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Nuclear Energy and The Global Problematique

Fred Boyd

This paper deals with nuclear power, i.e., the use of nuclear energy to produce electricity, and, thereby, the contribution of nuclear power in meeting energy demands. However, there are many other beneficial applications of nuclear science and technology, such as:

- ◊ *the use of radioisotopes for medical diagnosis*
- ◊ *food preservation*
- ◊ *well logging*
- ◊ *medical treatment*
- ◊ *industrial radiography*
- ◊ *polymerization*

Canada is a world leader in the supply of medical and industrial radioisotopes.

Background

The heart of a nuclear power plant is a nuclear reactor. All current nuclear reactors derive their energy from nuclear fission – primarily the splitting of the U235 isotope of uranium. Fission is induced by the absorption of a neutron and in the fission process an average about 2½ neutrons are emitted. If at least one of these can go on to cause fission in another U235 atom then a sustaining chain reaction can occur. However, the neutrons produced in fission have high energy and high speed. The likelihood of a neutron entering a U235 atom and causing fission is much greater if the neutron speed is slow. Hence, there is a need for a "moderator", a material which will slow the neutrons without absorbing them. "Thermal" reactors, the type used in all nuclear power plants, are essentially assemblies of uranium separated by a moderating material.

To be effective a moderating material must have a small nucleus, i.e., a small atomic number. The most efficient "moderator" is "heavy water" which is water in which the hydrogen atom is replaced by deuterium an isotope of hydrogen, written as D_2O. Other moderators which are used are ordinary water and carbon. With D_2O or carbon as a moderator, a self-sustaining "critical" assembly can be achieved using ordinary or natural uranium, despite the fact that U235 makes up less than 1% of natural uranium, most of which is the isotope U238. Ordinary water is a good slowing-down material but it absorbs neutrons. Therefore "light water reactors", which are used in the USA and many other countries, must use uranium fuel which is "enriched" in the isotope U235. Enrichment is a complicated and expensive process.

"Fast" reactors have been developed which can "burn" U238, thus extending the uranium resource by up to a factor of 60 or 70. However, these are much more complicated than thermal reactors and none has progressed to the commercial stage.

Some Early Canadian Nuclear History

Before proceeding with the main topic it might interest readers to know that Canada has had as long an involvement with nuclear science and technology as any country. In 1941, Dr. George Laurence, together with Dr. Bernard Sargent, built a " sub-critical pile" in the basement of the old National Research council on Sussex Drive in Ottawa. They used coke and uranium oxide (U_3O_8) to try to achieve a self-sustaining nuclear chain reaction. Because of the impurity of the ingredients they were not successful in that but did show the multiplication of and distribution of neutrons within the assembly. In 1942 the British government decided to move its embryonic nuclear research out of the UK and chose Canada, at least partially because of the work of Laurence. With the initial co-operation of the USA, the British and Canadian governments set up the Montreal Laboratory in a building of the new University of Montreal, with scientists from the UK, several who had escaped from Europe and a number of Canadians. Some of the Europeans had brought with them almost all of the heavy water then in existence, which ended up providing the focus for the work at the Montreal Laboratory and the subsequent Canadian program.

Despite off-and-on relations with the USA, the Montreal Laboratory group developed the theory of nuclear reactors and began the design of a large natural uranium–heavy water research reactor that could also produce plutonium (which could be used in nuclear weapons then under development).

In 1944 the decision was made to build the reactor and a remote site on the Ottawa River, about 200 km west of Ottawa was chosen. This was the beginning of the Chalk River Laboratory. When WW II ended the Canadian government decided to continue the research for peaceful purposes. Just a year later, in September 1945, the first reactor outside the USA, the "Zero Energy Experimental Pile (ZEEP) went "critical". ZEEP was a small assembly of natural uranium rods clad in aluminum in a large tank of heavy water. ("Pile" was an early term for a nuclear reactor, derived from the pile of carbon blocks and uranium of the first reactor at the University of Chicago in 1942).

Just a year after the end of WW II, in 1946, the Canadian government passed the Atomic Energy Control Act, one of the first such legislation in the world, which declared "atomic energy" to be of national importance and made its control a federal responsibility. That Act established the Atomic Energy Control Board which is still the regulatory agency for nuclear activities. A new law, the Nuclear Safety and Control Act, was passed in 1997 and is expected to be put in force in 1998 when all the new regulations are ready. Under this Act, the AECB will change its name to the Canadian Nuclear Safety Commission. The AECB operated for a decade and a half with a very small staff. George Laurence became its first full-time president in 1962 and began the development of the 400 person agency of today.

In 1947 the large research reactor whose design was begun at the Montreal Laboratory, started up. The NRX reactor had an initial power of 20 megawatts (thermal). It was fuelled with natural uranium, cooled with ordinary water and moderated by heavy water. After a serious accident in December 1952, NRX was re-built to have a power of 40 MW(thermal). Over the more than four decades that it operated (until 1989) NRX was for a time the most powerful nuclear test reactor in the world. It also produced many radioisotopes which led Canada to become a major supplier for the world.

The design for the first, demonstration, Canadian nuclear power plant was begun in 1955, the design modified in 1958, and the 20 MW (electrical) NPD started up in 1962. It was the forerunner of the CANDU design whose main features are heavy water cooled and moderated, natural uranium in the form of UO_2, pressure tubes containing the fuel and pressurized coolant, on-power refuelling.

NPD was followed soon afterwards by the 200 MW(e) Douglas Point prototype, and the first four 500 MW(e) units of the Pickering Nuclear Generating Station. Over the next two decades there was a rapid expansion of Canada's nuclear power plants:

Bruce A	1970s	4 x 900 MW(e)
Pickering B	1980s	4 x 500 MW(e)
Bruce B	1980s	4 x 900 MW9e)
Point Lepreau	1980s	1 x 600 MW(e)
Gentilly 2	1980s	1 x 600 MW(e)
Darlington	1990s	4 x 900 MW(e)

Electricity Use

About 1/3 of total energy use, world wide, is in the form of electricity. Electricity usage, like energy usage generally, varies considerably world wide. Approximate per-capita figures are:

- Canada/USA/Sweden: 15,000 kWh/yr.
- Japan: 7,500 kWh/yr.
- Korea: 5,000 kWh/yr.
- China: 1,000 kWh/yr.

With its rapid industrialization the demand for electricity in China is increasing at a rate of 10%/yr, which is typical of many developing countries. Currently, China uses coal for approximately 75% of its electricity production. Although It has stated a target of 50% for by the year 2020 even so the use of coal will double (with attendant environmental effect).

Role Of Nuclear Power

Currently nuclear power produces about 17% of the world's electricity. The percentage varies greatly in different countries. Among OECD countries France has had the strongest and most successful nuclear program and now produces about 77% of its electricity from nuclear sources. Not only has this greatly reduced France's dependency on foreign sources of oil but it has also allowed it to export electricity to its neighbouring countries. The percentage of electricity from nuclear power in other OECD countries ranges from 17% in Canada, 26% in the UK, 32% in Japan and 57% in Belgium.

In 1996 there were 442 nuclear power units in operation and another 36 under construction. Most of the expansion is occurring in east Asian countries, China, Japan, Korea, Taiwan.

Ontario Hydro's Nuclear Program.

As noted above, Ontario Hydro has 20 large nuclear power units, all of which are the CANDU type. In 1996 nuclear power provided about 2/3 of the electricity in Ontario.

Over the past few years there has been evidence of poor performance of the nuclear plants. In late 1996 the then president of Ontario Hydro brought in a team of consultants from the USA. That group initiated an intense review of Ontario Hydro's nuclear operations under the title of Independent Integrated Performance Assessment (IIPA). The report of that assessment was released in August 1997 and was scathingly critical of the management of Ontario Hydro's nuclear plants. That led to a "recovery" plan, given the name Nuclear Asset Optimization Plan (NAOP), which involves shutting down seven of the oldest units (one was already shutdown because of serious problems with its steam generator) and devoting all of the organization's efforts to improving the operation of the 12 remaining units.

The IIPA report used repeatedly the term "marginally acceptable". The US consultants emphasized that the plants were still safe but that the management was very poor . An indication of this is that the average "capacity factor" (percentage of power produced of the design power) had fallen from over 80 % in the early to mid 1980s to about 60 % in 1997.

Factors To Be Considered

Economics of nuclear power

A study conducted by the OECD in 1996 provided the following estimated "levelized unit energy costs" of electricity generated by nuclear, coal and natural gas. This was based primarily on the situation in western Europe but also took into account American and Japanese data. The costs are shown in units of 10^{-2} ECU (1995) per kWh.

Discount rate	Nuclear	Coal	Gas
5%	3.06	3.29	3.57
10%	4.49	4.18	3.96

Although the study examined "low", "medium" and "high" price scenarios for fossil fuels the above chart just shows the figures for the "medium" prediction. Because nuclear plants are large and "capital intensive" their economic competitiveness depends very much on the price of money (discount rate).

Proliferation

One of the concerns people have about nuclear power is that its existence will enhance the likelihood of nuclear weapons. In 1970 the international community passed the Treaty on the Non-Proliferation of Nuclear Weapons, commonly referred to as the NPT. Under that Treaty countries have given up an unprecedented amount of sovereignty to allow international inspectors to monitor the use and movement of all nuclear materials in their territory. The program and inspections are carried out by the International Atomic Energy Agency, a sister agency of the United Nations which was created in 1956Over 185 countries have signed and ratified this convention; the only significant hold-out being India. Existing nuclear weapon states at the time of the treaty were allowed to maintain their weapons programs but other treaties have since been signed among them to reduce nuclear weapons stocks. Since the NPT came into effect there has been no identified diversion or loss of a significant amount of nuclear material.

Canada has been in the forefront of non-proliferation policies and practices. Since the mid 1970s Canada has required adherence to NPT or submission to equivalent IAEA safeguards inspection for nuclear export or assistance.

Safety

Nuclear power is (probably) the most regulated industrial activity. All countries with nuclear programs have specific nuclear regulatory agencies. In Canada it is the *Atomic Energy Control Board*, which was set up in 1946.

The regulatory process involves extensive "what-if" analyses – during design and continually during operation. A concept called "defence-in-depth" has been adopted internationally for a number of years (except FSU). This involves several layers of protection in the form of physical barriers and procedural controls to prevent or mitigate possible failures or events. As an example, Canadian nuclear power plants have **two** safety systems, an emergency core cooling system, and containment, which are completely separate and independent of the operating systems and of each other. There is extensive international collaboration in the area of nuclear safety – through IAEA, Nuclear Energy Agency of the OECD and other intergovernmental fora and industry alliances such as International Nuclear Power Organization, and World Association of Nuclear Operators. In 1996 the international Nuclear Safety Convention came into force with 65 signatories (40 ratified to date). This treaty requires periodic reviews of nuclear safety programs which are subject to "peer" review. The first such review will take place in 1999.

Chernobyl

The accident to one of the nuclear power units at Chernobyl near Kiev in the Ukraine in 1986 was undoubtedly a catastrophe. Officially 28 died within 3 months from radiation and 3 others from other injuries; 14 died over the next several years but not all from radiation. Thousands of square kilometres were contaminated with radioactive fallout and a considerable amount of agricultural produce was taken off the market throughout eastern Europe. Some of the action has been judged, retrospectively as extreme. Most of the contaminated land in the Ukraine has been put back in use, except that immediately around the plant.

The major identified and confirmed health effect has been over 800 cases of radiation-related thyroid cancer in children due to ingestion of radioactive iodine fallout. Of these, three had died as of 1996. While tragic, this form of cancer is treatable. The prediction of thousands of premature cancers is based on an improper application of a theory of linear dose-effect relationship for radiation, which is now very much in question.

The cause of the accident has been attributed to an inadequate design which would never have been approved in the west and operational errors that involved an unusual test in which safety procedures were ignored and safety systems by-passed.

Waste

Radioactive wastes are generally categorized as: "low-level", "medium-level" and "high-level". The first two consist primarily of "garbage" from nuclear operations, e.g., rags, clothing, some equipment, and has mostly short-lived radioactivity. Some of this is incinerated (in special incinerators), some buried in concrete bunkers "High-level" waste is primarily spent nuclear fuel from reactors. However, this is not necessarily "waste", since the fuel coming out of a reactor still contains considerable energy. In fact, tests are underway to take the "spent" fuel from a "light water reactor" and place it (after some re-configuring) in a CANDU. The LWR fuel is initially enriched and even at discharge has more U235 than natural uranium.

"High-level" waste (spent fuel) is highly concentrated. The total from a 1,000 MWe plant for 1 year is only about 50 to 100 tonnes. An equivalent coal-fired plant would produce about 1 million tonnes of ash in the same period. Currently spent fuel is stored in water pools at nuclear plants or, after a few years of "cooling", in concrete "silos". Several countries (Canada included) have researched and developed deep geologic disposal methods, some in salt (Germany), some in clay (USA and others), some in ancient rock (Canada). The Environmental Panel which has been reviewing the Canadian deep geologic disposal concept for eight years issued its report in mid March 1998, concluding that the concept was technically adequate but that there was not yet sufficient public acceptance to proceed with an actual disposal facility.

Environment

In December 1997, at the Kyoto conference on the environment Canada joined with other western countries in adopting targets for the reduction of emissions of "green house" gases, i.e., those gases in the atmosphere that tend to trap thermal energy and are predicted to cause global warming. Canada's target is a 6% reduction from 1990 levels by the year 2010.

In this context it is instructive to note the comparative annual emissions for an electrical generating plant with a capacity of 1000 MW(e).

Coal

CO_2	6.5 million tonnes
NO_2	4,500 tonnes
SO_2	900 tonnes
Particulates	1,300 tonnes
Ash *(Including heavy metals)*	1 million tonnes

Nuclear

- essentially no atmospheric emissions
- 35 tonnes (3 m^3) highly radioactive spent fuel
- 1200 m^3 intermediate radioactive waste
- 500 m^3 low level radioactive waste

Renewables

Solar, wind, and biomass are all very diffuse sources of energy. For example, to produce 1,000 MW(e) it would need installations of:-

- biomass: 3000–5000 km^2
- solar/wind: 50–60 km^2 *(and these are intermittent)*

Renewables (excluding the use of wood in undeveloped countries) are estimated to supply, currently, about 2% of total energy, world wide. Given their very low energy density, it is very unlikely that renewables (excluding hydro electric) could provide more than a few per cent of the world's energy needs.

Conclusion

Nuclear power offers a source of electricity:

- with no "greenhouse" emissions.
- with ample fuel supply (which has no other use)
- that is economically competitive in many areas of the world.
- with concentrated waste products that can be (and are being) safely managed
- that is safe.

Many countries, especially in Asia, recognize these advantages and are planning for extensive development of nuclear powered electrical generation.

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