Canada's Nuclear Achievement Technical and Economic Perspectives

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The following paper was prepared for the "Celebration of Canada's Nuclear Heritage" marking the 50th anniversary of the start-up of the ZEEP reactor in 1945.

Introduction

Canada's leading role and eminent accomplishments in nuclear development now span more than half a century. They encompass aspects as diverse as the design and sale of nuclear power reactors and research reactor technology, to the establishment of a corps of scientists, engineers and technologists with the expertise to address a wide scope of important nuclear science issues. The success of a country of modest technical and financial resources, like Canada, in the highly technical and very competitive nuclear field is surprising to many Canadians, and does not fit the usual image we have of ourselves as "drawers of water and hewers of wood". For this reason alone, Canada's nuclear achievement makes an interesting and timely story.

To address the many facets of Canada's nuclear activities over the past 50 years would obviously require space far beyond that available in this paper. We have therefore limited this review to highlights we judge to be the most pertinent and interesting from an historical, technical and economic perspective. We also indicate briefly our view of the future of nuclear power in the overall context of energy needs in a world that is becoming more industrial and increasingly environmentally conscious.

A Brief History

Canada's formal entry into the nuclear age was not enmeshed in technical or political jargon. It was heralded by a simple yet compelling phrase. "Okay, let's go," said C.D. Howe, Minister of Munitions and Supply in the Canadian wartime cabinet, on 1942 August 17.[1]

Howe's decision was the culmination of a year-long discussion with Britain and the United States to move to Canada the heavy water and uranium dioxide research that was then being done at the Cavendish Laboratory in Cambridge, England. By that time, the nuclear story was taking on dimensions of intrigue and adventure worthy of a Hollywood movie. Indeed, 25 years later, Kirk Douglas and Richard Harris portrayed the story of the heroic efforts to remove Norway's heavy water from the grasping hands of Nazi raiders in the film "The Heroes of Telemark". In good screenplay fashion, the predictable "blow-up-the-factory" plot has Douglas and Harris battling with each other more than with the enemy soldiers overrunning Norway. In historical fact, the 185.5 kilograms of Norwegian heavy water – the only heavy water in the world at the time – ultimately found its way to Canada, via France and Britain. It was indeed a saga of adventure.

By the time Canada's own heavy water was first produced in 1943, as a by-product of Cominco's operations in Trail, British Columbia, the AngloCanadian project was under way, and Canada's nuclear story was beginning to unfold. It began in a military context, with the transfer of technology from Britain to Canada, continued with the development of cooperation with the United States, and later moved into a situation where Canada competed in reactor design and sales with its two erstwhile partners. It also moved into a situation where Canada pursued only the peaceful applications of nuclear energy.

As historian Robert Bothwell has observed, "Nuclear fission, nuclear weapons, and nuclear energy are an international phenomenon, and Canada's atomic energy project grew up in a context far beyond its borders."[1] But the context was indigenous as well as international. By the 1940s, Canada's nuclear pedigree was well-established, having begun before the turn of the 20th century when Ernest Rutherford set up a laboratory at McGill University in Montreal for research into the structure of the atom and radioactivity. Rutherford contributed to modern atomic theory with his concept of ion behaviour. "Ions are such jolly little beggars; you can almost see them," he quipped.[2]

In 1931, prospector Gilbert Labine discovered Canada's first uranium deposit at Great Bear Lake in the Northwest Territories. Maclean's magazine reported at the time that "At one stroke the northward thrust of civilization through the Northwest Territories to the borders of the Arctic Sea has

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been given an impetus and objective."[2] Eventually, Canada became the world's largest uranium producer and exporter.

In 1940, George Laurence, protege of Canada's chief scientist, Chalmers Jack MacKenzie, began experimental work on nuclear fission at the National Research Council laboratories in Ottawa. This work was continued in laboratories established at the University of Montreal as part of the Anglo-Canadian project. It was a favourable environment allowing C.D. Howe, a former professor of engineering and a successful businessman familiar with the management of large projects, to keep his finger on the pulse of an enterprise fraught with technical and intellectual challenge.

An early remarkable achievement of the Canadian nuclear program occurred on 1945 September 5. By then, the Montreal project had moved to the Chalk River Laboratories (CRL). From there, Lew Kowarski, who had followed the prized heavy water on its travels from France to England to Canada, sent a cryptic telegram to Ottawa. It said simply, "Operational condition reached."[3] This understated message referred to the first self-sustaining nuclear chain reaction in the Zero Energy Experimental Pile reactor (ZEEP). The event marked the beginning of a half-century of progressive achievement and universal recognition for the Canadian nuclear industry.

The possible use of nuclear energy for electric power production was discussed in the early years of the nuclear research program, but the first definitive key decision came early in 1953 when C.D. Howe stated in the House of Commons, "Here in Canada we believe that the time has come to undertake the development of atomic power in this country, and discussions are going on as to ways and means of bringing about that development. We feel that the production of power is the concern of those who distribute power, organizations like the Hydro Electric Power Commission of Ontario, or the major privately-owned power companies."[4] Half a century after Rutherford's discoveries, Howe, MacKenzie and Laurence were pushing Canada into 20th century high technology. "Canadians were no barefoot water-boys when atomic science matured into nuclear technology," writes Ray Silver, a journalist and author who has been observing the nuclear scene for more than 40 years.[2]

Howe's conclusion led quickly to another key decision when Atomic Energy of Canada Limited (AECL) agreed to set up a study team, headed up by Harold Smith of Ontario Hydro, to look at a small power reactor. In addition to Ontario Hydro staff, the team had representatives from other utilities, industry and consulting engineers. The specific goal was to have generating stations with excellent safety, environmental, and reliability characteristics, developed and made in Canada, so as to provide an overall benefit to the Canadian community.

W.B. Lewis, an outstanding scientist of world stature, and his colleagues at AECL's Chalk River Laboratories, provided the scientific impetus that the engineers translated into practical plans. Lewis pursued the preservation of neutrons with evangelical intensity. His commitment to neutron economy resulted in low fuel costs for CANDU reactor plants, and this became a significant factor in their success.

In 1987, the centennial of engineering in Canada, the CANDU reactor was ranked as one of the country's top ten engineering achievements. In a commemorative publication,[5] CANDU reactor development was described as follows: "The CANDU (Canada Deuterium Uranium) nuclear reactor is a case where Canada carried through with the development of new technologies created during the war. In 1945, the ZEEP reactor at CRL became the world's first nuclear reactor in operation outside the United States. This was followed in 1947 by NRX, the world's most powerful research reactor, and by the NRU reactor at Chalk River in 1957. These reactors provided the base for the development of fundamental nuclear power technology."

The commemorative document also noted that, "During this same period, Ontario Hydro was looking for new sources of electricity to satisfy the rapidly growing demand in the province. The joint industry-government approach that had proved so successful in Canada in the past was followed. AECL, Canadian utilities and private industry concluded that the CANDU reactor was the route to pursue."

The Present

It is now 40 years since the partnership was formed between Atomic Energy of Canada Limited, Ontario Hydro and Canadian General Electric to build Canada's first nuclear power plant called NPD for Nuclear Power Demonstration. This small station was the prototype of the flagship of the nuclear industry – the CANDU reactor – which occupies a prominent position among world nuclear power reactors for its safety, dependability and performance. More specifically, the outcome was a power system that was the product of the combined forces of creative intelligence, persistent sense of purpose, tenacious pursuit of practical remedies to complex engineering challenges, and innovative solutions to make nuclear power commercially feasible. Outstanding engineering developments made a demanding technology into a reliable, safe, economic and tolerant one that has stood the test of time.

The CANDU reactor has three major features that distinguish it from the two U.S. designs which constitute its major competitors, the PWR [pressurized (light) water reactor] and the BWR [boiling (light) water reactor]. These distinguishing features are:

- its use of indigenous natural uranium as fuel, as opposed to fuel enriched in the fissionable isotope of uranium, 235U;
- the use of pressure tubes rather than a large pressure vessel to hold the fuel; and,
- the use of heavy water, rather than ordinary or light water, as coolant and moderator.

A schematic of the CANDU reactor is shown in Figure 1.

The location of the fuel, pressure tubes and heavy water, which together constitute the heart of the CANDU reactor system, are shown here, along with other major components of the overall generating system, that is, the containment building, the turbine and the generator.

The pressure tube design gives the CANDU reactor another unique advantage: the ability to refuel the reactor without shutting it down. On-power refuelling is a major contributor to the economic competitiveness of a natural uranium reactor. It provides four major advantages:

- it enables the unit to have a high capacity factor which lowers the total unit energy cost;
- it allows for increased burn-up of CANDU fuel and therefore lowers fuelling costs;

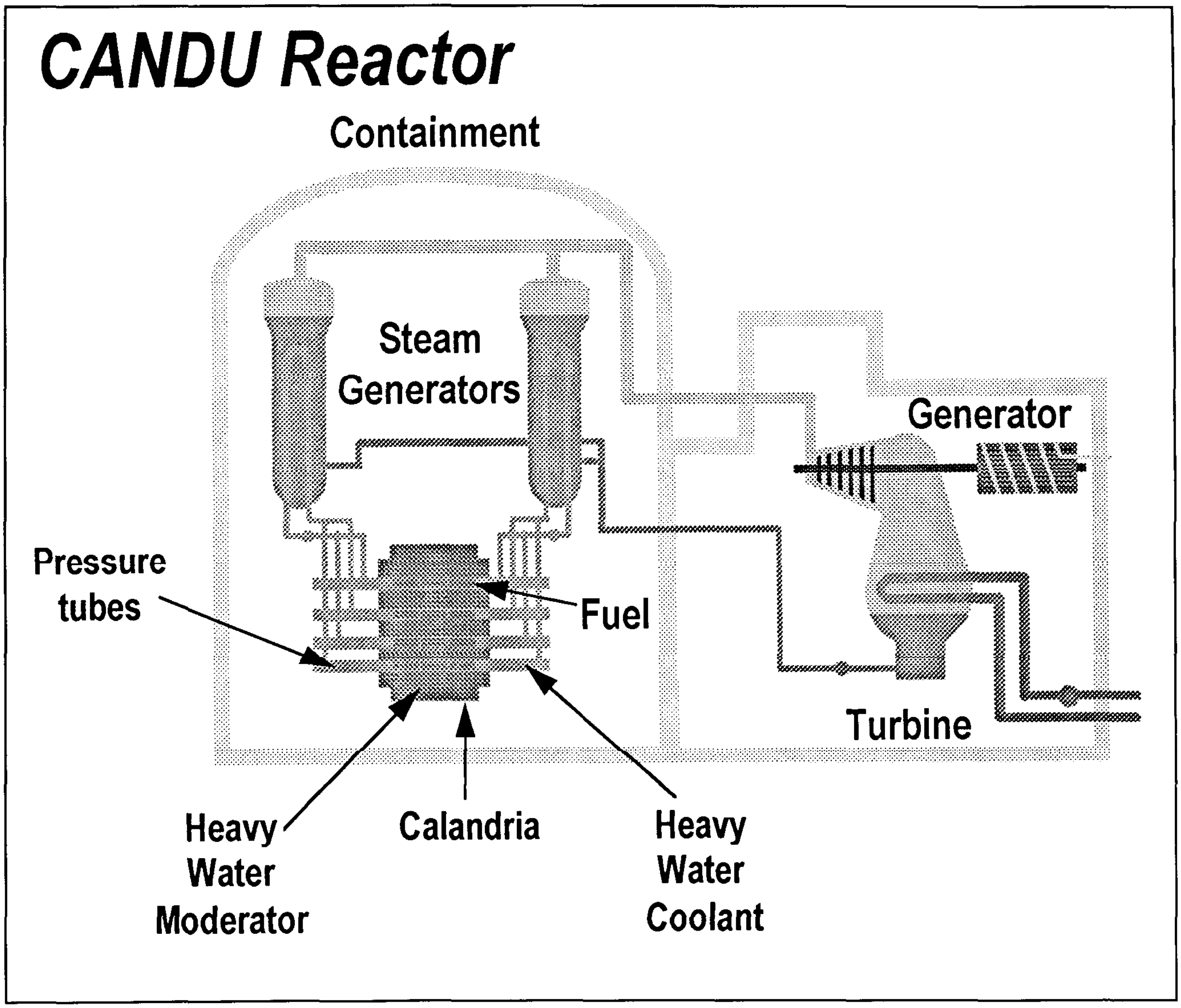

Figure 1: Schematic of the CANDU reactor

- it permits on-power removal of defective fuel, and
- it permits the scheduling of maintenance shutdowns independent of refuelling requirements.

These characteristics, as well as the engineering and operating excellence that has become the CANDU reactor hallmark, have consistently placed CANDU reactor units among the world's best-performing reactors, as shown in the next figure.[6] Of the world's 371 power reactors over 150 MW in generating capacity, six of the top 25 are CANDU reactors.

There are currently 22 CANDU reactors operating in Canada, and one in each of Korea and Argentina. Five more are under construction, three in Korea and two in Romania. In the late 1960s, Canada supplied one reactor to Pakistan and two to India. The latter subsequently built similar reactors without Canadian involvement.

Economic Benefits

The economic benefits flowing to Canada from the development and sale of CANDU reactors have been, and continue to be, significant. A recent study by Ernst & Young,[7] summarized in Figure 3, shows that, among other benefits,

- over the period 1952-1993, an investment of $4.7 billion in funding to AECL resulted in a $23 billion contribution to Canada's GDP;
- foreign exchange savings of $17 billion were realized from 1965-1989, and electricity cost savings in Ontario amounted to $5 billion;
- in 1992, 30,000 people were directly employed in the nuclear industry, and 10,000 indirect jobs were created;
- over 150 private sector suppliers have received business in goods and services. For example, in the period 19891993, this value was $9.4 billion. The distribution of these businesses across Canada is shown in Figure 4.

Another economic benefit of note is that the nuclear industry was only one of two high-technology industries in the period 1990-1993 that had a positive balance of trade, the other being aerospace.[8]

Technology Spin-Offs

As indicated in Figure 3, another economic benefit from Canada's nuclear development has come from technology spin-offs. Among these have been:

Lifetime World Power Reactor Performance to December 31, 1994* from among 371 reactors over 150 MW.

Rank	Country	Unit	Type	Year of First Power	Capacity Factor %†
1	Germany	Emsland	PWR	1988	91.4
2	Canada	Point Lepreau	CANDU	1982	91.4
3	Germany	Neckar 2	PWR	1989	88.8
4	Germany	Grohnde	PWR	1984	88.0
5	Canada	Pickering 8	CANDU	1986	87.9
6	Belgium	Tihange 3	PWR	1985	87.7
7	Canada	Pickering 7	CANDU	1984	87.2
8	Finland	Loviisa 2	PWR	1980	86.7
9	Hungary	Paks 2	PWR	1984	86.1
10	Switzerland	Beznau 2	PWR	1971	85.9
11	Germany	Philippsburg 2	PWR	1984	85.4
12	Hungary	Paks 4	PWR	1987	85.2
13	Hungary	Paks 3	PWR	1986	85.1
14	Canada	Darlington 4	CANDU	1993	84.9
15	Canada	Pickering 6	CANDU	1983	83.9
16	Switzerland	Gösgen	PWR	1979	83.8
17	Germany	Grafenrheinfeld	PWR	1981	83.8
18	Korea	Wolsong 1	CANDU	1982	83.7
19	Finland	TVO 1	BWR	1978	83.3
20	Spain	Almaraz 2	PWR	1983	83.3
21	Spain	Asco 2	PWR	1985	83.2
22	Belgium	Tihange 2	PWR	1982	83.0
23	Finland	Loviisa 1	PWR	1977	82.8
24	Finland	TVO 2	BWR	1980	82.8
25	Hungary	Paks 1	PWR	1982	82.7

the world's top 25 reactors

* Source: *Nuclear Engineering International*

$$\dagger\ \text{Capacity Factor} = \frac{\text{(actual electricity generation)}}{\text{(perfect electricity generation)}}$$

Figure 2: The World's Top 25 Reactors

- ***the supply of molybdenum-99 (99 Mo) used for medical diagnostic purposes***. Currently, about 80 percent of the world's supply of 99 Mo is produced in AECL's research reactor at CRL and further processed and marketed by Nordion International Inc.;
- ***research reactor designs based on AECL's MAPLE (Multipurpose Applied Physics Lattice Experiment) technology***. The 30 MW HANARO research reactor in Korea, which commenced operation this year, is based on MAPLE technology;
- ***design and supply of linear electron accelerators (IMPELA) for radiation processing applications in medical sterilization and materials properties enhancement***. Two IMPELA units were recently sold into a market that is projected to grow significantly over the next few years;
- ***eddy current probes for non-destructive examination of steam generator tubing.*** This technology is now used by Westinghouse Nuclear Energy Services under licence to AECL; and
- ***neutron and gamma dosimeters, used for example in under sea and outer space applications***. These detectors are produced and marketed by Bubble Technologies Industries Inc.

Environmental Benefits

The environmental advantages of nuclear power can be categorized in general as two-fold: first, nuclear electricity generation entails a process that does not involve chemical combustion of fossil fuels that produces carbon dioxide (CO_2), a major contributor to what is known as the "Greenhouse Effect",[9] and other atmospheric pollutants such as sulphur dioxide, nitrogen oxides, carbon monoxide and particulates. Second, nuclear power entails the practice of containment rather than dispersal of the wastes produced. Some representative data, contrasting a nuclear plant with a coal-fired plant, are given in Figure 5.[10]

Concern has been growing steadily about the extent to which the greenhouse effect is resulting in global warming. It is estimated that CO_2 today accounts for

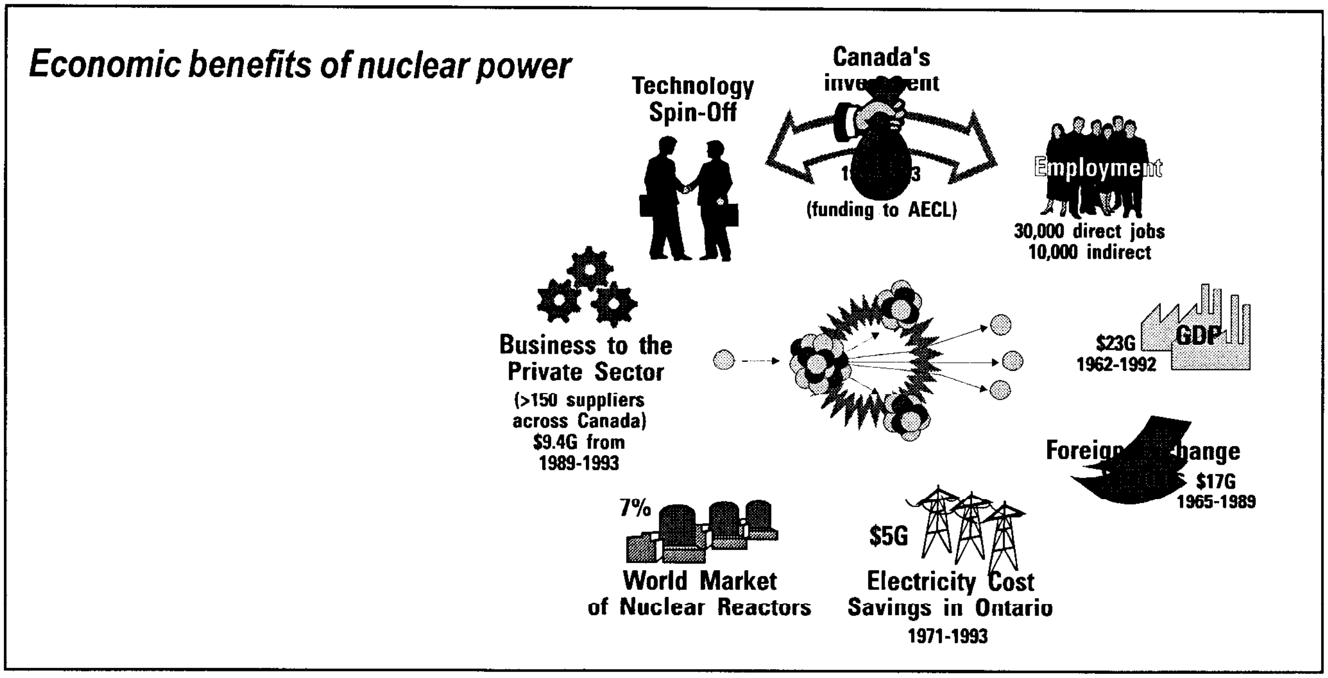

Figure 3: Economic benefits of nuclear power

more than 60 percent of the greenhouse perturbation.[9] Most current climate models suggest that when the concentration of CO_2 in the atmosphere reaches twice preindustrial levels (approximately 1.2 trillion tonnes of carbon versus about 760 billion tonnes today), the global mean temperature will increase by 1.5 to 4.5C.[11] Temperature increases of this magnitude could result in climatic disruptions such as major storms, droughts, heat waves and flooding of coastal areas. In important food producing areas, large changes could be disastrous.[12]

One can conclude from these data, even recognizing that the consequences of the greenhouse effect (global warming) may not be as dire as now predicted, that avoiding the release of CO_2 to the atmosphere to the maximum extent possible makes prudent environmental and economic sense. The risks of doing otherwise are simply too great. We would note that if nuclear electricity were replaced today by coal burning generation, emissions of CO_2 world-wide would rise by seven percent or two billion tonnes per year.[13] In Canada, nuclear versus coal burning electricity generation by Ontario Hydro, in the period 1971-1990, has obviated the release of 609.5 million tonnes of CO_2 in Ontario.[14] Similarly, avoidance of the production of the other pollutants from fossil fuel burning, noted above, has a significant beneficial effect given that these pollutants affect both human health and vegetation.

The radioactive wastes produced by the nuclear generation of electricity are for the most part retained within the plant. While a small fraction is released (strictly controlled within regulatory-allowed limits), the vast majority of wastes are contained and isolated on site until a decision for final disposal is taken.[15]

Although the technology for disposal of all radioactive waste (low-, intermediate- and high-level) has been or is being developed, it is the last that has required most attention. More than 15 years ago, on behalf of the Canadian government, AECL initiated an extensive research and

Geographic Distribution of Suppliers to the Canadian Nuclear Industry

Location	*No. of Suppliers*	*Percentage*
British Columbia	3	2.0
Alberta	21	13.6
Saskatchewan	4	2.6
Ontario	89	57.8
Quebec	18	11.7
New Brunswick	4	2.6
United States	15	9.7
Total	154	100.0 %

Source: Ernst & Young, "The Economic Effects of the Canadian Nuclear Industry," Oct. 1983.

Figure 4: Geographic Distribution of Suppliers

development (R&D) program for the safe and permanent disposal of nuclear fuel waste (high-level waste).[16] The program has involved many scientific disciplines, including geological and environmental sciences, physics, chemistry, mathematics, metallurgy, engineering and social sciences. Much of the work has been conducted by AECL at its Whiteshell Laboratories in Manitoba, (which include the Underground Research Laboratory), at its Chalk River Laboratories in Ontario, and at several field research areas in the Canadian Shield. Other organizations have also participated in the R&D on disposal, including Ontario Hydro, Natural Resources Canada, Environment Canada, universities and consultants in the private sector. The technical aspects of the program have been continuously reviewed by representatives from learned scientific and engineering societies in Canada. Also, AECL has consulted broadly with members of Canadian society to help ensure that the proposed disposal concept and the way in which it would be implemented are technically sound and represent an acceptable disposal strategy.

The proposed disposal concept entails geological disposal in which the waste is sealed in long-lasting containers emplaced in a disposal vault excavated at a nominal depth of 500 to 1000 metres in plutonic rock of the Canadian Shield. Each container is surrounded with a sealing material, and all excavated openings and exploration boreholes are (eventually) sealed to form a passively safe system. Humans and the natural environment would be protected from contaminants in the waste by multiple barriers: the container, the very low-solubility waste form, the vault seals and the geosphere.

This disposal concept is now being reviewed by a federal Environmental Assessment Panel. Acceptance of the concept would not imply approval of any particular site or facility. If the concept were accepted and implemented, a disposal site would be sought, a facility would be designed specifically for the proposed site, and the potential environmental effects of the facility at the proposed site would be assessed. Concept implementation would occur in stages and would entail a series of decisions about whether and how to proceed.

Nuclear Research and Development

Throughout its history, AECL has maintained a very broad base of scientific and engineering expertise. The relative prominence of the various disciplines has of course evolved over the years as the technology has expanded and matured. In the early period, the various sub-disciplines of physics dominated as reactor concepts were explored and the necessary fundamental data were accumulated. The importance of chemistry in its many manifestations grew over the early period and has continued to grow as the R&D has increasingly focussed on the areas of reactor and steam generator equipment maintainability, and fuel cycle diversification. The life sciences were also important in the earliest period given that health and safety were recognized from the start as critical issues. And the life sciences, particularly radiation biology, have continued in importance as AECL explores the fundamental interactions of radiation with humans and the environment. The environmental sciences have grown considerably in application over more recent years, particularly in conjunction with the waste management program. Throughout, engineering disciplines, particularly mechanical, chemical and electrical, have played vital roles as the basic and applied science has been transformed into operating reality. A survey of the various disciplines, and their area of particular application, is given in Figure 6. A comprehensive technical history of AECL, as seen from its research laboratories, has recently been compiled and will be published in 1996.[17]

AECL also conducts scientific research which, while related to its primary mandate to develop and apply nuclear power technology, and CANDU reactor technology in particular, contributes more directly to the overall understanding of nuclear and related science in general. These R&D activities, which have given AECL the role of Canada's de facto national nuclear laboratory, fall into several categories of which the highest profile are:[18]

(i) heavy-ion physics, primarily through the operation of the Tandem Accelerator Superconducting Cyclotron. This basic nuclear science activity, to investigate the fundamental properties of matter, has kept AECL and Canada at the forefront of nuclear physics research since the 1940s;

(ii) condensed matter science, involving thermal neutron scattering to probe solids and liquids at the level of interatomic and intermolecular interactions. The supply of neutrons from the NRX, and later the NRU, research reactors has allowed AECL researchers, and researchers from other organizations, to compete successfully in this important field for over 40 years. In 1994 the

Nuclear versus Coal-Fired Electricity Generation (1000 MW)

	Coal	***Nuclear***
Fuel (tonnes / year)	**2.5 - 3.0 M**	**125**
Wastes (tonnes / year)	**• Ash 300-700 k** **• CO_2 6 - 7 M** **• SO_2 40-120 k** **• NO_x 20-25 k**	**• Used fuel 125** **• Low- and Intermediate-Level Radioactive Waste 200-600**

Figure 5: Nuclear versus Coal-fired Electricity Generation

Nobel Prize in Physics was awarded to Bertram Brockhouse for his pioneering work in neutron scattering at CRL in the 1950s and early 1960s;

(iii) neutrino physics, through participation in the Sudbury Neutrino Observatory (SNO), an internationally-sponsored project located in a deep mine at Sudbury, Ontario. SNO is intended to measure the properties of neutrinos through the detection of solar neutrino emissions;

(iv) accelerator technology development, for the design and construction of major accelerator facilities. This work has led to a technology spin-off, the IMPELA, as noted earlier; and

(v) radiation applications that exploit AECL's long-standing expertise in radiation chemistry to develop a wide array of industrial applications for radiation, and particularly to support the marketing and sales of the IMPELA accelerator.

The Future

Future developments will concentrate on AECL's flagship product, the CANDU reactor. In the shorter term, these developments will be evolutionary and will be designed to meet emerging utility design and performance requirements by building on the CANDU reactor's unique strengths and by integrating new technologies as they are developed.[19] The proven features of the CANDU reactor that will be retained include:

- horizontal channels (pressure tubes),
- heavy water moderator,
- fuelling flexibility resulting from high neutron economy,
- on-power refuelling,
- simple, low cost fuel bundles, and
- zirconium alloy pressure tubes.

while the high-level goals to be addressed are:

- maintenance of capacity factors greater than 90 percent,
- reduction of capital and operating costs,
- further development and exploitation of fuelling flexibility,
- further enhancement of safe operation (including reduced frequency/consequences of human error), and
- increased level of plant protection.

One of the most important features of the CANDU reactor under active development focuses on its fuel cycle flexibility.[20] As shown schematically in Figure 7, the CANDU reactor's neutron economy permits the use of not only natural uranium (0.7% 235U) but other sources ranging from slightly enriched uranium (1.2% 235U) to used fuel recovered from PWRs.

In the longer term, more dramatic changes in the design of future CANDU reactors, such as the use of more thermodynamically efficient coolants, for example organic liquids, are envisaged. But whatever changes may be pursued through innovative R&D, the goal will remain the same: to maintain and improve the excellent safety, reliability and competitive performance of the CANDU reactor, and to carry its outstanding record into the 21st century.

And what does the future hold for nuclear power? Undoubtedly the intensity of lessons learned from history will help determine the brightness or dimness of future prospects. The dawning of the second half-century of nuclear fission presents a renewed sense of challenge.

Internationally, nuclear energy is on high-level agendas where world-wide issues of economic development, energy supply, environmental protection, safety, health and quality of life are being addressed. The concept of sustainable development is no longer a debating point but a point of departure. And it gives nuclear power an edge over energy sources that do not involve the safe containment and disposal of wastes.

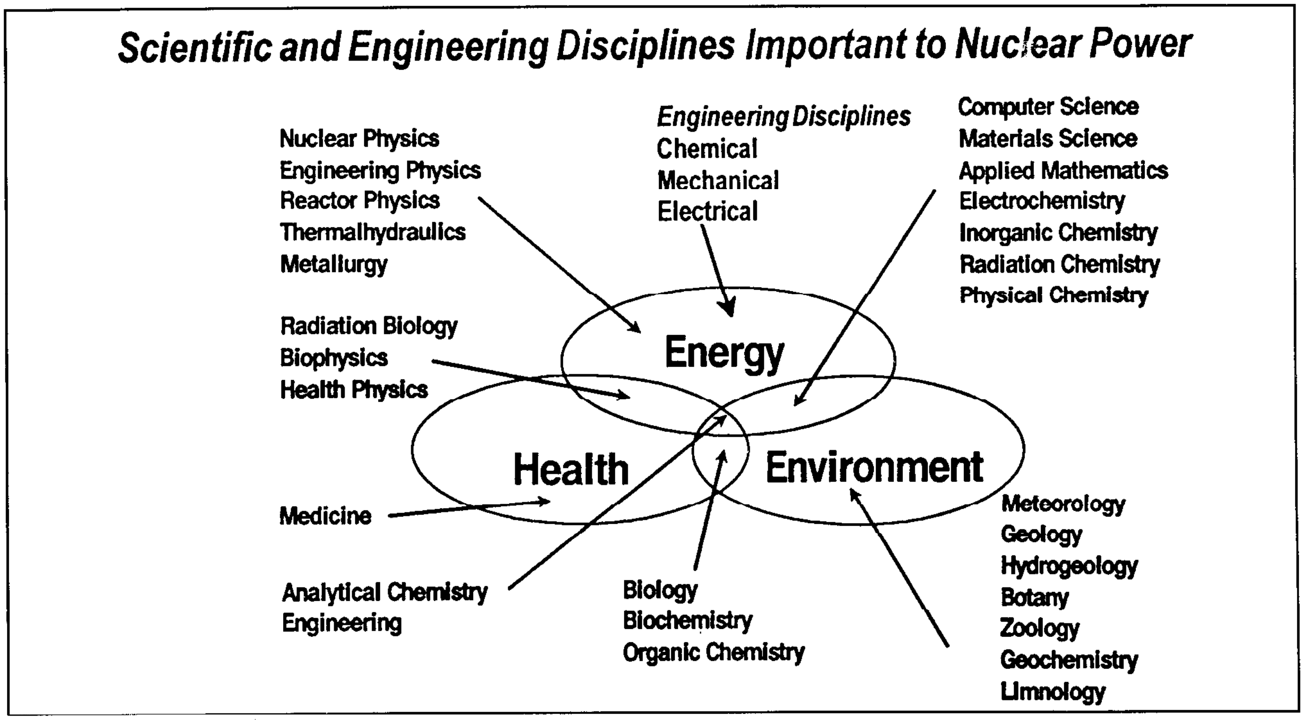

Figure 6: Scientific and Engineering Disciplines Important in Nuclear Power

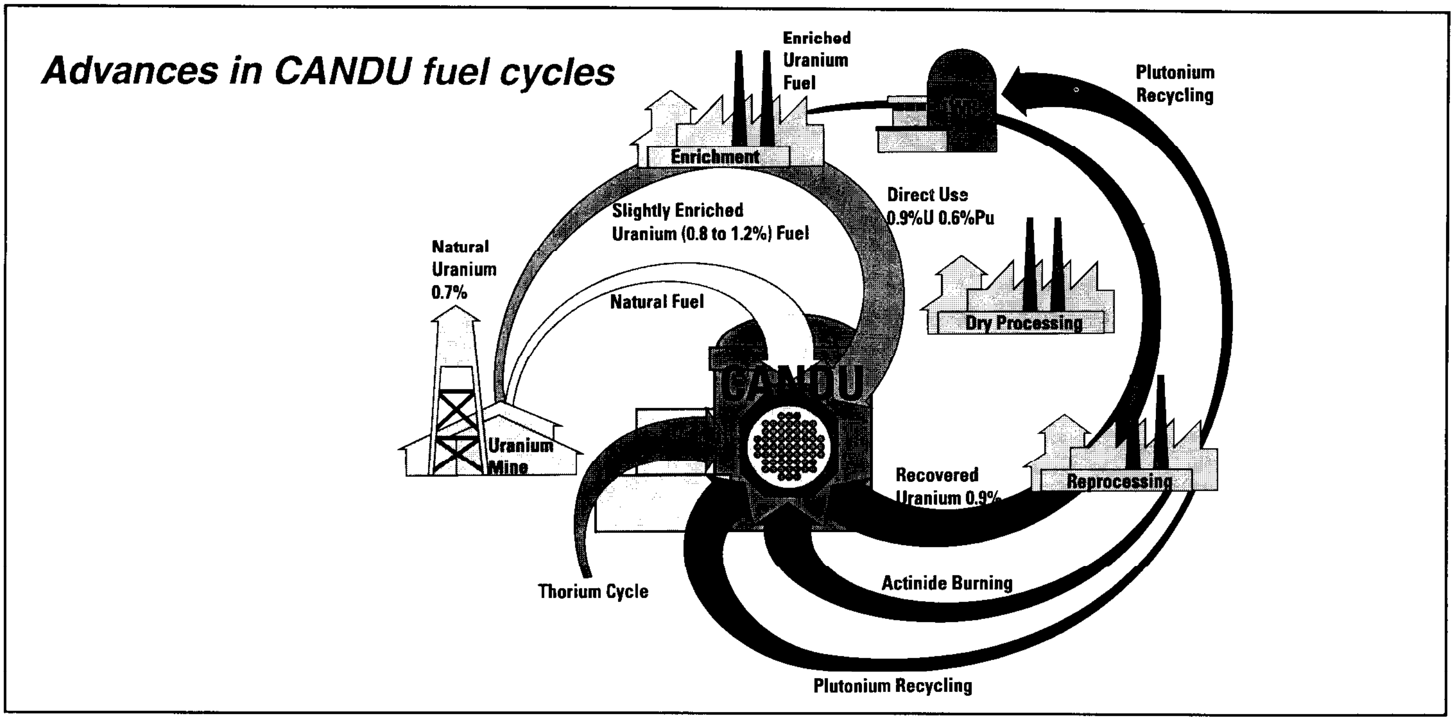

Figure 7: Advances in CANDU Fuel Cycles

The global energy challenge is to meet the potentially vast demands of the next century, while maintaining a healthy environment. Even the most intractable conservationist would find it hard to deny the need for more energy or the right of billions of people, not to luxury, but to the basic necessities that electricity can provide.

The developed nations today have a population of about 1.2 billion people, and that number is projected to remain approximately the same at least up to the middle of the next century.[21] In the same period the population of the developing countries, now 4.5 billion, is predicted to reach 8.6 billion. If one assumes, as one must, that this dramatic population growth is going to be accompanied by economic development, one must ask where the energy is going to come from to power the development and nourish the people. Currently, about 90 percent of the world's energy comes from burning fossil fuels, releasing approximately six billion tonnes of carbon to the atmosphere annually.[22] Coal, oil and gas will continue to be the energy sources of first choice for emerging nations because of the relative accessibility of these sources and the speed with which they can be integrated into growing economies. Growing energy demand will also spur the use of hydro-electric power but, because its accessibility is limited, its proportion of the energy mix will not increase. Similarly, the renewable sources such as biomass, wood, solar and wind will increase but their relative proportions will remain small.

Meeting the needs of the developing world is hard to imagine without recourse to nuclear power. Equally hard to contemplate is the heavy environmental burden that future generations will bear if a massive increase in the burning of fossil fuels precludes the alternatives.

Despite the need for nuclear power, it would be naive to think that the opposition to it will suddenly lessen. Those in the nuclear industry must therefore work harder to ensure that the public receives a balanced picture. While we may not be able to match the rhetoric of the opposition, we are at least accountable, and we owe the public the facts that will help them to make up their own minds. In the final analysis, it is only the appropriate degree of balance in the views of the public that will permit nuclear power to make its proper contribution to the energy supply and to the well-being of the world in the years to come.

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