which steps up the voltage to high voltage and delivers the electrical energy into the high voltage transmission system.

The major features of the CANDU reactor are (See Figure F2):[14]

- the natural uranium oxide fuel is in the form of short bundles and is manufactured with high quality at low cost in a process that is semi-automated (See Figure F3);[15]
- the highly efficient (low neutron absorption) heavy water moderator permits high uranium burn-up and low fuelling cost;
- the heavy water moderator is contained in a horizontal tank called a calandria, which operates at low pressure and low temperature so there are no worries about pressure vessel failure;
- pressure tubes are horizontally arranged in the horizontal reactor. These tubes are made of neutron transparent zirconium niobium alloy;
- the design is forgiving because it provides for the assumption that pressure tubes and all other components will fail infrequently without undue public risk;
- the heat transport system also uses heavy water, which is pumped through the pressure tubes and transports the heat produced in the

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13 Figure F1 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.
14 Figure F2 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.
15 Figure F3 – Ontario Hydro Presentations to the Ontario Nuclear Cost Inquiry – November 1988.

fuel to the boiler (steam generator). The design and operation assumes heavy water leakage may occur. Liquid and vapour recovery systems ensure low heavy water cost during operation; and

- fuelling machines are provided, which permit the fuel to be changed while the reactor is operating at full power. No shutdowns are required to change fuel, which increases the capacity factor and lowers the total energy cost.

The following are comments about regulating, protective and emergency systems:

- the regulating system used to control the reactor in normal operations is separate from the protective systems, which detect and respond to abnormal situations;
- the design of the reactor and the characteristics of the material result in basic physical limitations on the rate at which the power can be changed;
- each reactor has two independent shutdown systems;
- all protective circuits are triplicated. An appropriate control action results whenever any two of the three indicate an abnormality. This concept ensures high safety and high capacity factor; and
- other safety features include emergency cooling and emergency injection.

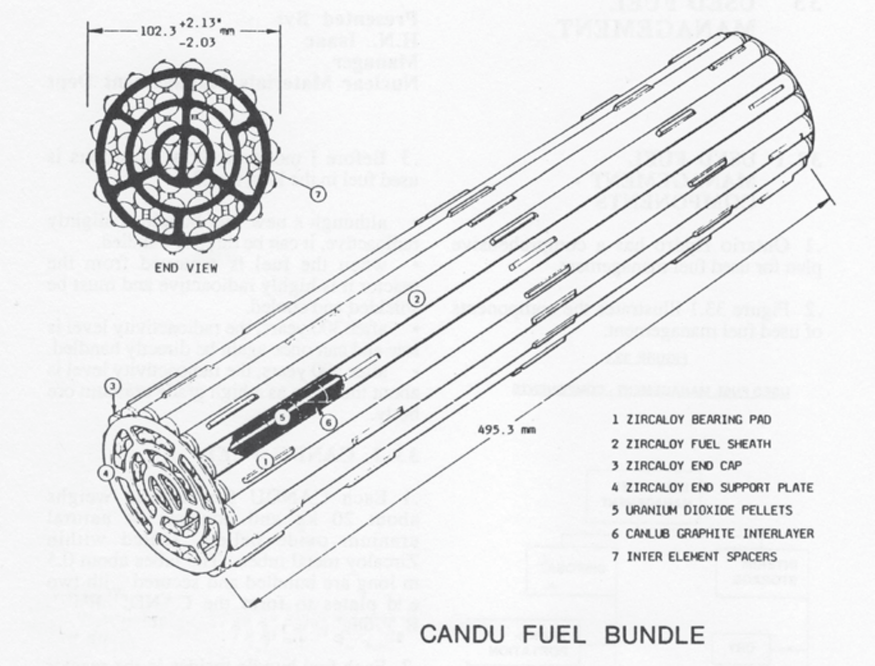
Simplified flow sheet

The flowsheet in Figure F2 illustrates the CANDU concept on which Bruce A, Bruce B and Darlington A nuclear stations are based.

The reactor consists of the following:

- a horizontal tank called the calandria;
- four of the 480 pressure tubes are shown;
- 13 fuel bundles are in each pressure tube (four are shown) (see Figure F3);
- heavy water moderator in the calandria; and
- the calandria operates at low pressure and low temperature.

Figure F3



Heavy water is pumped through the pressure tubes to transport the heat from the fuel bundles to the boilers (steam generators).

The CANDU concept features replaceable pressure tubes. Full-scale replacement of pressure tubes has been successfully performed.

Containment (see Figure F1)

The reactor and associated systems are contained in a sealed reactor building. The reactor buildings are connected to a vacuum building. In the event of an accident that results in steam release, the steam passes to the vacuum building where it is condensed. Following such an accident, there is no positive pressure and the radioactivity is contained.

CANDU lifetime

When the CANDU-PHWR was conceived in 1957, the reference economic station lifetime was assumed to be 30 years. The reference pressure tube lifetime was assumed to be 15 years, requiring one retubing after 15 years. For planning purposes, the pressure tube lifetime of a new station is now assumed to be 30 years, while the base estimate for a future station corresponds to a 40-year station lifetime.

Sensitivity analysis has been used to calculate the Levelized Unit Energy Costs, assuming the lifetime of the reactor and pressure tubes is both higher and lower than the basic planning values.

Within limits, large nuclear-electric units more economic

Consider building one 800 MWe unit versus eight 100 MWe units. In Ontario, the total unit energy cost of one 800 MWe unit will be much lower than the eight 100 MWe units. The costs of sites, design, construction and operations will all be lower for the single large unit.

Consider building one 2000 MEe unit versus two 1000 MWe units. In this case the 2 unit station will have a lower total unit energy cost. Industry does not have the current ability to deliver all components for a 2000 MWe size and such a large size would require a very large research and development program. Although larger size will usually lower cost, there is an upper limit in size available in any given year. Also unit sizes in every utility are

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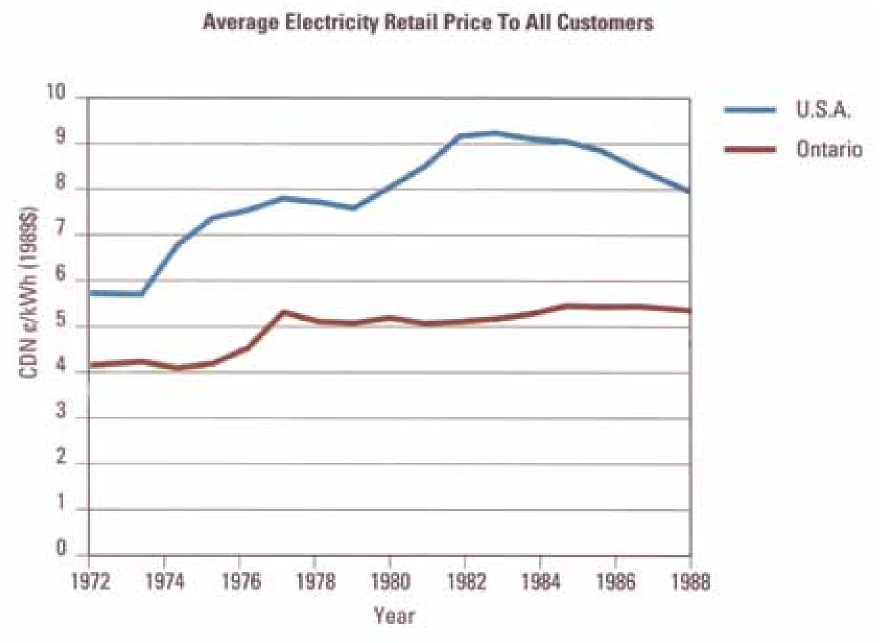
Figure F4



further limited by total system reliability considerations.

The large size of units built in Ontario has been a major factor in keeping Ontario Hydro rates lower than the U.S. average (see Figure F4).[16] Many of the small private utilities in the United States must install much smaller units. The low costs in France also depend upon the large units that were built there.

High level of standardization
Standardization is a well known concept to reduce costs. On a given site, building two generating units rather than one generating unit results in a substantial savings. In the case of the Ontario Hydro nuclear program, the Series 2 standard covered the 12 units of Bruce A, Bruce B and Darlington A. On the other hand, engineers are very creative people and are always looking for ways and means to lower costs and to improve efficiency. Thus, there is a balance that has to be achieved between standardization savings and savings through creative ideas.

In the case of power plants, there is a strong desire to minimize costs by getting competitive tenders for equipment and supplies. For example, the turbine-generator for the Bruce A supply may be a different supplier than for Darlington A. Therefore, two power plants are rarely identical in design.

Car manufacturers may have nearly 100% standardization and produce thousands of cars. For power plants, however, complete standardization is more difficult to achieve.

In the case of Ontario Hydro, considerable savings were achieved by standardizing both the 12 units at Bruce A, Bruce B and Darlington, and the eight units at Pickering A and Pickering B.

Very large commercial nuclear program
Nuclear programs have fixed costs that are independent on the size of the program (utility), and variable costs that are proportional to the size of the program. A large program will enjoy a lower unit energy cost than a small program, for example, in areas of research and development to solve major problems, or in staff required to make major modifications to several units of the same design.

By any standard, the Ontario Hydro nuclear program is a very large program (eight times the capacity of hydro generation at Niagara Falls).

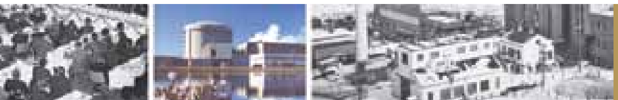
Multi-unit concept
Compared with utilities around the world, Ontario Hydro enjoyed a siting advantage because of the Great Lakes. This permitted Ontario Hydro to not only build large units, but also to build multi-unit stations with direct water cooling. This is one of the reasons that costs of nuclear energy in Ontario have been a little lower than France up until 1990.

Acquisition process for a new nuclear plant
The merits of the one concept—one organization approach (with competitive supply) were presented in Section E of this paper.

Competitive supply of plant components and fuel
A large country like the United States can afford to have competing organizations for the design and/or supply of large power plants. To maximize industry within Canada, we must be much more careful in the selection of what we do and how we do it. Although, Ontario Hydro was managed through public enterprise, the costs have been maintained at a low level because most of the material and equipment in Ontario Hydro plants have been procured through a competitive private enterprise process. Most of Ontario Hydro expenditures are through private enterprise (more than 70%). However, few or no private utilities have had lower operations and maintenance costs than Ontario Hydro.

Funding of capital for power plants
If the owner of a utility is a private company, funding of new projects can be done by financing through the issue of company shares or funding through bonds (debt). The electricity consumer must pay for depreciation of the asset, must pay dividends to the shareholders and must pay for interest on the debt. For a public company such as Ontario Hydro, which does not receive any taxpayer support, the funding is done through issue of bonds (debt).

[16] Figure F4 – Ontario Hydro 25 Year Demand/Supply Report – 1990 to 2014.



The funding costs of Ontario Hydro have been much lower than for most companies in North America, and no profit has to be paid in the form of dividends. This funding advantage has helped Ontario Hydro minimize its total energy costs.

Recruitment and training

The creation of the nuclear option in Ontario from 1952 to 1977 and the rapid building of 20 commercial nuclear units from 1964 to 1993 required the establishment of a large number of qualified managers, supervisors, operators and maintainers. The Canadian labour market did not possess such staff with the requisite knowledge of nuclear reactors.

As part of the necessary nuclear infrastructure, Ontario Hydro established training courses and nuclear training centres to recruit and train the necessary staff. This was done carefully and efficiently so that all of the commercial nuclear stations are manned with competent staff.

High utility performance

Sir Adam Beck established Ontario Hydro so that it would be run by professionals (not elected people). Electric utilities worldwide continue to be monopolies. Ontario Hydro has always been willing to buy electricity generation from any non-utility generator if the cost is lower than its own generation cost. The construction costs and the operating costs of Ontario Hydro have been amongst the lowest in the world.

Although Ontario Hydro was a monopoly, it wanted to be a high performance utility. Accordingly, it made regular comparisons of its performance (five basic objectives) with other utilities throughout the world. As a result, Ontario Hydro maintained a high performance in respect to design, construction, research, planning and operations.

Ontario social achievements: CANDU

In addition to the five basic objectives, key authorities and key leaders had other considerations that influenced decisions.

The following are major achievements other than the five basic energy objectives:

- it is my opinion that the pressurized water reactor (PWR) concept (adopted in most countries), which requires enriched uranium, is a good nuclear concept, but the CANDU concept is better tailored to providing jobs in Canada;
- the detailed design of all the nuclear reactors for Ontario Hydro was performed by Canadians;
- most of the major components other than the reactors were designed and manufactured by Canadians. One major exception was that the steam turbine-generators were designed and manufactured in other countries (Britain, the U.S., etc.). A second exception is the supply of zirconium from the U.S;
- all of the nuclear fuel is being manufactured in Canada on a competitive basis;
- most of the capital cost was achieved through Canadian labour;
- the natural uranium fuel is indigenous to Canada. Canada does not have enrichment capacity and these reactors do not need enriched uranium.

In contrast, the largest cost for coal-fired generation in Ontario Hydro was for coal procured from the United States. The second major benefit from the CANDU program is that the nuclear option kept the delivered cost of electricity in Ontario below the average delivered cost of electricity in the U.S. This kept Ontario industry in a competitive position insofar as electricity was a factor.

Conclusion

Canadians in Ontario committed, built and operated nuclear-electric generating stations, which now provide about 50% of the electricity in Ontario using uranium, which is a Canadian resource.

In 1989 the CANDU concept provided operating and planned electric power in Ontario equivalent to eight Niagara Falls, at the lowest cost in the world.

The CANDU concept is tailored to Canadians, uses Canadian resources and provides jobs to Canadians.

Re-establishing capability

This paper has focused on 1942 to 1977, the period during which the CANDU was developed and became commercially competitive. Some information also was presented about the commitment, construction and excellent performance of the first four commercial reactors in Ontario. The two nuclear utilities with the lowest total energy cost in the world were Ontario Hydro and EDF in France.

The acquisition of the five Ontario Hydro nuclear stations was achieved through the former Design and Construction Branch of Ontario Hydro and the Nuclear Power Plant Division of Atomic Energy of Canada Limited.

It is with pride and recognition of the many men and women of the nuclear industry in Canada that we look forward to the future of Canadian nuclear technology. ■

RAPS I control room