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CANDU: THE CASE FOR NUCLEAR POWER

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by

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ABSTRACT

This report, written largely to appeal to both those who are familiar with nuclear power generation, and those who would like to be, focusses its attention on the problems of energy production in general, and specifically considers nuclear power and the issues in the current nuclear debate. By providing quantitative arguments and citing comparisons with the other energy alternatives, while addressing each issue in turn — from the questions of energy supply and demand, to operations, economics, safety, and waste disposal — it is hoped that the case for nuclear power, and the CANDU* reactor system in particular, will become abundantly clear. On a more sociological level, the influence of energy utilization on the quality of life is considered, and the public perception of nuclear power is analyzed, with primary emphasis on the management of public opinion, and the role of this opinion in market determination. In all, this report seeks to summarize the pertinent aspects of nuclear power operation, showing quantitatively, that CANDU reactors, today and in the future, promise to provide the world with a safe and economical energy system, capable of meeting the growing demands for thousands of years to come.

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* CANDU is derived from CANadian Deuterium Uranium.

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1.0 INTRODUCTION

Man's rapid technological developments in recent history have left him to depend ever-increasingly on what has at various stages appeared to be a less than ample supply of energy resources.

The benefits of progress are evident in today's modern society. However along with these benefits, technology carries with it a responsibility to maintain ample means and resources such that the quality of life of future generations is not detrimented by the actions of the current populace. It has become apparent that the maintenance or further improvement of the global standard of living will be realized only through the concerted and unified efforts of all those involved in the energy production sector, for it is only with a secure and economic energy supply that such an objective will be manifest.

It is the contention of this paper that nuclear power, properly utilized, can and should be instrumental in the global efforts to improve the quality of life. In a close evaluation of nuclear energy and its alternatives, the choice of the optimal major energy source becomes abundantly clear: the nuclear route best satisfies man's goals. The argument supporting this contention shall comprise the bulk of this report, with the advantages and disadvantages of all energy sources being examined, and the energy issues each in turn being addressed.

2.0 BACKGROUND

Before considering the questions of energy supply and demand one must first address the question of whether large supplies of energy are needed to bring about the desired objectives of present and future generations. The need for heavy industrialization to ensure a satisfactory standard of living should not be assumed without detailed consideration. It is only after such fundamental questions are answered, that mankind may address the quantitative problems of deciding how much energy is required and how it shall be supplied.

2.1 Energy and The Quality of Life

One of the aims of man in the world today is to reduce the economic gap between developed and developing countries. History has shown[1] that per capita income is proportional to per capita energy consumption*, and thus economic equality can only be achieved through a shifting of energy resource utilization or through an overall increase in energy utilization in the developing countries. These alternatives are examined in Section 3.3.

* Strictly speaking, energy is not consumed, but merely down-graded and added to the natural heat flow of the planet.

Not only does income rise with per capita energy consumption but so too, does the amount of time available for recreation, fulfilment, and cultural contribution[2]. In a low technology society (with a correspondingly low per capita energy use and income), most of a person's waking hours must be spent providing for his own subsistence, and free time cannot be used effectively because income is low, and hence excess funds for recreation are not available.

Increasing energy usage reduces the time required to provide for the daily subsistence of an individual, while at the same time it increases the wealth of society, resulting in a larger amount of more effectively spent leisure time. In almost every facet of our lives, technology has brought about more efficient, time-saving devices that tend to increase the wealth of society and provide more time for enjoying life's pleasures. Technology, however, brings along with it, new demands for energy -- demands that must be met if society wishes to implement its latest developments.

One must also consider the effect of an increasing population on the quality of life, and the role energy utilization plays in this scenario.

Consider a primitive society over its developmental history[2]. Initially as the population grows, the society can make increasingly effective use of the resources available to it. The productivity of the society increases. The resources, however, are finite. Sooner or later the good land is fully occupied, water supplies become inadequate, or food supplies are depleted. Productivity falls, and the society as a whole suffers.

Population growth being the rule, rather than the exception, there exists some level of population, above which no primitive society can rise without adversely affecting the quality of life. This problem is exactly that which is being faced by many Third World countries today.

Technological advances can allow a population to expand beyond these primitive natural limits. Productivity rises and peaks at a higher population level[2].

The application of technology has two effects: it not only raises the productivity of labour, but also increases the volume of production from a given land area and resource base.

However the trend cannot continue, for even in a high technology society, it appears[2] that at a certain level of population density and productivity, the growth of the population ceases, due either to changed individual motivation (as in advanced countries) or social discipline (as in China, perhaps).

Hence technology and its corresponding increase in energy utilization, allows a population to expand beyond its natural limits, but by facilitating the development of a "Value Society"[2] (one that places a high value on the individual's time), it offers the prospect of a stable population match to the capabilities of a finite environment.

2.2 The Global Situation

The more-or-less abstract scenarios discussed in Section 2.1 do not reflect the grim realitives of the actual global situation. Today there are many nations throughout the world that are suffering because they do not have sufficient technology or its energy complement to meet the demands of the ever-growing populations.

These harsh truths are discussed in Reference 3, and to cite a few examples of how technology-induced wealth has a great health effect on society, consider the following (from Reference 3):

i) The poorer countries of Africa have average life-spans of 30 to 45 years. (In North America the average is about 72.)

ii) The average lifespan is 52 years in Egypt; 45 years in India and Indonesia; 40 years in Haiti.

iii) The situation is similar in Europe as well, where the average person in the poor countries like Portugal and Yugoslavia lives to 65 years of age, while the corresponding figure is 71 in France and Germany, which are the richest European countries.

iv) The internal distribution of wealth within a country also affects the average life-span. In the U.S.A., for example, blue collar workers live approximately four years less than white collar workers. (This of course is also due to the fact that white collar workers usually have safer jobs than blue collar workers.)

Further, the emotional effects that arise when a population exceeds its natural limits can also be quite devastating. Without sufficient technological development to support a large population, unemployment will ensue. This in turn leads to depression amongst the people, frustration, and loss of hope. These culminate in increased suicide and murder rates. Indeed the psychological impact can be much more devastating than the direct health effects[3].

The poor nations of our world cannot be expected to sit idly by and watch the economic split between them and the richer nations widen. There is no reason to suspect that the world will stop progressing with three-quarters of its population having ten or twenty per cent of the material conveniences that the other quarter enjoys[4].

The technologically advanced nations have a moral obligation to work together to aid that sizeable fraction of the global population living in poverty. And the assistance provided to improve the standard of living in these poor countries will inevitably result in an increase in their per capita energy consumption[5].

As W.B. Lewis has stated[6]:

> Mankind now has the responsibility of making the abundant energy prospectively under his control available to raise not only the lifespan and standard of living of most of the world population but also to improve the quality of life. Not only adequate food, clean air to breathe, wholesome water to drink or to swim in for the whole population of the world, but also a high quality in the cultural arts, in travel, communications, and other aspects of life could result from co-operation.

And so, the global implications of energy supply are quite evident. Procuring an adequate energy supply is undoubtedly the most important problem facing our world today. As West German Chancellor Helmut Schmidt said when opening the 1980 World Energy Conference, "Energy is not only the central problem of human co-existence but also of the future of mankind itself."[7].

3.0 ENERGY REQUIREMENTS

If the world is to live in reasonable peace and harmony, an energy supply must be available that is both adequate for the needs of a fast expanding population, and its aspirations to reach a reasonable standard of living[7]. The forecasts for future energy requirements are built upon several hypotheses which can be supported only by trends observed in the past, and which can be verified only with the progression of time itself.

3.1 Energy-Future Prognostications

Numerous authors have predicted how energy demands will increase[8], and many have come up with a demand forecast similar to that depicted in Figure 3-1. The prediction assumes that the present "population explosion" cannot continue indefinitely and that some means will be found to provide a levelling off at about fifteen billion people. It is further assumed in Figure 3-1 that the average energy used per capita throughout the world by that time will be approximately five times the present average for the U.S.A. and Canada[8].

Actually this represents the high end of the energy requirement forecasts considered by Lewis[9], who examined the forecasts of energy experts and estimated that with an equilibrium world population of 15 billion, the per person equivalent-thermal-power requirement would be between 5 and 50 kilowatts, with an average value of about 20 kilowatts per person. For a population of 15 billion, this 20 kilowatts per person would amount to a power requirement of 300 million megawatts (3×10^{14} W) or about 9 Q per annum (1 Q = 10^{18} BTU = 1.06×10^{21} J). (At 50 kW per person the demand is about 22 Q per annum, which is in line with Figure 3-1.)

3.2 Past and Present Consumption Levels

Today, the average per capita consumption of primary energy in the world is equivalent to 5 litres of oil per person per day. For the 3 billion people in the Third World it is less than 2 litres of oil-equivalent per person per day; 5 litres per person per day in Southern Europe; 8 litres in Japan; 10 litres in the U.S.S.R. and Eastern Europe; 11 litres in Northwest Europe and 27 litres in the U.S.A. and Canada[4].

The form of this energy supply and demand is changing as technology progresses. For example in the U.S.A., the present total electrical generating capacity is approximately 600,000 MW(e), that is, 600,000 million watts of electrical power[10], and consumption of electricty is about 2 billion MWh(e)/a (i.e. two-billion-million electrical watt-hours per year)[11]. This represents 31% of all primary energy use in the U.S.A.[10]. Prior to World War II, electricity accounted for 15% of the primary energy use in the U.S.A., and by 1990, if the expansion continues, this figure will rise to 40%[10].

In Canada, total primary energy use has been rising at a rate of 3 to 4% per annum (except in the period from 1960 to 1973 when growth was exceptionally rapid)[12]. 15% of all primary energy consumed in Canada is supplied in the form of electricity. Non-electrical space heating accounts for 25%. Industrial non-electrical consumption accounts for 30%, transportion 24%, and the remaining 6% is from miscellaneous uses including farming[13].

Electricity is also forming an increasingly large fraction of Canada's primary energy consumption. Historically electrical use has increased by 6.7% annually in Canada, (though with conservation, and a general slowing of the population growth, near-future prognostications tend towards a figure of about 3.7% annual electrical demand growth in Canada)[14]. The 6.7% annual increase represents a penetration of electricity into the energy supply of an extra 3% per year[12].

The trend towards higher energy use is also quite prevalent in developing countries. For example, from 1962 to 1979, the South Korean economy experienced an average growth of 9.3% each year, and energy consumption grew at an average rate of 10% per annum[15].

Figures 3-2 to 3-5 (obtained from Reference 16) show how the population and the demand for energy have increased in Canada and in the world over the past century. The trend shall continue for some time to come.

3.3 Conservation, Improved Technology, and the Redistribution of Supply

It has been suggested that a consolidated energy conservation program and a drive towards more energy-efficient technologies may curb the appetite of our energy-hungry world. Conservation can extend the energy resources, and new technologies to improve upon existing technologies can further reduce the demand. This latter point has proven itself in the recent history of Canada, where, for example, today about 30% less energy is required to generate a constant dollar of Gross National Product than in 1926[17]. The effects of conservation, too, are evident in Canada with the recent decline in the growth rate of primary energy consumption[12].

But conservation simply cannot have a significant impact on the global energy problem[2].

Energy consumption continues to grow and in the future we can expect to see the growth rate increase as the population of the world rises. The per capita energy requirement also will rise as countries become richer. Further, technology, no matter how energy-efficient it becomes, will have to be applied to processing materials from a dwindling resource base. For example, the recovery of low-grade metals, heavy oil, and an increased emphasis on pollution control will lead to an eventual increase in energy use for the production of a unit quantity of a given commodity[5].

In Section 4 the energy resource situation is examined, and in comparison with the world population data presented earlier, it becomes evident that today's total energy utilization rate is dictated more by the magnitude of the global population rather than by individual national consumption levels. In Reference 2 it is shown that per capita energy consumption averaged over the world population is only one-sixth that of North America. If it were possible to share all energy equally, there would be a drastic impact on North America, bringing U.S. and Canadian per capita energy consumption down to a level which could no longer sustain a "Value Society"(2), while creating little improvement in the rest of the world. Hence redistributing the current amount of energy consumption equally throughout the world will not relieve the global energy situation.

In all, mankind can expect to see a large increase in energy consumption over the coming decades, as the world on the whole steadily continues to build and strengthen its industrial base, and as technology continues to enter even more deeply into man's way of life. It is important to the future of the world to ensure that the ever-increasing energy demands are met by economically acceptable means.

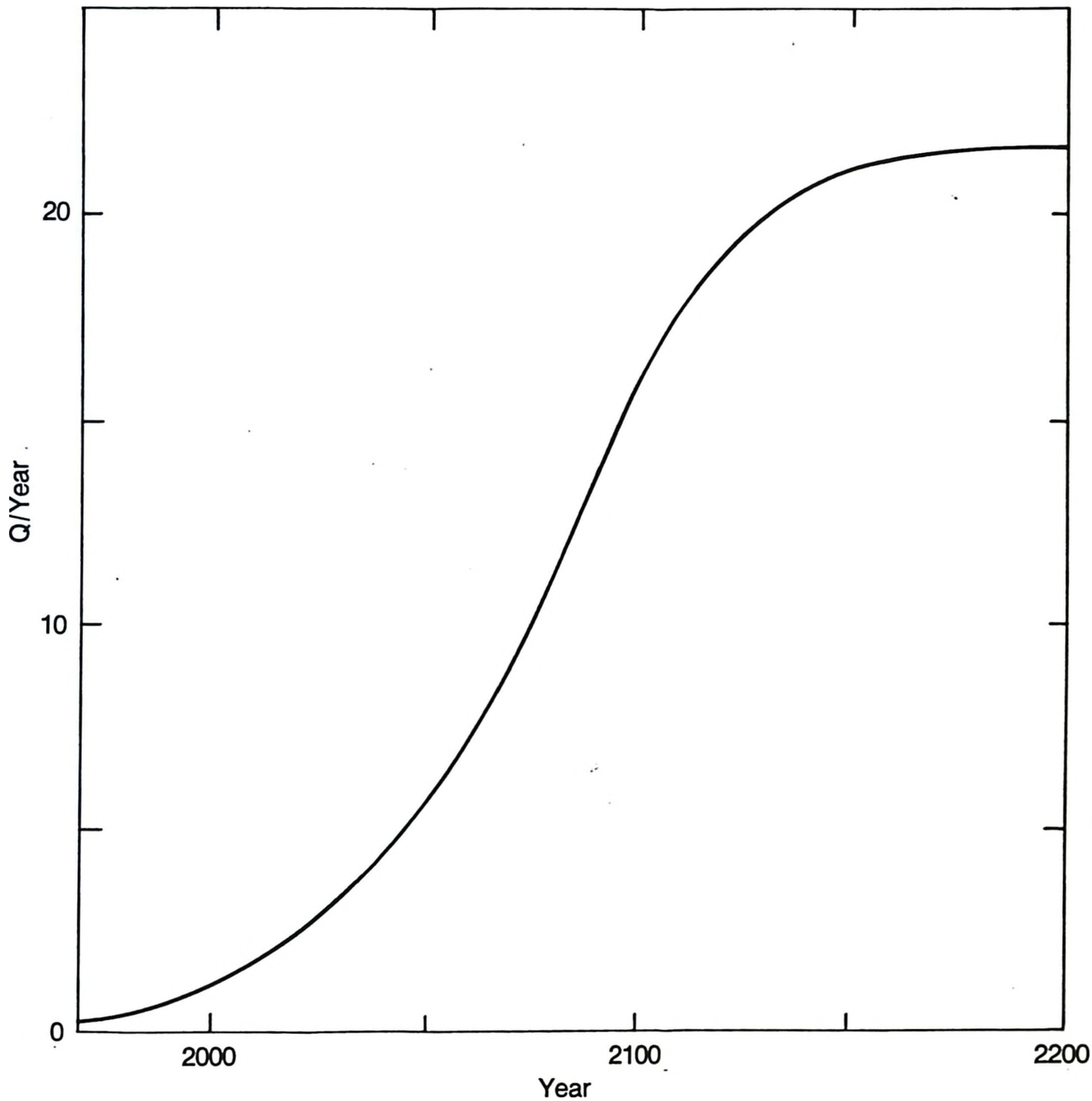

FIGURE 3-1 PROJECTED WORLD ENERGY DEMAND FROM ALL SOURCES [8]
(IQ = 10^{18} BTU $\simeq 10^{21}$ J)

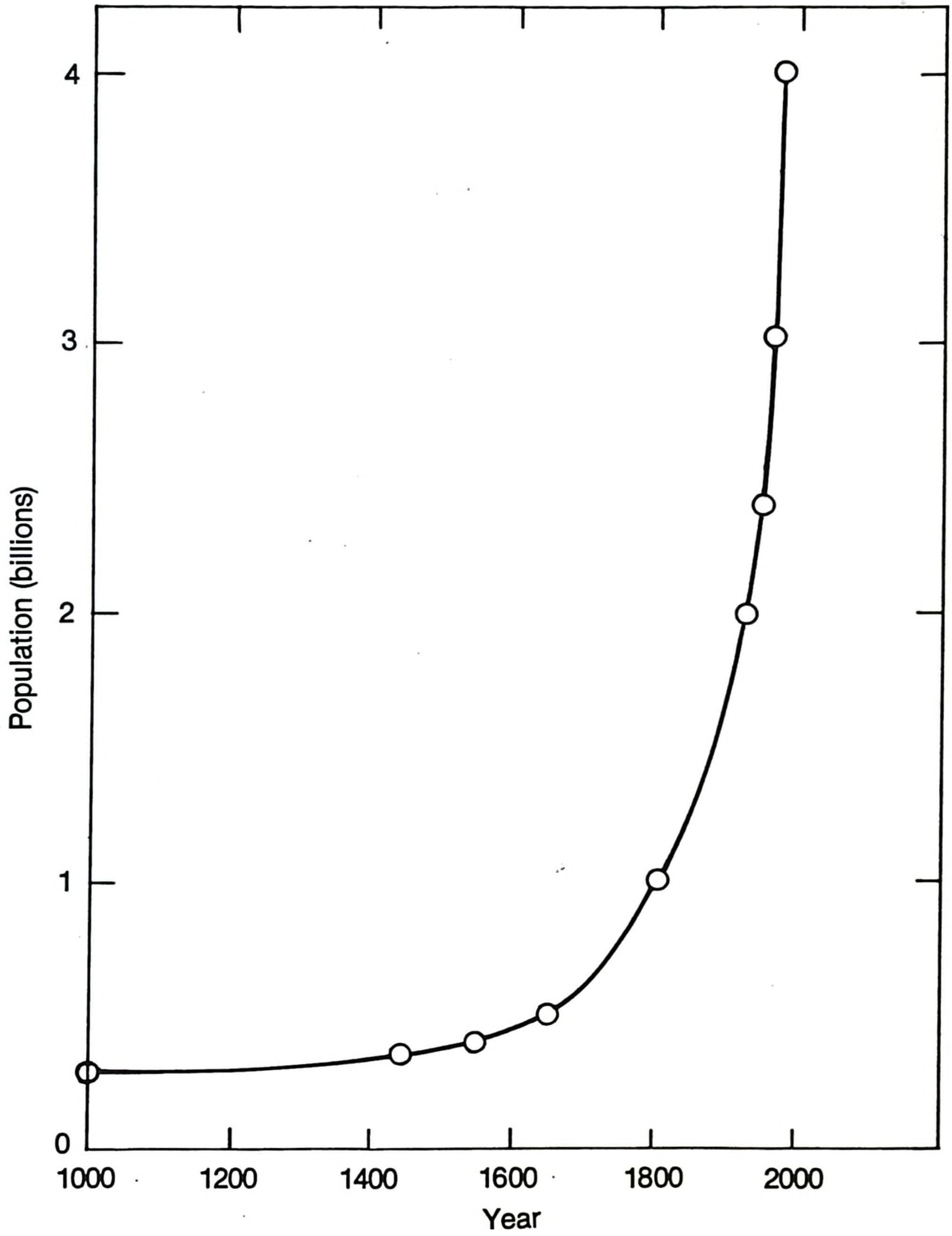

FIGURE 3-2 WORLD POPULATION GROWTH

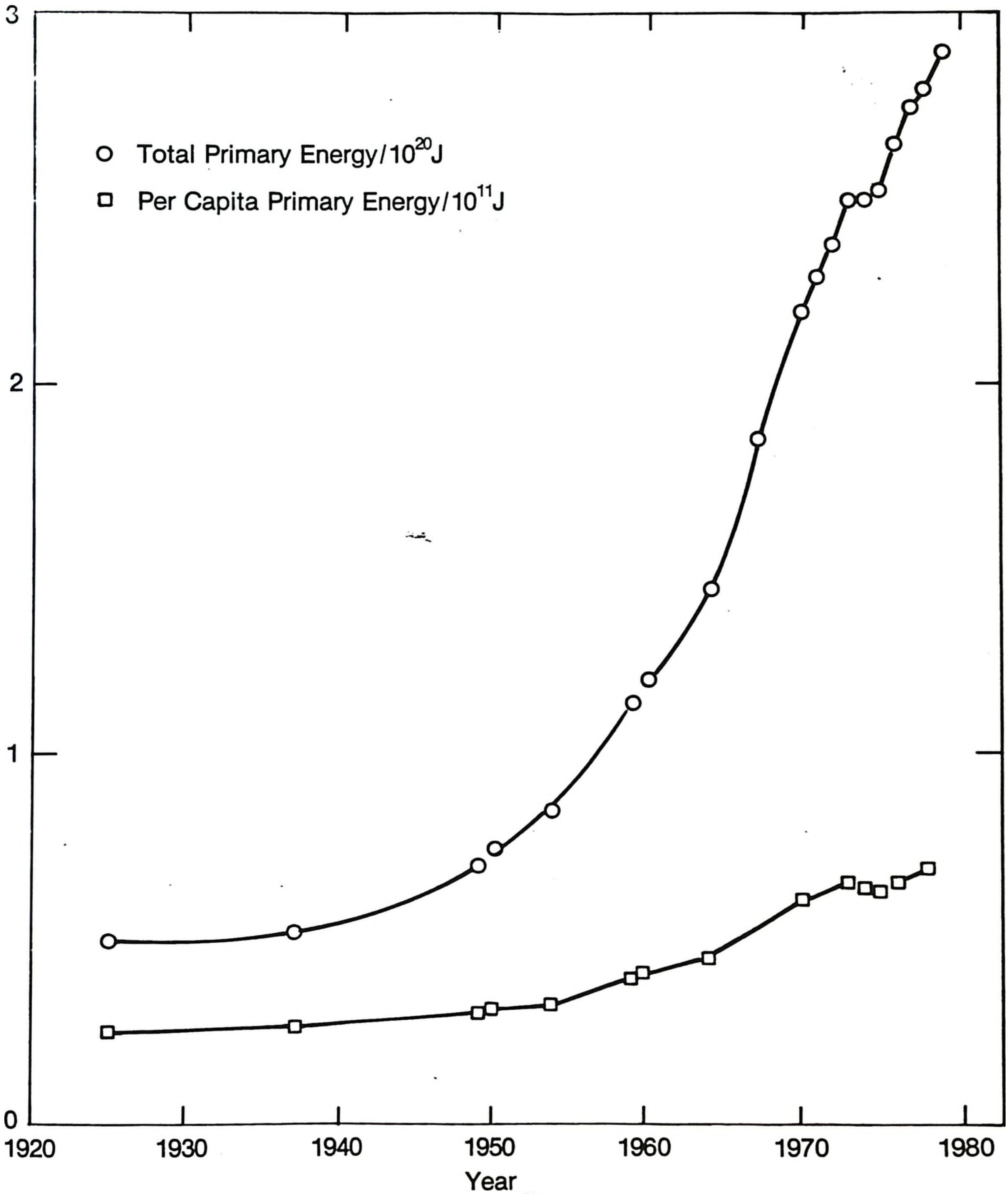

FIGURE 3-3 WORLD PRIMARY ENERGY CONSUMPTION

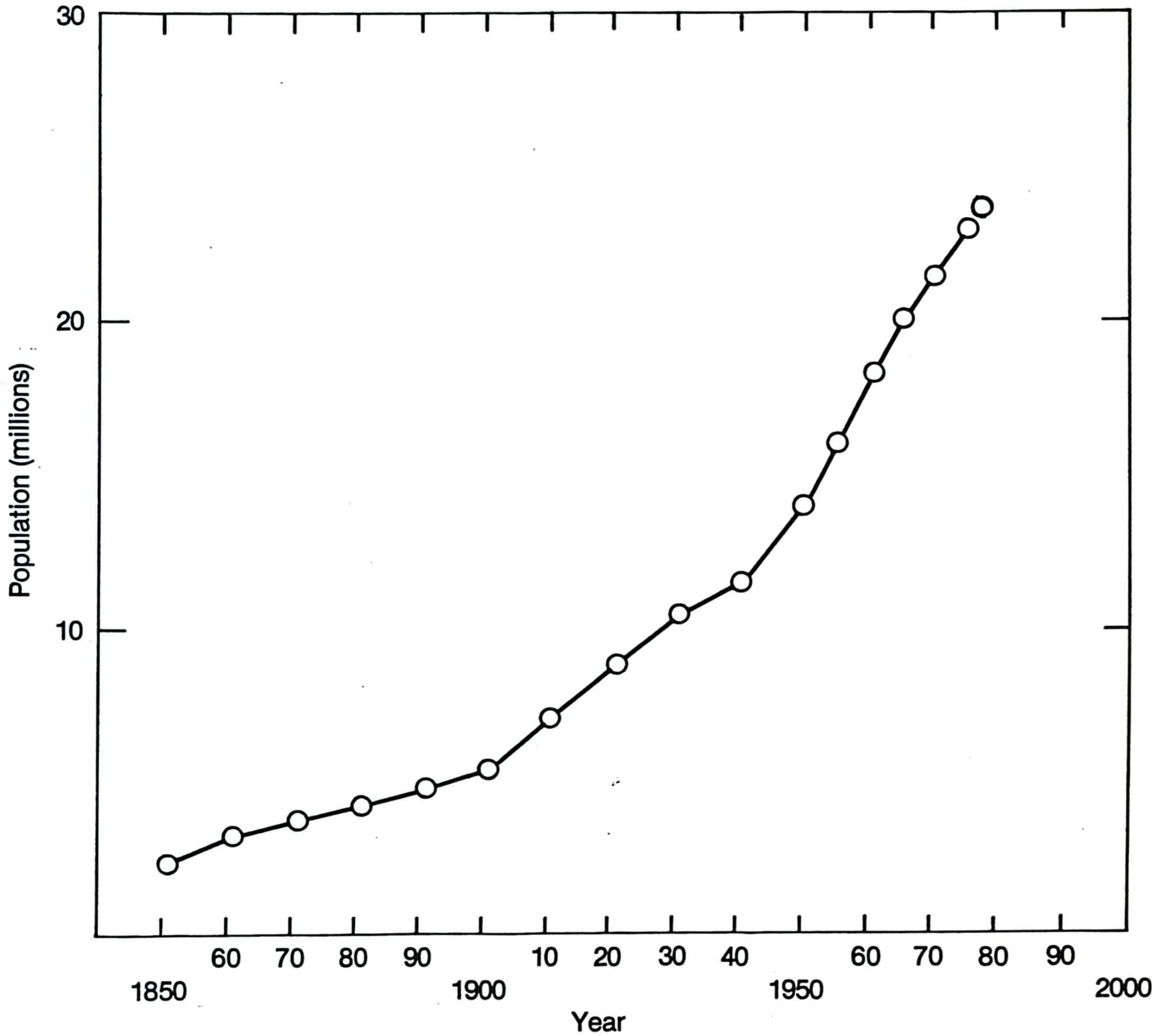

FIGURE 3-4 GROWTH OF POPULATION IN CANADA

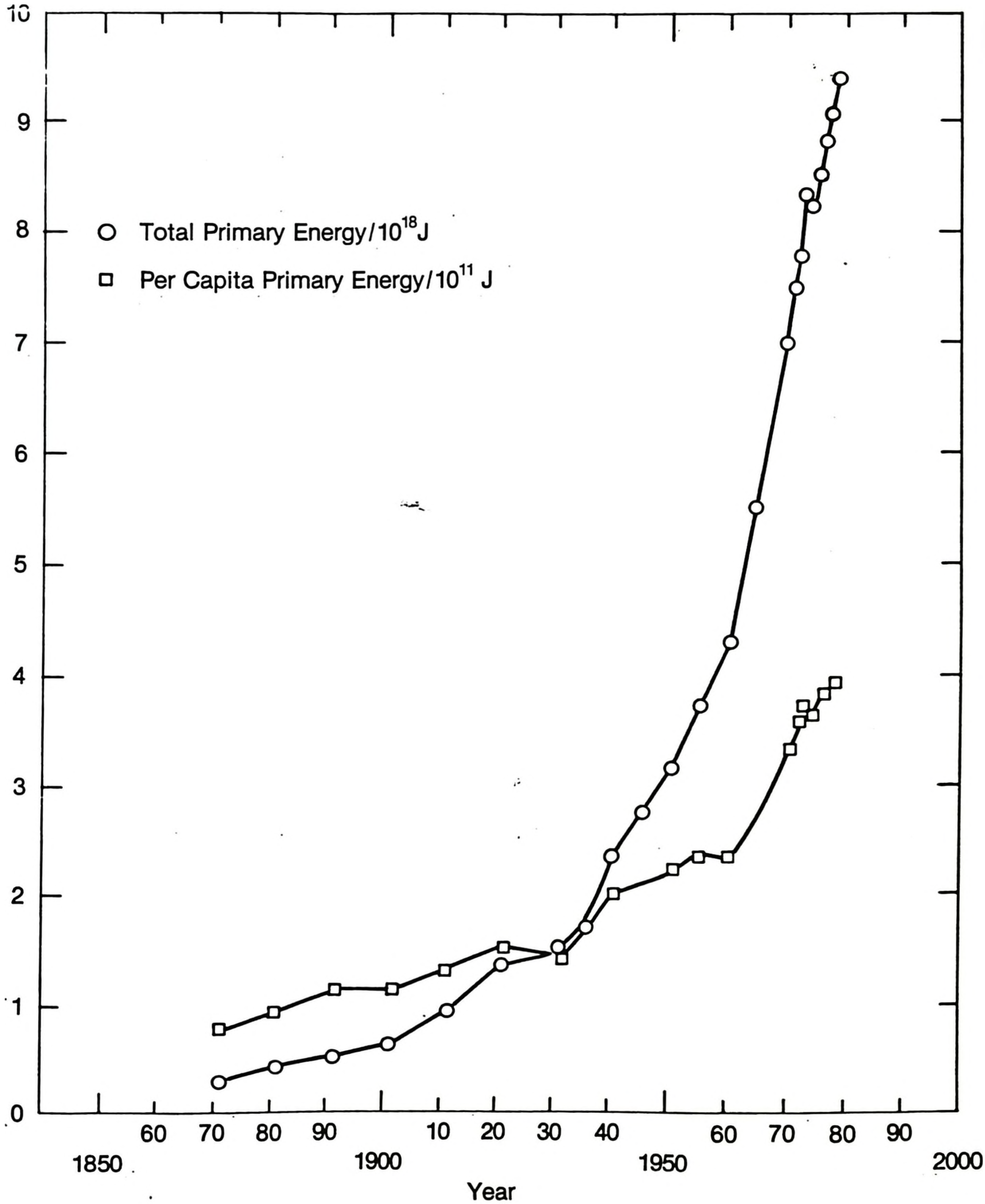

FIGURE 3-5 PRIMARY ENERGY CONSUMPTION IN CANADA

4.0 THE SUPPLY OF ENERGY

Given the past and predicted-future growth for energy requirements presented in Section 3, the world must address with extreme care and consideration, the question of supply.

4.1 The Resources Meeting Today's Energy Demands

Today the world depends on fossil fuels for 98% of its primary energy[18].

In the United States, 75% of all energy utilized comes from oil and gas, 17% comes from coal, 4% from hydro-electricity, and 4% from nuclear power plants[10].

Presently in Canada, petroleum products provide about 43% of all primary energy utilized. Hydroelectricity contributes 23%, natural gas 18%, coal 9%, nuclear energy 4%, and biomass 3%[16].

The world burns more than three billion tonnes of oil each year, and by the year 2000 this is expected to reach four billion tonnes per annum[4].

The pertinent questions that must be addressed regarding energy supply, are whether the world energy resources can continue to satisfy the ever-growing demands, and which individual or combination of energy sources should be utilized to meet this demand.

The first of these questions is answered in Section 4.2, and the answer to the second question will require a detailed examination of all of the available energy resources, and will consitute most of the discussion in the remainder of this report.

4.2 Overview of the Total World Energy Potential

It is necessary to first consider the viable options in the world energy scene — viable in a supply availability sense of the word, and then to consider the economics of the situation, the risks, and the benefits derived from the utilization of the various resources.

Energy experts have done extensive studies to determine the world supply of energy resources with a good deal of certainty(19). Table 4-1 summarizes these results, showing the total energy content of all of the sources of energy available to the world.

The potential of hydro power, tidal, geothermal, and wood sources are left as question marks in Table 4-1, since indeed if we tapped every stream and every wave, or took all of the heat energy from the core of the earth we would have a very large supply of energy, but due to the impracticality of these schemes on such a gradiose scale, the actual potential has never seriously been considered.

It should also be noted in Table 4-1 (and also in Table 4-2 through 4-5) that the availability of fusion energy assumes that lithium-produced tritium will be used in the fusion reactions. However, as shall be explained in Section 5.9, at high enough temperatures, no lithium or tritium is required in the fusion reaction and hence this supply limitation is lifted.

To put the discussion in perspective, the world now uses about 0.2 Q of energy each year[19].

Indeed any one of the energy sources listed in Table 2-1 has the potential to meet the energy requirements of the world for some time to come. However, the question of practicality arises. Here it is necessary to consider which deposits of the particular energy resources are of sufficient concentration to make their extraction economically and technically feasible; how much of the wind energy exists at velocities which make recovery practical; and other similar problems. Some of these questions have been explored in much greater detail than others.

For example, it is now generally considered that coal resources are practical only when they exist in seams over 36 cm thick and at depths above 1.2 km under ground[19]. Also, current economic analyses indicate that uranium and thorium resources (fuels for nuclear fission reactors (q.v. Section 5.10)) should be put in the practical category only when they exist in concentrations of 100 μg/g (i.e. 100 parts per million) within 2.4 km of the surface[19]. Clearly these definitions will change as the costs of energy alternatives change, but, as explained in Reference 19, they are unlikely to change in the "near to medium future".

Table 4-2 presents the practical world energy supply picture, from which it can be seen that if the estimates of the resource situation presented here are correct, coal and lignite could fuel a 0.2 Q society for 950 years, but could fuel a 9 Q society for only 21 years. Oil and natural gas could fuel a 0.2 Q society for about 120 years but could fuel a 9 Q society for less than 3 years. Hydro-electricity could make a significant contribution to the energy needs of a 0.2 Q society, but in a 9 Q society its contribution will fall far short of the total energy requirement.

It should be noted that most of the practical world energy resources have not as yet been located. If one introduces the concept of "Reasonably Proven Resources", and includes in such a category proven reserves, inferred, assured, reasonably assured, prognosticated, and other similar categories, it can be seen, as shown in Table 4-3, that the geologists have a great deal of work ahead of them in order to identify all of the practical energy resources of our world.

Only a very small fraction of the practical nuclear fuel resources are listed in the Reasonably Proven column. This is because until recently, the price of uranium was not high enough to encourage exploration[19]. There still is no economic incentive to look for thorium or lithium[19]. However it should be emphasized that the total fission reactor fuel resource is well defined by thermal flux and cosmic abundance methods[19], and it is only the distribution that is in doubt.

In fact, identified uranium resources have been increasing annually by approximately 10% in recent years[20], and this trend should continue to be realized in the future.

4.3 The Canadian Energy Resource Scene

Energy is of course an international commodity and certainly over the long term it is the world picture that is likely to dominate[19]. However, for the considerations of a national energy strategy, the national resource picture is of importance.

Table 4-4 gives the practical resource picture for Canada[19]. To put it in context, Canada now uses about 0.008 Q of energy per year[19], and if the world's current population of 4 billion people used the same amount of energy per capita as in Canada and the U.S.A., the world would use about 1.3 Q per year[19].

From Table 4-4 it can be seen that the general picture for Canada tends to parallel that for the world. Coal and lignite could fuel Canada's 0.008 Q society for about 300 years but oil and gas from Western Canada could meet that requirement for only 10 to 20 years. Frontier oil and gas resources, if confirmed, could meet current Canadian requirements for 140 to 200 years, and the tar sands and heavy oil deposits could add another 200 years.

As far as the impact of other energy sources, the question becomes one of economics. Both hydro-electricity and tidal power could play a greater role in Canada than they do on the world scene, but the costs of further developments in these areas in relation to other alternatives may be too high[19]. Estimates by Hart[19], indicate that wood might have a significant role if the economics are right in Canada, and he suggests that work should be done to assess this possibility.

It is clear that in the long term, Canadians, like the rest of the people in the world, will have to look to nuclear fission, nuclear fusion, or solar energy to meet most of their energy needs.

Table 4-5 gives figures for the Canadian energy scene in terms of proven resources in relation to the estimated resources. In this table, the nuclear fission value in the reasonably proven column assumes the use of all of the resources in a breeder or self-sufficient fuel cycle (q.v. Section 7.4). If used in this way, it could satisfy a 0.008 Q requirement for 8,250 years. If used in a conventional natural uranium fuel cycle, (q.v. Section 7.4.1) it could supply the 0.008 Q requirement for about 40 years[19].

4.4 Energy Resource Summary

In summary, one can say that the world energy supply position has become quite precarious. On both the world scene and the Canadian scene, oil and gas are in short supply, and the days of inexpensive energy from these sources are quickly drawing to a close. Coal is abundant and will become increasingly important over the next few hundred years. However, for the very long term, the world will have to depend on nuclear fission, nuclear fusion, solar energy, and possibly wind for the bulk of its energy needs[19]. In Canada, conventional oil and gas resources are likely to become depleted more quickly than they will on a world average basis[19], and Canadians will have to depend on frontier oil and gas and/or oil from the tar sands in order to meet much of the future domestic requirements for liquid fuel.

The world has practical energy alternatives and nations must determine the optimal mix of such resources in order to meet the energy demands of the future, while at the same time maintaining the natural beauty of the world and the health and happiness of its people.

Source	Total Energy Available
Fossil	10 000 Q
Nuclear Fission	10^9 Q(1)
Nuclear Fusion	10^9 Q(2)
Solar	5230 Q per year(3)
Wind	9 Q per year
Hydro	?
Tidal	?
Geothermal	?
Wood	?

(1) Based on total uranium and thorium within a mile of the earth's land surface.

(2) Based on total lithium within a mile of the earth's land surface. (Lithium is required for the production of tritium which is "burned" in fusion reactors).

(3) Based on total solar energy intercepted by the planet.

? Means all data purely speculative.

TABLE 4-1 OVERVIEW OF THE TOTAL WORLD ENERGY POTENTIAL

Source	Energy Content
Coal and Lignite[1]	190 Q
Petroleum[1]	11 Q
Natural Gas[1]	10 Q
Tar Sands[1]	1.7 Q
Shale Oil[1]	1.1 Q
Nuclear Fission[2]	10^6 to 10^8 Q
Nuclear Fusion[3]	10^6 to 10^8 Q
Solar[4]	15 Q per year
Wind	0.03 to 0.6 Q per year
Hydro	0.09 Q per year
Tidal	0.002 Q per year
Geothermal (Natural)[5]	0.002 Q per year
Wood	?

(1) Based on distribution in known geologic formations and the assumption that similar distributions exist in similar geologic formations in the earth's crust.

(2) Based on an analytical method developed by Johan Brinck and tested on other metals. Uses concentration distribution in known mining areas and the average concentration in the earth's crust. Assumes use of all the uranium and thorium in breeders. The lower number includes resources in large deposits only; the higher number includes small deposits.

(3) Assumes that the amount of energy is limited by availability of lithium and that the same fraction is recoverable as for fission fuel.

(4) Assumes that it is practical to use 1 percent of the land area.

(5) Excludes the as yet unknown potential from pumping water into areas where hot dry rocks exist close to the surface.

? Means all data purely speculative.

TABLE 4-2 PRACTICAL WORLD ENERGY RESOURCE PICTURE

Resource	Energy Content (Q)	Reasonably Proven (Q)
Coal and Lignite	190	31
Oil	11	2.4
Natural Gas	10	*
Nuclear Fission	10^6 to 10^8	320[(1)]
Nuclear Fusion	10^6 to 10^8	?

(1) Excludes communist countries as their reserves have not been reported. Assumes all burned in thorium and uranium breeder cycles (q.v. Section 7.4).

? Data not available.

* Data varies considerably source to source.

TABLE 4-3 REASONABLY PROVEN WORLD ENERGY RESOURCES

Source	Energy Content
Coal and Lignite	2.4 Q
Western Canada Oil	0.022 to 0.032 Q
Arctic and NWT Oil	0.14 to 0.30 Q
East Coast Oil	0.20 to 0.24 Q
Oil Sands	1.4 Q
Alberta Heavy Oil	0.15 Q
Western Canada Gas	0.057 to 0.131 Q
Arctic and NWT Gas	0.45 to 0.63 Q
East Coast Gas	0.33 to 0.43 Q
Nuclear Fission(1)	6×10^4 to 6×10^6 Q
Nuclear Fusion(1)	6×10^4 to 6×10^6 Q
Solar(2)	0.5 Q per year
Wind(1)	0.002 to 0.04 Q per year
Hydro	0.005 Q per year
Tidal(3)	0.001 Q per year
Geothermal	?
Wood(4)	~ 0.01 Q per year

(1) Assumes that since Canada has 6.7 percent of the world's land mass it also has 6.7 percent of the world's resources as listed in Table 4-2.

(2) Based on 1 percent of land mass assuming solar insolation at the 49th parallel.

(3) Approximately half of the world's tidal power potential exists in the Bay of Fundy area.

(4) Rough estimate made in Reference 19.

? Data not available

TABLE 4-4 PRACTICAL CANADIAN ENERGY RESOURCE PICTURE

Resource	Energy Content (Q)	Reasonably Proven (Q)
Coal and Lignite	2.4	0.2
Total Conventional Oil	0.4 to 0.6	0.047
Oil Sands	1.4	*
Alberta Heavy Oil	0.15	*
Total Conventional Gas	0.8 to 1.2	0.069
Nuclear Fission	6×10^4 to 6×10^6	66
Nuclear Fusion	6×10^4 to 6×10^6	66

* Data varies considerably source to source.

TABLE 4-5 REASONABLY PROVEN CANADIAN ENERGY RESOURCES

5.0 THE CONTENDERS IN THE BATTLE FOR ENERGY SUPPLY SUPREMACY

The major potential sources of energy in our world today are:

i) oil and gas,

ii) coal,

iii) hydro,

iv) solar,

v) wind,

vi) tidal and wave energy,

vii) geothermal,

viii) biomass,

ix) nuclear fusion, and

x) nuclear fission.

It is prudent at this time to examine each of these options separately in order to appreciate their technological similarities and differences, and to better understand the significance of their inclusion as major energy resources in the future, for better or for worse.

5.1 Fossil Fuels

5.1.1 Oil and Gas

Oil is the primary source of energy utilized in our world today, but as clearly shown in Section 4, the world must be prepared for major oil and gas shortages in the not too distant future, and the corresponding price hikes that will follow.

Nations must develop technologies that will leave them less dependent on oil. If one considers Canada, for example, where approximately 50% of the oil consumed is used in stationary applications (heating and industry) and 50% in transportation[21], it can easily be seen that a great deal of the oil consumed (the entire stationary consumption portion) can be replaced by other energy forms such as coal or nuclear energy.

In Canada, 15% of the oil consumed in 1979 was imported[21]. Hence, if energy self-sufficiency is the aim of the Canadian government, the nation could simply replace 30% of the stationary oil consumption with indigenous nuclear power to realize the goal.

And self-sufficiency in energy is an important objective. Countries that depend on foreign energy often lose control over their own economies. Inflation rates are closely linked to energy prices. In fact, energy prices can greatly influence the entire state of the economy. For example, a one-dollar per barrel increase in the average price of oil consumed in Canada, unless offset by policy initiatives such as tax cuts, will result in an additional 10,000 Canadian workers unemployed, and will drive the inflation rate up 0.5% per annum[22].

Of course, building up the Canadian oil and gas industries could also eliminate the need for imported oil, but overall, it would best suit Canada and the world to rely less on dwindling oil resources and concentrate more on the oil alternatives, for it is only through the utilization of alternative forms of energy that mankind will be able to resolve his energy supply difficulties and contend with other concerns of his existence.

5.1.2 Coal

Coal use in Canada in 1978 was 18.5 million tons[23]. In 1980, the U.S.A. burned 525 million tons of coal in utility power plants[24]. (This represented 70% of the total U.S. coal production for that year.)

It is expected that coal will become an increasingly important resource in the coming decades. Coal will be used for combustion, and also for conversion into liquid hydrocarbons, coal gasification, and production of a wide range of chemical products. As a result, a report commissioned by the Canadian Minister of Energy, Mines, and Resources, in February 1979 stated that an indicative target of increased coal production in Canada, is a five-fold increase by the year 2000, and a further doubling of production by the year 2020[23].

Similar growth patterns are expected in the U.S.A., where, if projections for new utility capacity and conversion to coal are realistic, the utilities will consume 1000 million tons of coal in 1990[24]. In 1990, total coal production in the U.S.A. is expected to be 1450 million tons, without any consideration of what might be consumed by the synthetic fuels industry, which could require an additional 300 million tons per year. These heavy requirements will tax the U.S. transportation system.

With the large anticipated energy demands, coal, in combination with nuclear power, will be an important energy option capable of meeting future world energy demands, though environmental impacts (q.v. Section 8.3.1) and the cost of environmental protection equipment will be key forces resisting the push towards increased utilization of coal.

5.1.3 The Conversion of Fossil Fuels Into Useful Energy Forms

In modern fossil fuel fired power plants, coal, oil, or gas is burned (oxidized), in a process whereby chemical energy is transformed into kinetic (motion) energy. The combustion process produces very high temperatures which convert water within the tubes surrounding the furnace to steam. The steam in turn drives a turbine which causes an electrical generator to spin and generate electricity.

5.2 Hydro-Electricity

In the production of hydro-electricity, falling water instead of steam is used to drive the turbines. Today hydro provides approximately

2% of the world's primary energy, though over the next 40 years this percentage may increase four-fold[4], as the world desparately attempts to tap this renewable resource to its practical and economic limits.

5.3 Solar Energy

Harnessing the ever-present, but ever-elusive energy from the sun has proven to be a monumental task. The difficulty with solar energy is that though an extremely large potential supply exists, its intensity at the earth's surface is very small (and even that is intermittent), making collection and conversion of the solar energy quite difficult.

The sun continually casts 1.7×10^{14} kW of power upon the face of the earth[9]. In comparison, 15 billion people using 20 kW(th) of energy would require a power supply of 3×10^{11} kW. It is estimated that the amount of solar energy reaching the earth over a period of one month has the energy equivalent of all of the world's coal, oil, and natural gas deposits[4].

Even so, a solar powered thermo-electric generating station in Southern Ontario would require 130 km^2 of collection area for each 1000 MW(e)[19], and a yet non-existent storage system.

Solar energy conversion systems range from direct heating, to thermo-electric devices which use solar energy to boil water (much as in a fossil fuel fired power plant), to photovoltaic cells which directly convert solar energy into electricity[25].

Solar conversion systems are very expensive. Solar-powered thermo-electric plants will not become economical before a five-fold cost reduction is realized. Price estimates for the photovoltaic conversion process suggest that price reduction factor of 20[26] (and as high as 50[19]) are needed before solar cells become competitive with present methods of generating electricity. Advances in thin film technology[25], and price increases in competitive energy alternatives will significantly improve solar cell economics.

Solar energy can be an important power source in the world of tomorrow, though the intermittent supply, the maintenance effort required for individual roof-top models, and the resource and land use strain will certainly be key factors in determining the size of the impact. The future role of solar-energy will depend on the development of such new technologies as space-based collectors which will eliminate the problems of intermittent supply and land-use strain. However these technologies will require many decades of development before they become a viable part of the energy production sector.

5.4 Wind Energy

Strictly speaking, wind is a form of solar energy, considering that the variations in air pressure, which result in wind production are caused by the non-uniform heating of the atmosphere.

To produce electricity, the wind turns a windmill propeller connected to an electrical generator. At an average wind speed of 19 km/h, and there are a few places in Canada that have average wind speeds that high, one would require 40,000 windmills, 30 m in diameter, for each 1000 MW of electricity required(19). Appropriately spaced, so they would not steal wind from one another, they would require an area of about 33,670 km^2 (13,000 square miles)(19). Power costs of close to 100 mills/kWh (Canadian 1977 dollars) of electricity, excluding storage system costs, are expected.

Wind power may play a significant role in energy production in the future, once the economic situation changes. However the supply is uncertain and intermittent. And considering the mechanical problems with large windmills, and aesthetics, and wind rights (who could stop one person from putting up a large windmill that effectively shielded his neighbour's windmill from the prevailing winds), there will have to be a significant amount of research and legal work done before wind energy can be deemed a viable option.

5.5 Tidal and Wave Energy

Closely associated with wind energy is wave energy. The mechanical power associated with the rising and falling of ocean swells is tremendous, but like the wind energy that drives the swells, the supply is intermittent. The harnessing of tidal power is also being explored (for example, in Canada, in the Bay of Fundy), though technologically the method is somewhat different than wave energy conversion[26].

However, tidal and wave power are expensive — at least twice the cost of conventional power[26] — and the optimal sites are not near large population centres, so transmission of power will also be a problem[26]. This should not deter further engineering research from being done in an effort to bring costs down. Though, at the moment, economics dictates that tidal and wave power are not to be considered as viable energy options in the short term.

5.6 Geothermal Energy

The interior of the earth is heated primarily through the natural radioactive decay of heavy elements such as uranium[34]. By releasing this energy from deep inside the earth, man can have at his disposal, an extremely large resource base.

Four types of geothermal resources are of prime interest:

a) dry steam,

b) wet steam,

c) hot dry rock, and

d) geopressure.

The technology to use clean dry steam is well developed (similar to steam produced in fossil plants), however technology has not been developed to use the other types of reservoirs which contain the majority of the geothermal energy resources.

Estimates(27) indicate that 1 to 5% of the U.S. electricity supply in the year 2000 is likely to come from geothermal resources depending on how rapidly wet high-salinity steam fields can be developed. Limiting factors include: likely resource locations distant from population centres; leasing problems on federal lands; environmental problems including noise and air pollution, ground water contamination, and land subsidence. Technological problems include the need for the development of rock facturing methods; brine fouling and corrosion problems; accurate reservoir evaluation; and limited extraction and conversion experience(27).

5.7 Energy From Biomass

In the biomass energy resource, vegetable matter, refuse, crushed sugar cane, wood and bark, coffee grounds, peanut hulls, etc. are considered as fuels.

This energy form can be burned to produce steam, or distilled to form a combustible liquid. The technology to take advantage of the resource is developed and commercially available. It provides an economical use of waste products, while freeing up the limited supply of fossil fuels.

There is however difficulty in burning some waste products. Collecting, sorting, and storing wastes on a continuing basis is required. The resource is also competing for the food and housing market.

Forests once set aside as sources of lumber for new homes (or even just left as parks) will be cut down and burned in energy production if this energy form is given the opportunity to grow. In fact, estimates[(19)] show that a 1000 MW(e) plant would require an energy forest of about 2600 km^2 in the southern United States. In the area around North Bay, Ontario, because of the shorter growing season, an energy forest with an area of up to 21,000 km^2 would be required to satisfy the fuelling needs of 1000 MW(e) power plant. (Of course for each tree cut down in the forest, a new one must be immediately planted.)

Similarly, grains and corn, which act as food for humans and livestock, may be diverted to the furnaces of electrical power plants, or sent to ethanol distilleries for the production of liquid fuels.

As oil, gas and other energy resource prices increase, the temptation for the diversion of food staples to energy production will intensify unless food prices increase accordingly. This may place undue inflationary pressures on a society. However, in a more modest application, where only the "left overs" from food, feed, and lumber production are utilized, the resource can be an excellent source of energy to help meet the demands of the future.

5.8 Commentary on the "Soft" Energy Resources

Many public interest groups today adamantly oppose large scale power plants (such as nuclear power stations) and strongly support the softer energy forms operated on a personal or neighbourhood basis. They suggest that large plants spell the demise of individuality and are the epitome of modern corporate dehumanization. But this argument lacks any real substance, for it is the immediate availability of energy afforded with these large plants that allows man to contend with the chores of domestic life as quickly as possible, and leaves him ample time to develop and pursue happiness in whatever manner he sees fit.

No doubt large power plants are not any more pleasant to the eye than any other mass of concrete, but the plants are generally few and far between. The countryside is still green and not cluttered with solar collectors or windmills, and the economies of scale that can be achieved when such a plant is operated will be felt all through the society by virtue of low energy prices, and hence, lower prices for all commodities.

Further, individual energy operations would require continual maintenance as well, requiring home-owners to monitor and repair their energy supply systems, hence further detracting from their free time.

Large power plants symbolize the co-ordinated efforts of the people in today's society, and it is important to realize that such co-ordination does not come about easily. Much planning, and organized deliberation is required to ensure the outcome of such a large endeavour. Neighbourhood-type operations would also require such planning procedures. Setting up such a system would further reduce the spare time individuals have available. It would certainly be another problem to be contended with, which would tend to increase the stress level in society as a whole. If individuals can have energy with the flick of a switch from a central energy plant it makes little sense to require each individual to procure a separate supply to satisfy his own demands and contend that this would make the world a better place in which to live.

5.9 Nuclear Fusion

Nuclear fusion is the process whereby two light nuclei ("nucleus" refers to the positively charged central core of an atom) combine to form a heavier nucleus. The heavy nucleus is, however, lighter than the sum of the individual nuclei. The mass difference is accounted for in nature by the release of a large amount of energy.

The heavier elements of hydrogen (deuterium (which occurs naturally in water at a concentration of ∿145 parts per million (ppm)) and tritium (which can be produced synthetically from lithium)) are the prime fusion fuels.

In order to allow the fusion reactions to take place, extremely high temperatures are required to overcome the electrostatic forces. At temperatures of 100 million ^{o}C[28] (the core of the sun is only 15 million ^{o}C) man can cause tritium and deuterium atoms to fuse in specially designed reactors[29]. At temperatures ten times higher than this[28] deuterium alone can be used in the reaction.

The most promising fusion reactors are magnetic containment bottles and laser fusion devices. In the former, strong magnetic fields hold a gas of deuterium fuel as it heats to become a plasma (a mass of separated electrons and positive ions). In the latter method, pulsed lasers fire at a pellet of fusion fuel and heating occurs as a result. This so-called "snow-ball in hell" approach may be more appropriate to nations like Canada with only a moderate technological infrastructure.

Extensive engineering research must yet be done in order to develop a commercial fusion reactor unit. Countless billions of dollars, and staunch political support will be required. It is believed that the technology will not become available for some years to come, and when it does, though the fuelling costs may be small, estimates show that the capital costs will certainly be large, and as a result, economic competitiveness is difficult to predict[30]. The technical problems of plasma heating and confinement, plasma instabilities, impurity control, fuel injection, tritium processing and containment, maintenance and waste management, all have yet to be resolved satisfactorily, though recent and future breakthroughs will no doubt dispel any non-belief in the system.

5.10 Nuclear Fission

Nuclear fission refers to the process whereby a heavy nucleus (such as uranium) splits into two lighter nuclei and often two or three neutrons, with a resultant net mass loss and liberation of energy.

In uranium, natural radioactive decay occurs very slowly. However, if subjected to bombardment by free neutrons, the break-up of the atoms will occur much more quickly. This, in essence, is what occurs in a controlled fashion in a fission reactor.

Fission reactors can be divided into three basic categories: thermal reactors (the type presently in commercial operation), fast reactors (which are currently in the development stages), and intermediate reactors (which have received minimal attention to date).

The distinction is made according to the average energy of the fission-inducing neutrons.

5.10.1 Thermal Fission Reactors

Thermal fission reactors, such as Boiling Light Water reactors (BLWs), Pressurized Light Water Reactors (PWRs), or the Canadian designed CANDU-PHW* reactors require an inventory of fissile fuel (q.v. the Glossary) (U-235, Pu-239, U-233, etc.) to sustain the reaction. The fissile fuel inventory is often maintained through the conversion of fertile isotopes (U-238, Th-232, etc.) into fissile isotopes.

The free neutrons liberated as a result of the fission process (q.v. Figure 5-1) are highly energatic, and are slowed to thermal energies by a moderator (light water, heavy water, graphite, etc.). The heat from the reactions is carried away to steam generators by a coolant system (light water, heavy water, organic liquids, gases, etc.).

5.10.2 Fast Reactors

Fast reactors have no moderator. They primarily use liquid metals to transfer the heat from the system to the heat exchangers. Plutonium is one of the best fuels for fast reactors for it is one of few materials with a high propensity for fissioning when subjected to an environment of fast neutrons[37].

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* CANDU-PHW is derived from Canadian Deuterium Uranium-Pressurized Heavy Water.

Plutonium is obtained by bombarding uranium-238 (natural uranium is 99.3% U-238 and 0.7% U-235) with neutrons.

Fast reactors must obtain their initial charge of plutonium from a thermal reactor or from some other synthesis method. Once the process begins, a fast reactor is capable of producing enough plutonium to sustain itself, and in fact, fast reactors can become Fast Breeder Reactors (FBRs) capable of synthesizing more fissile fuel than they consume.

5.10.3 Fuel For a Fission Reactor

With the present nuclear technology, only uranium and thorium can be considered as potential raw fission reactor fuels. U-235 is the only natural fissile material, though both U-238 and Th-232 can be converted into fissile materials in either fast or thermal reactors[(31)].

5.10.3.1 The Supply of Uranium

The crustal abundance of uranium averages 3 g/Mg of earth[(32)]. In the entire crust of the earth there are more than 100 million million tonnes of uranium[(9)]. There are 2.5×10^{12} tonnes of uranium within one mile of the earth's surface under dry land[(9)]. If this was all burned in fission reactors, the world would have one billion Q of energy at its disposal[(32)]. This would be sufficient to meet the entire projected energy demands for the world for tens of millions of years to come. Even without improving technology to achieve better fuel utilization than that which is currently obtained from today's commercial reactors, the world's inventory of uranium would be sufficient to satisfy the world's forecasted energy demands for many thousands of years[33]. Estimates show that if man was able to tap that same proportion of uranium as is thought to be recoverable in the case of fossil fuels, there would be sufficient energy to power a world population of 15 billion at current North American standards for more than 6000 years with reactors no more efficient than those proven at a commercial level of confidence[34].

5.10.3.2 Thorium: An Alternative Nuclear Fuel

One may also consider the element, thorium, (which has a crustal abundance of 10 g/Mg[32]) as a potential fuel for fission reactors[35].

In nature thorium exists primarily (almost entirely) as Th-232, which is fertile but not fissile (similar to U-238). Upon subjection to a neutron flux, Th-232 can be transmuted to U-233 which is fissile. U-233 yields more neutrons upon fissioning than any other fissile isotope. Hence thorium is potentially an excellent fuel for thermal fission reactors, and provided an initial U-233 inventory can be built up in the reactor, a thermal reactor fuelled with thorium can be operated as a breeder -- yielding more U-233 than it consumes. This shall be discussed in more detail in Section 7.4.4.

5.10.3.4 Uranium Mining and Present Resources

The uranium mining industry is rather young, and the price of uranium has not been sufficient to stimulate a great deal of exploration. Because of this only a small fraction of the uranium resource base has been developed. Estimates of the world uranium resources[36] and requirements tend to reflect this infancy in the uranium mining and exploration sector. Table 5-1 depicts the Canadian and world uranium situation.

A 1000 MW(e) natural uranium CANDU reactor consumes approximately 134 Mg of uranium per year when operating at 80 percent capacity[36]. Thus, over a lifetime of 30 years it will consume about 4 thousand tonnes of uranium (about 5 thousand tonnes of uranium oxide (U_3O_8)). The uranium policy of the Canadian Department of Energy, Mines, and Resources (EMR) includes an objective to ensure at least a 30 year reserve of nuclear fuel for all existing reactors plus any reactors to be committed and planned for construction during the next ten years[36]. In Table 5-1 the "30a COMMIT" column refers to the amount of uranium that must be set aside for the life of these reactors according to the EMR policy.

It can be seen from Table 5-1 that for Canada, the reasonably assured resources of uranium will be sufficient to meet the demands well into the beginning of the next century, even allowing for a considerable export market. Canada's favourable position is not reflected on a world scale. Sixty per cent of all currently identified world resources will have been consumed by the year 2000 and the commitment will exceed resources by a factor of about three.

Clearly then, it would be prudent to follow two approaches which can assure an adequate supply of nuclear fuel for the foreseeable future:

i) the confirmation of more uranium resources through a stepped-up exploration program, and

ii) the development of new nuclear fuel cycles which make more efficient use of uranium.

Both of these options are being pursured with great fervour. In recent years, as was mentioned in Section 4.2, the world has witnessed an average increase in proven uranium resources of about 10% per annum[20]. Advanced fuel cycles, thorium utilization, and fuel reprocessing have been considered, and preliminary studies (q.v. Section 7.4) indicate that enormous increases in uranium utilization can be realized with these innovative schemes. The resources are there. The technology is growing. It is up to mankind to properly utilize the more than ample supply of fission reactor fuel provided, in order to secure an energy base sufficient to meet the world's ever-growing demands, and thereby provide stability for the future.

5.10.4 Fission Reactor Design

Today, commercial or committed fission reactor designs fall into one of seven categories:

i) Heavy water moderated, heavy water cooled, pressure tube type reactors (such as the CANDU-PHW),

ii) Heavy water moderated, boiling light water cooled, pressure tube type reactors (such as the CANDU-BLW),

iii) Heavy water moderated, organically cooled, pressure tube type reactors (such as the CANDU-OCR),

iv) Graphite moderated, gas-cooled, pressure vessel type reactors (AGRs),

v) Light water moderated, light water cooled, pressure vessel type reactors (PWRs),

vi) Light water moderated, boiling light water cooled, pressure vessel type reactors (BWRs), and

vii) Un-moderated, liquid metal cooled, pressure vessel type fast breeder reactors (FBRs).

5.10.4.1 Pressure-Tube-Type Reactors: The Canadian Choice

PHWs, BLWs and OCRs are pressure tube type reactors. In these reactors, which are usually fuelled with natural or slightly enriched (q.v. the Glossary) uranium in the form of uranium dioxide, the fuel is held within tubes which run through the length of the reactor as shown in Figure 5-2. The coolant passes through the tubes under high pressure and sends heat to the steam generators. In an OCR or PHW a heat exchanger is required, as the coolant is not allowed to boil (to any great extent). In a BLW, the boiling light water coolant passes directly to the turbines.

5.10.4.2 Advanced Gas-Cooled Reactors (AGRs)

AGRs have become popular in Britain and France[37]. These graphite moderated reactors are fuelled with slightly enriched uranium (1.4 to 3.0% U-235) in the form of uranium dioxide fuel elements. The elements are arranged in such a way that carbon dioxide gas can pass smoothly between the fuel and the moderator (q.v. Figure 5-2). One of the great advantages of gas cooled reactors is their high thermal efficiency (up to 42%[37] — as high as the most efficient fossil fuel plant available today and about ten percent more efficient than current CANDU-PHW reactors). AGRs can be made to operate using natural uranium, however the resultant increase in the size of each reactor to accommodate only natural uranium would greatly increase the capital cost of the reactors, rendering them economically uncompetitive.

5.10.4.3 Pressure-Vessel-Type Reactors

BWRs and PWRs (Figure 5-2) operate using enriched uranium and are light water cooled and moderated. The U.S.A. has chosen this type of reactor to provide nuclear power until the introduction of Fast Breeder Reactors (FBRs) which are expected to be available as commercial power units by the end of the century. BWRs and PWRs are housed in heavy pressure vessels that require a great deal of engineering work supported by a complex and well-developed industrial base for construction.

Pressure vessel type reactors must be shutdown to be refuelled thereby losing valuable energy production time. Immediately after refuelling,the high system reactivity must be artificially controlled by special neutron absorbing materials.

In BWRs and PWRs, the moderator and coolant are one and the same, and the entire vessel is maintained under extreme internal pressure.

5.10.4.4 Fast Breeder Reactors

FBRs (q.v. Figure 5-2) are purported to be one of the ultimate sources of fission power, producing more fuel than they consume[37]. They operate at very high temperatures and are cooled by metals such as sodium which are heated to such a high temperature that the metals change to a molten state. Plutonium fuelled, these reactors promise excellent fuel utilization, though, as shall be shown in Section 7.4.8, CANDU reactors can be operated on fuel cycles that give similar utilization characteristics.

5.10.4.5 Rationale Behind the Canadian Choice of Reactor Design

The variation in design among the fission reactors has been the response of nuclear scientists and engineers to the development of nuclear power starting with industrial and technical data bases at different stages of development. For example countries like the U.S.A. with a mature industrial base have the technological capability to design and construct the massive pressure vessels required for their PWR and BWR reactors. Further, the nuclear industry in the U.S.A. had at its disposal the enrichment plants used for military purposes to produce enriched fuel for their reactors. And in addition, the U.S. reactor development program was first geared to submarine powering, for which the relatively compact cores of light water reactors were particularly well suited.

Canada, on the other hand, realized early in its nuclear power program that Canadian industry could not readily construct the massive pressure vessels required for large BWRs or PWRs, and Canada was also aware of the complex engineering studies that would be required each time it was necessary to design a larger vessel for a larger reactor unit. Further, Canadian expertise had been built up in heavy water technology during World War II, and uranium enrichment facilities were non-existent. Not wishing to rely on foreign-produced fuel or reactor vessels, the

Canadian nuclear pioneers chose the CANDU pressure tube type reactor employing natural uranium as a fuel, and heavy water as a moderator. With relatively easily produced pressure tubes as "building blocks", the design of reactors with an ever-increasing number of pressure tubes and the corresponding increase in reactor power, is quite straight forward.

Further reactor intercomparisons will be made in subsequent sections of this report as the specifics of nuclear power production and the energy issues are brought forth.

	Uranium Resources (GgU)*					Uranium to Year 2000 (GgU)	
	Reasonably Assured		Estimated Additional		Total	Cumulative Consumption**	30a Commit.***
	Measured	Indicated	Inferred	Prognosticated			
Canadian @ $160/kgU†	82	107	318	388	895	85	459
Rest of the World @ $130/kgU†	1 823		1 507		3 332	2 415	~11 500
Total	2 014		2 213		4 227	2 500	~12 000

*** Estimated on the same basis as the Canadian Department of Energy Mines and Resources commitment.
** No reprocessing assumed.
† Canadian resources are classified on the basis of price, world resources on the basis of recovery cost (1977 Canadian dollars).
* 1 GgU = 1300 short tons U_3O_8.

TABLE 5-1 WORLD URANIUM RESOURCES AND REQUIREMENTS (1977 DATA)

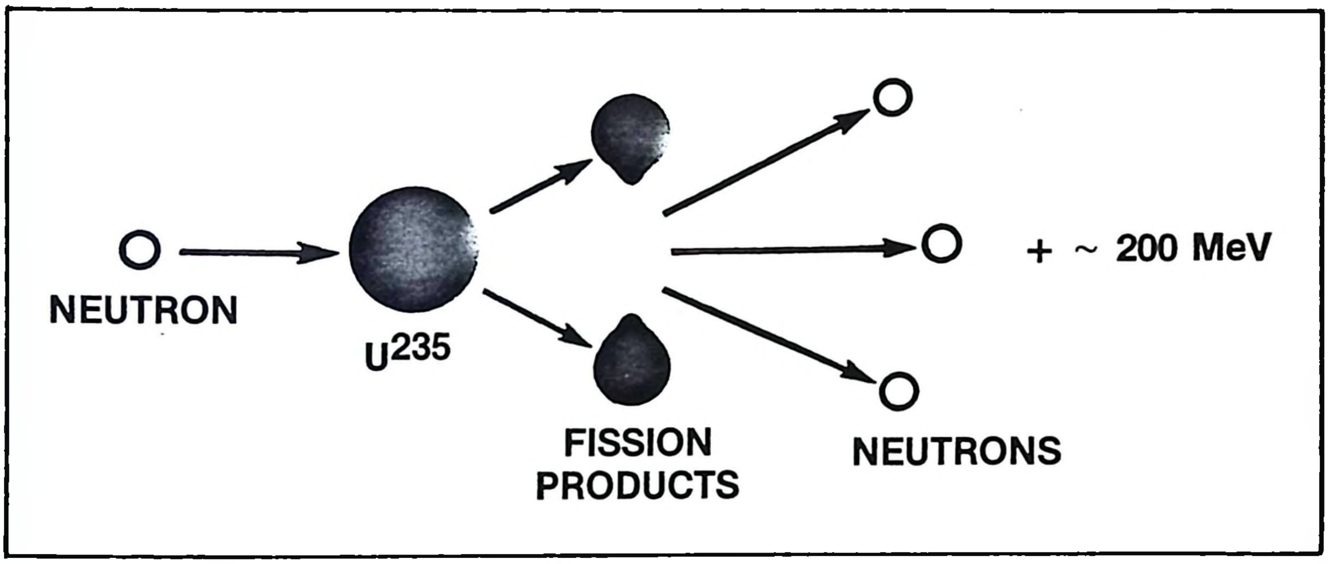


FIGURE 5-1 SIMPLIFIED DIAGRAM OF THE FISSION REACTION

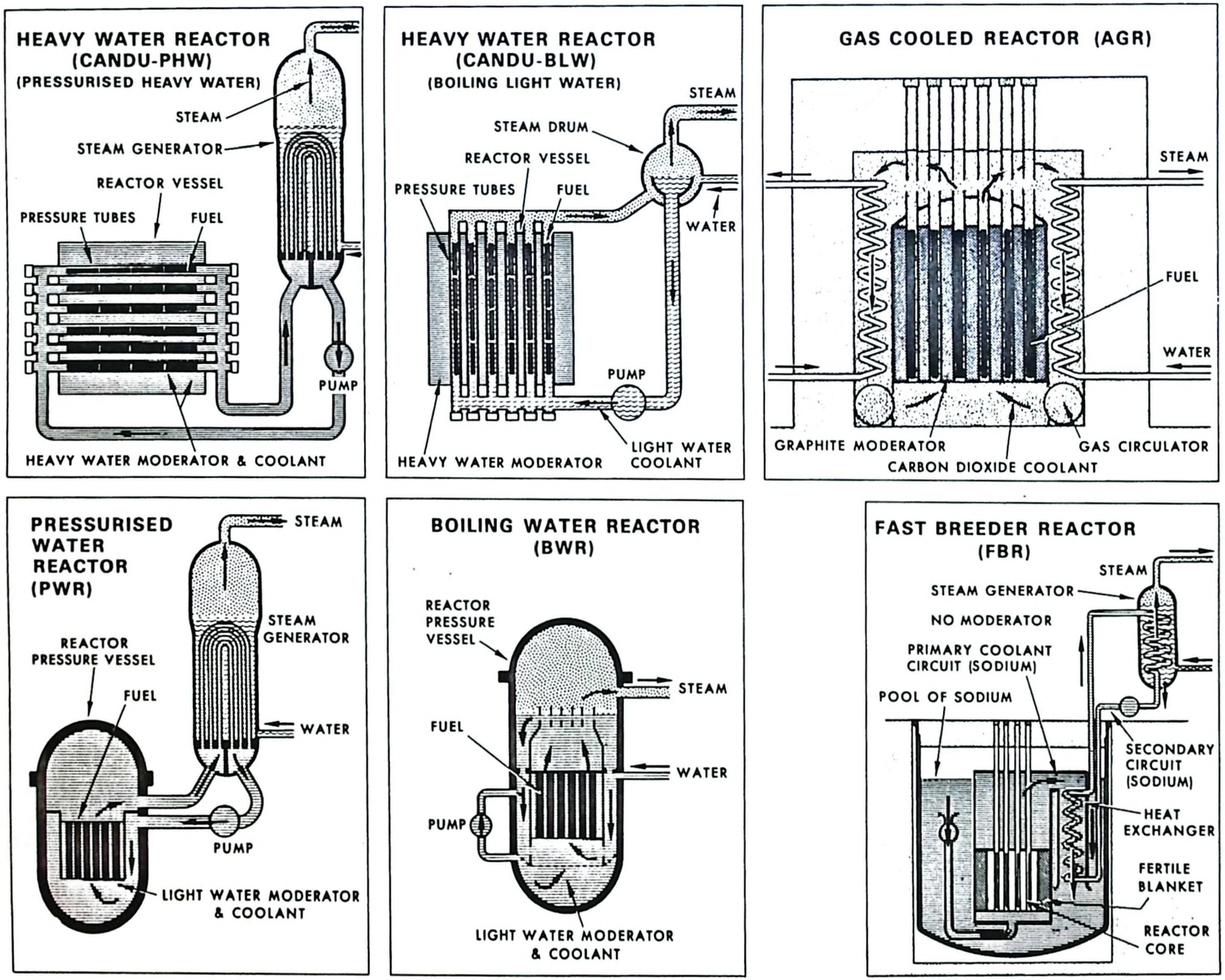


FIGURE 5-2 SCHEMATIC REPRESENTATION OF BASIC FISSION REACTOR TYPES
(Diagrams courtesy of AECL-EC)

6.0 THE CANDU NUCLEAR POWER SYSTEM

In this and subsequent sections, the CANDU nuclear power system is evaluated and compared with the other energy alternatives. Problem areas are cited, dangers are pointed out, and throughout, safety aspects are stressed.

6.1 Atomic Energy of Canada Limited

Atomic Energy of Canada Limited (AECL) is a crown corporation of the Canadian government with a mandate to develop nuclear power and associated industries in Canada[38][39]. The various activities of the company are illustrated in Figure 6-1, and the structure of the company is shown in Figure 6-2.

6.2 Historical Background of the CANDU Reactor System

The history of CANDU is illustrated in Figure 6-3, where the genealogy of the CANDU reactor from its inception[40] to the current state of the art is given. Table 6-1 summarizes this graph in tabular form.

6.3 Technical Aspects of the CANDU-PHW System

The main characteristics of the CANDU-PHW system are as identified below[41]:

i) Moderator: Heavy water — prescribed on the basis of neutron economy, AECL know-how, ability to accommodate greater flexibility of fuel cycle, and ease of maintenance and replacement.

ii) Fuel: Currently natural uranium dioxide in a once-through cycle to avoid the complexity of fuel isotope separation, and to defer requirements for spent fuel reprocessing.

iii) Reactor Form: Insulated pressure tube primary coolant containment to establish reactor replaceability, to reduce risk of heavy water loss from the moderator, to facilitate large reactor ratings with natural uranium fuel, and to be more suitable for Canadian manufacturing facilities.

iv) Fuel Form: Zirconium-alloy-clad short fuel bundles to simplify on-power fuelling mechanisms, to limit failed fuel rejection, to provide flexibility in selecting burnup to neutron flux relationships and flux shaping, and to offer simplicity and handling advantages in fuel element manufacture.

v) Refuelling: On-power bi-directional fuelling to assist in achieving high capability factors, to permit on-power removal of failed fuel, and to increase average burnup.

vi) Primary Coolant: Pressurized heavy water to maximize fuel burnup and minimize the positive void coefficient of reactivity (q.v. Section 6.4.5.2). In this choice, initial cost and possible chronic operating loss of heavy water were of serious concern, and boiling light water or organic coolants are being considered as possible CANDU coolant alternatives.

6.3.1 General Plant Description

The overall layout of a typical CANDU reactor core (the CANDU-PHW 600 MW(e) (CANDU-600) with 380 fuel channels), is given in Figure 6-4. Each pressure tube is isolated from the heavy water moderator by a concentric calandria tube (q.v. Figure 6-5). This configuration results in the moderator system being operated independently of the high pressure ($\sim$ 9.5 MPa) coolant in the pressure tubes. Thus the calandria operates at nearly atmospheric pressure thus obviating the need for a high strength pressure vessel. Due to the physical separation of coolant and moderator, the latter operates at a relatively cool temperature of $\sim 70^{\circ}C$.

The reactor is held inside a reactor containment building with walls made of reinforced concrete, ranging from 3.5 to 6 feet (1.1 to 1.8

meters) in thickness. The reactor building also houses many other components required for power generation as shown in Figure 6-6. The turbines, electrical generators, control room, and other necessary component systems are shown in Figure 6-7. Figure 6-8 provides a schematic representation of the reactor systems. Figure 6-9 shows the components of the CANDU nuclear steam supply system, and the integration of the steam supply system into the entire power operation is depicted in Figure 6-10.

6.3.2 Reactor Control

In CANDU reactors, the power level and neutron flux distribution are controlled by a number of specially designed control mechanisms. The normal control mechanisms (primarily absorber units mounted interstitially between the fuel channels) provide the required power shaping during day-to-day reactor operations. These mechanisms operate independently of the reactor safety shutdown systems which are used to rapidly stop the neutronic chain reaction.

The reactivity control mechanisms and shutdown systems for the CANDU-600 are shown in Figures 6-11 and 6-12. All devices are positioned in the low pressure moderator environment. There exists no mechanism for rapidly ejecting any of these rods, nor can they drop out of the core. This is a distinctive safety feature of the pressure tube reactor design[42].

6.3.3 CANDU-PHW Fuelling

CANDU-PHW reactors are fuelled with natural uranium oxide fuel bundles (q.v. Figure 6-13) each of which is approximately 50 cm in length. (c.f. LWRs which use fuel rods that extend through the entire length of the core). In the CANDU-600 reactors twelve bundles are placed end-to-end in each channel. The fuel is comprised of seven component parts which are mass-produced using conventional shop processes[(43)(44)].

The early fuel bundles for CANDU reactors did not have the CANLUB graphite coating (q.v. Figure 6-13) on the fuel pellets. However, it was found[(45)] that the graphite coating reduced the susceptibility of the fuel sheaths to stress-corrosion cracking, causing the defect rate to drop correspondingly (q.v. Section 7.1.3).

With the short CANDU fuel bundles, it is easy to replace failed fuel and handling problems during refuelling are minimized. Also, since CANDU reactors employ on-power bi-directional refuelling, the shorter bundles allow operators to finely control the power distribution in the reactor[(46)].

6.3.4 CANDU Development

In all aspects of CANDU design, simplicity has been a key factor, for reactors are man-made machines, and hence fallible — though fallibility is minimized when design complications and extraneous accoutrements are avoided when at all possible. Consider for example, the NPD reactor which has a steam supply system with an average of 100 valves per megawatt[47]. By comparison, in the recent Bruce B (756 MW(e)) and Gentilly 2 (CANDU-600) reactors (q.v. Figure 6-3 and Table 6-1), this has been reduced to less than 1 valve per megawatt[47]. Each Pickering A reactor (q.v. Table 6-1) has 16 main pumps, while there are only 4 in the Bruce B reactors[47]. There are 12 steam generators in each Pickering A unit, 8 in each Bruce B unit, and 4 in the CANDU-600[47]. Each of these design modifications was made on the basis of valuable lessons in design and operation, learned through first-hand experience with the previous units[48]. And it is this type of plant simplification that promises lower capital costs and operating expenses, as well as improvements in overall plant safety.

The reactors of current design, though efficient, safe, and commercially proven, still are open to an enormous scope of possible modifications[49] to improve the capital cost position and lower operating costs as well. Higher power densities could be achieved with in-core boiling. Strong high-temperature alloys could be found for high-temperature operation without the risk of introducing defects in fuel cladding. (The zirconium-alloy cladding currently used has only one-third the strength of stainless steel of equal thickness, but due to the strong neutron absorption properties of stainless steel, the steel would have to be seven times stronger than it is before its strength-to-neutrons absorbed ratio would make it a better material for this application than the zirconium-alloy[50].) Further system design simplifications could lower capital costs and increase availability. Manufacturing feedback and construction and operational experience will lead to further design changes in plant components. Controlling losses of expensive heavy water, engaging in coolant chemistry studies to reduce radioactivity in the primary heat transport system, experimenting with alternate coolants such as boiling light water or terphenyls (organic coolants), and the consideration of alternate fuel cycles, are all areas of study that must be carefully analyzed as the CANDU system comes of age.

And with the growing maturity in the CANDU plants, standardization will come to play an increasingly important role in capital and design cost reduction[41]. There will be reduced engineering and tooling costs associated with component manufacture; reduced component development and testing costs; reduced licencing and safety analysis costs. And from lessons learned in post projects, there will be fewer delays in construction. Further, once the plant is complete, there will be greater plant availability during the early operational period through the application of the experience gained in the first standard units. This design standardization already has a considerable effect on costing in the CANDU-600 series.

6.4 Safety Aspects of the CANDU-PHW Reactor System

Indeed nuclear power stations do produce radioactive wastes with the potential to take human lives, but it is important to note that radioactivity and radiation are natural phenomena man experiences every day. The facts regarding nuclear wastes shall be considered in a separate section on the risks of energy production (Section 8) but it is prudent at this stage to consider the built-in safety features of the CANDU reactor — the features that protect man from the dangers of radiation.

6.4.1 Barriers to the Release of Radiation

The hazard in a nuclear reactor comes from the radioactivity it contains. Over 99% of all readioactivity in a reactor comes from the fission of uranium in the fuel[51]. 90% of the fission products are held within the fuel pellets themselves, and the rest of the fission products are held (in the form of a gas) inside the fuel sheath[51] (q.v. Figure 6-13).

CANDU reactors, and in general most nuclear reactors, provide a number of barriers to stop the escape of the highly radioactive fission products into the atmosphere[52]. The first barrier in a CANDU-PHW reactor, as previously mentioned, is the uranium oxide pellets inside which the fission products are formed. However, as irradiation of the fuel continues, some hairline cracks occur in the fuel pellets allowing some of the radioactive gases to escape into the region between the pellets and the sheath. The cracking is a normal expected behavioural trait of the fuel. In normal operation these gases would be safely contained by the second barrier, the fuel sheaths, and would not escape into the other reactor systems.

However in some circumstances, abnormal reactor operating conditions may result in fuel defects. To protect the surrounding population several other safety barriers are provided in the CANDU-PHW system. First, the coolant system, consisting of the pressure tubes, calandria tubes, gas gaps, and coolant material can provide protection against the escape of much of the radioactive fission products. Beyond this is the calandria tank and its large heavy water supply which can contain much of the radioactive materials that escape past the coolant system.

Further, in a modern CANDU-600 station, the calandria assembly is embedded with a light-water-filled carbon-steel lined concrete vault. At each end of the reactor there is an end shield consisting of carbon steel balls and light water. Also, the entire reactor is housed in a containment building, and its reinforced or prestressed concrete walls and dome provide yet another barrier to the escape of radiation from the plant. The containment building (often referred to as the reactor building) is strong enough to withstand (or greatly suppress) overpressure caused by the flashing (sudden vapourization) of the coolant, that may occur under certain accident conditions[53]. Further, the containment building has a very high probability of withstanding the force of an incoming aircraft or any credible turbine missile[54], and as such operates effectively as a bunker to protect the reactor from an attack from outside.

A 1 km (radius) exclusion zone around the station acts as a final barrier, in that the radiation, if it should somehow find its way past all the structural barriers, would be greatly diluted before posing a threat to the general population. Under the worst weather conditions (atmospheric inversion layer, that keeps the radiation close to the ground, and non-dispersive winds), the atmospheric dilution factor of the radiation would be approximately 8000[55]. That is, at a 1 km radius, the atmospheric concentration of the radiation would be down by a factor of 8000 from what it was at the containment building walls. For average weather conditions, the dilution factor is 40,000[55].

6.4.2 CANDU-PHW Nuclear Reactor Accidents: General Aspects

For the purpose of safety assessment all major systems in CANDU reactors are categorized either as process systems or special safety systems[42]. All special safety systems are independent of all process systems, and of each other. Process systems are those required for normal reactor operation, and safety systems are those provided to limit radioactivity release if a failure in a process system should occur. The relevant systems are the following[42]:

a) Process Systems
   - i) Heat Transport
   - ii) Reactor Control
   - iii) Electrical Systems
   - iv) Fuel and Fuel Handling

b) Safety Systems (CANDU-600)

i) Shutdown System 1 (SDS1) (Injection of 28 Steel and cadmium rods)

ii) Shutdown System 2 (SDS2) (Dissolved gadolinium injection into the moderator)

iii) Emergency Core Cooling System

iv) Containment.

6.4.2.1 Single and Dual Failures

For accident analysis, the nuclear regulatory agency in Canada, the Atomic Energy Control Board (AECB), has presented guidelines based on the concept of "single" and "dual" failure events[42]. A single failure is a failure of a single process system. A dual failure is a coincident failure of a process system and the unavailability of any one of the special safety systems. To satisfy the AECB guidelines, process system failures (single failures) must occur less than once in three years[42]. Dual failures must occur less than once in 3000 years[42] for a given reactor.

Actual experience after several reactor years of operation readily establishes whether the target for single failure frequency is met. However, since the dual failure frequency must be kept so low, it is difficult to establish whether the design targets have been met. Therefore the unavailability rate is verified by a rigorous in-service testing program. The safety systems are designed to permit such testing with the frequency necessary to guarantee the claimed availability[42].

In the assessment of single failures all safety systems are assumed to perform as per their design intent. For dual failure analysis it is assumed that one of the special safety systems may fail to perform its function as intended. Furthermore, in all safety analysis, no credit is given for regulating system action when such action is beneficial in shutting down the reactor. However, when the regulating system would act in a manner which might worsen the consequences of an accident, such action is considered.

6.4.2.2 Common Mode Events

Common mode events are viewed as single events which could affect or influence more than one major component of a system, or more than one system, or an area of the plant, depending on the nature of the event. The main categories of common mode events considered in the design of CANDU reactors are[42]:

i) man-induced events — fires, missiles, uninhabitable control rooms, etc.

ii) natural phenomena — earthquakes, floods, etc.

iii) human error — design error, analysis error, manufacturing error, etc.

iv) cascading events — pipe whip affecting nearby components, harsh environment following a random initiating event, etc.

Protection against common-mode events is necessary from both an economic and a safety standpoint. The protective measures fall into the following general categories[42]:

i) consideration of the event in siting and design,

ii) high quality design, manufacturing, and operation;

iii) qualification (hardening), and

iv) duplication and diversity (the two group approach).

In CANDU reactor design, category i) covers the practice.of considering all natural and man-made events in site evaluation and selection. If events cannot be disregarded because of extremely low probabilities, they must be considered in the design[42].

Category ii) refers to high quality design, manufacturing, and operation. This is assured via the use of relevant standards and codes, engineered features such as pipe restraints and barriers, redundancy and diversity in process and safety systems, and on-power testing of all systems[42].

Category iii) refers to the special qualification of important systems to withstand certain events, such as earthquakes or the harsh environment following a break in the heat transport system[42] (a Loss-of-Coolant Accident, as discussed in Section 6.4.4).

Category iv) is known as the "two group approach" and refers to the concept of duplicating important reactor functions, and where possible using diverse designs and physical separation of these redundant systems[42].

CANDU reactors are adequately protected from common mode events. The containment building acts as a bunker to protect the reactor from outside attack. The plants are built above natural flood plain levels. All mechanical devices and piping are designed to withstand quite severe earthquakes. Also, as shall be detailed, the operating and shutdown systems are capable of acting under the most demanding situations, and the failure of any one system will not lead to significant reactor damage or radiation releases to the public.

6.4.3 System Response to Reactor Accidents

As mentioned earlier, the reactor regulating devices are themselves capable of shutting down the reactor in the event of minor incidents that may occur. Small pipe leaks, for example, may necessitate a reactor shutdown. However, the situation by no means would require the use of the special shutdown systems, since the use of these systems is warranted only when very rapid reactor shutdowns are required. Hence, by inserting negative reactivity via the reactor control mechanisms and ceasing all fuelling operations, the reactor can be slowly shut down.

Accidents, or incidents, range greatly in severity, and the reactors must be capable of withstanding the worst of these accidents. The probability of major accidents occurring is extremely small, though every CANDU reactor is constructed with hundreds of millions of dollars worth of safety features to mitigate the effects of even the most severe accidents plausible[56].

The CANDU-600 reactor shutdown systems are controlled by computers (with auxiliary backups), and are engaged if in-core self-powered detectors (separate sets for each shutdown system) indicate a significant perturbation in the neutron flux level in any given region in the reactor. There is triplication of detection[57], in that each region is fitted with three flux detectors, two of which must indicate a problem before the shutdown systems are activated. In this way, the failure of one detector will not lead to an unnecessary and extremely uneconomic shutdown. Further, the computers used for control and shutdown applications (separate machines) are completely self-checking and hence can be relied upon to announce all computer malfunctions. However, in the unlikely event that the computers fail to detect an accident, either due to computer malfunction, or the failure of a complete set of triplicated instruments, there is a diversity of other plant parameters which are monitored in a reactor such that these failures would not prevent a shutdown if required[57].

The shutdown systems in the CANDU reactors are failsafe[57], meaning that loss of electrical or computer control would disengage the hold-back mechanisms on the devices leading automatically to a shutdown. (That is, the shutdown systems will become engaged as soon as the operating system ceases to indicate that they should not be engaged.)

6.4.4 System Response to a Loss-of-Coolant Accident (LOCA)

The CANDU-PHW reactors are designed and constructed with various devices and safeguards to mitigate the effects of a LOCA. It is prudent to analyze these safety features to ascertain the effectiveness of the system responses to such an accident.

As previously outlined, CANDU-PHW reactors are constructed with safety shutdown systems to provide an immediate response to any accidents that sufficiently perturb the equilibrium operation of the plant. The systems, SDS1 and SDS2, discussed in Section 6.4.2, are physically separated, both inside and outside the reactor building. The shutdown systems are used in conjunction with other safety systems to provide two independent operational "groups", each capable of ensuring that the plant is in a safe shutdown state.

6.4.4.1 Group One Systems

Reactor shutdown is effected for Group 1 in the CANDU-600 by the SDS1 absorbing rods. Decay power is removed by discharge of steam from the steam generators with make-up supplied by an auxiliary feedwater system. During a LOCA, the SDS1 system is assisted by the Emergency Core Cooling System (ECCS) which consists of a pressurized water supply that is injected into the fuel channels to remove the excess heat. The ECCS cooling water rejects its heat to the ECCS recovery heat exchanger[52].

The CANDU-600 is divided into two essentially separate heat transport systems, one supporting the left side of the reactor, and one supporting the right, and hence a LOCA might occur on one side of the reactor or the other, or both. If it happens that a LOCA occurs on only one side of the reactor, decay power from the operational circuit (the side that did not experience the LOCA) is rejected in the normal fashion via the steam generators.

If the water supply in the ECCS holding tank becomes depleted, recovery pumps in the basement of the reactor building are used to replenish the supply by pumping water up from the reactor building floor.

These auxiliary systems, the reactor regulating system, and all process systems (such as the heat transport system) act in a coordinated fashion to form the Group 1 Safety System. This is shown pictorially in Figure 6-14.

6.4.4.2 Group Two Systems

In the Group 2 approach, reactor shutdown is effected by the liquid poison injection system SDS2. Gadolinium nitrate solution is pumped through horizontally distributed nozzles. The injection takes place under helium pressure. The containment building forms part of this safety system, maintaining a barrier between the radioactivity and the public. The Group 2 system is shown schematically in Figure 6-15.

Emergency electrical power is provided to act as an alternative source of electrical power for Group 2 safety and safety-support systems.

Decay thermal power removal is effected by a supply of emergency water to the steam generators. An emergency water supply system is also provided as an alternative source of water in the unlikely possibility that service water to the ECCS heat exchanger should fail.

The containment system, which forms part of the Group 2 systems is designed to withstand the great pressure surges that may occur during an accident as steam and gas build up in the reactor building. The system is designed to minimize the leakage of radioactivity and radioactive particles from the reactor building, and as a second design feature, the containment system contains an energy absorbing system which reduces the peak pressure and the duration of the pressure excursion[52].

The energy absorbing system comprises a source of dousing water, spray headers and initiating valves, and building air coolers.

For single unit stations, the dousing system is located above the reactor. For multi-unit stations, for example the 4-unit Bruce A or Pickering A stations, it is often more economical to employ a multi-unit dousing system (q.v. Figure 6-16). In this system, the reactors are joined together via a relief duct which is connected to a large vacuum building that is kept at low pressure. In the event of an accident in one of the reactor units, the high pressure vapours are drawn into the vacuum building from the reactor building. Dousing occurs only in the vacuum building itself. Hence only one dousing system is required for four reactors. Of course, when one reactor shuts down because of an accident that required the use of the dousing system, the other three reactors will also shut down.

6.4.4.3 Comment on System Response Effectiveness

AECL and various Canadian utility companies are continuing to investigate the system response to LOCAs, using ever-increasingly detailed analysis. The preliminary analyses has been very promising but further research and development must be carried out to increase the confidence that even under the most severe conditions, neither fuel melting nor fuel channel failure will occur[56].

6.4.5 Further Distinctive Safety Aspects of CANDU Reactors

The basic philosophy in CANDU reactor safety matters is the provision of defence in depth in order to protect the operating staff and the public. Defence in depth is often identified in three levels[52]:

i) First Level

Design, construct, and operate for maximum safety in normal operation and maximum tolerance for system malfunction. Safety begins in the design and is an important factor through all stages of construction. This calls for the highest quality in design and materials, a high level of manufacturing inspection, the testing of components and systems, and in service inspection. The use of redundant and failsafe systems ensures further that the system will perform as designed.

ii) Second Level

The reactor regulating system controls the reactor and steam raising equipment so that its operating parameters remain within conservative operating limits. It is in operation "full-time", and intervenes effectively against many incidents external to itself.

iii) Third Level

A third level of protection for the operating staff and the public is provided by reliable safety systems. These systems, discussed in Section 6.4.4 are designed to assure that any incidents will be prevented, arrested, or accommodated safely. Conservative design practices, adequate design margin, inspectability, and independent redundant detecting and actuating equipment are incorporated into the safety systems to ensure effectiveness and reliability.

Essentially all commercial nuclear reactor systems follow this defence in depth approach to safety design, however some designs prove to be better suited to specific safety philosophies than do others. The defence in depth approach in CANDU design has been briefly detailed throughout this chapter, and at this point it is prudent to consider several other distinctive safety aspects of the CANDU design. These features are discussed at length in Reference 42, and are somewhat technical in scope, but their mention is warranted in this context as well.

6.4.5.1 Pressure Tubes

The use of pressure tubes in a CANDU reactor allows the physical separation of the coolant and moderator. This means that the relatively cool moderator can act as a heat sink under certain accident conditions. Also, it means that the reactivity and control devices which are positioned interstitially between the pressure tubes operate in a low pressure, low temperature environment. This is important under accident conditions, since if excess fuel heating leads to a coolant temperature and pressure buildup, the moderator temperature and pressure increase will be much less significant than if the entire core had been originally under high pressure (as in the pressure vessel type reactors). The moderator would first have to absorb an enormous amount of energy before building up enough pressure to push the control or shutdown rods out of the core.

The forced ejection of shutdown rods is not relevant to pressure tube reactors, however in pressure vessel reactors, the possibility of rod ejection is an important consideration, and though secondary shutdown systems can act in such a case, this definitely is an intrinsic safety draw-back for the pressure vessel reactors.

Pressure tubes also provide an early warning problem detection system. Experimental evidence indicates that pressure tubes will leak before they break, since their thickness is less than the critical crack length. This is the expected failure mode, should there be such a failure. In addition, there is no experimental evidence to suggest that a break would propogate to other pressure tubes.

Pressure tube leaks can be readily detected by monitoring the moisture content and pressure in the gas space between the pressure tube and calandria tube. This is done on a continual basis. In addition, ultrasonic scanning devices are mounted on the fuelling machines for periodic in-service inspection of the pressure tubes. Consequently a sudden pressure tube rupture is very unlikely. Nevertheless, for licensing purposes the design must be shown to be able to cope with a sudden rupture in the pressure tube, ignoring the details of how such a rupture occurred.

A final safety feature of the pressure tube design is that it permits the subdivision of the primary heat transport system into two separate coolant circuits. This has beneficial effects in case of a loss-of-coolant accident in that it simplifies the design and reduces the burden on emergency injection and containment systems.

6.4.5.2 Void-Reactivity Effect

The coolant density coefficient of reactivity in a CANDU-PHW is negative (that is, an increase in coolant density decreases the reactivity). The void effect is therefore said to be positive. During a loss of coolant accident the void effect would increase the reactivity of the core. However three additional factors mitigate the power pulse that this void coefficient alone would incur. They are:

i) subdivision of the coolant circuit,

ii) a long prompt neutron lifetime, and

iii) a large delayed neutron fraction due to photoneutron contribution.

Subdivision of the coolant circuit has already been considered. The effects of the latter two factors are discussed in Section 6.4.5.3.

To put the void effect of CANDU-PHW reactors into context with the inherent characteristics of other reactors, it should be noted that all power reactors require rapid shutdown capability, regardless of their inherent feedback effects. Thus, a sudden void collapse in a boiling water reactor, or rapid cooldown on the secondary side of a pressurized water reactor, generates reactivity transients which must be quickly terminated. Furthermore, the inherent characteristics of reactivity feedback must be evaluated in the context of other design features. In a CANDU-PHW, for instance, shutdown system action cannot be impaired by a loss of coolant accident (since the devices enter the low pressure moderator environment), a quite different circumstance as compared to the pressurized environment of a light water reactor core.

Licensing requirements in the U.S.A. demand that a negative void coefficient exist. However, in view of the compensatory safety aspects of the pressure tube design with heavy-water moderation, there should be no difficulty in modifying the American licensing requirements to accept a CANDU-PHW type design with its inherent positive void coefficient[58].

6.4.5.3 Neutron Characteristics

When a fuel nucleus fissions (breaks up) in a reactor, neutrons are emitted. Some of these neutrons are emitted immediately, while others are delayed. That is, they are emitted from the fission products at a later point in time. In addition, delayed photoneutrons (neutrons produced via dislocation of deuterons (one proton and one neutron) in heavy water by high energy light rays (which are also given off in the fission process)) considerably enhance the delayed neutron fraction in heavy-water reactors. In a CANDU reactor about 0.755% of the neutrons are delayed in their emission. This delayed neutron fraction is much larger than for PWR and BWR reactors and contributes to slowing down potential power surges considerably.

CANDU reactors have prompt neutron lifetimes (ℓ^*) of approximately one millisecond[59], thirty times larger than for PWR reactors and about 3000 times larger than for fast reactors. That is, neutrons released at the time of fission in a CANDU reactor take much longer to interact with other nuclei than in other power reactors. This too contributes to slow down any power excursions that may occur, as indicated in Figure 6-17.

Transient 1 corresponds to a LOCA effect followed by shutdown system action. Transient 2 is a hypothetical transient with a reactivity insertion almost equal to the delayed neutron fraction (a condition called prompt critical). One can see that for reactivity transients well below prompt critical, the effect of the different ℓ^* values is small. However for reactivity insertions at, or near, prompt critical, the larger ℓ^* retards a power pulse significantly. In CANDU reactors this is an important consequence, since it reduces the demands placed on the shutdown system design to relatively modest performance requirements.

It should be noted that the analysis leading to the results in Figure 6-17 considered only an altered prompt neutron lifetime. All other feedback effects must be considered in a realistic evaluation of accidental excursions. It is important to emphasize again that no intinsic design characteristic, be it prompt neutron lifetimes or void reactivity coefficients, can be discussed in isolation from the other intrinsic features. In the CANDU reactor for example, even though there exists a positive void coefficient, the sum of all reactivity effects -- the power coefficient -- is near zero at nominal operating conditions[42]. This is the important parameter in safety analysis.

6.4.6 CANDU-PHW Safety Analysis

Due to the fact that a CANDU-PHW reactor has never experienced a serious accident, computer analyses simulating such events must be used to determine the effectiveness of the safety systems in the reactors.

The accuracy of the computer programs used in such analyses is tested by comparing the results of simulations in the areas of reactor physics, heat transfer, thermohydraulics, atmospheric dispersion, etc., with the large base of experimental data available. Of course none of the experimental data correspond to the high power loss-of-coolant accidents, for example, but the accurate simulation of low temperature loss-of-coolant accidents (induced), and multitudes of other verifications against experiment give reactor designers much confidence in the ability of the computer programs to accurately simulate all feasible reactor conditions.

A significant feature of the design process is the assurance derived from the Safety Design Matrix analyses[42] whereby the performance of process and safety systems is verified under postulated combinations of system unavailability. Fault tree analysis allows designers to follow the effects of a series of errors, accidents, and equipment failures to examine the outcome of such a chain of events[42][52]. This type of analysis points out problem areas that may not have been realized initially, and thereby allows for design modifications to correct the flaws.

The accident analyses for CANDU reactors cover a broad spectrum of postulated events. Both single and dual failure accidents are simulated for each reactor type and the licensing body, the Atomic Energy Control Board, must be satisified that the systems can successfully mitigate the effects of these accidents before granting an operating licence. In Section 8 the allowed radiation releases to the environment, set by the AECB are presented. The CANDU-PHW safety analysis has shown that the reactors can satisfy these release limits, even in the extreme case of a large loss-of-coolant accident with coincident impairment of either the Emergency Core Cooling System, the containment system, or a shutdown system[42].

NAME	LOCATION	TYPE	POWER MW(e) NET	NUCLEAR DESIGNER	DATE OF FIRST POWER
NPD	ONTARIO	PHW	22	AECL & CGE	1962
DOUGLAS POINT	ONTARIO	PHW	206	AECL	1967
PICKERING A	ONTARIO	PHW	515 x 4	AECL	1971/73
GENTILLY 1	QUEBEC	BLW	266	AECL	1971
KANUPP	PAKISTAN	PHW	125	CGE	1971
RAPP 1	INDIA	PHW	203	AECL	1972
RAPP 2	INDIA	PHW	203	AECL	—
BRUCE A	ONTARIO	PHW	740 x 4	AECL	1976/79
GENTILLY 2	QUEBEC	PHW	640	AECL	—
POINT LEPREAU	NEW BRUNSWICK	PHW	635	AECL	—
CORDOBA	ARGENTINA	PHW	600	AECL	—
PICKERING B	ONTARIO	PHW	516 x 4	AECL	—
WOLSUNG 1	KOREA	PHW	600	AECL	—
BRUCE B	ONTARIO	PHW	756 x 4	AECL	—
DARLINGTON A	ONTARIO	PHW	881 x 4	AECL	—
CERNAVODA	ROMANIA	PHW	600 x 2	AECL	—
		TOTAL	18,932 MWe		

TABLE 6-1 CANDU POWER REACTORS

AECL

- OPERATES LABORATORIES.
- PROVIDES NUCLEAR CONSULTING SERVICES.
- DESIGNS CANDU NUCLEAR POWER STATIONS.
- BUILDS AND MARKETS NUCLEAR PLANTS.
- BUILDS AND OPERATES HEAVY WATER PLANTS.
- PRODUCES AND MARKETS RADIOISOTOPES.
- LIAISES WITH INDUSTRY AND UNIVERSITIES.
- COOPERATES WITH OTHER COUNTRIES AND AGENCIES.

FIGURE 6-1 ATOMIC ENERGY OF CANADA LIMITED ACTIVITIES

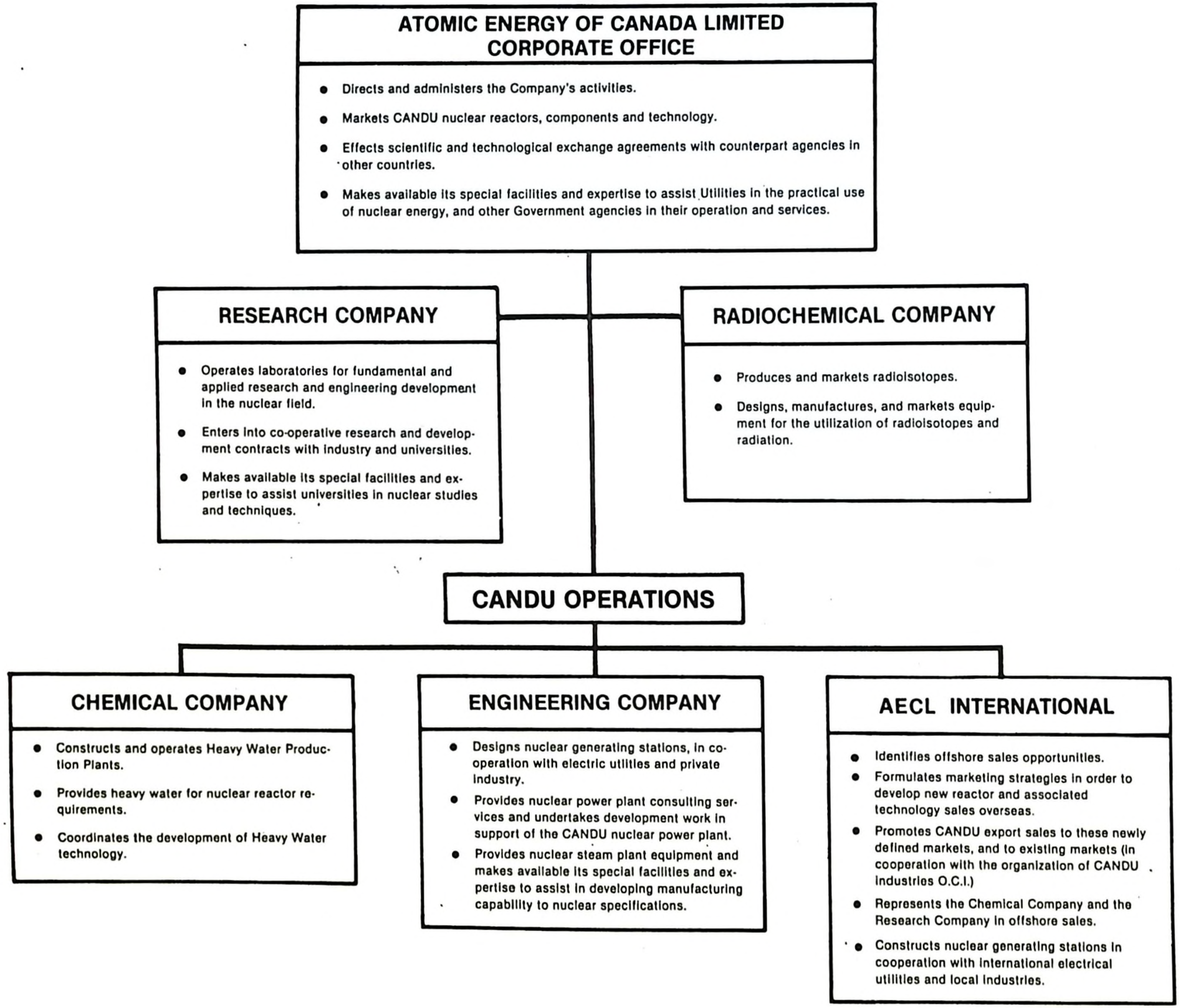


FIGURE 6-2 ATOMIC ENERGY OF CANADA LIMITED ORGANIZATION /RESPONSIBILITIES

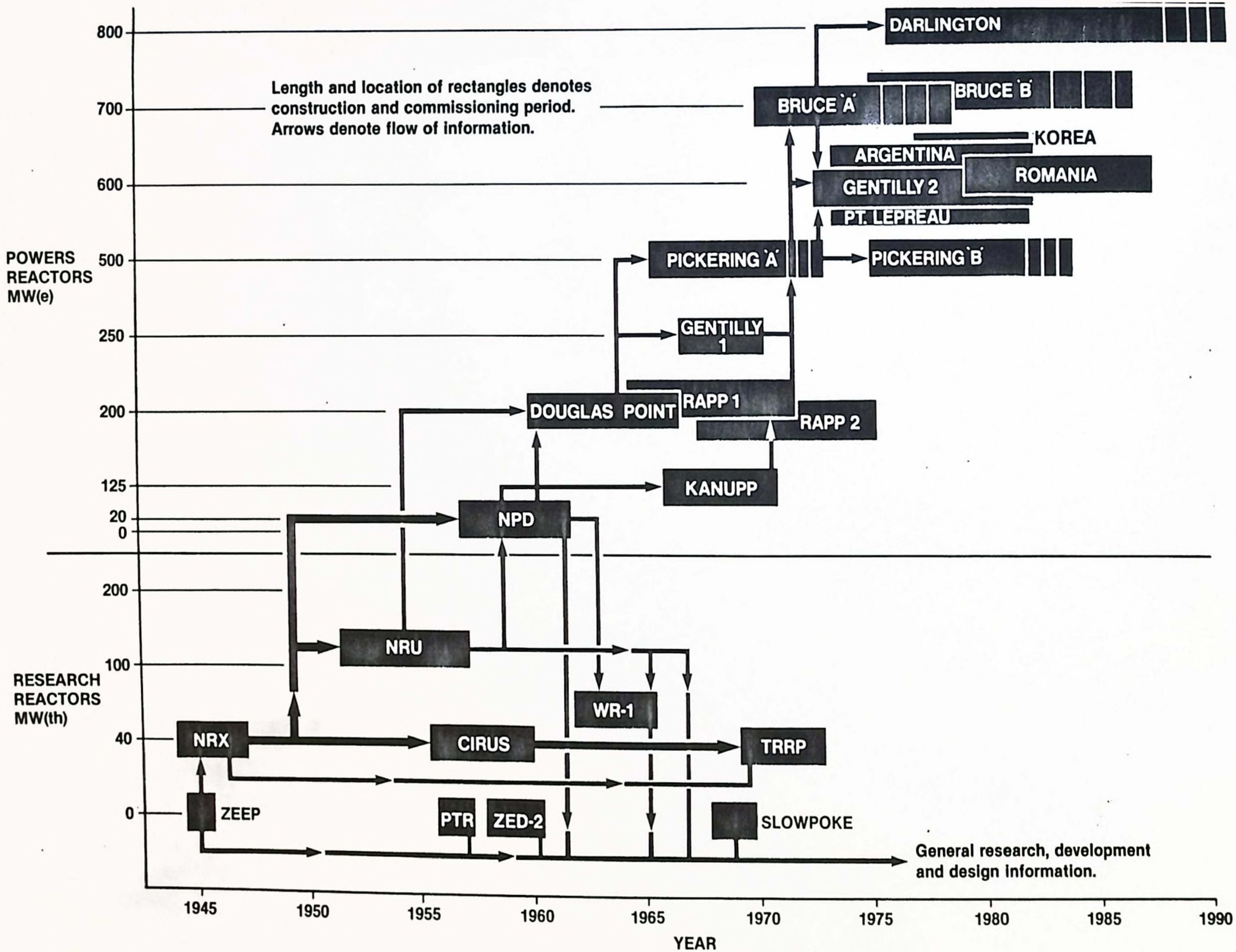
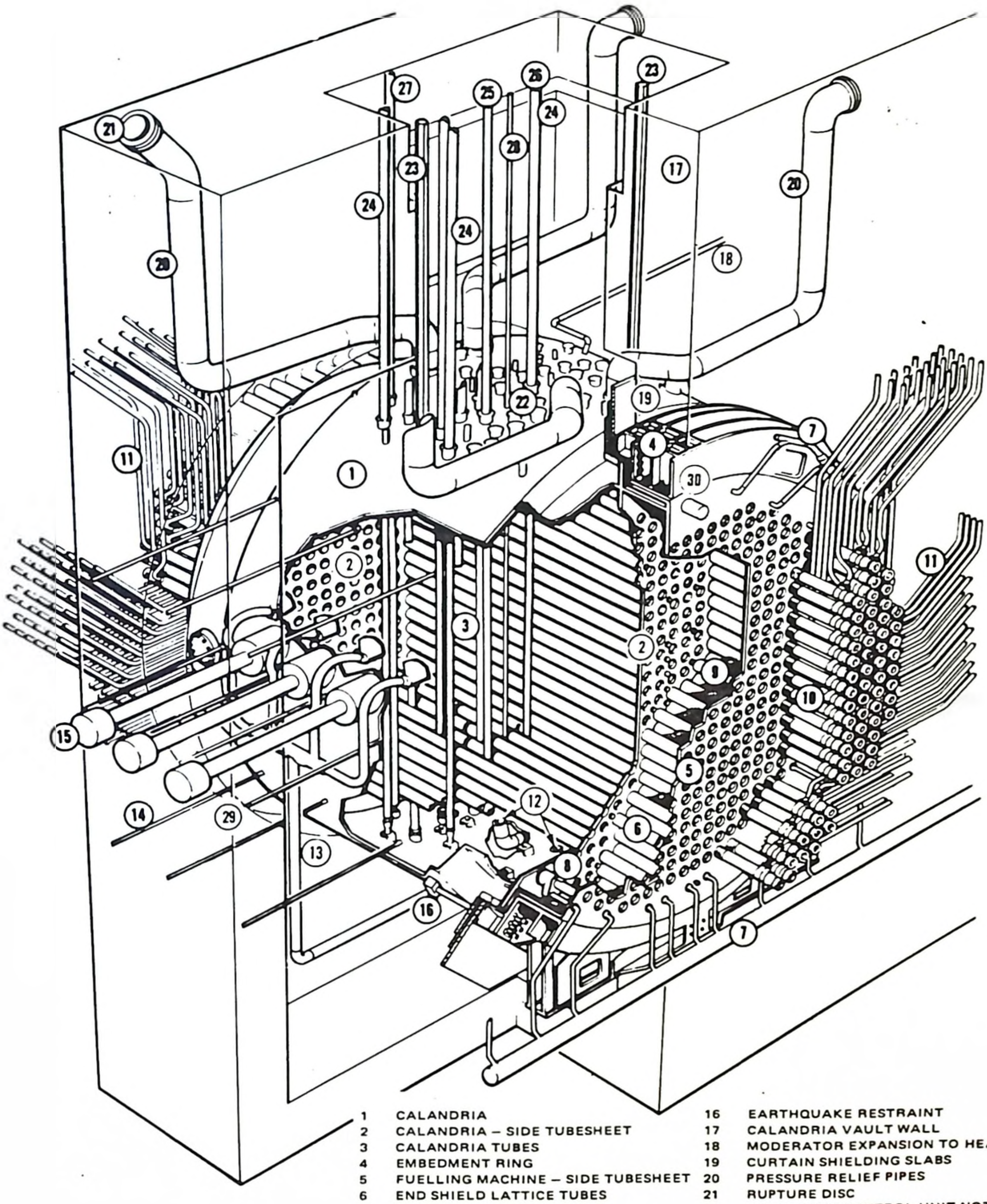


FIGURE 6-3 GENEALOGY OF CANDU REACTORS



1	CALANDRIA	16	EARTHQUAKE RESTRAINT
2	CALANDRIA – SIDE TUBESHEET	17	CALANDRIA VAULT WALL
3	CALANDRIA TUBES	18	MODERATOR EXPANSION TO HEAD TANK
4	EMBEDMENT RING	19	CURTAIN SHIELDING SLABS
5	FUELLING MACHINE – SIDE TUBESHEET	20	PRESSURE RELIEF PIPES
6	END SHIELD LATTICE TUBES	21	RUPTURE DISC
7	END SHIELD COOLING PIPES	22	REACTIVITY CONTROL UNIT NOZZLES
8	INLET-OUTLET STRAINER	23	VIEWING PORT
9	STEEL BALL SHIELDING	24	SHUTOFF UNIT
10	END FITTINGS	25.	ADJUSTER UNIT
11	FEEDER PIPES	26.	CONTROL ABSORBER UNIT
12	MODERATOR OUTLET	27.	ZONE CONTROL UNIT
13	MODERATOR INLET	28.	VERTICAL FLUX DETECTOR UNIT
14	HORIZONTAL FLUX DETECTOR UNIT	29.	LIQUID INJECTION SHUTDOWN NOZZLE
15	ION CHAMBER	30	BALL FILLING PIPE

FIGURE 6-4 REACTOR ASSEMBLY

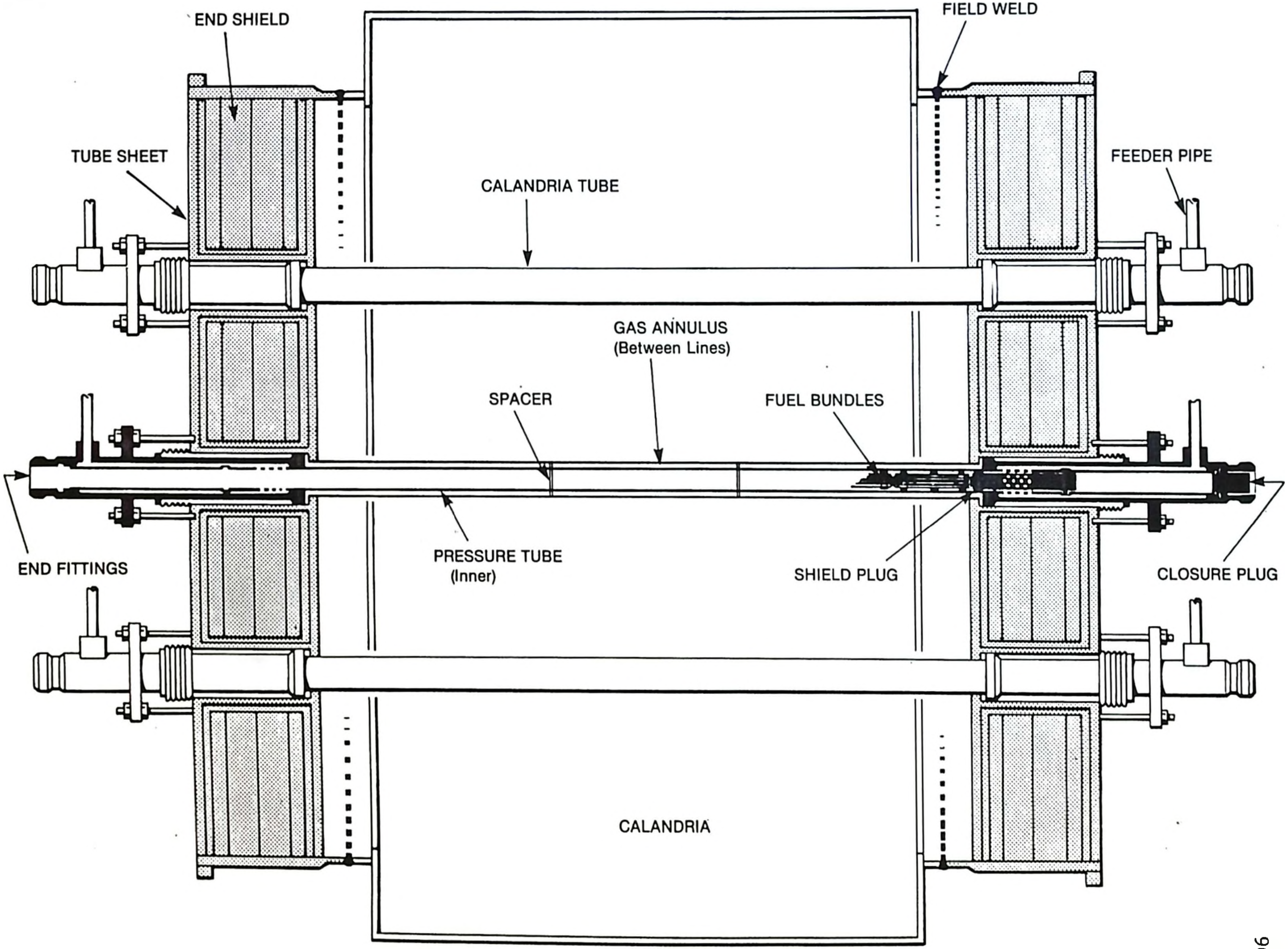
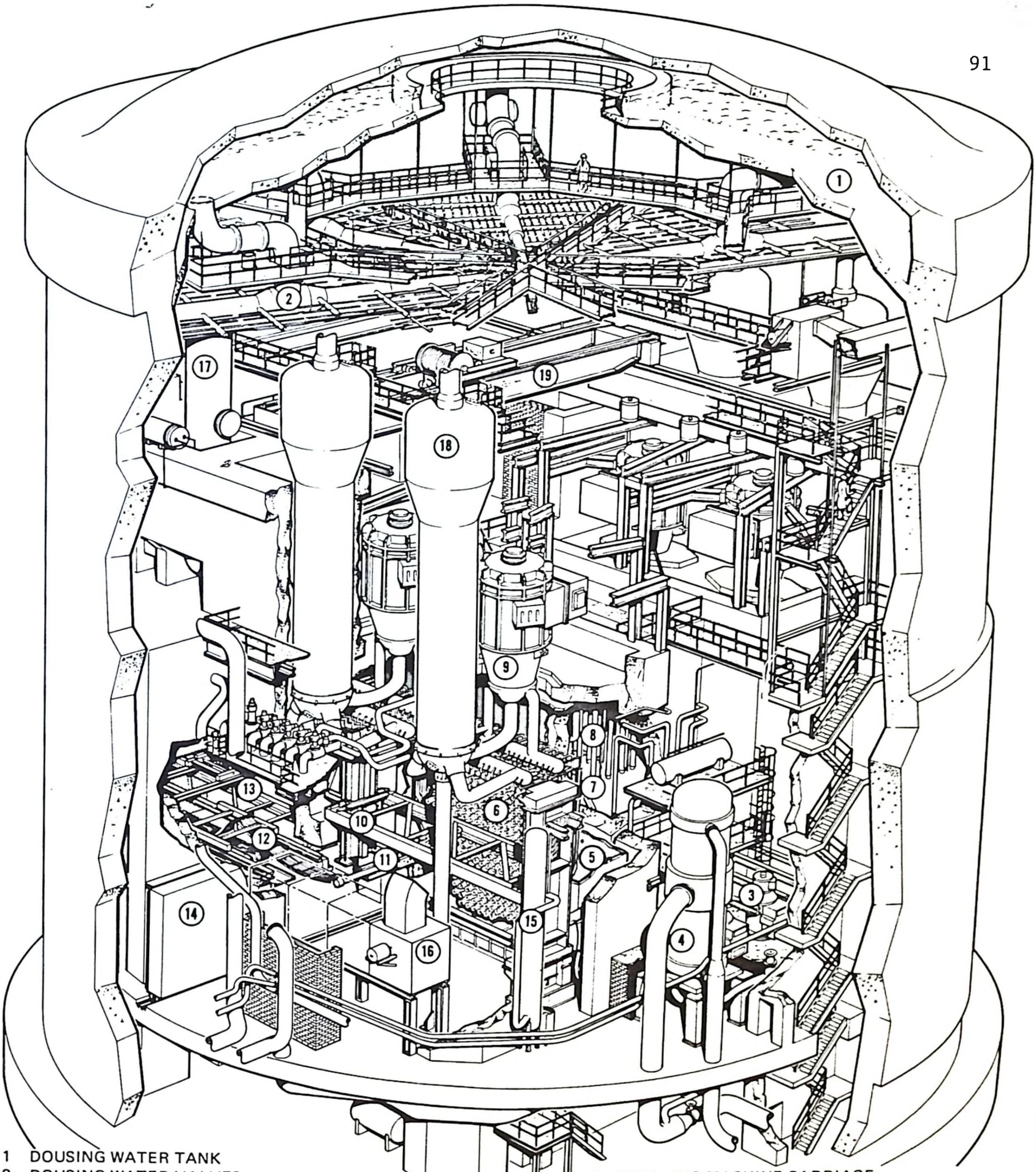
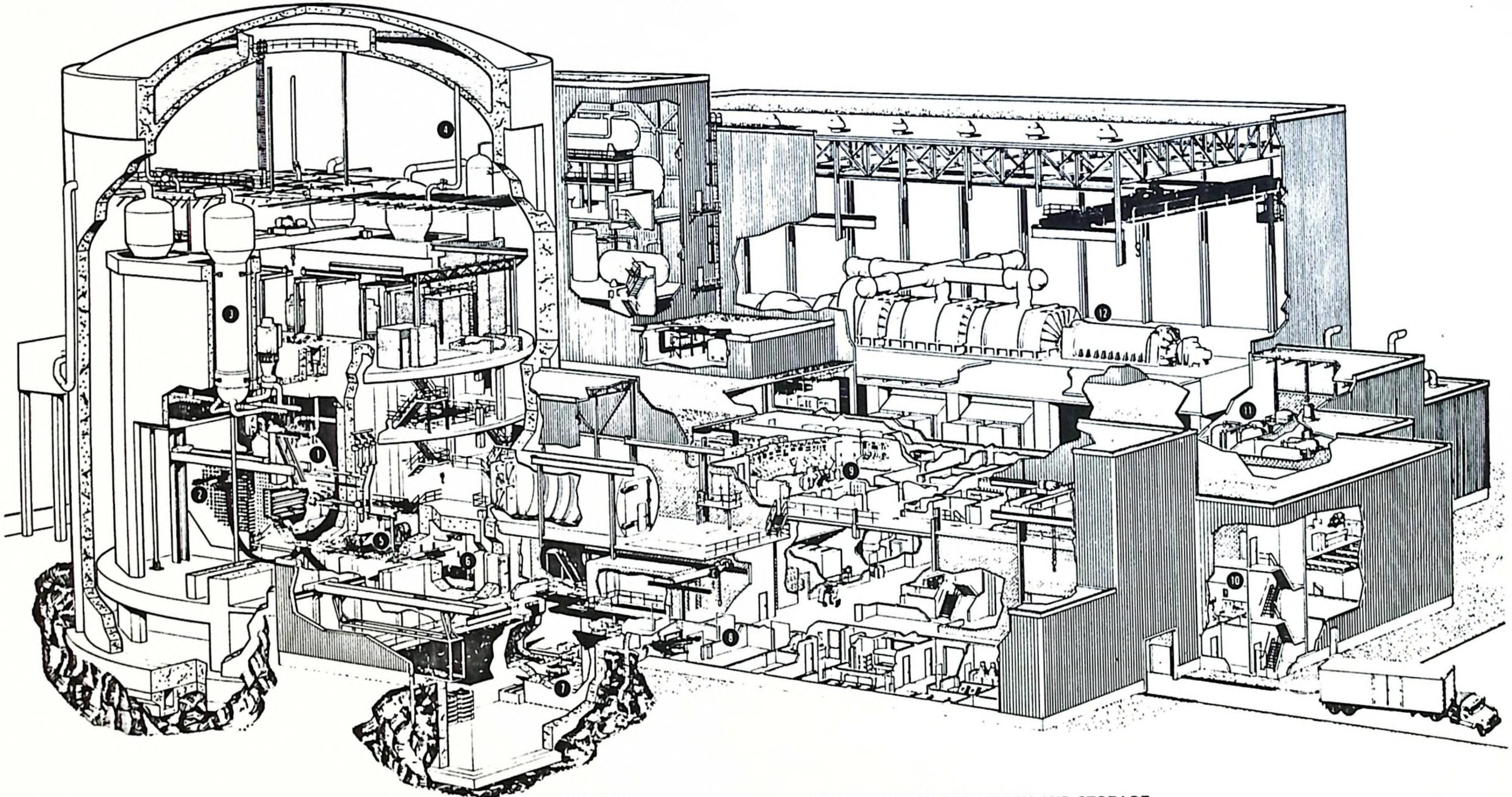


FIGURE 6-5 REACTOR CORE SCHEMATIC



1 DOUSING WATER TANK
2 DOUSING WATER VALVES
3 MODERATOR PUMP
4 MODERATOR HEAT EXCHANGER
5 FEEDER CABINETS
6 REACTOR FACE
7 REACTOR
8 REACTIVITY MECHANISM
9 HEAT TRANSPORT SYSTEM PUMP
10 FUELLING MACHINE BRIDGE
11 FUELLING MACHINE CARRIAGE
12 FUELLING MACHINE CATENARY
13 FUELLING MACHINE MAINTENANCE LOCK
14 FUELLING MACHINE MAINTENANCE LOCK DOOR
15 END SHIELD COOLING WATER DELAY TANK
16 VAULT COOLER
17 PRESSURIZER
18 STEAM GENERATOR
19 STEAM GENERATOR ROOM CRANE

FIGURE 6-6 CANDU-PHW 600 MW(e) REACTOR BUILDING CUTAWAY



1 REACTOR	7 SPENT FUEL INSPECTION AND STORAGE
2 FUELLING MACHINE	8 MAINTENANCE AND INSPECTION
3 STEAM GENERATOR	9 CONTROL CENTRE
4 DOUSING SYSTEM	10 MECHANICAL WORKSHOP
5 NEW FUEL HANDLING	11 WATER TREATMENT
6 SPENT FUEL HANDLING	12 TURBINE AND GENERATOR

FIGURE 6-7 CANDU-PHW 600 MW(e) NUCLEAR GENERATING STATION

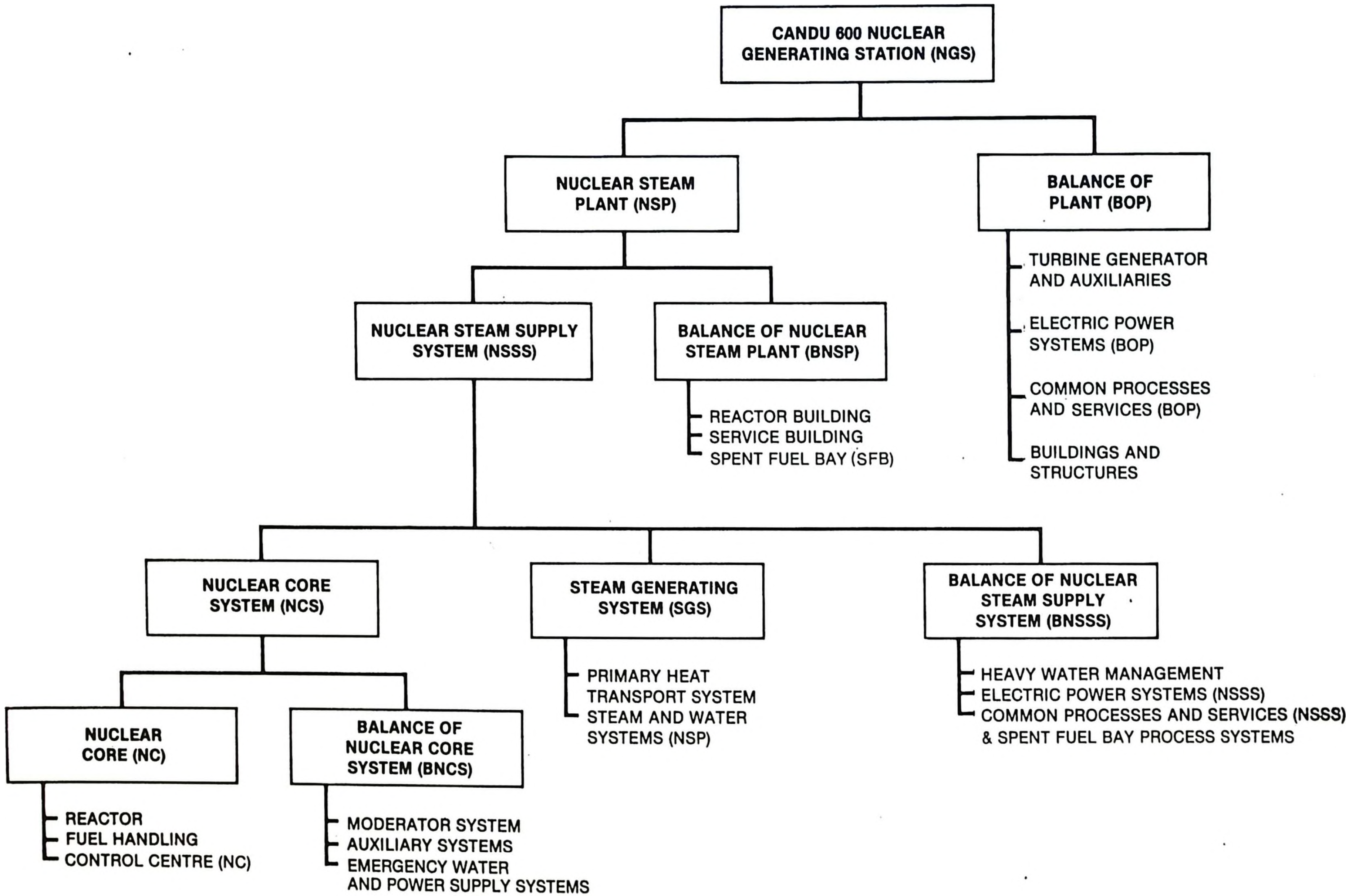


FIGURE 6-8 COMPONENT PARTS OF THE PLANT

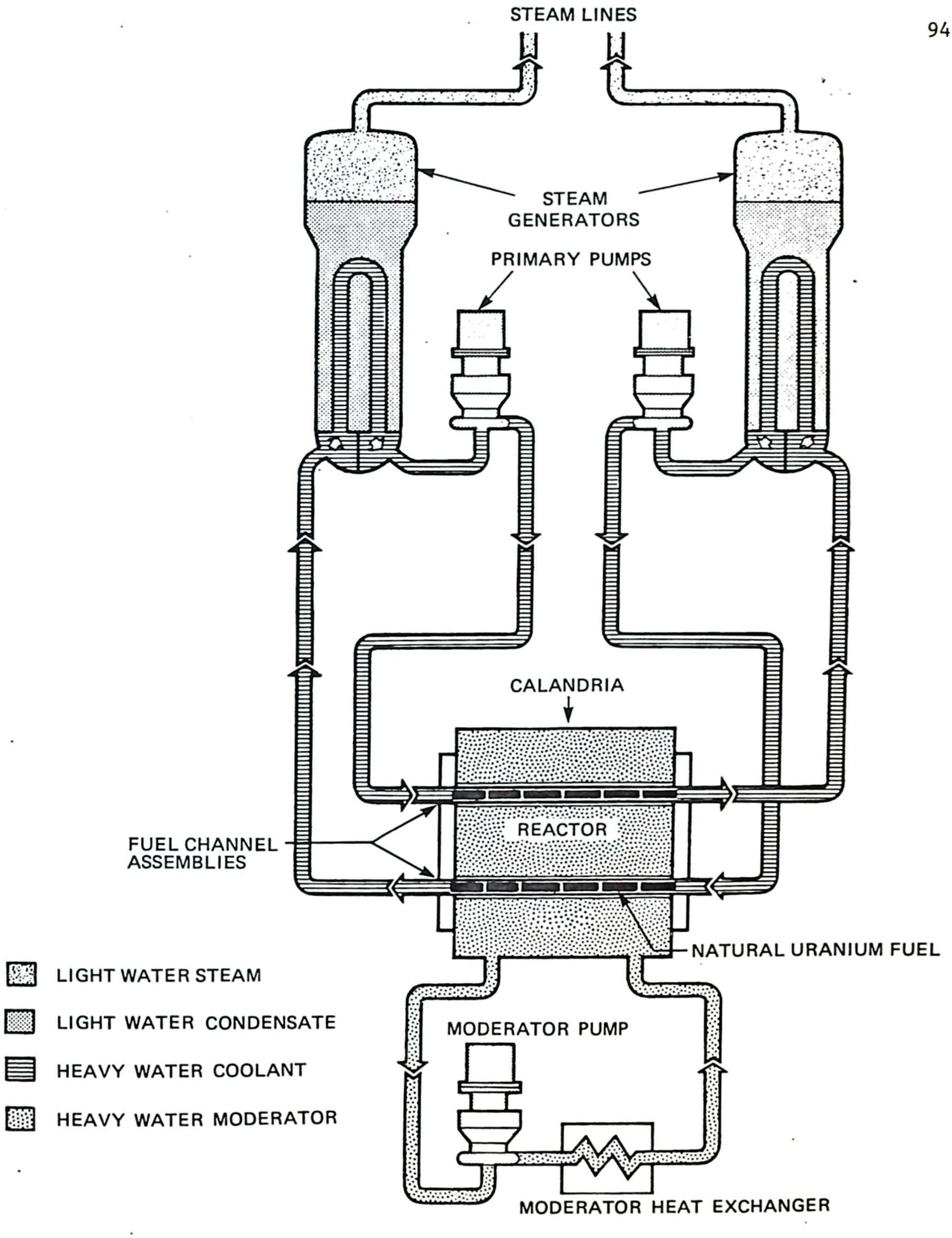


FIGURE 6-9 CANDU NUCLEAR STEAM SUPPLY SYSTEM

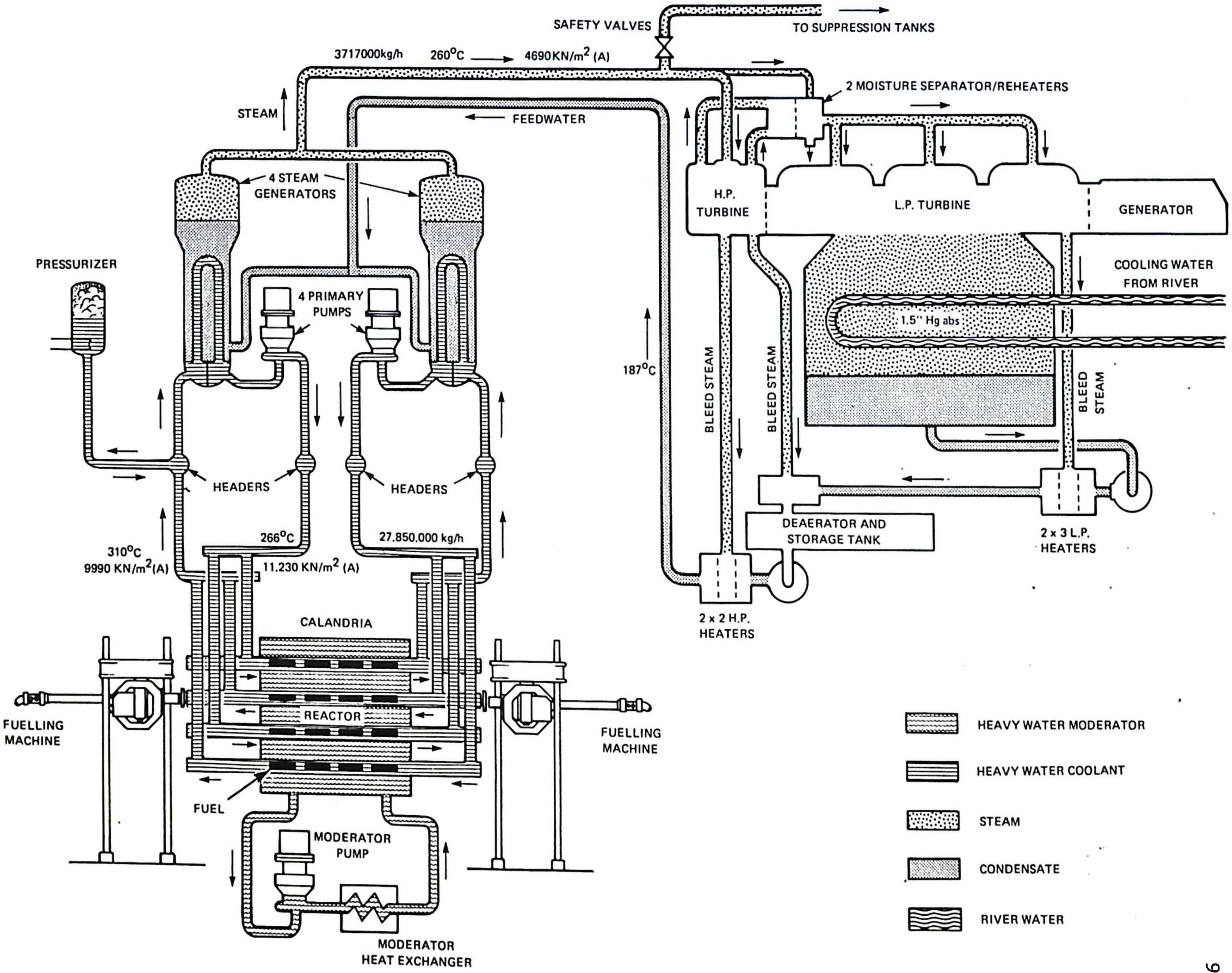


FIGURE 6-10 CANDU NUCLEAR POWER SYSTEM

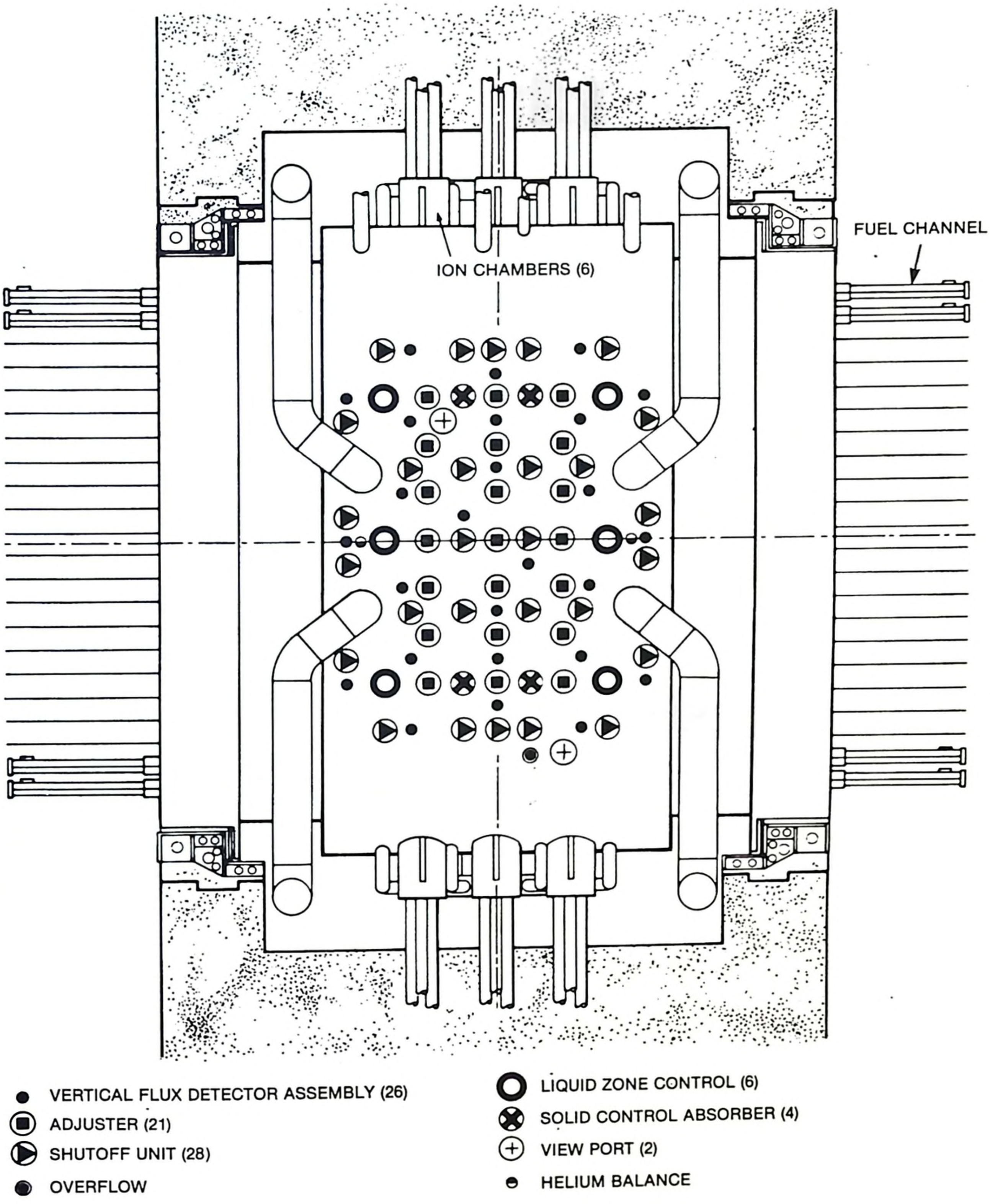


FIGURE 6-11 PLAN VIEW — VERTICALLY MOUNTED REACTIVITY CONTROL DEVICES

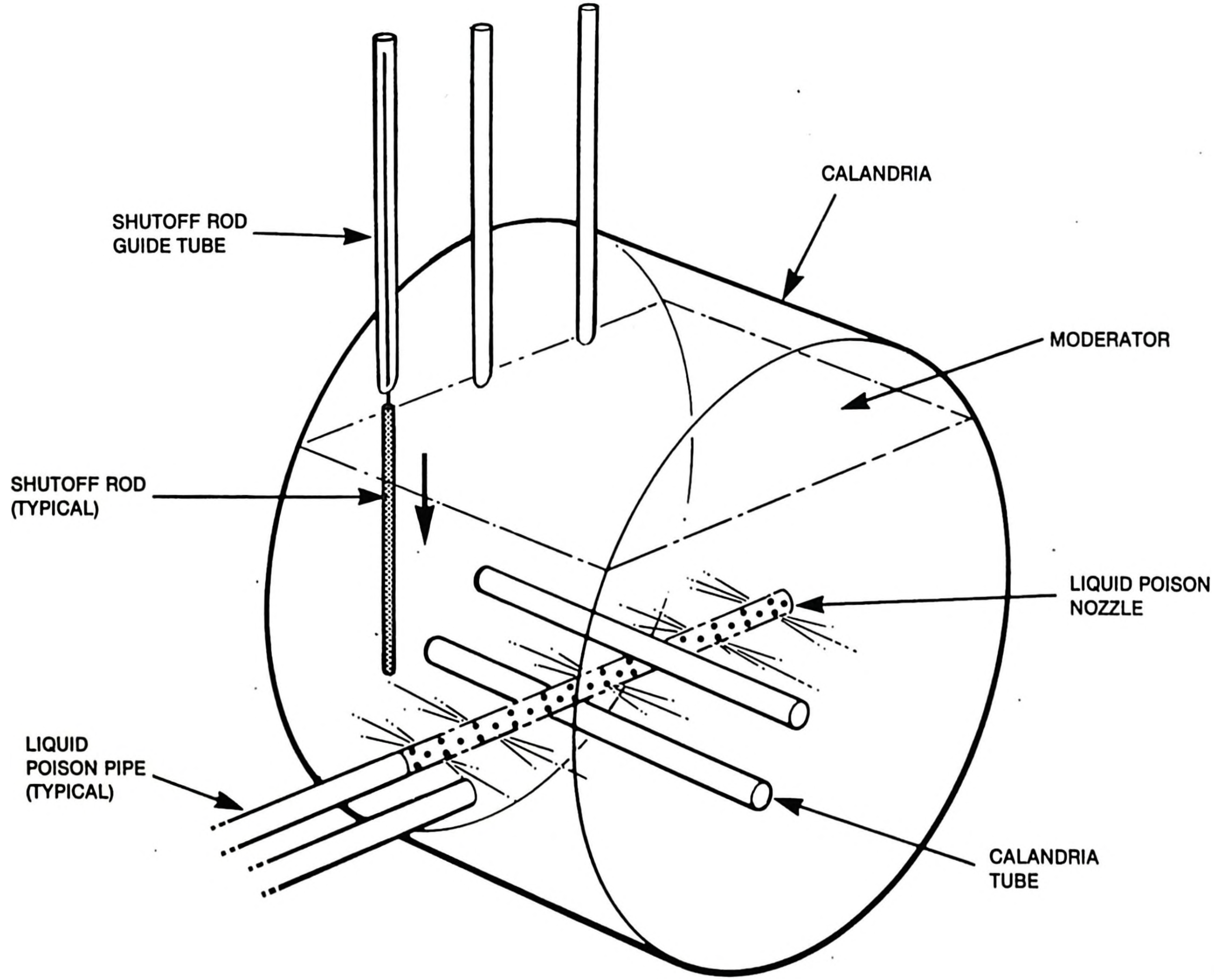


FIGURE 6-12 SHUTDOWN SYSTEMS: SHUTOFF RODS AND LIQUID "POISON" INJECTION

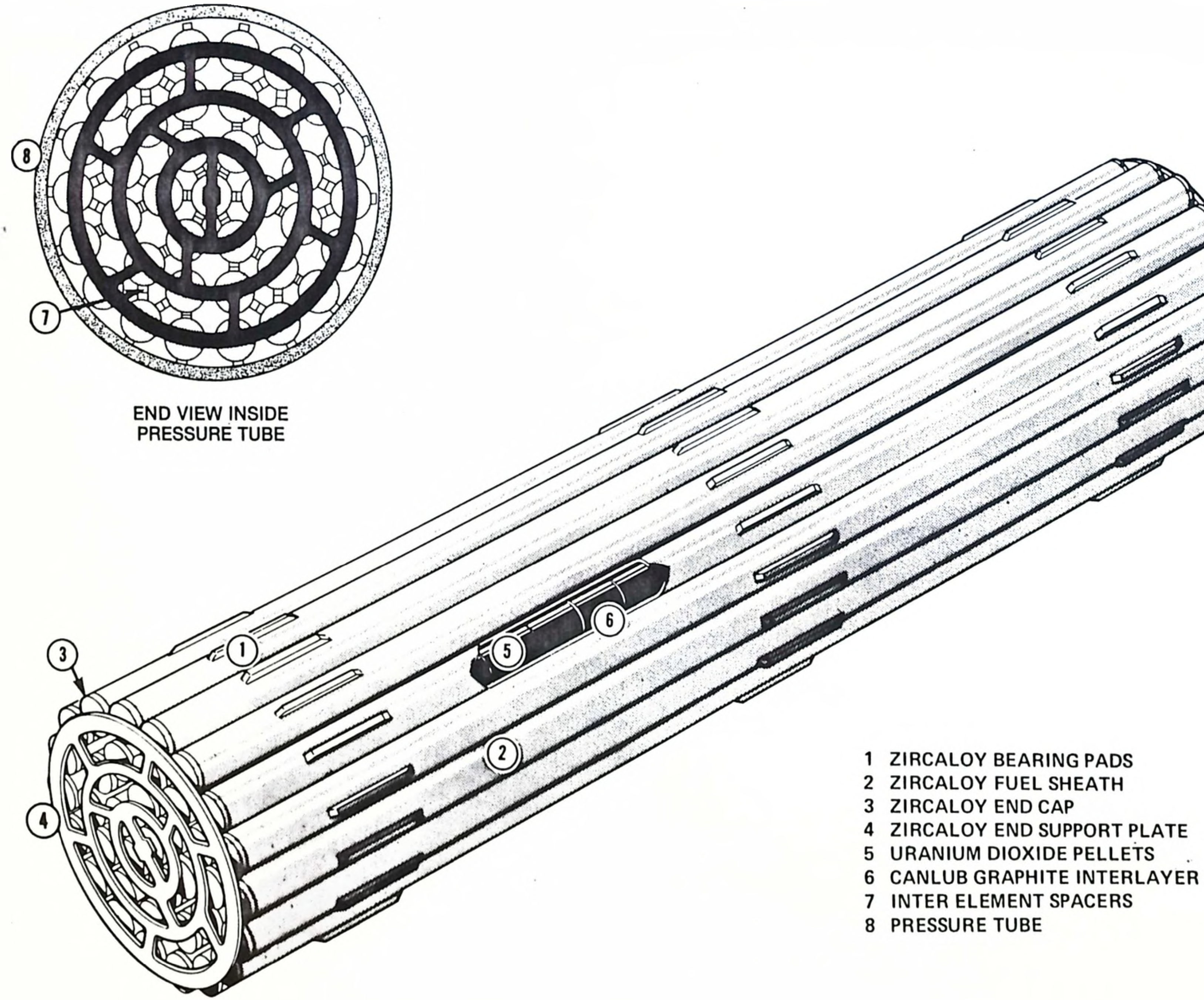


FIGURE 6-13 37-ELEMENT FUEL BUNDLE

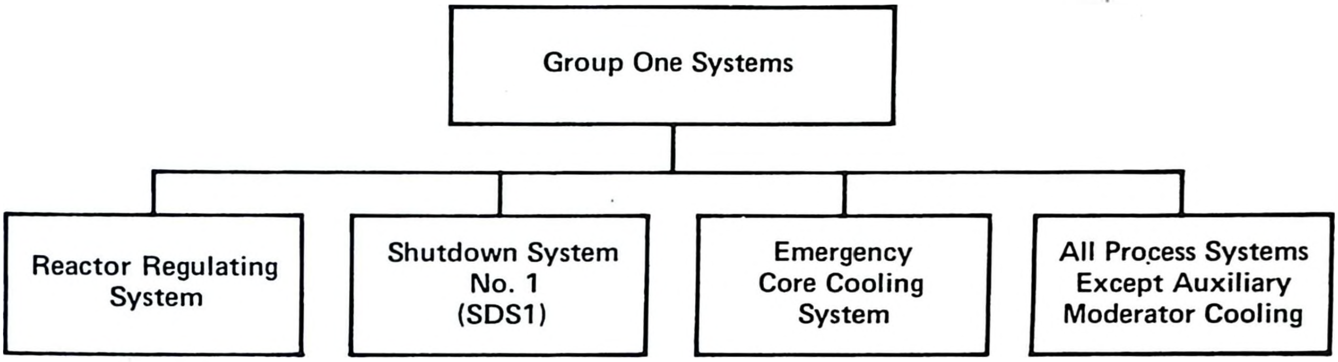


FIGURE 6-14 GROUP ONE SAFETY SYSTEMS

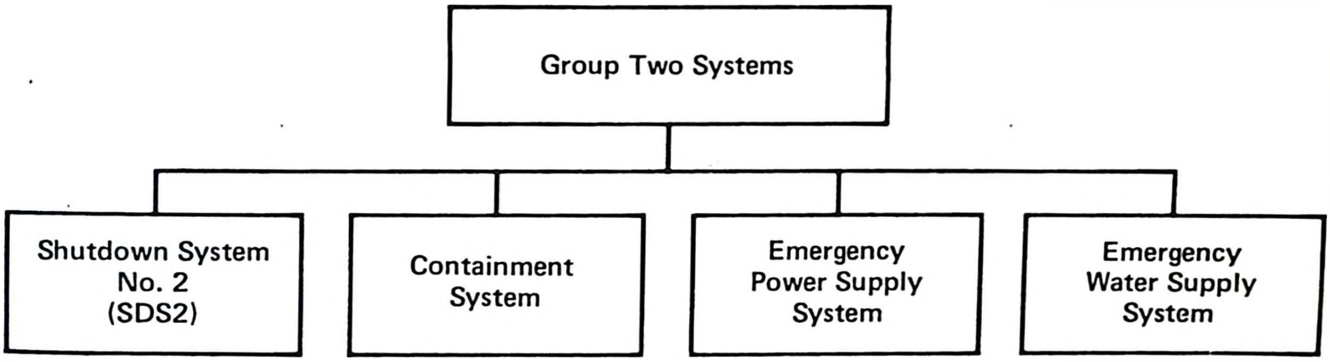


FIGURE 6-15 GROUP TWO SAFETY SYSTEMS

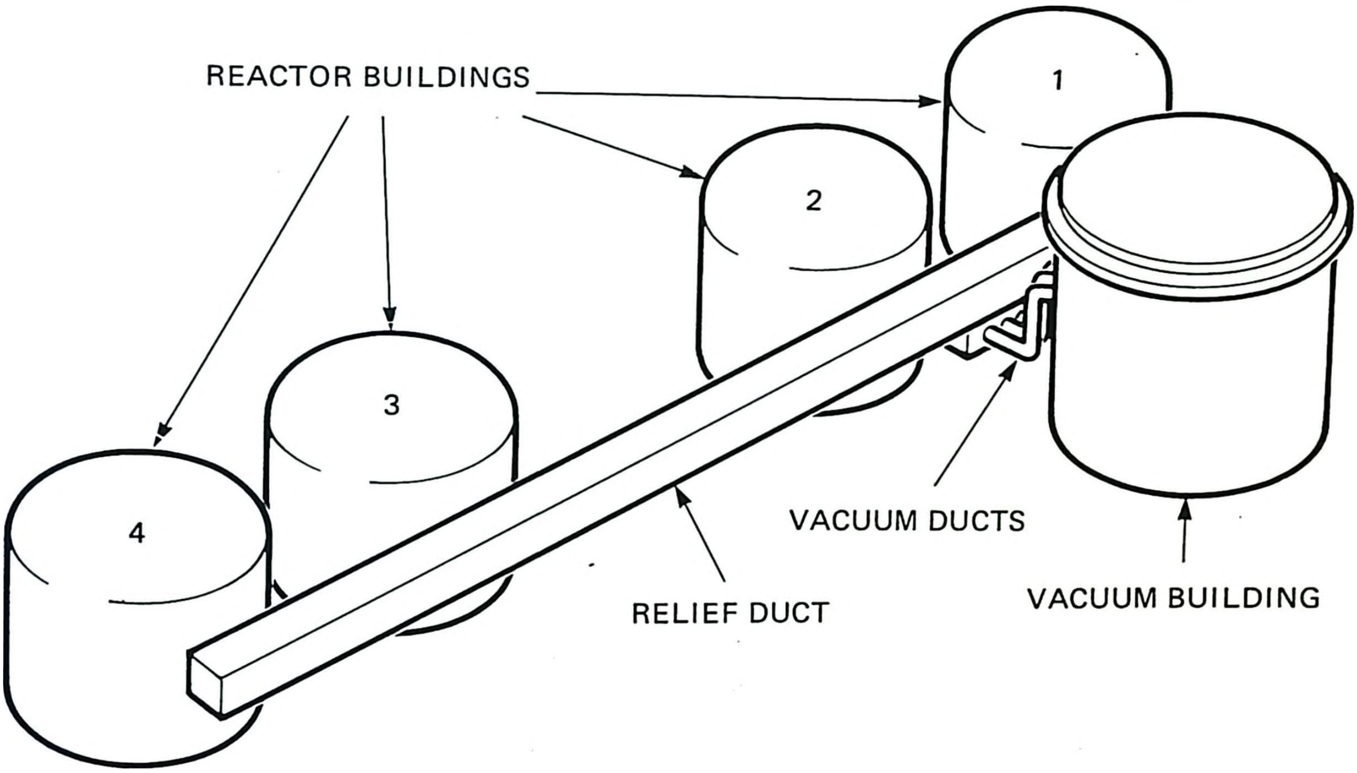


FIGURE 6-16 MULTI-UNIT CONTAINMENT

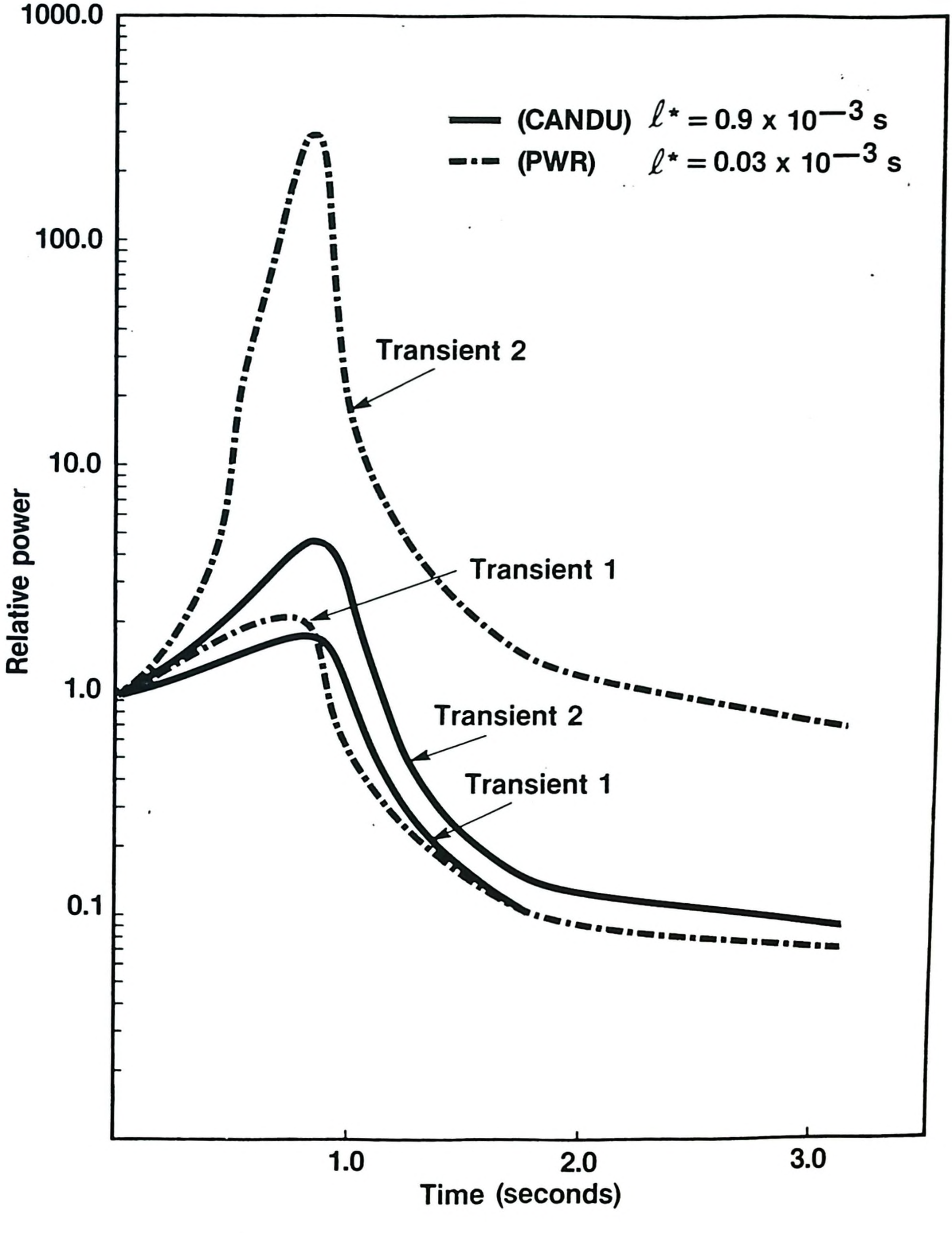


FIGURE 6-17 SENSITIVITY OF POWER EXCURSION TO ℓ^*

7.0 THE ECONOMICS AND OPERATION OF CANDU-PHW REACTORS

Design concepts may appear quite promising on paper but often the end product does not quite reflect the good intentions of the engineering personnel. This is especially a concern in the design of nuclear reactors, where a vast multitude of engineering skills and disciplines must match and meld together to produce a product that must be safe and cost-effective. Only operational experience can reveal the true character of a reactor, and only then can meaningful comparisons of operations and costs be made.

7.1 CANDU-PHW Operating Experience

Thirty-nine years of technological development and ninety-two reactor years of operating experience have brought about the current design of the CANDU-PHW reactor. There are currently 8 large (> 500 MW(e)) CANDU-PHW reactors in operation and as shown in Table 6-1, there are several more under construction around the world. Ontario Hydro, a crown corporation of the Ontario government, owns and operates all of the current large CANDU reactors, which have a total net capacity of more than 5000 MW(e), and in addition, Ontario Hydro has another 8612 MW(e) under construction. The performance of these plants has exceeded that of any other type of nuclear station in the world[60] due to the performance- and safety-oriented component design objectives, and high employee standards.

7.1.1 System Incapability

One of the most meaningful ways of quantifying the effect of equipment problems on operational behaviour is to express the effect in terms of System Incapability, expressed as a percentage of perfect production in the time period. If a generating unit is perfect, that is, able to operate at full power all of the time, the Incapability Factor would be 0.0%, and the Capability Factor would be 100%. In practice, the Capability Factor is less than 100% because of outages (full shutdowns) and deratings (less than full power). The Incapability Factor indicates the inability of a unit to operate at full power all of the time. (See also "CAPABILITY FACTOR" in the Glossary).

For the 8 large CANDU-PHW reactors in operation (4 at the Bruce A Nuclear Generating Station (on Lake Huron) and 4 at the Pickering A Nuclear Generating Station (on Lake Ontario)), the average Incapability Factor is < 20% (q.v. Tables 7-1 and 7-2). The average Canadian or U.S. coal-fired station (of 500 MW(e)) Typically has an Incapability Factor which is three percentage points higher than this[61] (that is, coal-fired stations are not available as often as a typical CANDU-PHW reactor).

Ontario Hydro has established standards for performance[60] based on being equal to or better than the average performance of fossil fuelled units of equivalent size operating throughout North America and reported by the National Electric Reliability Council in annual reports. CANDU-PHW reactors have continually surpassed these performance standards[60], though this is in part due to the extra levels of redundancy and large replacement part supplies which are provided at nuclear stations. The high realiability of CANDU-PHW reactors is due to:

a) On-power fuelling[60],

b) The use of pressure tubes that leak before they break[42][62] (hence allowing advance warning of failures and relatively easy replacement as required),

c) Carefully designed subsystems[60] (steam and electrical generators, etc.),

d) Detailed automatic computer-controlled instrumentation[60].

e) Strict control and monitoring of heavy water transport systems[63][64], quality[65], and production[66][67], and

f) Competent and qualified managerial and operating staff[61][68].

In the world today, Canada is the only country with a large operating pressurized heavy water power reactor system, however many other countries without military nuclear programs have also selected to develop similar systems[69]. Countries such as Belgium, Holland, Sweden, Switzerland, and later Germany and Japan all embarked on ambitious heavy water reactor development programs[69]. Many other countries not possessing a sufficient technological base to develop their own nuclear power programs have chosen to import heavy water reactors and the high technology that goes along with them, so they too could share in the benefits of such a program. But to emphasize again, to date Canada is the only country with a commercial heavy water reactor system with units delivering more than 500 MW(e) each.

7.2 An Operational Comparison of CANDU-PHW Reactors With World Power Reactors

7.2.1 Gross Capacity Factor Comparison

A very important criterion for comparing the performance of the power reactors operating in the world today is to compare their Capacity Factors, which is similar to a Capability Factor comparison, except Capacity Factors are defined as actual energy produced during a period divided by the maximum credible electricity generation level (that is, the lowest of the turbine and generator nameplate ratings), whereas Capability Factors refer to the actual amount of electricity produced plus the amount extra that could be produced divided by the perfect production level (q.v. also the Glossary).

Table 7-3 compares the world power reactor performance for the top 14 of the 131 reactors with gross electrical power output levels greater than 500 MW(e) for all of 1981. The eight CANDU-PHW units in the study ranked first, second, third, fourth, fifth, sixth, eighth and fourteenth, a truly impressive showing. Table 7-4 provides similar data for each year since 1977, and gives average capacities from the reactors' first electrical power date to the end of 1981. In this table, only the top 18 reactors ranked according to Gross Capacity Factor from first electrical power to the end of 1981 are given. The choice of the number of reactors shown in Tables 7-3 and 7-4 was to include all the large CANDU-PHW reactors in operation. Full comparisons of the 131 large power reactors operating in the world today are provided in Reference 70. Figures 7-1 and 7-2 provide a graphical comparison of the world's reactors.

The Lifetime (since first production of electricity) Gross Capacity Factors for the world's largest reactors, as shown in Figure 7-2, definitely illustrate that the CANDU-PHW reactors lead the way in performance. CANDU-PHW units have had an average Lifetime Gross Capacity Factor of 79%. They are followed by Pressurized Water Reactors (58%), Boiling Water Reactors (56%), and Gas Cooled Reactors (46%)[60]. The excellent lifetime reliability of CANDU-PHW reactors allows electricity to be available when required, thereby minimizing the need for backup generating equipment and consequently reducing the cost of the energy produced.

7.2.2 Fuelling and Fuel Consumption

CANDU-PHW reactors operating on a once-through natural uranium cycle (q.v. Section 7.4.1) have the simplest fuel cycle of any commercial power reactor existent or in prospect[31]. The reactors do not require enriched uranium fuel and hence obviate the requirement for extra control in manufacture that enriched fuels for other reactors demand. The simple fuel cycle is not however without its price in terms of uranium resource utilization.

In today's CANDU-PHW reactors only about one per cent of the uranium is fissioned to obtain an almost equal mass of fission products[31]. Another one per cent of the uranium is converted to heavier elements — the so-called transuranic elements. Plutonium is the most important of these.

In a CANDU-PHW reactor one-half of the power from a natural uranium dioxide fuel bundle is obtained from the fissioning of uranium-235 (U-235). The initial fresh bundle concentration of this fissile isotope is 0.7%. At the time of removal from the core as spent fuel, the U-235 concentration has dropped to approximately 0.2%[71].

The other half of the power from a natural uranium dioxide fuel bundle comes from the fissioning of fissile plutonium atoms produced in the core during the fuel cycle[71]. Initially there are no plutonium atoms in the fuel, but as neutrons bombard the uranium-238 (U-238) atoms (which make up 99.3% of the fuel), some of the U-238 atoms absorb one or more neutrons and become converted into plutonium atoms. Many of these plutonium nuclei absorb other neutrons and fission, producing heat as they do so. The rest of the plutonium atoms remain intact upon removal of the fuel from the core. In fact plutonium atoms account for 0.38% of the heavy element mass of a spent fuel bundle. (0.28% is fissile plutonium (Pu-239 and Pu-241), and 0.1% is non-fissile Pu-240 and Pu-242)[71]. Currently, as shall be detailed in Section 8, the spent fuel from a CANDU-PHW is safely stored in large water-filled pools, and no attempt is made to recover the fissile content of the spent material.

The overriding philosophy throughout the development of the CANDU system has been neutron economy and the achievement of economic fuelling based on a once-through natural uranium cycle. And even though such a small fraction of the uranium is utilized in the current CANDU-PHW fuelling cycle, the utilization of natural uranium in this cycle is more efficient than any other fuel cycle in commercial use today[63]. In fact, if one assumes, quite accurately, that in the PWR fuel enrichment process, the tailings that remain contain three grams of U-235 per kilogram of heavy elements (uranium, thorium, etc.), then overall, the CANDU once-through natural uranium fuel cycle has only about 70% of the natural uranium requirements of a pressurized water, pressure vessel reactor (PWR) (q.v. Table 7-5).

The reason for the improved fuel utilization in a CANDU-PHW reactor over a PWR is not only due to the elimination of fissile material losses in the enrichment process, but also due to the better control over in-core neutron losses afforded with a CANDU-PHW unit[72]. As shown in Table 7-6, PWR reactors lose almost 21% of their neutrons non-productively. The corresponding figure for a CANDU-PHW is about 16%. Because of this greater degree of neutron economy, the nuclear chain reaction can be sustained for a longer period in a CANDU-PHW reactor thereby increasing the fuel utilization. It should be noted that in Table 7-6 a small CANDU-PHW unit is compared to a relatively large PWR, and hence the comparison is biased towards the PWR, due to the fact that for a given reactor type, larger reactors experience less leakage per neutron than smaller units.

Improved fuel utilization means lower fuelling costs. In Section 7.3 the costs of energy production are compared, and in Section 7.4 schemes to get even more improved fuel utilization (at the expense of enrichment and spent fuel reprocessing) are considered. In this way it is possible to assess the options in the world's energy future, considering both economic and fuel utilization aspects. Section 8 is then entirely devoted to an assessment of the inherent risks of energy production techniques, to wrap up the case for nuclear power in general, and CANDU in particular.

7.3 Cost Considerations in Energy Production

Producing electricity economically is the aim of every power utility. For a system to be viable today it must be in a cost-competitive position with respect to the alternative energy sources. In this sub-section the cost of energy produced from CANDU-PHW reactors is compared with the energy costs from the major alternative sources: oil, coal, and nuclear energy from Pressurized Water Reactors (PWRs).

7.3.1 CANDU-PHW/PWR Cost Comparison

A detailed cost comparison of CANDU-PHW and PWR reactors is beyond the scope of this paper, and would require the use of quite technical economics and accounting theory. Instead, in this context, only the highlights of such a comparison will be presented to give an appreciation of the economic advantage held by CANDU-PHW reactors.

This cost comparison is taken from an official Ontario Hydro study (Reference 61) which compared the costs of an equivalent CANDU-PHW reactor and an assumed Light Water Reactor operating in Ontario. The study made use of the detailed insight the utility possesses on CANDU-PHW reactors with regard to costs and performance. Inasmuch as Ontario Hydro has no experience with PWR operation, the study considered extensive cost information from utilities in the U.S.A., and detailed performance information on PWRs throughout the world. The choice of a PWR rather than a BWR for this comparison was made because overall, PWRs have experienced a better performance than BWRs. It should be noted that the authors of the study invoked some degree of interpolative judgement when converting costs to fit the Canadian scenario, and when determining the cost-influence of PWR modifications required to make such a system licensable in Canada.

The highlights of the cost comparison are presented in Table 7-7. The Pickering A station was chosen as the CANDU-PHW station in the comparison. It was assumed to operate at a 79% Net Capacity Factor. This is the average CANDU-PHW Lifetime Net Capacity Factor (1981) (lifetime taken to be from the unit's first electricity production date). Four-unit PWR stations were considered in the study, with powers equal to that of the Pickering A station. This allowed a more meaningful cost comparison.

Two separate PWR stations, both hypothetical, and assumed to be operating in Ontario, were considered. One station was assumed to operate with a Net Capacity Factor of 58%, the world average (1981), and the other was assumed to operate with a 68% Net Capacity Factor. It was the opinion of the study's authors that, given time to properly develop a

PWR program in Ontario, Ontario Hydro PWRs could achieve this higher than average performance rating. This increase in performance would be attributable to the economies of scale with a four-unit station and to general overall employee competence. The judged 10% Capacity Factor superiority of the CANDU-PHW reactors assumes a judged 6% Capacity Factor credit for on-power fuelling, and a 4% Capacity Factor credit for other concept advantages.

Studies of the Specific Dry Capital Cost (cost per kilowatt for construction and commissioning -- not including the cost of the initial fuel load or heavy water inventory) of CANDU-PHW and U.S. Light Water Reactors in general[61] indicate no major cost differences in this particular area of consideration. This is supported by other studies[49] which indicate that the Specific Dry Capital Cost of Canadian versus U.S. reactors are spread over a ±10% band for a given initial in-service year.

It is the opinion of the authors of the study given in Reference 61 that if one assumes identical supply capability and manufacturing volume, the Specific Dry Capital Costs of a CANDU-PHW system should be less than for a PWR system due to the very demanding pressure vessel specifications in PWR systems as compared with pressure tubes in CANDU-PHW reactors, and also due to the PWR requirements for in-core high pressure regulating and shutdown devices and the like. However for the purposes of the comparison in Table 7-7, the Specific Dry Capital Costs were assumed identical for all systems.

It should be noted that the major differences between CANDU-PHW reactors and PWRs are in the steam raising equipment. In itself the steam-raising equipment accounts for only about 30% of the total capital cost of a reactor[73] and hence overall capital costs are not expected to be substantially different for the different reactor systems.

It was also assumed in the study, that there would be no significant differences in optimum staff levels (and hence in Operations, Maintenance and Administration costs) for four-unit CANDU-PHW and four-unit PWR stations in Ontario. Around the clock staffing with a full maintenance crew is economically warranted because of the high cost of burning coal (q.v. Section 7.3.2) whenever a reactor is shut down. As an example, in the Bruce A station, one per cent Capacity Factor is equivalent to the wages of about 100 people[61].

The fuelling cost evaluation was based on actual costs for Canadian production. Enrichment costs for the PWR stations were taken from U.S. data.

The comparison in Table 7-7 indicates that the Total Unit Energy Cost (TUEC) (the cost per unit electricital energy sent to the power grid) for a PWR operating in Ontario at the world average Capacity Factor (58%) would be approximately 37% higher than the TUEC actually experienced in the Pickering A CANDU-PHW units. The TUEC for a PWR operating in Ontario with a 68% Capacity Factor would be approximately 22% higher than the TUEC actually experienced in the Pickering A CANDU-PHW units.

The comparison shows that though CANDU-PHW units must contend with the cost and upkeep of their heavy water supply, this is more than offset by the higher Fuelling Unit Energy Cost of the PWR reactors. It should be noted also, that this cost comparison is based on a 30 year pay-back period. The reactors are probably going to last quite a few years more than this, but no matter when they must be replaced by new units, it is certain that the heavy water from the old units can be utilized by the new units, thereby lowering the heavy water costs for the replacement reactors. This was not taken into consideration in the cost comparison.

Hence, of the commercially available nuclear reactor designs, CANDU-PHW reactors have demonstrated that they are capable of supplying the least expensive electrical power with the best reliability, while still meeting the strict safety and licensing requirements set forth by the Atomic Energy Control Board in Canada.

7.3.2 CANDU-PHW Cost Comparison With Lambton Coal-Fired Station

The cost comparison between CANDU-PHW units and alternative sources of generation will depend on many factors which are particular to the electrical utility making the comparison.

Ontario Hydro is in a somewhat unique position to compare the cost of nuclear-generated electricity with coal-generated electricity. Ontario Hydro operates the Lambton Thermal Generating Station which is comprised of four 495 MW(e) (net) coal-burning units -- output which is comparable to the 4 x 515 MW(e) (net) output from the Pickering A Nuclear Station. Both stations were built at the same time (late 1960s) and both are of modern design and are fully operational with good performance records. A calculation of the cost of electricity production from such comparable stations should allow for a valid unbiased cost comparison of the two competing energy production concepts.

Table 7-8 shows the results of Ontario Hydro station intercomparison for 1981[61]. In the table, the actual 1981 Pickering A net capacity of 88.1% was assumed for both stations, though the Lambton station's Net Capacity Factor for 1981 was actually somewhat lower. This assumed increase in the Net Capacity Factor for the coal-fired station had the effect of lowering the TUEC for Lambton, since it spread the capital and depreciation costs over a larger production. The Fuel Unit Energy Cost was not altered by assuming an increased Capacity Factor.

The following should be noted from Table 7-8[61]:

i) the coal-fired capital cost is much lower than the nuclear capital cost,

ii) the coal-fired OM & A costs are less than the nuclear OM & A costs,

iii) the nuclear fuelling cost is very much lower than the coal-fired fuelling cost,

iv) the heavy water upkeep cost, which applies only to the nuclear station, is only a small percentage (less than 4%) of the Total Unit Energy Cost, and

v) for base-load application, Pickering A had approximately one-half the Total Unit Energy Cost of Lambton in 1981.

Figure 7-3 illustrates the results of the Pickering A-Lambton cost comparison (assuming Lambton operated at the same high Capacity Factor as Pickering A) for each year from 1975 to 1981. The graph clearly shows the steadily increasing cost advantage of the nuclear plant due to the continuing escalation of coal costs. Estimates(61) show that the Pickering cost advantage is expected to grow even further in the future. The forecasts from Reference 61 are presented here in Figure 7-4. (It should be noted that in Figure 7-4 a 10% interest rate is assumed. This is so since Ontario Hydro, being a Crown Corporation, enjoys the advantage of being awarded low interest capital loans.)

The low fuelling costs for a CANDU-PHW reactor offer countries some degree of inflation-fighting ability. For example, since in 1981, fuelling costs accounted for less than one-sixth of the TUEC for CANDU-PHW reactors, fuel prices would have to increase by a factor of seven before the TUEC would double. The same cannot be said for a coal-burning station, where more than 80% of the TUEC is fuelling costs.

This inflation-proof characteristic of CANDU-PHW reactors also puts the Canadian reactors at more of an advantage over Light Water Reactors, since, as shown in Table 7-7, a CANDU-PHW reactor's Fuelling Unit Energy Costs are less than half those for a PWR.

The importance of fuelling costs cannot be overstated. For a strong stable energy base, fuelling costs must either be controllable or they must be so small as to not significantly influence the total cost of the energy produced. CANDU-PHW reactors are as close to this latter alternative as is commercially achievable today, and still the cost of fuel over a CANDU-PHW reactor's lifetime is about equal to the cost of the reactor[39].

7.3.3 Predicted Energy Cost Trends

During the 1970s, high inflation in Canada caused energy costs in general to be driven rapidly upwards. As a result, new coal-fired generating stations such as Ontario Hydro's Nanticoke Station (8 x 490 MW(e) (net)) and new nuclear stations such as the Bruce A Station (4 x 740 MW(e) (net)) have higher capital costs.

The Specific Capital Cost of the Bruce A Station compared with that of Pickering A is affected by three major factors[61]:

i) Bruce A has lower costs due to the larger unit size.

ii) Bruce A has higher costs due to new regulatory equipment.

iii) Bruce A has much higher costs due to inflation of labour and materials.

The result is that the Pickering A Specific Capital Cost was 362.4 \$/kW(e) (net) and for Bruce A the Specific Capital Cost had risen to 662.5 \$/kW(e) (net)[61].

Table 7-9 gives the Bruce A Unit Energy Costs in 1980, while Figure 7-5 shows the lifetime trends (1977 to 1981).

Figure 7-6 displays forecast TUEC data to the year 2000 for base load application of five Ontario Hydro generating stations currently in service:

Coal-Fired:	Lambton (4 x 495 MW(e) (net))
	Nanticoke (8 x 490 MW(e) (net))
CANDU-PHW:	Pickering A (4 x 515 MW(e) (net))
	Bruce A (4 x 740 MW(e) (net))
Oil-Fired:	Lennox (4 x 495 MW(e) (net))

The figure is based on data assuming Ontario Hydro excalation forecasts of labour, materials, and fuel. These projections exclude the possible retrofit of sulpher-dioxide scrubbers (q.v. Section 8) in coal-fired stations, and exclude possible major retrofits in nuclear stations to meet new requirements.

The high cost of electricity produced from oil-fired stations (as evidenced in Figure 7-6) and the dwindling and uncertain supply of fuel for such stations has made this choice quite unattractive from a utility point of view. Hence a detailed cost intercomparison is not warranted here.

The forecasts in Figure 7-6 show that CANDU-PHW reactors will continue to have an economic advantage over fossil-fuel-fired stations in the years to come, and in fact, the base-load advantage of the CANDU-PHW system is expected to increase in time, displaying the "inflation-proof" characteristic of the CANDU-PHW reactors.

It should be noted again that these cost considerations are for base-load operation. It is not at all prudent to fire up a spare reactor for a few hours each day to supply energy during peak demand periods. The capital costs would be crippling. There would be a large capital cost spread over a small amount of electricity production. Instead, it is best to use a coal-fired station, with its relatively modest capital costs, to meet this extra demand. Since in base-load operation, the electricity costs from a coal-fired station are primarily fuel costs, the capital cost increase per unit electricity output for a station that is only used to meet peak demands, will not be substantially higher.

7.4 Advanced Fuel Cycles and Other Reactor Alternatives

In the future, the choice of reactor systems for nuclear programs throughout the world will be dictated by two controlling and inter-related forces:

i) economics, and

ii) resource availability.

Safety and waste management aspects can be dealt with in any choice of reactor variant, though the economic costs of providing safe operation and waste disposal will surely be important considerations in determining economic viability. It is important for a utility and a government to maintain an energy supply system that provides an inexpensive source of electricity from a fuel that is in good supply. In this changing world in which we live, governments and utilities are becoming very worried about the supply aspect and hence much research is being done in an effort to improve fuel utilization in both nuclear and fossil-fuel-fired systems.

Improving fuel utilization to the point where a very small amount of raw materials is required to fuel a station, will have two effects on the economics of energy production:

i) The amount spent on raw fuel materials per unit energy produced will be less; so much so that energy costs may become virtually independent of the raw fuel costs.

ii) The complications introduced in the fuel cycle will cause the fuelling costs to rise.

These two competing factors will open a whole host of fuel cycle choices, and politicians and utility managers will have to decide the route to take.

In this sub-section these choices are examined in an effort to shine some light on he direction that nuclear power programs will be going in the years to come. Variants on the CANDU-PHW theme will primarily be discussed.

7.4.1 The Natural Uranium Once-Through Fuel Cycle

Because it uses the most efficient moderator — heavy water — and its core has been designed for maximum neutron economy, the CANDU-PHW reactor is the most efficient commercial reactor with respect to resource utilization[21]. The basic, one-through natural uranium fuel cycle currently being used in CANDU-PHW reactors is shown in Figure 7-7. This is the simplest of all fuel cycles since it requires no uranium enrichment, no fuel reprocessing, and no fabrication of highly radioactive fuel. Uranium is mined, refined, fabricated into fuel, used in the reactor, and stored as spent fuel after use.

As shall be outlined in the following pages, the CANDU-PHW system can be easily modified to handle advanced fuelling schemes and different coolant materials, as may be required in an effort to cope with changing economic and resource situations that may arise. It will be shown that advances in CANDU nuclear technology can be made in an evolutionary manner that will ensure sufficient nuclear resources for many generations to come[72].

7.4.2 Low-Enriched Uranium Cycle

The CANDU-PHW system is conducive to operation with a slightly enriched uranium cycle. By artificially raising the concentration of U-235 in the CANDU-PHW fuel to about 1.2% (as opposed to 0.7% in natural uranium), the cost of the electrical output from the plant would be reduced by 10 to 18% (corresponding to a fuelling cost reduction of 27 to 32%), and uranium utilization would be increased by 33% over the natural fuel case[74]. The modified fuel cycle is depicted in Figure 7-8.

It is anticipated that essentially no changes would be required in the CANDU system design to employ the once-through low-enriched uranium (L.E.U.) cycle[75]. Minor modifications in design may be required in the fuel storage and handling areas to accommodate the more reactive fresh fuel, and some modifications to the control and safety mechanisms may be required to preserve their performance. These minor changes will not significantly affect output electrical costs.

The introduction of an L.E.U. cycle requires a utility to have access to enrichment facilities. As the program gets initiated it would be prudent to begin by procuring enrichment services from abroad, if they are not locally available. There exists a buyers market for enrichment services in the U.S.A., France, Britian, and the U.S.S.R.[74]. As the program expands, increased requirements may warrant a domestic enrichment facility. This may be beyond the technological capability of some developing nations and possibly a cooperative international enrichment centre could be developed to serve the needs of such countries.

7.4.3 Plutonium-Uranium Fuel Cycle

Extraction of plutonium from irradiated natural or enriched uranium fuel would give CANDU-PHW-equipped nations the flexibility to use new fuel cycles that are even more efficient in uranium utilization[21][73].

7.4.3.1 Plutonium Production in Nuclear Fuel Cycles

The spent fuel from a natural uranium CANDU-PHW reactor contains 3.8 grams of plutonium per kilogram of heavy elements. The corresponding figure for the L.E.U. cycle is 6 grams of plutonium per kilogram[74]. (These figures include all plutonium isotopes.)

Fissile plutonium is an extremely concentrated energy source. In fact, in one pound of fissile plutonium, there is the energy equivalent of a pile of coal that would fill Yankee Stadium[11]. It is expected that by the year 2000, the energy content of the fissile plutonium accumulated in Canada will be approximately equivalent to that in the present recoverable reserves of conventional oil in the province of Alberta[72].

CANDU-PHW reactors, operating on a once-through natural uranium fuel cycle are the most efficient power reactors for producing plutonium. In the spent natural uranium fuel there is 2.8 grams of fissile plutonium for every kilogram of natural uranium metal processed. The corresponding figure for the current design of light water reactors is 1.1 grams; and for the CANDU-PHW with a 1.2% U-235 fuel cycle, 1.7 grams of fissile plutonium remains in the spent fuel for every kilogram of natural uranium metal processed[34]. However, the concentration of fissile plutonium in the spent fuel of a natural fuel CANDU-PHW is small compared to the concentration in the spent fuel from an enriched-fuel CANDU-PHW (about 5 grams per kilogram of heavy elements), which is in turn smaller than the concentration of fissile plutonium in the spent fuel from a light water reactor (q.v. Table 7-5). Hence it is more expensive to extract the plutonium from the spent fuel from a natural uranium fuelled CANDU-PHW due to its low concentration.

7.4.3.2 Plutonium Recycle Option

In a plutonium-uranium fuel cycle, plutonium from the spent fuel could be recycled with uranium to provide an extra supply of fissile atoms in the fuel, thereby allowing a bundle to produce power for a longer time before it is required to be removed from the reactor.

The cycle, for natural uranium feed, is shown in Figure 7-9.

7.4.4 The Thorium Fuel Cycles

As stated in Section 5.10.3.2, thorium, which is more than three times as abundant on earth than uranium, may be used to fuel a fission reactor. Further, thorium is not in high demand in the world and hence it is expected that the price will remain relatively stable[74]. (Consider that Ontario Hydro pays approximately fifty 1980 Canadian dollars for each kilogram of uranium[74] (the spot market price is over 100 dollars[74]) with an expected real price (over inflation) escalation rate of between 2 and 3.5% per annum, whereas thorium is expected to continue to be available at a real price of about fifty dollars per kilogram[74].)

Substantial quantities of uranium can be saved through the adoption of a thorium fuel cycle in fission reactors, and in the long term, this cycle promises the security of the supply of fissile material available to the world.

The basic thorium fuel cycle is illustrated in Figure 7-10. The fuel cycle requires an initial supply of fissile material to "spark" the reaction. Plutonium-239 or uranium-235 (and eventually U-233) can be used to satisfy the fissile requirements.

Depending on the burnup and the period between refuelling and processing, the thorium fuel cycle may require additional fissile isotopes to be added during each refuelling operation[21], or a self-sufficient thorium cycle can be developed[76], where, once an initial supply of fissile material has been introduced, the uranium-233 produced in the thorium can be reprocessed to satisfy all the fissile requirements of the reactor[77].

The advantage of thorium cycles to the Canadian nuclear industry lies in the fact that the thorium cycles could be used directly in the existing concept of CANDU reactors with only small modifications[63]. No major reactor development program would be required. Existing licensing processes, reactor construction, and utility operational structure could move gradually and smoothly to handle thorium fuelling as economic and resource strategy dictates. And with the self-sufficient fuelling cycle option, CANDU-PHW reactors fuelled with thorium can open up energy resources equivalent to those from fusion energy and with no need for a convulsive change in reactor technology[78].

7.4.5 The CANDU-BLW and CANDU-OCR Reactor Systems

Not only can the CANDU design be modified to handle advanced fuel cycles, but it can also use different coolant materials as the economic situation dictates. With the high market interest rates, CANDU-designers are seeking ways to lower the initial capital investment required in a CANDU-PHW system. To this end, designers are looking at the use of less expensive coolant materials to effect a substantial capital cost reduction. Two coolant alternatives are being considered: boiling light water (CANDU-BLW), and organic fluids (oils) (CANDU-OCR). Both systems promise capital cost savings of the order of 10 to 15 per cent[79], but at the same time, they introduce increased fuelling costs due to the fact that these alternative coolants do not provide the optimal balance of neutron slowing down power to neutron absorption. The economic and political situation in a country would dictate the best choice of reactor coolant material. Again, no convulsive change in reactor technology would be required to handle the alternate coolant materials[49].

A prototype CANDU-BLW reactor has been built at Gentilly in Quebec, however control instability problems (which were eventually solved) and administrative and employee difficulties forced the operation to be abandoned. A small organically cooled pressure tube research reactor, WR-1, is operating successfully at the AECL laboraties at Pinawa in the Canadian province of Manitoba[80].

In CANDU reactors without heavy water coolant, tritium radiation problems are reduced considerably. Further, in CANDU-BLW reactors the number of subsystems is reduced — no separate steam generators are required (the reactor itself is the steam generator), and in the case of the CANDU-OCR, higher coolant temperatures under lower pressures can be used. These two features tend to increase the thermal efficiency of these reactors over the CANDU-PHW system.

The prospects for the future look good. And any country that decides to build their nuclear system upon the CANDU system can easily control the evolution of their system to take advantage of new developments as they become available, and the advantage of the developments in the CANDU program is that the experience and expertise that a country gains through the operation of any one CANDU system, can be easily and directly applied to any of the other systems.

7.4.6 Spallation and Fusion

The CANDU reactor system can provide one of the first areas of application of controlled nuclear fusion. In CANDU reactors, less fuel reprocessing is required when the initial fissile content of the fuel is high. This is due to the fact that by using fuel with a high fissile content, the chain reaction in a fission reactor can be sustained for a longer period of time even with the increased parasitic absorption of neutrons that takes place as fuel burnup increases. By using a fission reactor, even one that is not self-sustaining (that is, even one that consumes more energy than it delivers, as the first available reactors shall do), scientists can synthesize fissile materials for use in fission reactors.

By placing a blanket of uranium around a fusion device, and a blanket of thorium around that, high energy neutrons (about 14 MeV) from the fusion reactions in the central core can be used to drive neutrons from the uranium blanket. This causes about five neutrons to be produced for every neutron absorbed. These neutrons can in turn be absorbed by the fertile thorium atoms to provide an extra quantity of fissile material (in this case, U-233) which can be used to "top" up the fuel for fission reactors[81]. The energy given off from the combination of the fusion reactions and the fertile-to-fissile atoms conversion process may be enough to sustain the fusion reactions, or else some power from a fission reactor could provide the energy difference[81].

Alternatively a spallation process may be used to supply neutrons to build up a fissile fuel supply. In this process, a proton accelerator fires a 1 GeV (1 GeV = 1 billion eV) proton at a natural uranium or other heavy target. This interaction produces about 4 GeV of heat and an extra 50 neutrons. The heat can be converted to electricity to drive the proton accelerator, and the neutrons can be used to convert fertile thorium to fissile U-233[81].

Both of these neutron production methods are quite expensive, requiring either cheaper accelerators and fusion reactors, or uranium prices that are considerably higher than they are today in order to make such devices economical[28].

7.4.7 The Fast Breeder Reactor: A Spectral Shift

Fast Breeder Reactors (FBRs) are very different from conventional thermal fission reactors, and hence to develop and introduce such a system involves an extremely complicated and expensive research and development program.

The FBR system, as explained in Section 5.10.4.4, uses plutonium fuel which is produced by surrounding the FBR with a blanket of fertile uranium which is converted to plutonium when subjected to a neutron flux. With a fuel utilization some fifty to seventy times greater than the available in the present CANDU-PHW fuel cycle, the world is anxiously awaiting the introduction of the first commercially available fast breeder power reactors, which may be in operation early in the twenty-first century.

Just as with CANDU-PHW reactors operating on a self-sufficient thorium cycle, FBRs require an initial fissile fuel load. Over the next century, if FBRs are indeed introduced, it seems likely that they will have to depend heavily on other types of power reactor for their initial plutonium supply. If, as expected, it will take a given FBR about twenty years to produce as much fuel as it consumes, thermal reactors would still be required for a considerable length of time to produce plutonium for use in the FBRs.

CANDU-PHW reactors and FBRs can operate in a complementary fashion. A quick and early introduction of an FBR system will create a bullish market for plutonium, and hence the cost of the CANDU-PHW fuel cycle will drop significantly due to the value of the spent fuel[49]. A very gradual FBR system introduction with its high return of energy per unit fissile nucleus mined, will stretch uranium supplies, thereby slowing the escalation of uranium prices and hence allowing time for the advanced CANDU fuelling schemes to be developed[82].

7.4.8 A Comparison of Resource Utilization

In the very long run, the deciding factor in the choice of a reactor system will be the degree of resource utilization achievable with the various systems. As resources become depleted prices will rise. All countries will search for reactors that can operate on fuel cycles that require such a small amount of raw feed material that the cost of electricity from the reactors would be essentially independent of the cost of raw feed material. In this way resources are utilized to their fullest potential, and nations will be insulated from any further increases in the price of the raw fuel.

Table 7-10 shows the approximate raw material requirements for the fuel cycles considered in this section once they have achieved equilibrium operation. Table 7-11 details the total fuel requirements including the amount of material required to initialize the reactor operation for the several CANDU-PHW fuel cycles considered.

It can be seen that the self-sufficient thorium cycle in a CANDU-PHW requires about the same amount of raw feed material as an FBR, though in the former case the raw material is thorium, and in the latter, the raw material is uranium. It should be noted that thorium fuel cycles can be utilized in an FBR. However, as was stated in Section 5.10, plutonium (made from U-238) is the optimal fuel in a fast reactor, and U-233 (made from thorium) is the optimal fuel in a thermal reactor (and it is particularly suited to CANDU reactors). Hence a design change to use thorium cycles in an FBR would require increased initial capital expenditures due to the inefficient nature of the thorium fuel in a fast reactor. If one looks at it in this light it is plain to see the complementary nature of the two systems. FBRs make extremely efficient use of natural uranium, and CANDU-PHW reactors provide the most efficient thorium utilization, and together these systems can provide the world with an energy base that rivals the potential of an ambitious nuclear fusion program that is based on the tritium-deuterium nuclear reaction.

Four Units 37.6 Unit Years of Operation
Capability Factor: 80.2% Incapability Factor: 19.8%

CAUSE OF INCAPABILITY	INCAPABILITY (%)
On-Power Fuelling	0.8
Fuel	<0.1
Heat Transport Pumps	0.2
Pressure Tubes	4.9
Boilers (Steam Generators)	0.5
Turbine and Generators	5.8
Instrumentation and Control	0.7
Heat Exchangers	0.9
Valves	0.4
Other	5.6

TABLE 7-1 PICKERING NUCLEAR GENERATING STATION A LIFETIME* INCAPABILITY TO DECEMBER 31, 1981**

Four Units 15.5 Unit Years of Operation
Capability Factor: 83.5% Incapability Factor: 16.5%

CAUSE OF INCAPABILITY	INCAPABILITY (%)
On-Power Fuelling	0.8
Fuel	0.0
Heat Transport Pumps	0.2
Pressure Tubes	0.3
Boilers (Steam Generators)	2.4
Turbine and Generators	6.6
Instrumentation and Control	1.7
Heat Exchangers	0.0
Valves	0.0
Other	4.5

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

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

TABLE 7-2 BRUCE NUCLEAR GENERATING STATION A LIFETIME* INCAPABILITY TO DECEMBER 31, 1981

RANK	COUNTRY	UNIT	GROSS MAXIMUM RATED ELECTRICAL POWER (MW)	YEARS IN SERVICE	TYPE	1981 GROSS CAPACITY FACTOR (%)
1.	Canada	Bruce-1	791	4	PHW	96.6
2.	Canada	Pickering-4	542	8	PHW	91.6
3.	Canada	Bruce-2	791	4	PHW	89.6
4.	Canada	Bruce-3	791	4	PHW	89.5
5.	Canada	Pickering-3	542	10	PHW	89.4
6.	Canada	Bruce-4	791	3	PHW	89.1
7.	Japan	Genkai-2	559	1	PWR	89.0
8.	Canada	Pickering-1	542	10	PHW	88.0
9.	Taiwan	Chinshan-1	636	3	BWR	87.3
10.	USA	Point Beach-2	524	9	PWR	84.9
11.	Japan	Mihama-3	826	5	PWR	84.9
12.	W. Germany	Neckar	856	5	PWR	84.7
13.	USA	Quad Cities-1	832	9	BWR	84.4
14.	Canada	Pickering-2	542	10	PHW	84.3

TABLE 7-3 WORLD POWER REACTOR PERFORMANCE: 1981

(TOP 14 OF 131 REACTORS >500 MW(e) (GROSS) IN SERVICE AS OF JANUARY 1, 1981)

COUNTRY	UNIT	TYPE	GROSS MAXIMUM RATED ELECTRICAL POWER (MW)	YEARS IN SERVICE	GROSS CAPACITY FACTOR (%) 1977	1978	1979	1980	1981	F/E*
Canada	Bruce-3	PHW	791	4		86.9	73.6	91.7	89.5	84.3
W. Germany	Stade-1	PWR	662	10	93.6	95.2	76.5	75.0	83.7	82.6
Canada	Pickering-2	PHW	542	10	91.1	84.5	85.1	83.3	84.3	81.7+
Canada	Bruce-4	PHW	791	3			81.1	76.7	89.1	81.4
Canada	Pickering-1	PHW	542	10	85.8	95.1	83.5	74.1	88.0	80.3+
Canada	Pickering-4	PHW	542	8	91.1	89.9	90.1	82.2	91.6	79.7+
Japan	Genkai-2	PWR	559	1					89.0	78.8
Canada	Bruce-1	PHW	791	4		72.1	77.1	86.5	96.6	78.7
USA	Point Beach-2	PWR	524	9	82.7	88.0	84.6	82.0	84.9	78.7
Canada	Pickering-3	PHW	542	10	95.7	82.4	79.7	92.1	89.4	77.5+
USA	Calvert Cliffs-2	PWR	880	5	84.7	71.3	74.7	87.2	73.8	77.0
W. Germany	Unterweser	PWR	1 300	2		22.1	75.5	86.2	83.8	75.9
USA	Prairie Island-2	PWR	560	7	91.3	85.2	91.1	75.5	67.3	75.6
USA	Haddam Neck	PWR	602	14	80.1	93.6	82.0	71.1	81.0	75.5
Sweden	Barsebaeck-2	BWR	590	5		77.8	79.5	72.0	76.8	75.2
USA	Kewaunee	PWR	560	8	75.9	83.3	73.7	77.7	80.7	74.6
Spain	Vandellos	GCR	500	10	78.2	75.2	73.3	77.6	69.9	74.2
Canada	Bruce-2	PHW	791	4		65.5	68.1	93.7	89.6	72.5

* Gross capacity factor from first electrical power date to the end of 1981.

+ Data includes the 1972 labour strike.

TABLE 7-4 COMPARISON OF GROSS CAPACITY FACTORS OF CANDU-PHW NUCLEAR UNITS TO WORLD POWER REACTORS

(TOP 18 OF 131 REACTORS >500 MW(e) (GROSS) IN SERVICE AS OF JANUARY 1, 1981)

	CANDU-PHW	PWR
Enrichment Tails Concentration, wt. % U-235	no enrichment	0.2 0.3
Fuel Enrichment, wt. % U-235	natural (0.71)	3.2
Fuel Burnup, (MW · d)th/kg U	7.5	33
Fuel Burnup, (MW · d)th/kg natural U	7.5	5.6 4.7
Discharged Fuel, wt.% U-235 wt.% fissile Pu	0.22 0.28	0.84 0.66
Net Station Efficiency, %	29.1*	32.5
Fuel Consumption Rate, kg natural U/(MW · a)(e)	166	200 240
Annual Natural Uranium Consumed by 1000 MW(e) Station at 80% Capacity Factor, MgU/a	134	160 192

Notes:

i) Fuel Burnup is in units of megawatt-days of thermal energy per kilogram of enriched or natural uranium.

ii) Concentrations are in terms of grams of element under consideration per gram of heavy elements in the fuel.

iii) Fuel consumption rate is in units of kilograms of natural uranium per megawatt year of electricity.

iv) wt. % refers to weight percent of heavy elements.

v) The PWR data is actually two separate sets of data, corresponding to the varying range of efficiency in the enrichment process.

* Pessimistic value: actually between 29.5 and 31.0%.

TABLE 7-5 COMPARISON OF CANDU-PHW AND PWR FUELLING

SOURCE OF LOSS IN REACTOR	PERCENTAGE NEUTRON LOSS		
	1000 MW(e) PWR	500 MW(e) PHW	PHW ADVANTAGES
Moderator and Coolant (H_2O vs D_2O)	6.2	1.6	+4.6
Pressure and Calandria Tubes (Pressure vessel vs pressure tubes)	—	3.1	−3.1
Control Absorbers — incl. Xe override (Batch vs on-power fuelling)	4.5	1.5	+3.0
Fission Products	5.9	5.9	+0.0
Fuel Sheath and Structure	1.0	0.6	+0.4
Leakage	3.3	3.2	+0.1
Total	20.9	15.9	+5.0

TABLE 7-6 COMPARISON OF NEUTRON LOSSES: PWR VERSUS CANDU-PHW

PARTICULARS	CANDU-PHW	PWR	
	PICKERING A	HIGH NCF	AVERAGE NCF
Station Size (MW(e) net)	2 060	2 060	2 060
Net Capacity Factor (NCF %)	79	68	58
Capital UEC			
Dry Capital	5.42	6.30	7.38
Commissioning	0.19	0.22	0.26
Fuel	0.08	0.40	0.47
Heavy Water	1.46	—	—
Capital UEC	7.15	6.92	8.11
OM & A UEC	5.08	5.90	6.92
Fuelling UEC	2.17	5.76	5.76
Heavy Water Upkeep UEC	0.77	—	—
Total UEC	15.15	18.58	20.79

Notes:

UEC refers to unit energy cost.
All UEC data are in mills/kW-h (Canadian 1981 dollars)
NCF refers to Net Capacity Factor
OM & A refers to Operations, Maintenance and Administration.

TABLE 7-7 CANDU-PHW/PWR COST COMPARISON: 1980

COST ITEM	UEC m$/kW · h (net)**	
	PICKERING A (NUCLEAR)	LAMBTON (COAL)
Interest and Depreciation	6.41	1.89
Operation, Maintenance and Administration	4.56	1.72
Fuelling	2.17	19.48
Heavy Water Upkeep	0.69	—
Total Unit Energy Cost (Net)	13.83	23.09

PICKERING AND LAMBTON NET CAPACITY FACTOR 88.1%*

	PICKERING	LAMBTON
Capacity (Maximum Continuous Rating) Mw(e) net	4 x 515	4 x 495
In Service Date	1971-1973	1969-1970
Initial Capital Cost (M$ Canadian escalated)	746.5	257.0
Specific Capital Cost ($/kW)	362.4	129.8
Economic Lifetime (years)	30	30
Depreciation Method	Straight Line	Straight Line
Interest Rate (%)	11.45	11.45

STATION DATA

* Assumes Lambton also operated at base load with net capacity factor of 88.1%.

** 1981 Canadian dollars.

TABLE 7-8 PICKERING/LAMBTON COST COMPARISON: 1981

Net Capacity Factor = 91.0%

COST ITEM	UEC mils*/kW·h (net)
Interest and Depreciation	10.27
Operation, Maintenance and Administration	3.46
Fuelling	2.80
Heavy Water Upkeep	0.50
Total Unit Energy Cost (Net)	17.03

STATION DATA	
Capacity (Maximum Continuous Rating) MWe net	4 x 740
In Service	1977-1979
Original Capjtal Cost (M$ Canadian escalated)	1 961.1
Specific Capital Cost ($/kW)	662.5
Economic Lifetime (years)	30
Depreciation Method	Straight Line
Interest Rate (%)	11.45

* 1981 Canadian dollars.

TABLE 7-9 BRUCE A COSTS: 1981

REACTOR	FUEL CYCLE	FUEL CONSUMPTION (kg/MW-year)(e) URANIUM	THORIUM
CANDU	Natural uranium once-through	167	—
	1.2% Enriched uranium once-through	118	—
	Plutonium/uranium	70	—
	Plutonium/thorium	45	1
	Uranium-235/thorium	32	1
	Thorium self-sufficient	—	2
LWR*	Enriched uranium once-through	200	—
	Uranium recycle	170	—
	Plutonium/uranium recycle	125	—
LMFBR**	Plutonium/uranium	2	—

* Light water reactor fuelled with enriched uranium.

** Liquid metal fast breeder reactor fuelled with plutonium and uranium-238.

TABLE 7-10 APPROXIMATE EQUILIBRIUM FUEL CONSUMPTION

FUEL CYCLE	"INVENTORY"[a] MgU	EQUILIBRIUM FEED kgU/(MW·a)(e)	MgU/a[b]	BURNUP MW·d/MgHE[c]
Natural U, Once-through	144	166	133	7.5
U/Pu[d]	194	70	56	18.0
Th/U[e] [f]	680[h]	32[h]	26	37.4
Th/U[e] Self-sufficient[g]	871	0	0	10.0
Th/Pu[f]	1385[h]	62[h]	50[h]	37.2
Th/Pu Self-sufficient[g]	1826[h]	0	0	10.0

(a) "Inventory" is defined as the difference between actual requirements over a long time period and requirements determined from equilibrium feed rate applied from in-service date.

(b) Based on 80% capacity factor.

(c) Burnup per pass of Heavy Element, uranium or thorium.

(d) Pu from CANDU natural uranium; consumption is for combined cycle.

(e) U-235 feed with 0.2% tails, U-233 recycle.

(f) High burnup fuel cycle optimized for cost.

(g) Low burnup fuel cycle for maximum uranium utilization.

(h) Uranium figures shown are the amount of spent natural uranium CANDU fuel required to provide fissile Pu.

TABLE 7-11 URANIUM CONSUMPTION IN CANDU-PHW FUEL CYCLES
(Assuming Electrical Output of 1000 MW)

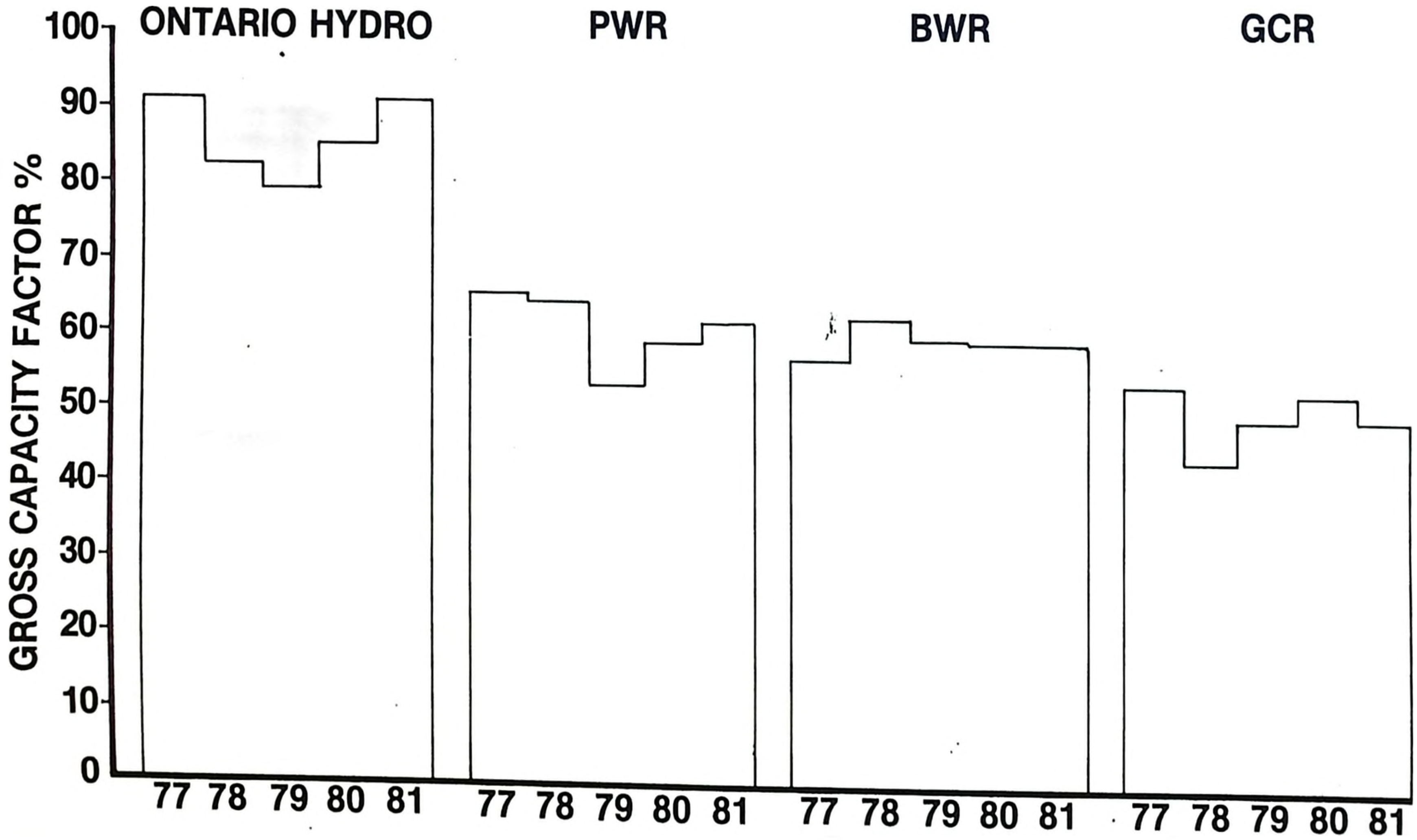
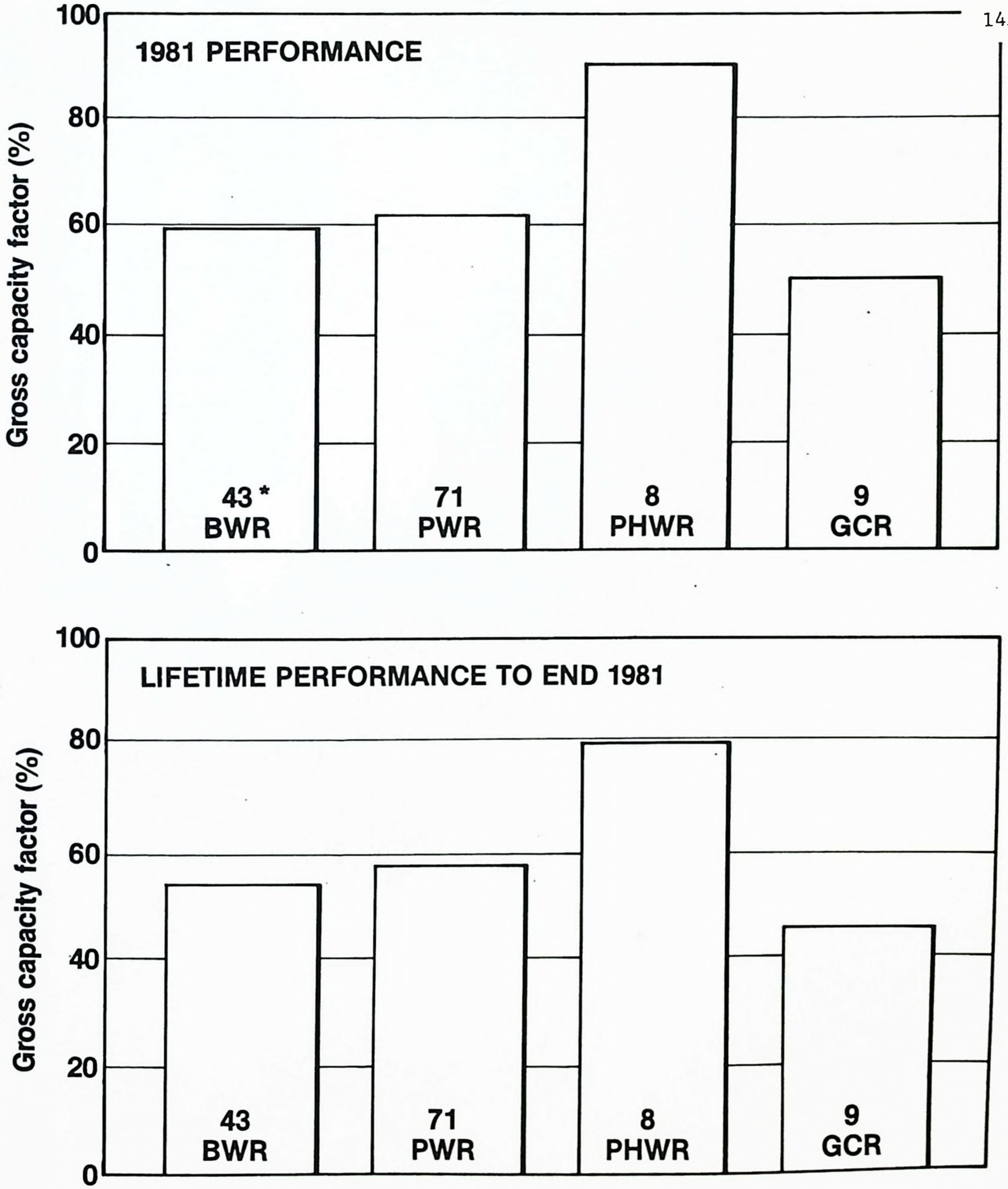


FIGURE 7-1 COMPARISON OF AVERAGE GROSS CAPACITY FACTORS CANDU-PHW AND WORLD POWER REACTORS ABOVE 500 MW(e) (GROSS)



(Includes all Units>500 MW(e) (Gross) and In-Service as of January 1, 1981)

* Indicates the Number of Reactor Units of the Type Indicated

FIGURE 7-2 WORLD POWER REACTOR PERFORMANCE BY TYPE

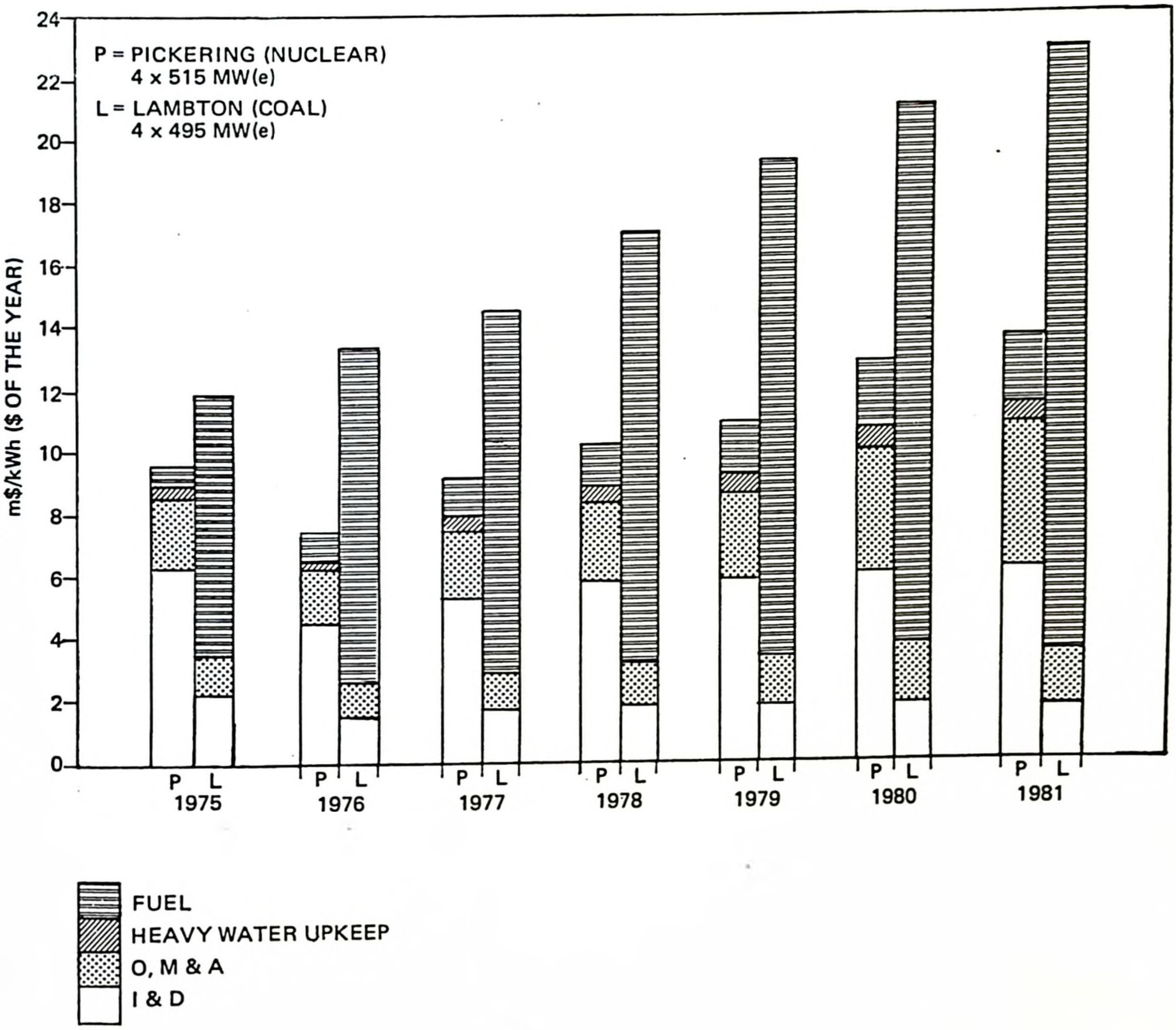


FIGURE 7-3 TOTAL UNIT ENERGY COST COMPONENTS THERMAL VERSUS NUCLEAR (1975-1981)

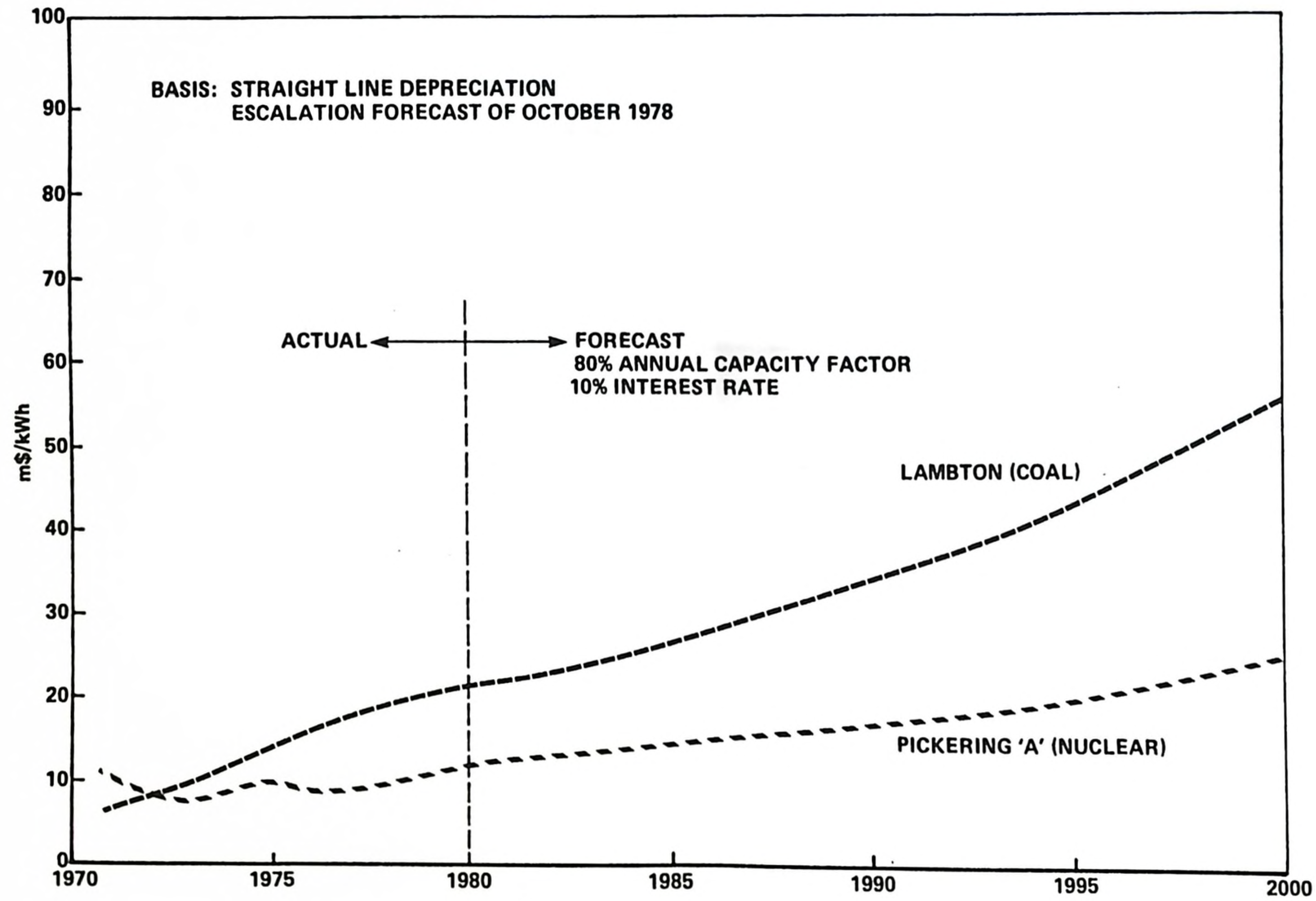
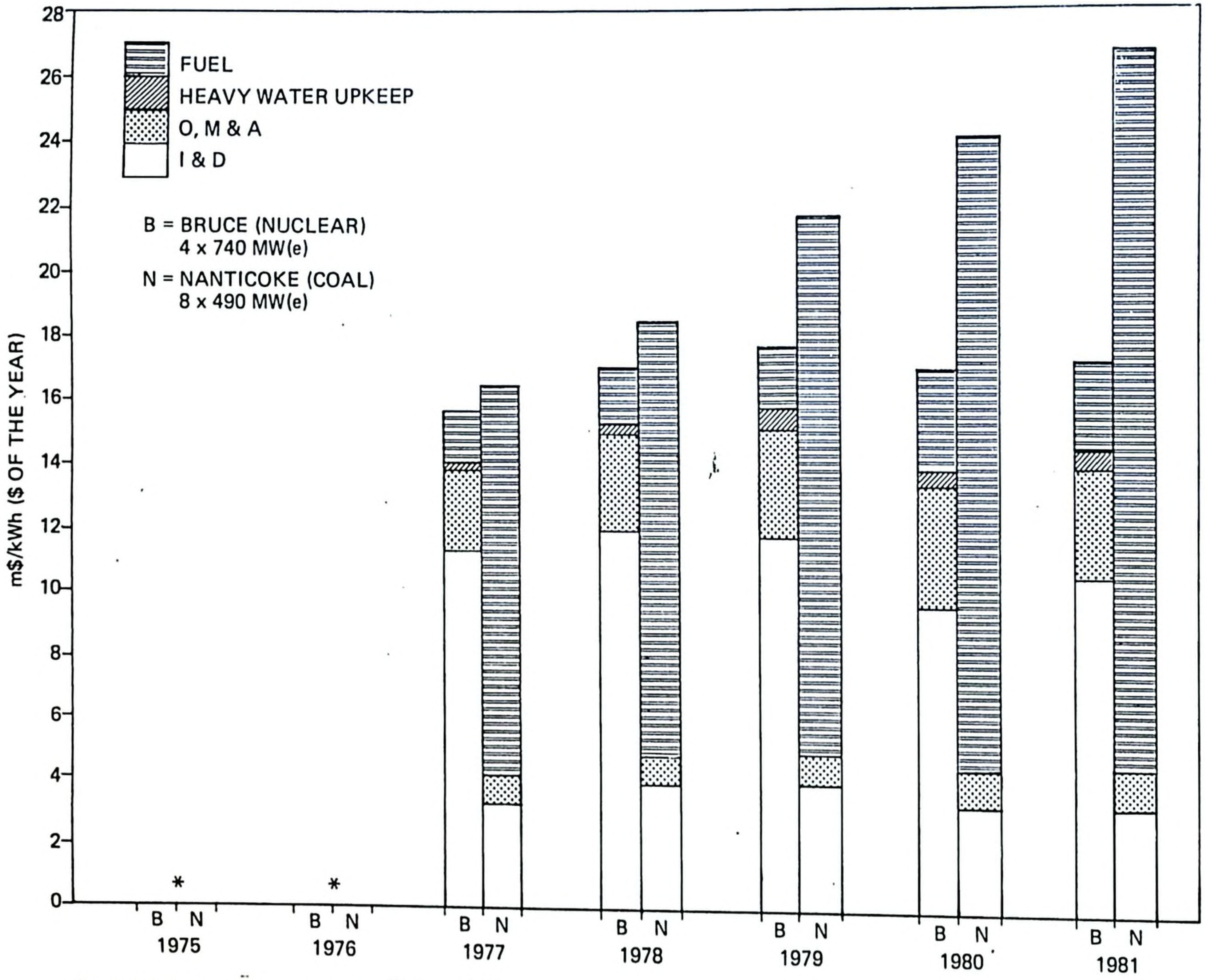


FIGURE 7-4 TOTAL UNIT ENERGY COST FOR PICKERING AND LAMBTON



* BRUCE NGS–A WENT INTO SERVICE IN 1977

FIGURE 7-5 TOTAL UNIT ENERGY COST COMPONENTS THERMAL vs NUCLEAR (1975–1981)

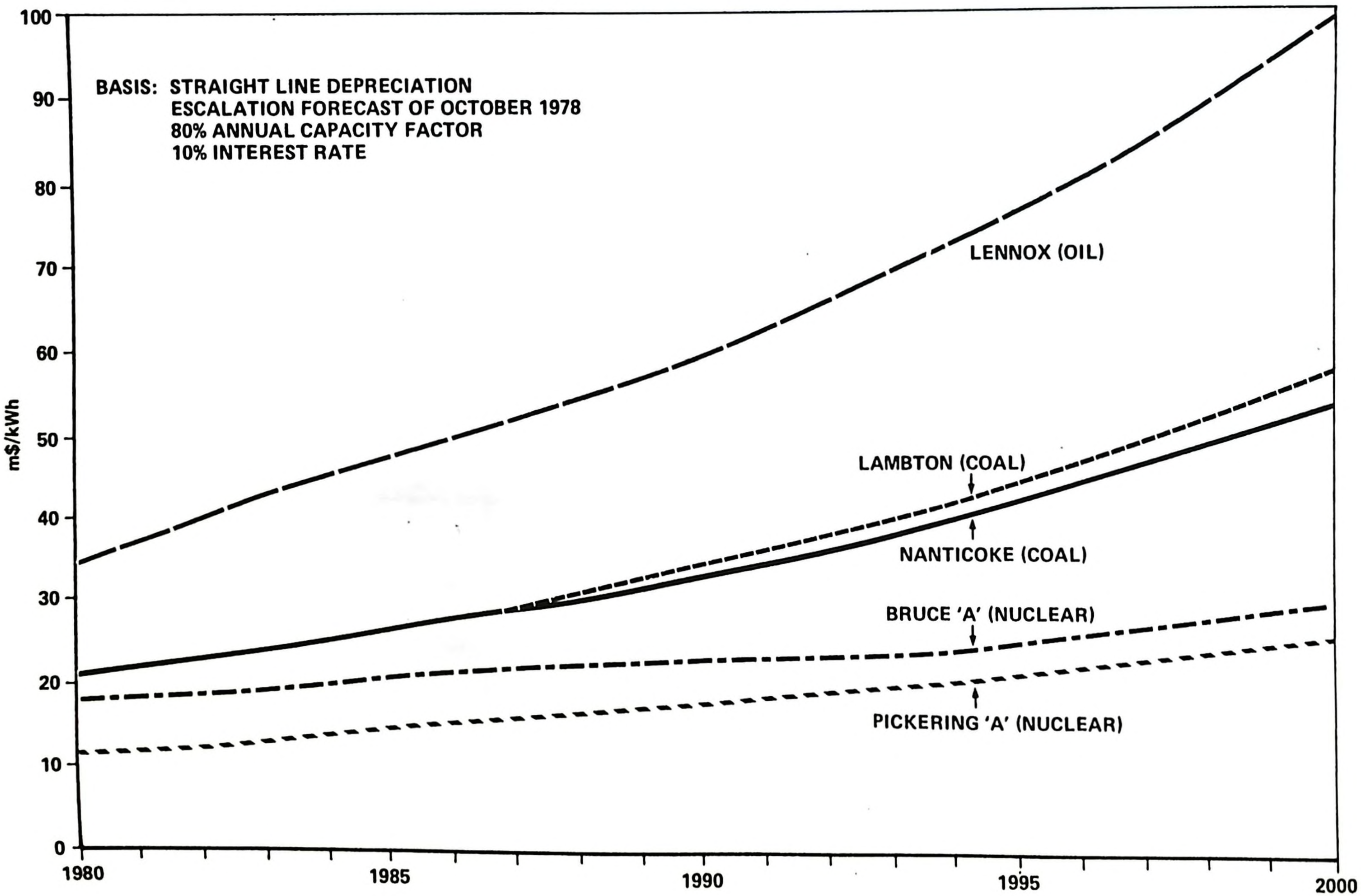


FIGURE 7-6 PROJECTED TOTAL UNIT ENERGY COST FOR MAJOR OPERATING POWER STATIONS

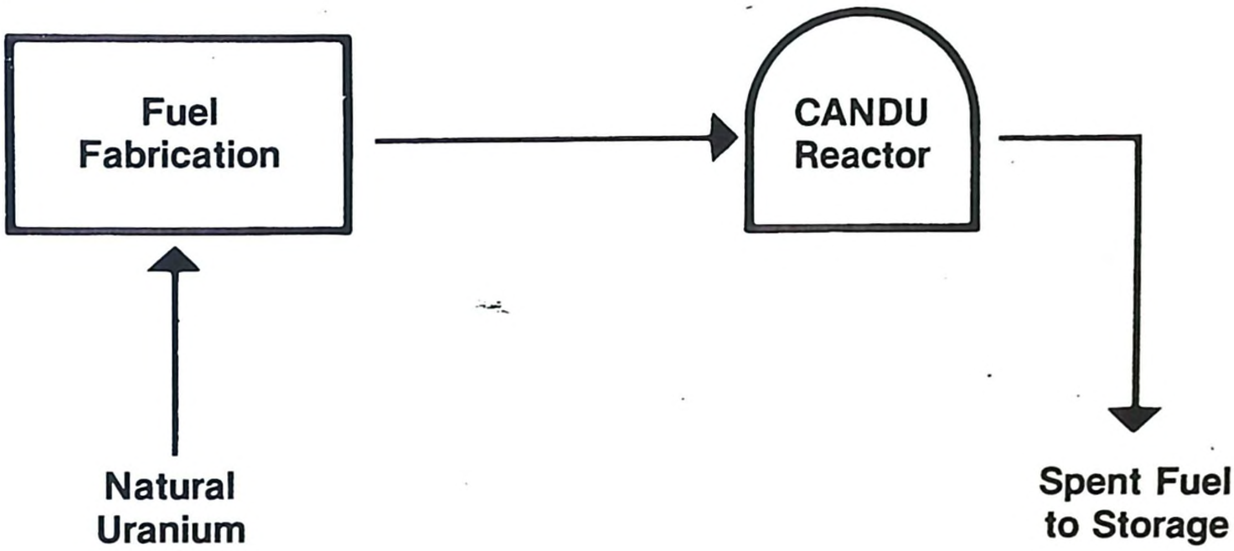


FIGURE 7-7 ONCE-THROUGH NATURAL URANIUM FUEL CYCLE

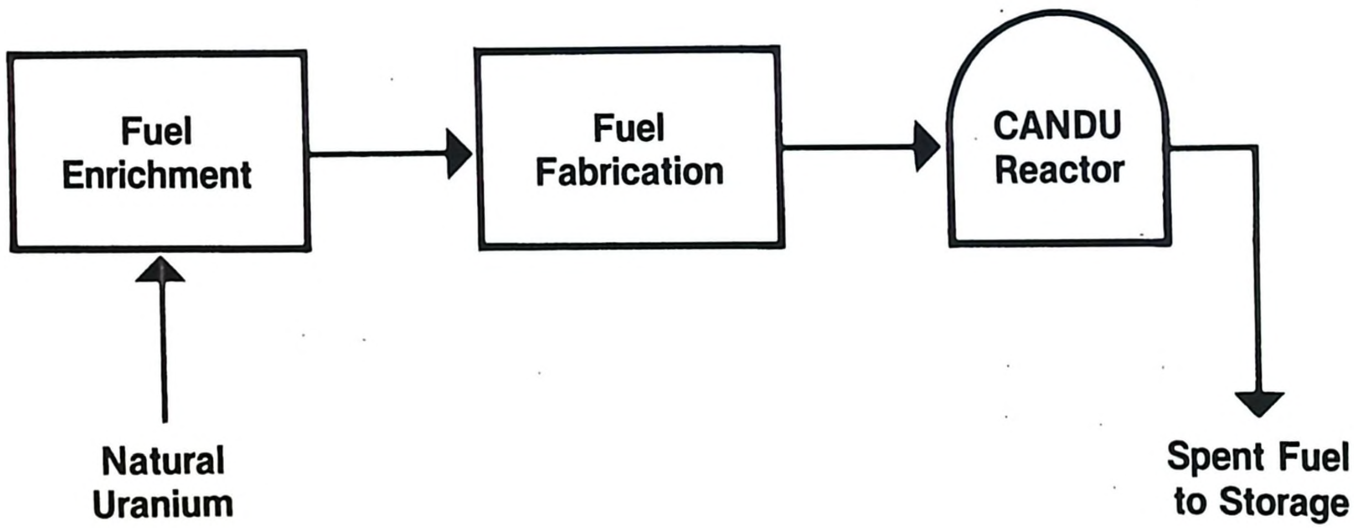


FIGURE 7-8 ONCE-THROUGH SLIGHTLY ENRICHED URANIUM FUEL CYCLE

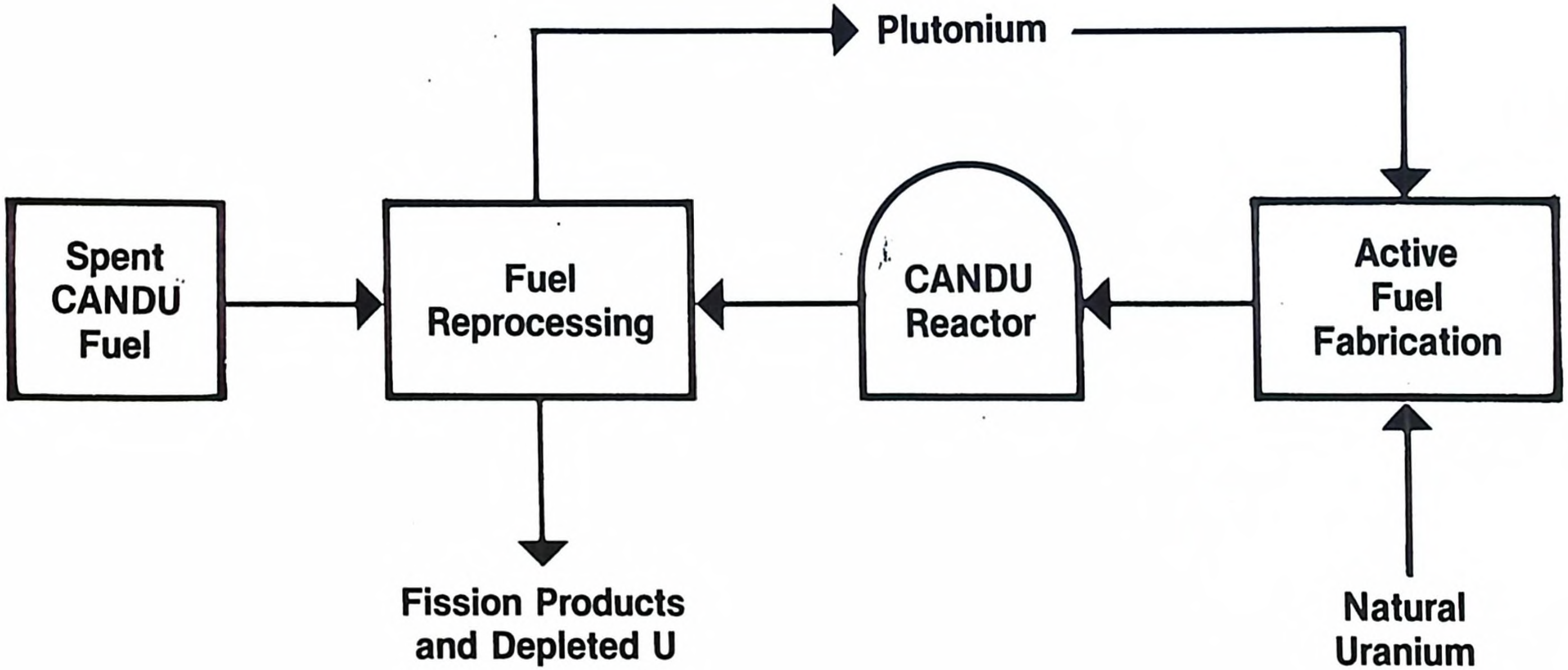


FIGURE 7-9 PLUTONIUM-URANIUM FUEL CYCLE

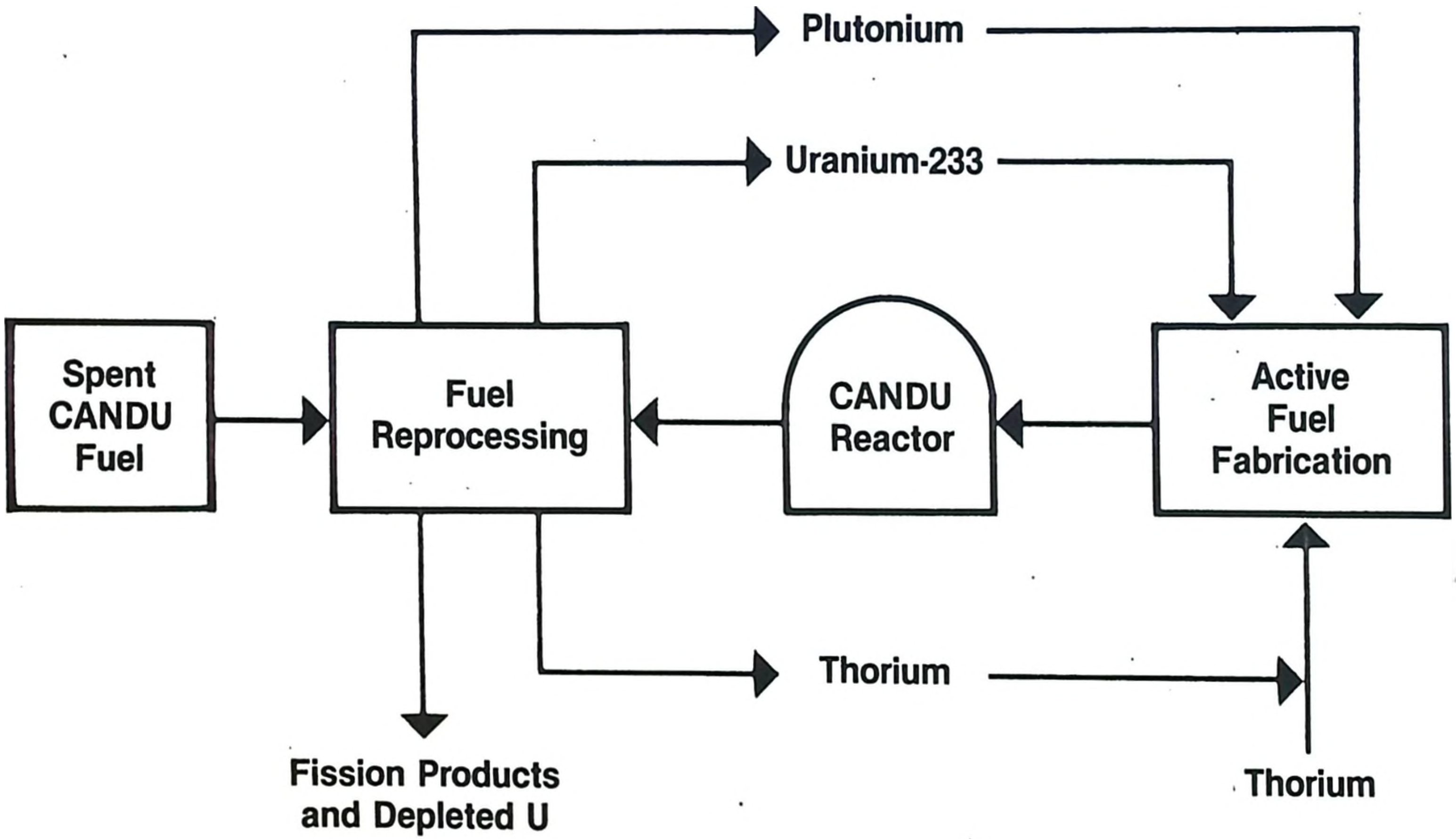


FIGURE 7-10 THORIUM FUEL CYCLE

8.0 THE RISKS OF ENERGY PRODUCTION

Risk enters into every aspect of man's day-to-day existence. Indeed many of the risks faced by man can be eliminated (sky-diving, race care driving, etc.), but virtually everything that man does has some degree of risk associated with it, however small.

The production of electricity also carries with it an intrinsic risk for society, a risk that cannot be avoided as long as man wishes to take advantage of the benefits that go along with the utilization of the energy produced. The risks facing a society through the introduction of a given energy system must be weighed against the positive aspects of such a program, in what is essentially a simplified form of cost-benefit analysis. This frequently leads to the need to place a value on a human life -- a virtually impossible task. And hence, an actual dollar value comparison shall be avoided here.

The benefits of an energy program to society have been discussed previously (Section 2), and it is the costs -- the risks -- that will be discussed in this section. An energy program imposes costs in terms of mortality (deaths), morbidity (days lost from normal activities), and genetic effects in humans and animals, as well as direct social costs (such as damage to paint and brick work), and indirect social costs (such as aesthetic concerns)[83]. These costs to society have been studied extensively for some forms of energy production (most notably the nuclear operation[84],[85]) though for other energy forms, serious society costs were never considered before the introduction of the systems, and only now are their true dangers coming to light. Coal burning fits into this latter category. It is ironic that in a world where ignorance of long term effects of most pollutants is practically complete, and indifference to the risks is all too common, the one industry (the nuclear industry) that knows enough to make a credible estimate of consequences, exerts strenuous efforts to keep pollution far below permitted levels, and has a safety record of which it has every right to be proud, should be selected for the most bitter attacks[85].

In this section, the risks associated with the various energy options are compared with each other and put into perspective with the other risks man faces today, in an effort to explain that while the risks of electricity production from all options are very real and warrant genuine concern on the part of industry, government, and society as a whole, these risks do not spell the impending doom of the world. Indeed, as anti-energy spokesmen are quick to point out, the potential for disaster does exist, however the actual hazards faced by society through the development of an extensive energy program are quite minimal when compared to the benefits reaped from its utilization.

8.1 Radiation: An Invisible Threat

While most people are aware that the dangers from a nuclear program stem from the radiation given off by the radioactive material that is either produced in the reactor or is mined from deep inside the ground and brought into contact with society, few people are aware that the combusion of fossil fuels also poses a radiation hazard to our world. In this sub-section the types, causes and effects of radiation will be studied in order to appreciate the nature of the hazard, and thereby eliminate some of the fear that naturally goes hand-in-hand with this phenomenon.

8.1.1 The Biological Effects of Ionizing Radiation

Intrinsic to an understanding of the hazards of radiation is an appreciation of just what constitutes the radiation man is exposed to, and how it can harm the cells in the human body.

8.1.1.1 The Nature Of Ionizing Radiation

There are four major types of ionizing radiation:

i) Energetic Neutrons

ii) Gamma Rays

iii) Beta Particles, and

iv) Alpha Particles

Energetic neutrons come from a nuclear fission reaction and can be slowed down and absorbed by water or metals such as steel and cadmium. Gamma rays and beta and alpha particles are born during the decay of a radioactive atom or in a nuclear fission process. Gamma rays are high energy light rays which can penetrate considerable distances (depending on their energy). For example, it would take more than four centimeters of lead to lower the intensity of a gamma ray from the decay of a cobalt-60 atom by a factor of ten[10]. Beta particles are free electrons and positrons (electrons with a positive charge). For normal emission energies, they can travel about three meters in air, or approximately one third of a centimeter in water before they are almost completely absorbed[86]. Alpha particles are just helium nuclei (two protons and two neutrons). At average emission energies, they can be stopped by about four centimeters of air or 0.005 centimeters of water[86].

Alpha particles will just penetrate the surface of a man's skin. Gamma rays can pass through a human body, but they would be almost completely absorbed by three feet of concrete[87]. The penetration of neutrons depends on their energy, but since the neutrons are confined to nuclear reactors, the public is normally not susceptible to the dangers of these particles.

8.1.1.2 The Interaction of Ionizing Radiation with Living Tissue

As radiation passes through matter it loses energy. The energy is transferrred to the atoms and molecules of the material it comes close to. If the material through which the radiation passes is living tissue, chemical changes in the cells can result directly from this energy transfer or from the cells absorbing free radicals and hydrogen peroxide formed in the liquid surrounding the cells as the radiation passes. It is possible that this interaction will kill the cells. If a sufficient number of cells in an important organ of the body are destroyed in this way, death of the exposed victim, or at least loss of function of the organ may result.

In addition, the chemical changes in the affected tissue cells may so alter the cells' internal structure that they may bein to multiply in an uncontrollable fashion, leading to the formation of a cancerous tumour, or to cancer of the blood (leukemia).

If the radiation chemically alters the DNA in a cell, genetic damage may occur. The DNA, which carries the genetic blueprints for all life processes, must be faithfully copied each time a living cell divides to form two daughter cells. It is subject to all kinds of spontaneous chemical alterations as well as those caused by ionizing radiation, by environmental chemical agents and by the ultraviolet component of sunlight; and yet the DNA has been able to survive through millions of years and millions of copyings. The apparent stability of the DNA molecules in each cell is caused by redundancy and very efficient repair systems intrinsic to the DNA molecules[88].

8.1.1.3 The Inheritance of Genetic Defects

Mutations are inherited changes in the genetic information of a cell. They can arise spontaneously because of mistakes during normal cell replication, but are more likely to arise during the stress of DNA repair[(88)]. These mutations can be passed on to one's offspring if the damage affects the operation of the reproductive system.

Chromosomes, which are composed of compacted DNA molecules and proteins (acids), are found in all cells. In humans, each cell contains 23 pairs of chromosomes. One of each of these chromosome pairs was ultimately derived from each of the parents of the individual. These chromosomes contain very similar genetic information derived from each parent. This means that individuals normally carry duplicate copies of each gene. (DNA molecules are made up of many small units called "genes".)

The redundancy of information helps to protect man from harmful mutations. It is known that nearly all humans harbour at least some abnormal or mutant genes. However, most people are spared from the ill effects of these mutations because a second copy of the same gene is present in the other member of the chromosome pair. Individuals who carry one defective gene and one normal gene are called carriers. Newborn infants who are unfortunate enough to receive a chromosome containing a bad gene from both parents may suffer the full effects of some genetic disease. It is because of the redundancy of the genetic information that such hereditary diseases are relatively rare. In addition to the redundancy of the genetic information, genes are protected by another mechanism called enzymatic repair of the DNA. Repair processes can eliminate 99% or more of the initial damage suffered by a DNA molecule when exposed to harmful chemicals or radiation, or when spontaneous alterations occur[88].

8.1.1.4 Units of Radiation Measurement

It has been found that the radiation damage effects in living tissue are proportional to the amount of energy deposited per unit mass. For this reason, the basic unit of absorbed dose, the rad, is defined as: one rad is an absorbed dose of 1×10^{-4} Joules of energy per gram.

Although for a given type of radiation, the magnitude of the biological effect is proportional to the absorbed dose in rads, it is found that heavy particles, such as neutrons and alpha particles, produce greater biological effects per rad than gamma rays or beta particles[37]. In order to express the dose received by an individual on a scale common to all ionizing radiations, the absorbed dose must be multiplied by a "Quality Factor", which depends upon the amount energy lost per unit path length of the radiation. The Quality Factor is 1.0 for X-rays, gamma rays, and most beta particles, but is about 10.0 for fast neutrons and alpha particles. The new unit of dose, which is now on a common scale, is called the rem. One rem consists of 1000 millirem.

Of late, there has been a trend towards the use of SI units in reporting radiation doses. The SI equivalent of a rad is a Gray. The SI equivalent of a rem is a Sievert. 1 Gray = 100 rads. 1 Sievert = 100 rems.

8.1.2 The Radiation Sources in Modern Society

A radiation leak from a nuclear reactor will constitute a front page story in newspapers throughout the world. The words "lethal radioactivity" and "deadly radiation" have been seen together so many times in recent magazine and newspaper articles that to many people, radiation must appear to be infinitely dangerous.

But contrary to the beliefs of some, radiation has always been a part of our natural environment, with more than 15,000 particles bombarding every one of us every second of our lives[89]. A typical X-ray bombards us with a hundred billion particles[89]. But the chance that any one of these particles will cause a cancer is only one in 30 quadrillion[89]. The odds indeed favour survival.

Man's day to day activities bring him into contact with various sources of radiation[90]. The air we breathe, the food we eat, and the fluids we drink all contain some radioactive material. The bricks and wood that all homes are constructed of are also somewhat radioactive and emit harmful radiation. Cosmic rays from space continually deposit energy in our cells. Modern technology - jet flight, and colour television also contribute to the radiation dose an individual will receive each

each year of his life. Table 8-1 lists some common sources of radiation that an individual may encounter during a year, and in Table 8-2, the average radiation dose received by an individual of the Canadian public is presented. In Table 8-1, the nuclear plant average dose represents the maximum allowable individual dose to any member of the public living at the one kilometer exclusion zone boundary of a CANDU reactor. (The average dose to the population on the whole is even further reduced since few people live so close to the reactors.)

It is very important to note that the natural background radiation received by an individual varies considerably with geography. For example, in the mountainous areas of Canada, the natural background radiation is twice the average[(89)]. There are areas in India and Brazil where the uranium and thorium rich soil have caused the natural background radiation level to be fifteen times the average North American background level. However, studies have shown that the people living in these areas show no observable evidence of excess cancer, even though they are subjected to a yearly radiation dose of some 1500 millirem[(89)].

The choice of dwelling an individual chooses to inhabit will also alter the radiation dose received each year. While both wood and stone are radioactive, stone is generally moreso, and hence one receives an extra millirem every three weeks by living in a brick or stone house instead of a wooden one[(89)]. Some building stones (like those used in Grand Central Station in New York) have much higher than average amounts of uranium, so people working in those buildings get an extra millirem of exposure every two or three days[89].

Finally, at high altitudes, cosmic rays are more intense than on the ground and hence a jet aircraft flight will subject an individual to yet an additional radiation dose (q.v. Table 8-1).

8.1.3 The Health Effects of Ionizing Radiation

Extensive studies have been done to investigate the biological effects of ionizing radiation. Studies such as those done by the U.S. National Academy of Science (the BEIR report), studies by the International Commission on Radiological Protection (ICRP), studies by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and other reliable investigations (q.v. Reference 91), have considered the dangers of radiation in detail, and generally support each other in their results. The mortality rates and genetic disease incidence rates that they have found in these studies were derived using data from quite high exposure levels, and then extrapolated downward assuming that the dangers were strictly and directly proportional to the total radiation dose, regardless of the size and time over which the dose was delivered. The possibility for long-term repair mechanisms to correct some of the damage was not considered.

It is important to note that the main body of scientific evidence, as derived from studies on lower organisms and animals, suggests that low levels of sparsely-ionizing radiation (X-rays, beta particles and gamma rays) produce less biological effect per unit than predicted by the direct linear extrapolation from the measured effects at high doses and high dose rates. Hence, though the results of such reports are invariably used when discussing all types of radiation doses, the actual risk at low doses may be lower than that implied by a deliberately cautious assumption of proportionality. This has been acknowledged by both the ICRP and UNSCEAR[91].

These studies have led to the determination of risk probabilities associated with radiation exposure, and as they are listed below, it should be kept in mind that the maximum radiation exposure for a person living one kilometer from a CANDU reactor core (that is, the so-called "fence-post" individual) is 5 millirem per year, and in practice the average exposure is kept significantly lower.

8.1.3.1 Radiation and Cancer

Using the very cautious assumptions made in the international studies, an individual stands an additional one in ten thousand chance of dying from cancer with each rem of radiation received[84]. Other interpretations[88] say that if one million people are each exposed to one rem of radiation over their entire body, there will be an additional 150 cancer deaths, and about 100 curable cancers (mainly of the breast and thyroid). Of the cancer deaths, twenty would result from leukemia[92]. The natural incidence of fatal cancers in North American is 200 thousand per million persons, and about the same number of curable cancers would result through the lives of an average group of one million North Americans[88].

It should be noted that the radiation hazard is often quoted in terms of X incidents per 10^6 man-rem. That is, if one million persons are exposed to one rem of full-body radiation, X incidents would occur. But due to the cautious proportionality assumption, X incidents would also be assumed to occur in a population of 200 million persons ($1 \times 10^6/(5 \times 10^{-3})$) exposed to 5 millirem of full-body radiation each.

Radiation from all sources in North America accounts for less than one percent of the incidence of fatal cancer in the population in North America[89], and as it is clear to see, the number of incremental cancer deaths due to a small increase in radiation exposure is not statistically significant.

8.1.3.2 Radiation and Genetic Disease

If a population is exposed to a million man-rem of radiation over one generation, less than forty additional cases of genetic disease will occur. It is a common misconception that induced genetic effects multiply continuously from one generation to another and that a single defect will permeate the whole human race. In fact, the best scientific evidence indicates that the incidence of these genetic defects will stabilize at a level related to the magnitude of the repeated insult to the system, and that removal of the insult results in a decline in the evidence of the defects back to the original level[18]. The genetic hazard at equilibrium (each generation irradiated) is an additional 300 cases per million man-rem[88]. Note that this is a cautious theoretical value and there is reason to believe that this should be more like 10 to 30 instead[88]. In natural incidence, once in ten people have some genetic defect[88], and statements about radiation harming the human race are without foundation, as the very long-term genetic effects of radiation are truly negligible and may even be slightly beneficial[89].

8.2 The Risks of Nuclear Energy Production

The International Committee on Radiological Protection (ICRP) has published limits on the dose that members of the public may receive from non-medical use of ionizing radiation. These limits are frequently reviewed by this international body of radiobiological scientists and are of such a magnitude that exposure at the limits is considered an acceptable risk. This is, of course, a judgement, but available radiobiological evidence indicates that the risk to an individual when exposed at these limits is very low. The Atomic Energy Control Board in Canada has set dose limits which follow the recommendations of the ICRP[55]. These limits are given in Table 8-3. Ontario Hydro sets emission operating targets that are 1% of these limits.

The nuclear industry poses a radiation risk to society in all aspects of the fuel cycle — from mining and production of the fuel, to reactor operations, to spent fuel management. The risks that these processes impose upon man shall now be considered.

8.2.1 Fuel Production

Each day, a 1000 MW(e) CANDU-PHW reactor requires one-half tonne of uranium dioxide fuel to keep it in operation[93]. This must be drawn from the earth as U_3O_8 and converted into UO_2 pellets.

The natural uranium ore required for reactor fuel production contains not only uranium, but thorium, radium, lead, and other heavy metals. These impurities (an unintentionally some uranium) are separated from the U_3O_8 as a slurry containing 25% to 40% solids (tailings)[94]. To date, Canada has produced over one hundred million tonnes of uranium tailings[94]. The principal constituents of the uranium tailings include particles of rock forming minerals (gangue), sulphides of heavy metals, precipated heavy metal hydroxides and radionuclides such as radium-226, thorium-230 and lead-210. About 15% of the total natural radioactivity of the ore is accounted for in the uranium mill product itself, while the remaining eighty-five percent is discharged with the tailings[94]. Radon gas, a decay product of radium, is emitted to the atmosphere from the tailings. Radon and its decay daughters form an important component of radiation from the uranium.

The uranium tailings also contain small proportions of process reagents such as ammonia nitrates and sulphates which are hazardous to man.

The tailings are stored in basins, from which the contaminants can spread through the ground and surface water, or through the food chain, or by direct radiation from the tailings. Acids may be formed, which will drive fish from nearby lakes and ponds.

To provide protection for society, the slurry is made slightly alkaline. This causes the heavy metals, thorium, lead and radium to be precipitated out. Barium chloride aids in the radium precipitation. The precipitate can often be stored in the uranium mines, from which it came in the first place, though the feasibility of such an operation varies from mine to mine[94]. In any event, burial of the solids will prevent much of the spread of the contamination.

It is important to note that fuel production does not create radioactive materials, but merely brings radioactive materials to the surface. There is little danger to a city two kilmeters away from an uncovered tailings pile[84]. The maximum estimated risk to an average household dweller in Elliot Lake, Ontario (adjacent to the Elliot Lake Uranium Mines) is that in a given year this individual will have one more chance in one hundred thousand of contracting a fatal cancer as compared to the average Canadian.

The use of advanced fuel cycles will lead to a considerable decrease in the amount of uranium (or, similarly, thorium) required to be mined. This will lower the risks of death resulting from the initial fuel fabrication process, but the fuel refabrication and the radiation and tailings from this operation will somewhat compensate for this.

It might also be noted that an increased attention to building materials and ventilation in homes, in order to reduce the natural radon daughter levels (building materials currently account for some 97% of total population exposure to such daughters), would have a greater impact on predicted health hazards than efforts to reduce the effects of radon daughters from uranium mines and milling operations[91].

8.2.2 Reactor Operation

CANDU-PHW reactors have maintained a truly commendable safety record from an operations standpoint. CANDU-PHW reactors, as most power reactors, are designed to minimize the release of radiation to society and to the station workers. The endless drive to improve the safety of the reactors, in an attempt to eliminate every last possible risk from the production of nuclear fission energy, is forcing up the capital cost of reactors to such an extent that they may eventually start to lose their intrinsic cost advantage over other energy forms such as coal.

It shall be shown in the following pages that the drive to further improve reactor safety is not a prudent way to allocate the finite global financial resources. It is the total population radiation dose that determines the total harm. Reductions in this total dose are best obtained wherever they can be achieved most inexpensively without reducing services to society. This leads to a discussion of the dollar value of a man-rem avoided. Values as high or higher than $1,000 (1978 Canadian) per man-rem avoided have been suggested as applicable to CANDU reactors, which is equivalent to about 10 million dollars per cancer avoided[91]. But the introduction of such simple measures as replacing the shield cones on older X-ray machines could be many orders of magnitude more cost-effective in reducing the total population dose[91]. In fact, it has been estimated that a one percent reduction in diagnostic radiation in North America would reduce the population dose of radiation by more than the elimination of the nuclear power industry to the year 2000[91].

Some may argue however that the risks of the nuclear industry are thrown upon them. There is no choice in the matter. They are subjected to the exposure, but unlike medical X-rays or colour television exposure, the risk cannot be avoided by a refusal to participate. And this aspect of the industry is often greatly resented. To counter such statements regarding lack of choice, one may simply cite the fact that such is the case in many aspects of modern life. For example, in the U.S.A., in 1974, of the 46,200 traffic fatalities that year, 8,700 were incurred by pedestrians who made no choice other than to go for a walk[18].

8.2.2.1 Worker Safety

The highlights of the CANDU-PWH reactor worker safety performance are as follows[60]:

i) From 1962 to 1981, nuclear operations employees have worked 74 million man-hours.

ii) There has never been a fatality of a nuclear operations employee at work for any reason.

iii) There has been a very low frequency of temporary disabling injuries. Specifically, the frequency has been 2.3 injuries per million man-hours for the decade from 1972 to 1981 inclusive.

iv) No employees have ever been injured due to radiation.

v) There has never been a serious radiation exposure greater than 25 rem/annum.

vi) The highest whole body exposure which exceeded the regulatory limit of 5 rem per annum was an exposure of 7.3 rem.

vii) Over-exposure (exceeding whole body regulatory limits) to an employee are very infrequent corresponding to 0.22 incidents per million man-hours worked.

viii) Nuclear workers have been much safer at work than when not at work.

ix) Worker safety at nuclear plants has been better than at Hydro, and thermal (coal or oil) plants, although safety at all three types has been good.

Worker safety means that electricity can be produced at a generating station with a minimum of injuries to the employees. Although no injuries is the ideal target, it is recognized that in every industrial process some injuries will occur and standards are defined in order to assess safety performance. Two or less fatalities per 100 million man-hours worked, two or less permanently disabling injuries per 10 million man-hours worked, and six or less temporarily disabling injuries per 1 million man-hours worked are the standards aimed at for nuclear operations workers. These standards of employee safety meet the following specifications:

i) Employees must be safer at work than not at work.

ii) Nuclear employees must be safer than non-nuclear employees.

iii) Nuclear employees must be safter than employees in all other industries.

Over the past decade, all of these standards have been met, with all injury types being well within the limits set by the above criteria[60].

The average combined dose to the 600 station personnel at the Pickering 'A' CANDU-PHW Nuclear Generating Station is about 1250 man-rem per year, or 0.58 man-rem/MW(e) per year[95]. The value excludes the dose received by operating personnel during pressure tube replacement, which amounted to 500 man-rem in 1974, 800 man-rem in 1975, and 250 man-rem in 1976[95].

The average Pickering A dose is a great improvement over the Douglas Point average dose of about 3 man-rem/MW(e) per year[95]. This downward trend is expected to continue to be a feature of the CANDU-600 MW(e) design. This is due to two factors: first, an increase in knowledge of the factors which determine station radiation fields, and, secondly, the ability to reduce these fields both by changes in station design, and changes in station operating procedures[95]. At maturity, with an equilibrium radiation field built up, a CANDU-600 MW(e) station is expected to operate with a worker radiation dose of 350 man-rem per annum[95]. This does not include considerations for man-rem expenditure required for such unusual occurrences as pressure tube replacement.

If this level of radiation is deemed to be excessive in future, the CAN-DECON decontamination technique can be used to lower the dose still further[95]. Decontamination procedures have been tested for both the primary heat transport system (which accounts for 50% of the radiation dose received by operating personnel) and for the fuelling machines (which account for 20% of the operating dose). Decontamination Factors (radiation field before divided by radiation field after decontamination) ranging from 1.5 to 6.0 have been obtained for the primary heat transport system CAN-DECON procedures, with an expected average Decontamination Factor of about two being the norm for the CANDU-600 MW(e) units. Fuelling machine Decontamination Factors of about five are to be expected in the CANDU-600 MW(e) fuelling machine decontamination procedures[95].

Heavy water reactors are faced with a problem of controlling a build-up of radioactive tritium in their heavy water moderator and coolant systems. In current CANDU-PHW reactors, exposure to tritium accounts for 30% of the entire employee dose[95]. Light water reactors have a much smaller tritium problem since it is primarily only the heavy hydrogen atoms in water that absorb neutrons to become tritium. Improved reactor design layout; increased component reliability; improved ventilation systems to lower background tritium levels; better drainage systems for quicker removal of free standing D_2O in the reactor and service buildings; and separation of high and low tritium systems to avoid cross contamination, are all methods built into the new CANDU-600 design to reduce tritium exposure of personnel by about 50% (or a savings of approximately 100 man-rem per year).

Though tritium gives off no gamma rays and its beta particles are not strong enough to penetrate the skin, the contaminant is of considerable danger when ingested or inhaled. It takes the body about ten days to rid itself of half the tritium taken in[86]. While the tritium build up is a concern that is somewhat unique to heavy water reactors, by proper control of plant systems, the use of decontamination techniques, tight chemistry control, and management awareness of man-rem problems, it is possible to keep tritium and all contamination levels very low in CANDU-PHW reactors, thereby providing a healthy environment for reactor employees.

In the future, as tritium management becomes more advanced, the tritium could be transferred to fusion reactors, where it is considered a valuable fuel.

8.2.2.2 The Radiation Risk of Nuclear Reactors to Society

The average risk to the public in Canada for all types of accidents is approximately 600 premature deaths per annum for every million persons[60]. Ontario Hydro has set a standard on public radiation exposure from its plants such that there must be less than one chance in a million per annum that the most exposed individual will suffer a premature death[60]. This includes both routine emissions of radioactivity and accidental releases (such as in a loss-of-coolant accident, etc.). (Reactor accidents will be considered in more detail in Section 8.2.3.) To meet these criteria, the maximum whole body exposure allowable corresponds to 10 millirem per annum, or an infant thyroid dose of 100 millirem per annum. These limits have continually been met quite easily since no CANDU-PHW reactor has experienced an accidental radiation release of any consequence.

During the 92 reactor years of CANDU-PHW operation in Canada, there has never been a fatality nor has there been an injury of any kind for any reason to a member of the public as a result of CANDU operations, and there has never been a release of radioactivity from any CANDU-PHW station that resulted in a measurable dose to any member of the public[60].

The day-to-day emissions of radioactive materials from a CANDU-PHW station are kept to a minimum to make a negligible impact on the radiation dose received by members of the public. Licensing requirements set dose limits at a level consistent with the recommendations of the ICRP (q.v. Table 8-3). To ensure rigorous everyday control, these limits have been converted into emission rate limits called Derived Emission Limits (DELs). DELs are also licensed limits and are controlled in Canada by the Atomic Energy Control Board. These limits are divided into six categories. By meeting these limits in each of the six categories the total emission is such that a person at the fence post of a CANDU station would receive less than 500 millirem of radiation from these emissions each year.

While the regulatory dose limit and the DELs provide a perfectly acceptable level of individual protection to the public, it has long been Canada's policy to maintain public radiation doses at the lowest practical level. Ontario Hydro, since the early 1970s, has adopted a target of maintaining emissions for each of the six categories at one percent or less of the DELs[60]. This ensures that the still cautious standards of 100% DELs will be met.

The operational releases at Pickering A and Bruce A are presented as percentages of the DELs in Figures 8-1 and 8-2 for the year ending 1981 December 31. The results show Ontario Hydro's excellent record of maintaining public safety in nuclear reactor operations in Canada. The same commendable performance has been maintained in the past[42] and in the future, as the CANDU-PHW program matures, it is expected that the already excellent record will be improved even further.

The low emission from CANDU-PHW stations means that the incremental risk to society is kept quite low. For example, the Pickering A NPD, and Douglas Point Nuclear Generating Stations' combined releases provide the average member of the public in Canada with an extra radiation dose of 0.003 millirem per year[55]. When compared to the 200 millirem per year average exposure that each Canadian receives from non-nuclear energy causes, the true risk becomes almost negligible. (For each millirem of radiation absorbed the chance of contracting cancer is increased by about one in eight million[89].) In fact, even if an individual lived at the fence-post of a CANDU-PHW reactor, and received the full five millirem dose operating target maximum, this would do him as much harm during the year as smoking one-third of a cigarette[90].

8.2.2.3 Thermal Effluent from Nuclear Reactors

All heat engines waste heat. Nuclear plants are no exception. Canadian CANDU-PHW stations are capable of converting only about 30% of their heat energy into electricity[55], compared to approximately 32.5% for light water reactors[63] and near 39% for modern fossil-fuelled plants[55]. The coolant in a pressurized heavy water reactor is simply not as hot as the coolant in a light water reactor, which in turn has a lower temperature than the combustion gases of oil or coal. As a result, a less efficient turbine cycle must be used. (The coolant tubes must be thin to reduce their capture of neutrons, but this limits their strength, and thus limits the pressure (or temperature) of the coolant they contain.)

The waste heat is transferred to the water systems adjacent to the reactors (usually a lake), and eventually is distributed throughout the whole environment. There have been few effects on bottom dwelling plants and animals in the heat "plume" from the present Canadian reactors, but algae growth can become a problem if general phosphate levels increase in the Great Lakes.

Thermal discharges from all types of industrial activities and electrical power production have always been a concern for scientists, though it is expected that these will not pose a problem for at least a few centuries[31]. In fact, in the cold Canadian waters, some may consider the effects as thermal enhancement instead. The entire thermal effect is presently quite small. For example, by the year 2000, the change in heat content of Lake Ontario (into which the Pickering 'A' station discharges its waste heat) due to all man-made heat sources will be six percent of the normal seasonal variation.

In future, however, steam turbines like those used today may be replaced by such mechanisms as gas turbines or magnetohydrodynamic devices which promise increased thermal efficiency when used in conjunction with nuclear fission reactors[96], thereby reducing the amount of waste heat.

8.2.3 Reactor Accidents

A CANDU-PHW power reactor has never experienced a serious accident and hence much of the analysis done concerning behaviour of a CANDU reactor in an accident situation (q.v. Section 6.4) is hypothetical in nature. However, by combining conservative reliability estimates for all reactor components, a good upper limit to accident frequency can be estimated. In Canada, the Atomic Energy Control Board (AECB) has set limits on the maximum number of failures allowable at a reactor in a given year, and corresponding radiation exposure limits to the public as a result of such accidents[42]. These limits are given in Table 8-4. It should be noted that these exposure limits must be met in the worst accident cases, and hence the radiation dose for "average" accidents will be considerably lower. Also comparing Table 8-4 with Table 8-1, it can be seen that the AECB exposure limits for single failures (q.v. Section 6.4.2.1) are exactly the same as the ICRP guidelines for normal plant operation for one year.

8.2.3.1 The Incident at Three Mile Island

On the 25th of March, 1979, the world experienced its worst nuclear reactor accident to date. Committees are continuing to investigate the event to discover why five independent failures - both human and mechanical - occurred on that fateful day in Pennsylvania[11]. The Three Mile Island (TMI) PWR incident is still creating repercussions that are being felt all over the world.

The incident caused a release of radioactive material from one of the four PWR units at the station. However the emission levels, though extremely well publicized, were not very substantial. A person standing naked at the boundary surrounding the TMI station through the entire incident would have received a total radiation dose of 190 millirem[90]. This is equivalent to about one chest X-ray. The average incremental exposure to the public in the area around TMI was 1.2 millirem[89]. This represents a risk equivalent to five extra street crossings, or four puffs on a cigarette, or eight kilometres of extra automobile driving[89]. In numerical terms, people living near the TMI plant have one chance in seven million of getting a fatal cancer due to that exposure; since there were two million people involved, there is about a thirty percent chance (two million chances in seven million), that one of them will die of cancer as a result[89].

To see the effect the radiation dose from the TMI incident had on infants in the vicinity, the Pennsylvania State Department of Health conducted a study after the accident. In a news releae[97], the Department reported the results. The rate of infant deaths (under the age of one year) was 19.3 per thousand live births within a ten-mile radius of TMI during the first and second quarters of 1979.

If the accident caused an increase in infant deaths, that increase would have been seen throughout the remainder of 1979 because of the timing of the exposure in terms of the gestation period[97]. Instead, it was found that the death rate went down (12.7 per thousand in the third quarter, 13.4 per thousand in the last quarter of 1979). There was no evidence that radiation influenced this drop in the statistics. Fluctuating statistics have been recorded both before and after the accident at TMI[97]. However, one can be sure that had the fluctuations occured in the other direction, opponents of nuclear energy would certainly have cited this as a case in point for their side of the debate.

8.2.3.2 The Extent of Damages in a Nuclear Reactor Accident

The safety features discussed in 6.4 will mitigate the effects of even the worst accidents possible at a nuclear reactor. A very important point to make clear is that CANDU-PHW reactors simply cannot blow up like a nuclear bomb[55]. The same holds true for the light water power reactors throughout the world.

Other worries are that in the case of an extreme accident, a tremendous build-up of steam could occur and the pressure would be enough to breach the containment building. In actuality, there is no way a steam explosion could get up enough force to blow out the containment building in any well-built reactor (most Free World reactors fit into this category) unless the fuel broke into little beads which simultaneously touched water and then focussed the steam to act as a missile[98]. What is more likely to happen is that the fuel will remain in chunks inside the reactor and self-shielding will prevent such an extreme pressure build-up. Of course the dousing system in a reactor would also help to prevent such a build-up of steam.

The public is also worried that in a serious accident, zirconium may interact with water to create a giant hydrogen bubble that could explode, sending radiation blasting throughout the environment. However, what is more likely to happen is that small fires and explosions would occur. (Hydrogen is flammable at a concentration of 4% and explosive at concentrations greater than 15%.) (The hydrogen concentration at TMI never rose much more than 2%[98].) Even if one big hydrogen bubble were to be formed, an explosion caused by its ignition would not be expected to breath the containment[98].

People are also concerned with the effects of hot fuel melting through the floor of a reactor, and deep into the ground. This is a highly improbable situation expected in only one percent of all meltdowns[98]. Further, when the fuel does start melting through the ground, it would eventually come into contact with ground water which would be converted to steam. This steam would exert a pressure on the molten fuel resisting its downward motion while at the same time protecting the surrounding ground water from contamination. The molten fuel would cool and solidify days later. It would then form a glassy solid mass which could not be easily dissolved in water, so little or no ground water contamination would be expected[98].

Although there is a potential for disaster, the most likely consequences of even a meltdown -- the most serious reactor accident -- would still be minor[99]. In fact major reactor accidents are likely to contribute less then ten percent of the total radiation dose commitment due to nuclear power[99].

The Nuclear Regulatory Commission in the U.S.A. sponsored a study under the direction of N. Rasmussen[100] to examine the risks that Americans would be subjected to with 100 large commercial power reactors operating in that country. Though the study was conducted for light water reactors, a good estimate of the dangers for CANDU-PHW reactors can be obtained from these same results. Tables 8-5 and 8-6 show the probability of the occurrence of reactor accidents of various degrees of severity and the damage that would result from such incidents.

To interpret the figures in a somewhat different light, to understand the seriousness of each individual meltdown, the following statements can be made[98]: one in five meltdowns will cause 1000 eventual cancer fatalities in the U.S.A., one in a hundred will cause 10,000 eventual cancer fatalities, and one in a hundred thousand meltdowns (the worst case situation) will cause 45,000 eventual cancer deaths, which is almost the number of fatalities each year in U.S. traffic accidents. The emphasis here is on "eventual". These cancer deaths would occur over a period of about forty years, and hence the impact will not be felt as significantly as it may seem. In fact, the cancers would be distributed among ten million people over that period with the risk to each person increased by less than one-half of one percent over natural cancer death incidence[98].

One in 500 meltdowns will cause more than one hundred immediate deaths. One in 5000 meltdowns will cause more than 1000 immeidate deaths and one in 100,000 meltdowns will cause about 3500 immediate deaths[98]. (This is a worst-case situation[98].)

The odds against a meltdown of any kind are 200 to 1 per year for 100 reactors, and 98% of all meltdowns cause less than one illness or genetic defect[100]. In fatality terms, an individual's chances of getting killed in a reactor accident (assuming the Rasmussen scenario) are one in five billion per year[55]. This same individual is 2000 times more likely to be killed by hurricanes, tornadoes, and lightening; 100,000 times more likely to drown; and a million times more likely to die in a car crash[55].

Public concern, however, is focussed less on the average risk per unit of product than on the possible magnitudes of the improbable but severe accidents that conceivably could occur. There are people who feel intuitively that the potential for catastrophic accidents is something peculiar to the production of nuclear power[98]. To demonstrate the invalidity of such a contention, Table 8-7 provides a comparison of natural and man-made "disasters" and their probability of occurrence. Indeed the probability for disaster in a nuclear-powered society lies more in the day-to-day misfortunes imposed by nature and by the conventional pursuits of our modern age rather than in the production of the energy itself.

8.2.4 Reactor Sabotage

One final but very important aspect of nuclear power operation safety must be considered -- reactor sabotage. All reactors have security personnel and equipment to deter saboteurs, but infiltration of a reactor site by a determined group is nevertheless possible. However, even a well-armed, well-equipped band of saboteurs would find it extremely difficult to achieve the damage that must be assumed to happen in protecting against a major accident[101].

In a battle situation, conventional weapons would not easily breach a reactor's containment building. However a strike against a reactor by a nuclear weapon would be sufficient to induce significant damage. Even the gravest conceivable accident to a nuclear reactor would be far less destructive than the detonation of a nuclear weapon, even if it is imagined that the weapon causes harm only by radiation[102]. But a nuclear strike against a reactor would serve to intensify the weapon's radiation field, spreading radiation over a larger area, and for the most part, rendering a larger area uninhabitable for a longer period of time than if the weapon had been used alone[102].

In any case, a reactor's contribution to destruction in any sabotage or attack-induced release of radiation would have an upper limit that is approximately the same as the worst-case accident situation, with about 3500 immediate deaths (over a two-month period) and 45,000 more deaths over the following thirty to fifty years.

8.2.5 Waste Management

Once a fuel bundle in a CANDU-PHW reactor has produced about one million kilowatt hours of electricity, it must be discharged from the reactor[103]. The used fuel however contains all of the radioactive material produced within it and over 99% of all the radioactivity produced during reactor operation. This material must be dealt with in a manner that minimizes the radiation risks to the generation of people who produced the waste, and to all subsequent generations as well.

8.2.5.1 The Quantity and Nature of Nuclear Wastes

The average Canadian household uses about 7000 kWh of electricity each year[87]. In a CANDU-PHW reactor that amount of energy can be produced from 141 grams of natural uranium dioxide fuel, producing 1.1 grams of fission products and 0.56 grams of plutonium, and a very small amount of other heavier elements (transuranics)[87]. If the house were heated electrically the energy and fuel requirements would increase by a factor of two to four depending on the climate[87]. In all, the energy derived from one CANDU-PHW natural uranium fuel bundle in a once through cycle is enough to meet the demands of one hundred average Canadian homes for one year. It is estimated that by the year 2000, 140 thousand tonnes of spent uranium dioxide fuel will have accumulated in Canada[104]. Most of this mass will be unspent uranium. Fission products (xenon, iodine, etc.) and transuranics (plutonium and heavier elements) would make up the rest. The characteristics of CANDU-PHW fuel before insertion into the reactor, and after discharge, are provided in Table 8-8.

Some of the fission products and all of the transuranics are radioactive. As they decay, they give off heat and penetrating radiation which can be harmful to man and to his environment. Thus the wastes must be cooled, shielded, and prevented from escaping in any significant quantities to the environment. As the decay process proceeds, the hazard diminishes and the required degree of protection from the wastes also decreases.

When the fuel is discharged from the reactor, each bundle contains some two million curies of activity. (1 curie ≈ 3.7×10^{10} radioactive disintegrations per second) This activity decays rapidly so that after one year, the bundle activity has fallen to 16,000 curies (Point 'A' in Figure 8-3), and in ten years, to about 16000 curies. After this period, the actinide (q.v. the Glossary) decay primarily determines the radioactivity. For example, plutonium-239, an important actinide, has a radioactive half-life (see the Glossary) of over 24,000 years. That is, every 24,000 years, the activity of this material goes down by another factor of two. The radioactivity decays very slowly as is seen in Figure 8-3. In the very long run, the natural uranium-238 controls the fuel activity, and since this isotope has a half-life which is approximately as long as earth is old[87], the radioactivity eventually levels off and for all intents and purposes, remains at that value forever.

But it is not necessary to protect man from the radioactivity of the spent fuel forever, at least not in the sense that it must be bottled up and kept completely apart from the environment. Figure 8-4 shows the relative toxicity index[105] (the potential to kill) of irradiated fuel as a function of time, assuming the contaminants had somehow entered the water supply. A second plot on the same graph shows the toxicity for the case when all but one-half of one percent of the plutonium had been extracted from the fuel (as is done in the plutonium-recycle advanced fuel cycle discussed in Section 7.4.3). Also provided are the toxicity levels for other materials that are accepted as part of our environment.

After fifty years, natural spent fuel becomes as toxic as mercury ore. After another 150 years, its toxicity drops to the same level as lead[106]. From Figure 8-4, it can also be seen that after about two hundred years, the toxicity of the spent fuel becomes equal to that of naturally occurring rich uranium deposits. (In the case of uranium ore, the principal hazard is due to radium and its daughter products.) That is, after being stored for two hundred years, the fuel is no more toxic than some of the mines from which it was originally drawn. The uranium mines in Ontario are of a lower grade (0.2% U), and unless the fuel had a substantial amount of the plutonium removed, it would take about 10,000 years before the toxicity of the fuel would drop below the toxicity of these lower grade ores.

These comparisons by no means are intended to play down the dangers of the spent reactor fuel. Rather the intention is to demonstrate that man has been subjected for millions of years to an environment full of toxins and though a potential hazard has always existed, in actuality the true hazard has not been very significant. Similarly with the case of spent fuel. While anti-nuclear groups rally fears by pointing out that a chunk of plutonium the size of an orange contains enough toxic material to kill every human being on earth, they fail to say that it would be impossible to distribute the plutonium to cause such a disaster.

In air, plutonium is as dangerous to man as radium, and in water or food it is orders of magnitude less dangerous[31]. Yet in the top 450 meters of the earth's crust in Canada, there is some 14,000 tonnes of naturally occurring radium[107]. It is leached into our water supply at a concentration of 0.01 to 1.0 picocuries (1 picocurie = 10^{-12} curie) per litre[107]. The release has not resulted in a catastrophe and hence any small plutonium releases should not be considered particularly disastrous.

To further allay fears that spent fuel from nuclear reactors spells the impending demise of the world, it may be noted that over the past thirty years some four to six tonnes of plutonium and several tonnes of fission products have been put into the earth's atmosphere from the use and testing of nuclear weapons. This has become part of our everyday environment and has had no measurable effect on the health and well-being of our civilization[107].

8.2.5.2 <u>Closing the Nuclear Fuel Cycle</u>

When CANDU-PHW fuel bundles are removed from a reactor they are, as previously mentioned, extremely radioactive and at a very high temperature as a result. The spent fuel is stored in a large pool of ordinary water in order to cool it down. After one day of cooling each bundle produces less than two kilowatts of decay heat[71]. This quick-cool characteristic allows the bundles to be packed into the pool like cordwood. After thirty years of operation, a 1000 MW(e) CANDU-PHW would have a spent fuel supply that could fill an olympic-sized swimming pool[993)]. Each CANDU-PHW station is equipped with a spent fuel bay to safely hold the spent fuel inventory from five to ten years of reactor operation[(105)]. Each fuel bay is a double-walled reinforced concrete structure resembling a large swimming pool. The bays are partially subdivided into several sections by cover support beams[(105)].

Water is allowed to circulate through the bays to effect bundle cooling and to provide a shield against the radiation emitted from the bundles. For radiation protection purposes it is necessary to leave a water barrier between the upper level bundles in the bay and the water surface.

The spent fuel bundles from all CANDU stations currently reside in such fuel bays. Tests indicate that fuel bundles should be able to be safely stored in fuel bays for at least fifty years[(108)], and probably longer[(109)]. The fuel bundles stored to date show no signs of water corrosion or fission product stress-induced corrosion. Even studies on defective fuel bundles show that after storage in the special fuel bays for defective fuel, no additional fission product releases have occurred[(108)].

However, it will eventually become necessary to close the fuel cycle. Indefinite storage of spent fuel in spent fuel bays runs counter to the basic philosophy of not making future generations responsible for the wastes from the current generation. Some method of permanent disposal must be found.

Two distinct optional groups must be considered, and the group choice will depend on a decision of whether or not fuel recycling is a politically acceptable option. The group choices are depicted schematically in Figure 8-5. Either the fuel bundles themselves can be boxed up in a heavy-duty container and stored safely away from man, or else fuel recycling can take place, with the useful fissile and fertile atoms extracted from the fuel and only the true waste -- fission products, and actinides other than plutonium -- will have to be dealth with. If an advanced fuel cycle becomes the optimal CANDU fuelling option, then it would be necessary to invoke this latter method of closing the CANDU fuel cycle.

8.2.5.3 Options for Disposing of Nuclear Wastes

Several options for disposing of nuclear wastes exist. All options contain distinct advantages and disadvantages over the alternatives. The options include surface storage, underground storage, storage in outer space, and transmutation.

Canister Storage

After five years in a spent fuel bay, a spent fuel bundle produces about 0.4 W/kgU of heat from internal radioactive decay[107]. After this, it is no longer necessary to cool the fuel bundles in a water storage facility. Instead, they can be transferred by rail or truck to a central facility and placed in canisters similar to the one depicted in Figure 8-6. The canisters would store about 200 bundles each. The canisters would stand side-by-side on the earth's surface in an open-air facility relying on natural conduction to effect cooling. Initially each canister would send some 2 kW of heat out to the environment. This would be induced by a 65°C temperature gradient across the walls of the canister[110].

The radiation field at the surface of canisters presently experimented with would be almost 15 millirem per hour[110]. Currently design modifications are being studied to substantially reduce the field.

Transportation to a central storage site requires some radiation exposure risk, but the economies of scale and the added protection derived from the use of a single site, far outweigh the transportation risks. This is true in all of the disposal schemes that shall be considered in this report.

Further, since in-transit storage techniques for radioactive materials are quite well-developed, it is essential that the probability of a transit accident where radioactive material is released is about one in every 250,000 fuel shipments, while other estimates, still referred to as conservative, conclude that the chances of a release are more like one in every ten million fuel shipments[105]. If an in-transit release should occur, the radiation hazard would by very localized and would have an insignificant effect on the total average radiation dose received by the public.

The canister option with its open-air above ground storage facility poses somewhat of a risk in light of the possibility that unusual events, though quite infrequent, may lead to canister destruction and a consequent release of radiation. However the risks imposed by such unusual hazards as tornadoes, missile impact, failure of the canister to remain upright, and other events have been assessed and subsequently judged as acceptable[111].

The canister program option would require the smallest capital investment of any permanent disposal facility. However the canisters would have to be continually monitored and rebuilt every few hundred years for many generations. Since the basic waste management philosophy maintains that the responsibility for waste surveillance should not be placed on future generations, the canister option cannot be viewed as a viable long-term disposal method. It could, however, be used as an intermediate disposal method until a final decision regarding the wastes is made.

Underground Waste Disposal

By disposing of reactor wastes some 300 to 2000 meters beneath the surface of the earth, in a stable crustal formation with little water movement, pathways for the material to enter the biosphere are effectively eliminated[112].

The earth's crust has many salt-beds that have been stable for hundreds of millions of years, and there exists crystalline rock formations (plutons) throughout the world that have been stable for a billion years or more[113]. There are 1500 plutons in the Canadian Shield[103]. Plutons are an excellent choice to act as fuel disposal sites due to their low seismicity, but ground water may seep into cracks and fractures and spread the contaminates back into the biosphere. Salt is an excellent heat conductor and hence is capable of dissipating any heat that is generated by the disposed fuel. Further, its self-sealing characteristics make ground water penetration difficult[114].

The fuel bundles themselves could be stored in concrete, lead, and steel vaults in these rock or salt formations. Alternatively, the fuel could be reprocessed to extract the fertile and fissile atoms, and the rest of the material could be converted into a glass material, and this glass could be stored in the underground vaults. Again, a central site to serve many power stations would be warranted.

The fuel bundles themselves would act as the first barrier to release of the radioactive material if a decision not to recycle fuel is made. The UO_2 is very insoluable in water and the zircaloy sheath should hold back the waste for at least 100 years[115]. One square mile of salt including a buffer zone, would be sufficient to store all of the spent fuel bundles in Canada to the year 2000[115].

If the fuel is reprocessed, and the true wastes turned into glass, the vault structure deep in the ground would not be required to be of such integrity as in the case when the actual fuel bundles were buried. This is due to the fact that the glass wastes are so insoluble, that it would take more than one hundred million years for the wastes to dissolve[112]. This is much longer than the time required for the decay of the radioactive wastes to an acceptably insignificant level.

The underground location of the storage vault provides excellent isolation of the reactor wastes. The geological structure around the vault provides cooling and shielding, and with the proper choice of site, the vault should be undisturbed by earthquakes or another ice age[110]. The frequency of meteors impacting and causing a radioactive release from a vault has been estimated as once every million-million years (1 x 10^{-12} per year)[116].

Underground storage of radioactive materials should provide an effective and economical waste disposal method. Preliminary studies indicate that the insoluble nature of the waste form itself, the resistance of the vault to corrosion or mechanical damage, and the effectiveness of the massive geological barrier for hold-up and dilution of the radionuclides, should act to provide sufficient redundancy of protection to make underground storage acceptable to the scientific community as a safe reactor waste disposal method[116].

Glacial Storage

Storage of radioactive wastes in the polar ice caps has been studied[105]. Antarctica has been continually glaciated for at least five or six million years[105], and may offer a viable alternative to in-ground storage. However, transportation costs and dangers would be considerable, and, in addition, such activities are forbidden in Antarctica by international treaties[105].

Ocean Storage

Studies have been done by the U.S.A., Great Britain, and Japan to assess the feasibility of storage of nuclear wastes in deep holes beneath the ocean floor, thereby eliminating the need to sacrifice any surface land[105]. This would require special techniques to drill 1000 meter deep holes under 4000 meters of water. No technology exists today to do this[105].

Outer Space Storage

NASA in the U.S.A. has studied the feasibility of ejecting fission products and actinides into outer space for permanent disposal[110]. Rockets carrying the waste could be directed to the moon, to the sun, or into deep space. With further developments in space technology (such as the space shuttle) it could become economically attractive to separate the actinides, such as americium and curium and send these into space. It is doubtful that it would ever become economically feasible to send fission products or irradiated spent fuel bundles into space for the purposes of waste disposal. However, the fission products themselves require shielding and cooling for only about 300 years[114]. It is the actinides, which emit penetrating alpha particles, and have extremely long half-lives, that must be kept away from man for hundreds of thousands, if not millions, of years. Hence this option may be considered as a viable disposal option in the future. However, if a malfunction occurred during a rocket launch the consequences of widespread contamination would be significant[105].

Radionuclide Transmutation

Transmutation involves the conversion of long-lived radionuclides (fission products and actinides) into short-lived or stable isotopes by neutron bombardment in a nuclear reactor. A similar transmutation may be induced through the use of a particle accelerator. In this latter device, high energy particles (primarily protons) can be used to bombard the radioactive material to effect the transmutation. Both transmutation methods are theoretically feasible, though they would require high efficiency separation processes to cause a significant drop in the radioactivity of the waste, and in the case of the neutron-induced transmutation method, special irradiation facilities would have to be incorporated into the reactors[105]. Transmutation of the wastes in a reactor would incur a burnup penalty of about 15%. (That is, 15% more fuel would be required for each unit of electricity produced[110].)

8.2.5.4 The Costs of Waste Management

A recent study[71] calculated the cost requirements for various storage facilities -- pools, canisters and vaults. The study assumed one site would store all of the spent fuel bundles from 360,000 MW(e) years of energy production (about 30 years worth of electricity from six stations the size of Pickering 'A'). The cost per kilowatt hour of electricity production for extended period pool storage was determined to be 0.13 mills/kWh (1978 Canadian dollars). For canisters the cost was determined to be 0.12 mills/kWh, and for vault storage the cost was determined to be 0.10 mills/kWh. This includes a rough estimate of capital, operating and shipping costs. The extended period pool storage facility to store the spent fuel from 360,000 MW(e) years of energy production (about 47,000 tonnes of uranium, fission products, and actinides) was calculated to be 0.06 km^2 for the facility only, and when the buffer zone was included a total land area of 2.2 km^2 would be required. A canister facility would require 0.79 km^2 and a larger buffer region, bringing the total to 4.7 km^2. The vault facilities would require 0.12 km^2 of site area, and with the buffer zone included a total area of 2.4 km^2 would be required. This is a small price to pay in terms of electrical cost and land requirements for such an enormous quantity of energy output.

When fuel reprocessing comes into the CANDU fuel cycle (to date no decision has been made to incorporate the process), there will be a dramatic drop in the land requirements for storing the waste. The use of pools to store the fuel for a considerable amount of time before reprocessing would allow the waste glass to become cool enough to be packed close together in permanent storage vaults. This option is expected to cost about $19.75 (1979 Canadian dollars) per kilogram for transportation, glass formation, vault disposal, facility decommissioning, etc.[117], which would mean a total disposal cost per kilowatt hour of electricity of only 0.4 mills (1979 Canadian)[117], with no credit taken for the fissile materials obtained during fuel reprocessing. That is, a once-through cycle is still assumed. This tends to artificially increase the disposal cost per unit electricity produced. Further, if the transmutation of actinides becomes accepted practice, the wastes would require an even smaller storage area, and after a few hundred years, they would no longer be considered hazardous at all.

The prospects for the management of nuclear wastes using a safe economical and ecologically sound disposal method are encouraging, and with further careful study an acceptable process to deal with this important aspect of nuclear power will become a reality, allaying any doubts of technical and economic feasibility.

8.2.6 Plant Decommissioning

Nuclear power stations, like all man-made structures cannot last forever. Though CANDU-PHW reactors are designed to allow for relatively easy part replacement, eventually the reactors must be shut down and stored away (decommissioned). A minimum reactor lifetime of thirty years is often considered as the nominal time before the entire facility must be decommissioned, though it is reasonable to assume that a reactor will not be decommissioned until many years beyond this capital repayment period[118]. In fact, the containment building and other structures may be in good condition for almost a century. In the analysis considered here, however, a nominal thirty year lifetime will be assumed.

Radioactive wastes from the operation of power plants and radioactive plant components at the end of the productive life of a reactor (not including fuel or heavy water), constitute less than 0.1% of the total radioactivity of a nuclear station[118], but because they are appreciable in volume and diverse in nature, they require separate consideration.

The decommissioning process can be divided into three stages: mothballing, entombment and dismantling and removal[118]. Before any stage of decommissioning is achieved, all fuel and radioactive waste from normal operation (spent ion-exchange columns, filters, solutions, heavy water, etc.) must be removed.

The first stage, mothballing, involves surveillance and monitoring. The containment system is maintained so no more radiation is released to the environment than during normal operation. Nominally, this period would encompass thirty years[119]. This length of time is required to allow the natural radioactive decay process to considerably reduce radiation levels.

In the second, or entombment stage, all easily removable parts are dismantled and removed. Also removed are all components that have radioactivity associated with them of such a nature that they will remain a health hazard for a period longer than the entombment period. Radioactivity levels will still be quite high during this period, requiring the use of remote cutters to protect workers from high radiation levels. All radioactive components remaining are sealed into the reactor vault, and the containment building can then be removed. Surveillance would be kept to a minimum and radiation leakage would occur slowly and not required continuous monitoring[118].

In the third stage, all components are dismantled and all materials containing any radioactivity above acceptable levels are removed. Finally, the site would be released without restriction for other uses. No further surveillance, inspection or tests are required upon completion of this final stage[118].

The entire decommissioning process is expected to take about 40 years, including the time spent in pre-decommissioning activities (fuel and waste removal)[119]. Decommissioning the Pickering 'A' station (four reactors) will cost about 162 million dollars (1980 Canadian) and result in an 1800 man-rem radiation dose to workers (1400 man-rem in the final five years)[119]. Reactor operational wastes and radioactive decommissioning wastes could be handled in the same repositories (vaults) as spent fuel wastes without affecting either the size of the repository or the complexity of the handling operation[107]. This is due to the fact that these wastes are relatively low in radioactivity (compared with the spent fuel) and it is primarily the amount of heat generation that governs the size of a repository.

Because of the planning for decommissioning that went into the design of CANDU-PHW reactors and the dual-use depository facility, it is expected that pre-decommissioning and decommissioning costs will acount for no more than one percent of the Total Unit Electricity Cost for a CANDU-PHW station[120]. That is, for every dollar a utility spends to produce electricity, one percent should be put aside to be applied to decommissioning activities at the end of the reactor's productive lifetime. Again, this is quite insignificant, and it could be completely recovered by selling the heavy water from the expired reactor unit[120].

8.2.7 The Proliferation of Nuclear Weapons

Various international agencies control the spread of nuclear weapons development through spent reactor fuel exploitation. The International Atomic Energy AGency (IAEA) has developed technical and political safeguards to deter the diversion of nuclear materials to the production of weapons[20]. The International Nuclear Fuel Cycle Evaluation (INFCE) committee became institutionalized in 1977. This agency has forty member nations with a mandate to look at the methods of decreasing the proliferation of nuclear weapons while not jeopardizing the role of nuclear power[20].

It is well known that plutonium, or fissile uranium are eseential components in a nuclear fission bomb. As has been explained in this report, both are also major energy sources in nuclear fission reactors. CANDU-PHW reactors are the most efficient commerical power reactors at producing plutonium (on the basis of grams of plutonium produced per initial atom of the fissile material, U-235). However, as is evident in Table 7-5, the spent fuel from light water reactors has a higher concentration of U-235 and fissile plutonium than the spent fuel from CANDU-PHW reactors, and hence if material diversion were to occur, a smaller quantity of spent fuel from a light water reactor would be required for processing bomb-grade materials.

The use of power reactors to produce nuclear weapons is a genuine concern of the Canadian government, but rather than denounce nuclear energy, Canada has chosen to develop a viable nuclear system that incorporates precautions to ensure only peaceful uses of the technology. Canada has always required that nuclear facilities provided by it to other countries be used for peaceful purposes[31] as part of its own international philosophy and to discharge its commitments under the International Treaty on the Non-Proliferation of Nuclear Weapons[5]. Canada engages in bilateral agreements with its customer countries which specifically proscribe explosions and seek to control the disposition of goods and technology received from Canada[31].

The IAEA, which reports to the United Nations, supervises the technical safeguards undertakings in CANDU and all member power reactor systems[31]. These safeguards are implemented by applying administrative controls over materials inventories and flows. Permanent in-place mechanical tamperproof surveillance devices are used[5]. The purpose of the IAEA inspection services is not to prevent diversion directly, but to deter diversion by being in a position to detect it.

If it cannot be ascertained that diversion did not occur, inspectors report the case to the United Nations. At this point, heavy international political and economic pressures can be brought to bear against the offending nation. This, it is hoped, would deter a country from proceeding with a nuclear weapons program. Since spent fuel must be cooled for several years before it can be processed, ample proliferation warning would be available to the IAEA to initiate deterrent actions.

Plutonium may also be used as a weapons material by terrorist groups. As a toxin, just placed in a water supply, plutonium is less dangerous than KCN, selenium-oxide, or $HgCl_2$, and if inhaled, plutonium is as toxic as benzopyrene or nerve gas[18]. However all of these toxins are more readily attainable by terrorists than plutonium, and in the case of plutonium inhalation, it should be noted that plutonium compounds do not exist in gaseous form and dusts are hard to maintain.

Spent fuel may be stolen by ambitious terrorists with visions of constructing a nuclear weapon. However, even if the terrorists were successful in the theft of the tonnes of spent fuel that would be needed in such a venture, they would require complicated and very bulky equipment to transport the material, and a multi-million dollar chemical plant to separate out the plutonium[101].

In addition to the intrinsic safeguards of low uranium-235 and low plutonium concentrations, other fuel cycle safeguards can be employed to deter the theft of nuclear materials. These additional deterrents will be of particular importance in the fuel recycling processes in advanced fuel cycles, where highly concentrated fissile material may be present during part of the operation[34].

Co-processing is an important example of a proliferation deterrent. In the fuel reprocessing cycle, co-processing would entail a mixing of the new feed material with the spent fuel material and then a chemical separation of the fission products. At no time in the cycle therefore, does a weapons-grade material exist by itself.

To deter the theft of enriched fuel en route to reactors, some irradiation of the fuel prior to shipment would ensure that the theft of the material would be difficult, and extraction of the fissile atoms would not be possible for a considerable length of cooling time.

To deter the conversion of an enrichment plant into a plant to produce weapons materials, it would be best to operate the enrichment plants using the conventional diffusion-type uranium separation process.

Centrifuges are sometimes used in uranium enrichment. However, they can be easily modified to produce bomb-usable uranium by rearranging the piping so that the centrifuges run in series, not in parallel.

In thorium fuel cycles the addition of U-238 to the fuel would mean that any attempts to extract the fissile U-233 from the spent fuel would require a chemical separation plant and another plant to separate the two uranium isotopes.

These methods and others will be applied to future fuel cycles around the world to support the non-proliferation of nuclear weapons. However the political pressures and these costly technical deterrents may not be sufficient to stop a nation from developing a nuclear weapons program using spent reactor fuel. That possibility, unfortunately, will always exist. But the real question that the nuclear power industry and its opponents and supporters must address themselves to, is whether continuing the development of nuclear energy will significantly increase the chances of plutonium being misused[20]. If nuclear power ceased today it would not turn back the clock on weapons development. Plutonium has become a part of our world. There are at least seven other ways to produce it that are both easier and cheaper than the use of a power reactor[20]. It is true that the purchase of a reactor for electricity production provides the added "bonus" of plutonium production. However, a country determined to embark on a nuclear weapons program would certainly not have to look very far for an alternative means of producing enriched uranium or plutonium should a power reactor be unavailable to it. Hence, those who support the abolition of nuclear power on the grounds that it helps to support the proliferation of nuclear weapons should consider that today there are many ways to produce weapons-grade materials and hence, nuclear power reactors do not constitute a unique hazard.

8.2.8 Nuclear Power: The Risks in Perspective

Nuclear power does carry with it some risks as has been discussed. However, the risks are extremely minute compared to the other risks encountered each day. Taking into account the entire nuclear power program -- mining, fuel fabrication, reactor operation, waste disposal, and accidents -- it is expected that even the most extravagant nuclear programs will not appreciably alter the radiation dose that each person is subjected to. Mooradian[18] estimates that even the most ambitious nuclear program would expose a person to no more than 2 millirem of whole body radiation each year. Myers and Newcombe[91] quote a U.S. study that estimates that the future maximum radiation dose from nuclear power will average about 6 millirem per person per year[91]. This assumes a nuclear power capacity of 1 kW(e) per person. Other studies[20] show that a nuclear program this large would lead to an increase in the natural rates of cancer and genetic defects of about one-thirtieth of one percent. These studies are said to be cautious estimates. That is, the actual exposures and deaths that would result would be somewhat less than this. Myers[121] suggests that today the nuclear industry contributes less than 0.001% of the total natural incidence of cancer and genetic defects, while any prospective expansion of the nuclear industry is not expected to increase the incidence in the general public by more than 0.005% at maximum. Table 8-9, taken from Reference 90, summarizes the risk situation for a nuclear program producing 1 kW(e) per person. Table 8-10, taken from Reference 91, compares the cancer deaths caused by various carcinogenic agents in the U.S.A. The asumed future maximum from nuclear plants is somewhat less than the 230 deaths/year predicted for a population of 230 million from the data in Table 8-9. In any case, nuclear power will not ever cause a noticeable increase in the North American cancer rate.

The same logic that suggests that radon from uranium mine tailings to the year 2000 might increase lung cancer incidence in the U.S.A. by roughly 0.4 cases per hundred million persons per year would suggest that excessive emphasis on reduced ventilation to conserve heat in buildings would increase lung cancer incidence by roughly 20,000 cases per hundred million people per year[91]. The ratio of a 50,000 fold difference in predicted health hazards remains the same regardless of the risk estimate chosen to calculate the actual hazards of low level radiation to the general public. Indeed the concentration of effort to remove the dangers from uranium tailings seems to be quite misdirected.

While the disposal of spent nuclear fuel will continue to be a subject of interest, it is important to realize that the actual hazard to man is quite small. In fact, even if one assumed that the nuclear waste arisings from, for example, 400,000 MW(e) years of electricity production were spread randomly throughout the top 600 m of land mass in the U.S.A., 0.4 fatal cancers would be caused in the following million years, and 4 more fatal cancers would develop from this source over the next one hundred million years[122][123]. This assumes that the transfer probability to humans per unit mass of reactor waste is the same as that which is applicable to natural radium. It is assumed that no special shielding is placed around the spent fuel.

Of course, these studies are somewhat speculative in that the use of nuclear power is quite a recent undertaking and hence actual long term studies of waste movement and transfer to humans have been studied only in theory and just somewhat experimentally using time extrapolation techniques. But the waste movement theories have been found to be correct when applied to the Oklo reactor site in Gabon. Oklo is the site of what was a natural fission reactor some two billion years ago[107]. The reactor produced 15,000 MW-years of fission energy and left behind 5.5 tonnes of fission products and 2.3 tonnes of plutonium. A recent analysis of the stable daughter products from the long term decay of those wastes showed that the plutonium and fission products from the reactor, though they were not confined artificially, had remained in the formation until they had decayed to non-hazardous materials[107]. Such examples from nature seem to confirm that, similarly, properly confined reactor wastes will not spread and become a threat to our world.

8.3 The Risks of Energy Production: A Quantitative Comparison

In the preceeding subsection a comprehensive study of the risks of nuclear energy production was presented. At this point it is prudent to compare the risks of energy production from nuclear power with the risks from other sources of electrical energy.

8.3.1 Coal

Coal has been hailed as one of the energy saviours of tomorrow, but once the true hazards of its use become known, its political and social acceptance will surely be questioned.

While it has already been mentioned that a 1000 MW(e) CANDU-PHW reactor would use about 0.5 tonnes of UO_2 each day, and over a period of 35 years, would leave behind enough spent fuel to fill an olympic-sized swimming pool, it should be mentioned here that a 1000 MW(e) coal-fired power station would burn 10,000 tonnes of coal each day[93]. A coal storage pile 15 hectares in area and 15 meters high would be required on the land adjacent to the station[93]. And in terms of waste, some 1000 tonnes of fly-ash and slag would be produced each day. (The other 9000 tonnes would escape into the atmosphere as gases and particulates, some of which are extremely harmful.) After an operating period of 35 years, a coal-fired 1000 MW(e) station would produce enough slag and fly-ash to cover 40 hectares to a height of 8 meters[93].

Carbon-dioxide is emitted in large quantities from coal-fired stations. This can cause a greenhouse effect which could warm the atmosphere and alter the climatic conditions throughout the world. The particulate matter emitted from a coal-fired station has just the opposite effect, blocking the incoming warming rays of sunlight. The two effects do not cancel each other but rather combine to create an upheaval of the earth's weather conditions, suggesting that in the long term it may become very dangerous to depend on coal for a large portion of the world's energy. One redeeming quality of coal-fired plants is that they emit less waste heat per unit electricity production than the nuclear stations do. However, if thermal pollution does become a problem, reactors can be modified to be cooled by other means, though at some economic penalty[20].

In addition to carbon-dioxide, many other pollutants are sent into the atmosphere from coal-burning plants[20]: for example, combustion products such as the oxides of nitrogen and sulphur, polycyclic hydrocarbons, and benzopyrene, all of which are carcinogenic and/or mutagenic, and are present in all combustion processes; long-lived pollutants such as radium, uranium, and thorium; and everlasting pollutants such as arsenic, lead, and mercury. These emissions are by no means insignificant. Consider that Canadian power plants (oil and coal) emit nearly 16 tonnes of mercury into the atmosphere each year, and U.S. power plants emit ten times that amount[107]. And in terms of radioactive emissions, the

the rem dose per MW(e)-year from current coal-fired power stations operating with 97.5% fly-ash removal is probably equivalent to 0.1 to 1.0 times that for a nuclear power station[91]. Recall that nuclear wastes are primarily confined to the fuel itself, while coal wastes spread through society.

Coal-fired stations also contribute to the problem of acid rain that is killing many North American lakes. Ontario Hydro's coal-fired power stations have been recently cited as a major Canadian contributor to the acid rain problem. The pH of normal rainfall is about 5.7[124]. A liquid with a pH of 4.7 is ten times as acidic. (The scale is decade logarithmic.) In North America, the land area with rainfall having a pH less than 4.6 has expanded from a very limited area in 1955 to its current area which includes almost all of the eastern U.S.A. and southeastern Canada[124]. Much of this is due to increased emissions from the combustion of fossil fuels.

Air pollution from coal burning in the U.S.A. kills 10,000 Americans each year from cancer and other related diseases[98] and some estimates are many times higher. For nuclear power to be as dangerous as coal there would have to be a meltdown every two weeks in the U.S.A. (assuming the disaster probabilities from Reference 100)[98]. On the other extreme, the Union of Concerned Scientists (a group of nuclear critics that is an advisor to Ralph Nader), feels that nuclear accidents would cause ten times as much damage as the Rasmussen Report[100] determined[98]. Hence, using their figures, nuclear power stations and coal-fired stations would cause equal numbers of deaths in the U.S.A. each year if a reactor meltdown occurred every six months[98]. And as far as accidents are concerned, there has already been an episode from coal-burning that killed 3,500 people in one week[98]. This is the maximum number of people that would die in a two-month period following the worst conceivable nuclear reactor accident.

Property damage from coal-burning is estimated to be about 13 billion dollars (U.S. 1979 dollars) per year in the U.S.A.[98]. Using the cost figures from Reference 100, adjusted for the dollar value difference between 1975 and 1979, it can be shown that for the monetary costs to the public to be as large from nuclear power as it now is from coal-burning there would have to be a meltdown every three days in a U.S. power reactor[98].

The annual number of cancers and hereditary defects in the general population per unit energy production from today's coal-fired stations may be as high as ten times the number that could be attributed to the maximum future incremental radiation dose of six millirem per year from a complete nuclear power program[91].

Pollution levels in coal-fired plants can be significantly reduced through the use of anti-pollution devices (such as SO_2 scrubbers). Such devices could allow coal-fired stations to become as clean as nuclear stations, though the adoption of such a project, for Ontario Hydro for example, would cost several billion dollars.

Virtually all authorities agree that coal is substantially more dangerous than nuclear power, with coal:nuclear risk ratios per unit electricity production ranging from 3 to 120, depending on who does the study[91]. With coal there is more material mined and transported per unit energy production, and hence there is more accidents. Also, because of the increase in mining, there is a lot more material brought to the surface (and hence more mine tailings). This will eventually cause the radiation risk from coal production to exceed that of nuclear energy. In fact, based on radiation effects in the U.S.A., over a multi-million year time span, coal mining and burning, and all other activities that simply bring uranium to the surface (some uranium is mixed in with most coal deposits) have zero net effect on human radiation exposure. Nuclear energy, on the other hand will eventually save 35 American lives per hundred million watt years of electricity production[125]. This is due to the fact that radon gas is more important than all other radiation combined, and the burning of uranium and the covering of uranium tailings piles effectively keeps a fraction of the natural radon away from man. (Much of the uranium near the earth's surface would be brought to the surface by erosion over a period of several million years. Covering tailings piles slows down the process, allowing for more time for the radon emissions from the uranium to decrease.) In the shorter term, (500-year time span) the effects of radon emissions from coal burning and from uranium mining and milling residues are roughly equivalent[125] since radon levels are usually higher in uranium mines than in coal mines.

It is truly unfortunate that society in general is not aware of the harmful aspects of coal burning since every time a nuclear plant is turned down and a coal fired plant takes over, several hundred people are condemned to die prematurely[89].

8.3.2 Oil, Natural Gas, and Other Combustion Sources

The pollution problems associated with the combustion of oil and gas are the same as those associated with coal, though considerably less in magnitude. Oil causes only 20% as much pollution as coal per unit electricity output, but about the same amount of thermal pollution[3]. Natural gas causes even less air pollution but about the same amount of thermal pollution[3].

Oil fires can be very dangerous at refineries and at power stations. Natural gas fires, explosions and asphyxiation are hazards faced using that energy source. There may be gas explosions that could kill many hundreds of thousands, and perhaps even wipe out a whole city[98]. There may be oil fires that could create enough air pollution to kill hundres of thousands[98]. Oil spills on the oceans from supertankers and the subsequent devastation on the shores and beaches are problems to be considered. Also on-land transportation accidents during the shipment of these fuels result in lives lost.

Wood and other combustible sources of energy also have these problems associated with them, and because they are bulkier than fossil fuels, handling accidents and soot problems are increased. Further, wood burning may eventually result in asphyxiation due to the loss of these precious oxygen producers.

8.3.3 Hydro Electricity

The production of hydro electricity is quite clean. No increase in thermal pollution results from its utilization. However, its dependence on the construction of dams for the express purpose of energy production has resulted in dam failures that have in some cases caused a very substantial number of deaths. There are ten dams in the U.S.A. that have the capacity to kill tens of thousands to hundreds of thousands of people if they would rupture suddenly when filled (for example during an earthquake)[99]. In fact, the Rasmussen Report[100] as quoted in Reference 101, concluded that the risk of 1000 people being killed in a reactor accident is about 0.0001 times the risk of 1000 people being killed as a result of a dam failure should an accident occur. Even if the risks of nuclear accidents are underestimated by an order of magnitude in Reference 100, as the Union of Concerned Scientists (nuclear critics) believes, dam failures on average still are about 1000 times more likely to kill 1000 people than a nuclear reactor accident.

Actual catastrophic collapses of dams are relatively common, and in the last twenty years, there have been at least a dozen such events around the world involving large losses of life and major property damage[99]. In the same period, serious damage has been sustained by six dams, with actual catastrophe avoided, in some cases narrowly, but with an enormous potential for loss of life[99]. .

8.3.4 Solar Energy

While solar energy produces no additional thermal pollution and no real air pollution, and the only wastes are those from the initial device construction, there will probably always be a considerable number of deaths and injuries and associated with it. The power plants would be very large, requiring a tremendous amount of materials for the collection and storage of the energy and possibly a back-up system due to the intermittent supply. While it takes two years of full power energy production from a nuclear plant to pay back the energy spent in the production of the materials required for the reactor and the reactor construction, and a few percent of the energy produced thereafter would have to go into fuel production[20]; it may be considerably longer before a solar station begins to show an energy profit.

Each year an American has one chance in 11,000 of dying from a fall[100]. (Compare this to 1 chance in 5 billion of dying from a nuclear accident (based on 100 power reactors)[100]). If rooftop solar cells become fashionable this number will substantially increase.

If outer-space satellite solar collectors become a part of the solar scenario, there will be an additional threat of radiation due to the microwave signals that would be sent by such a collector, as well as the admittedly very minute possibility that the collector would fall out of the sky. These latter threats are no more significant than nuclear disasters, in that their probability of occurrence is very low, however, in all fairness, the potential for disaster has to be pointed out.

8.3.5 Wind, Thermal and Tidal Energy

Wind and tidal energy do not cause thermal pollution. Thermal energy drawn from deep inside the earth causes some extra heat to be brought to the surface which may be of concern in the future, but ocean thermal energy, that relies on the temperature gradient as a function of depth to produce electricity, does not cause any appreciable thermal pollution. The only air pollution caused by such systems is that which results from component manufacturing. Recall from Section 5 that these energy sources are quite unconcentrated and as a result much energy and human effort must be expended to set up the large facilities required for such operations. In addition to the systems themselves, energy storage facilities must also be supplied, and in some cases complete back-up systems would be required.

Transportation of the power from such plants must also be considered in the dangers of these energy options. Since cities are usually quite a distance from the ocean, the wave, tidal and ocean-thermal options require the construction of expensive and somewhat dangerous power transmission lines to get the electricity to where the demand for it exists.

When all of these aspects -- quantity of materials, the hazards of producing these materials, operation accidents, and the possible backup systems -- are considered, the seemingly innocent conventional sources of renewable energy become more hazardous than they may at first appear.

8.3.6 The Health Hazards of Energy Production

When the entire energy picture is examined option by option, comparing the whole cycle involved from component production to plant operations to waste disposal, and accidents, the relative risks of all of the electricity production methods can be compared. This has been done in Table 8-11, which shows the average values of risk derived from several independent studies (q.v. Reference 91), and also, in brackets, the range of risks from the various studies is provided.

It is clear to see that the risks from nuclear energy production, when the entire cycle is considered, are quite small in relation to most other energy options. In fact, U.S. government estimates show that if all U.S. power was produced from nuclear reactors, the average American's life expectancy would drop by 0.04 days[3]. The Union of Concerned Scientists think this would more likely be 4.0 days[3]. These decreases use as a reference life expectancy, some hypothetical value that would result if power could be produced without hurting anyone.

Though the risk estimates are preliminary in that even more thorough investigations of the risks of energy production will be essential in order to make more accurate assessments of the hazards of energy production, it is expected that the general trend will prevail. Nuclear power will continue to be a source of safe, economical electricity for many future generations to come.

SOURCE	AVERAGE DOSE (millirem/annum)
Natural Background	100
Chest X-Ray (1/annum)	100-200
Dental X-Ray (1/annum)	20
Jet Flight – 10 000 km	4
Luminous Dial Wrist Watch	2
Colour TV (1 hour/day)	2
Nuclear Power Plant (maximum exposure plant fence)	5

TABLE 8-1 RADIATION DOSE FROM VARIOUS SOURCES

SOURCE	AVERAGE DOSE (millirem/annum)
Nature	100
Medical (X-Rays, cancer treatment, etc.)	100
Fallout (from past nuclear weapons testing)	1
Occupational	0.3
Miscellaneous	0.3
Total (approx.)*	200

* This total does not include the effects of nuclear power stations though as shall be explained in Section 8.2, the inclusion of the effect would not alter the total significantly.

TABLE 8-2 AVERAGE ANNUAL RADIATION DOSES FROM NATURAL AND MAN-MADE SOURCES

CRITICAL ORGAN	ANNUAL DOSE LIMIT	
	INDIVIDUAL MEMBER OF PUBLIC	POPULATION OF CANADA
Gonads, red bone marrow and uniform whole body irradiation	0.5 rem	10^4 rem (whole body)
Skin, bone, and thyroid	3.0 rem (1.5 rem to thyroid of children up to 16 years old)	10^4 rem (thyroid only)
Other single organs or tissues	1.5 rem	—
Extremities	7.5 rem	—

For radiation workers individual dose limits are ten times larger than those for members of the public.

TABLE 8-3 ICRP RECOMMENDED RADIATION DOSE LIMITS FOR CANADA

	Single Failure	Dual Failure
Individual		
— Whole Body Exposure	0.5 rem	25 rem
— Thyroid	3.0 rem	250 rem
Population		
— Whole Body Exposure	10^4 man-rem	10^6 man-rem
Maximum Frequency	1 in 3 years	1 in 3000 years

TABLE 8-4 AECB LIMITS ON EXPOSURE UNDER ACCIDENT CONDITIONS

CHANCE PER YEAR	CONSEQUENCES				
	EARLY FATALITIES	EARLY ILLNESS	TOTAL PROPERTY DAMAGE (BILLION U.S. DOLLARS 1975)	DECONTAMINATION* AREA SQUARE MILES**	RELOCATION AREA SQUARE MILES
One in 200[a]	<1.0	<1.0	<0.1	<0.1	<0.1
One in 10 000	<1.0	300	0.9	2000	130
One in 100 000	110	300	3	3200	250
One in 1 000 000	900	14000	8	3200	290
One in 10 000 000	3300	45000	14	3200	290

(a) This is the predicted chance per year of core melt considering 100 reactors.

* Decontamination is effected by washing hard surfaces and deep-ploughing open fields.

** 1 square mile = 2.59 km^2

TABLE 8-5 EARLY CONSEQUENCES OF REACTOR ACCIDENTS FOR VARIOUS PROBABILITIES FOR 100 REACTORS

CHANCE PER YEAR	CONSEQUENCES		
	LATENT CANCER[b] FATALITIES (PER YEAR)	THYROID NODULES[b] (PER YEAR)	GENETIC EFFECTS[c] (PER YEAR)
One in 200[a]	<1.0	<1.0	<1.0
One in 10 000	170	1400	25
One in 100 000	460	3500	60
One in 1 000 000	860	6000	110
One in 10 000 000	1500	8000	170
Normal Incidence	17000	8000	8000

(a) This is the predicted chance per year of core melt for 100 reactors.

(b) This rate would occur approximately in the 10 to 40 year period after a potential accident.

(c) This rate would apply to the first generation born after the accident. Subsequent generations would experience effects at decreasing rates.

TABLE 8-6 LATER CONSEQUENCES OF REACTOR ACCIDENTS FOR VARIOUS PROBABILITIES FOR 100 REACTORS

TYPE OF EVENT	PROBABILITY OF 100 OR MORE FATALITIES PER YEAR	PROBABILITY OF 1000 OR MORE FATALITIES PER YEAR
Man-Caused		
Airplane Crash	1 in 2	1 in 2000
Fire	1 in 7	1 in 200
Explosion	1 in 16	1 in 120
Toxic Gas	1 in 100	1 in 1000
Natural		
Tornado	1 in 5	very small
Hurricanes	1 in 5	1 in 25
Earthquake	1 in 20	1 in 50
Meteorite Impact	1 in 100 000	1 in 1 000 000
Nuclear Power		
(100 Plants)	1 in 10 000	1 in 1 000 000

TABLE 8-7 PROBABILITIES OF MAJOR MAN-INDUCED AND NATURAL EVENTS (U.S. Population Assumed)

	FRESH	DISCHARGE
Thermal Energy Produced		
(MWh/kgU)	0	176
Gj/kgU)	0	650
U-235 Content (g/kgU)	7.1	2.3
Total Pu Content (g/kgU)	0	3.8
Fissile Pu Content (g/kgU)	0	2.8
Fission Products (g/kgU)	0	7.6

TABLE 8-8 CHARACTERISTICS OF CANDU-PHW FUEL

KINDS OF EFFECTS	RELEVANT DOSE AVERAGED OVER THE POPULATION* (millirem/year)	CASES PER MILLION PEOPLE PER YEAR
FATAL CANCERS		
Population		
Whole body exposure	1.5	0.2
Krypton-85 betas to skin	5	0.5
Iodine-129 to thyroid	0.5	
Occupational		
Whole body exposure	4.2	0.6
Radon to lungs in mines	—	0.05
Partial body, reactor and reprocessing† operations	—	0.1
Total		1.0
HEREDITARY DISEASES		
Population		
Genetically significant dose	0.8	0.15
Occupational		
Genetically significant dose	1.1	0.2
Total		0.35

* Assuming 1kW electrical production per person.

† Reprocessing is not now, nor has any decision been taken for it to be, part of the Canadian nuclear fuel cycles. It is possible, however, that it will be such a component in the long-term future and for this reason has been included in the Table.

TABLE 8-9 CANCERS AND HEREDITARY DISEASES FROM NUCLEAR ENERGY

CARCINOGENIC AGENT	CANCER DEATHS PER YEAR
Asbestos (in combination with cigarette smoking)	≥13,900
Petroleum products	9,100
Chromium (hexavalent compounds)	7,900
Arsenic	7,300
Nickel oxides	7,300
Natural radon (in combination with cigarette smoking)	5,700
Natural background radiation	2,300
Medical and dental X-rays	1,600
Benzene	1,400
*Nuclear power (future maximum)	140
Nuclear power (1975)	0.5
All causes	~370,000

* Assuming 1kW electrical production per person.

TABLE 8-10 TENTATIVE ESTIMATES OF EXPECTED NUMBERS OF FATAL CANCERS ASSOCIATED WITH EXPOSURE TO SPECIFIC AGENTS IN THE U.S.A.
(ASSUMED TOTAL POPULATION 230 MILLION)

ENERGY SOURCE*	TOTAL MAN-YEARS LOST PER MW(e)-YEAR	
Wind	1.2	(0.65-2.3)
Coal	0.8	(0.1-5.7)
Solar (thermal or photovoltaic)	0.6	(0.2-1.9)
Oil	0.4	(0.03-5.3)
Hydro	0.10	(0.08-0.13)
Ocean thermal	0.08	(0.07-0.09)
Nuclear	0.01	(0.005-0.028)
Natural gas	0.007	(0.003-0.016)

Note: Figures in brackets show the range of values determined from various studies.

* Refers to electricity production only.

TABLE 8-11 PRELIMINARY ESTIMATES OF HEALTH HAZARDS OF VARIOUS SOURCES OF ENERGY

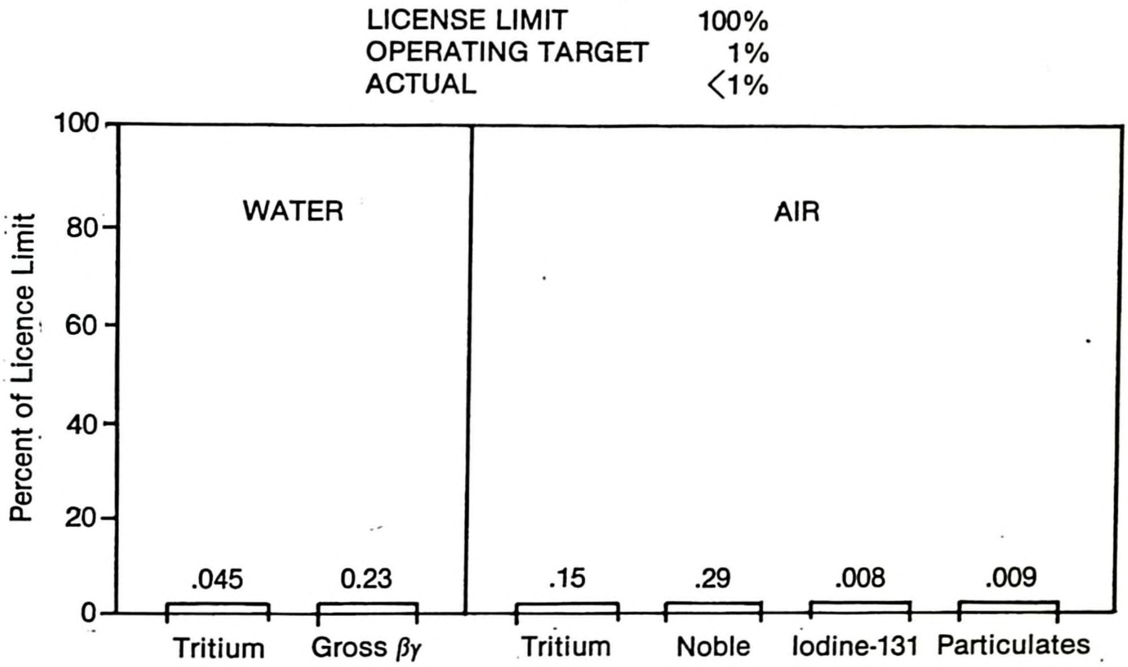


FIGURE 8-1 RADIOACTIVE EMISSIONS 1981: PICKERING A

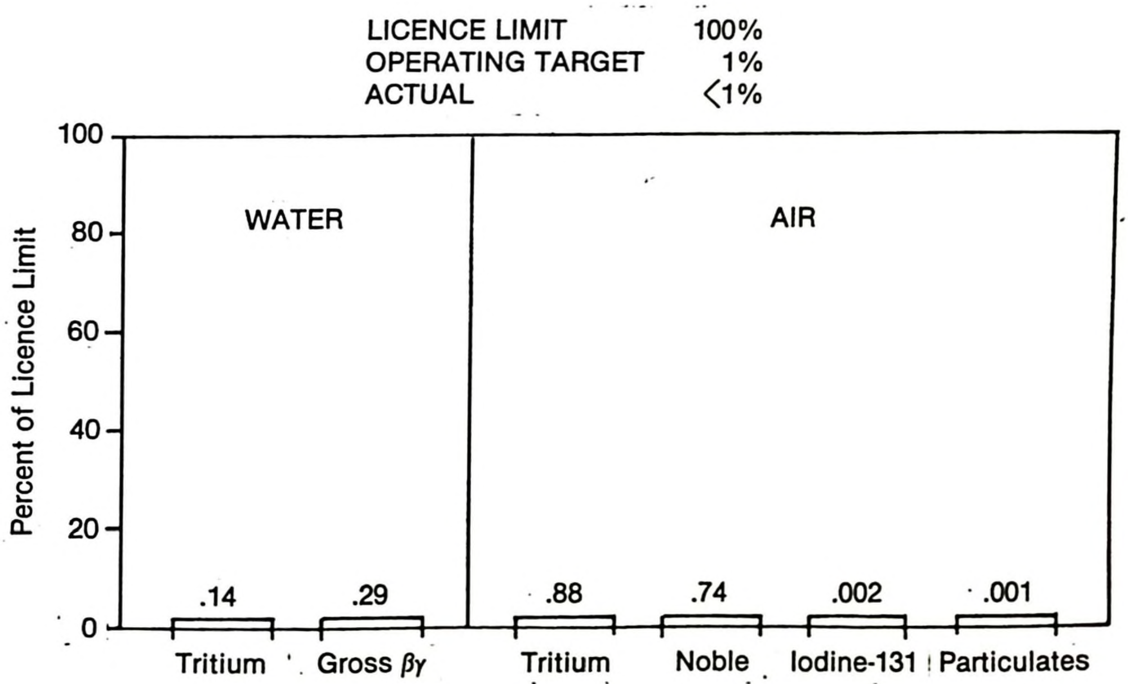


FIGURE 8-2 RADIOACTIVE EMISSIONS 1981: BRUCE A

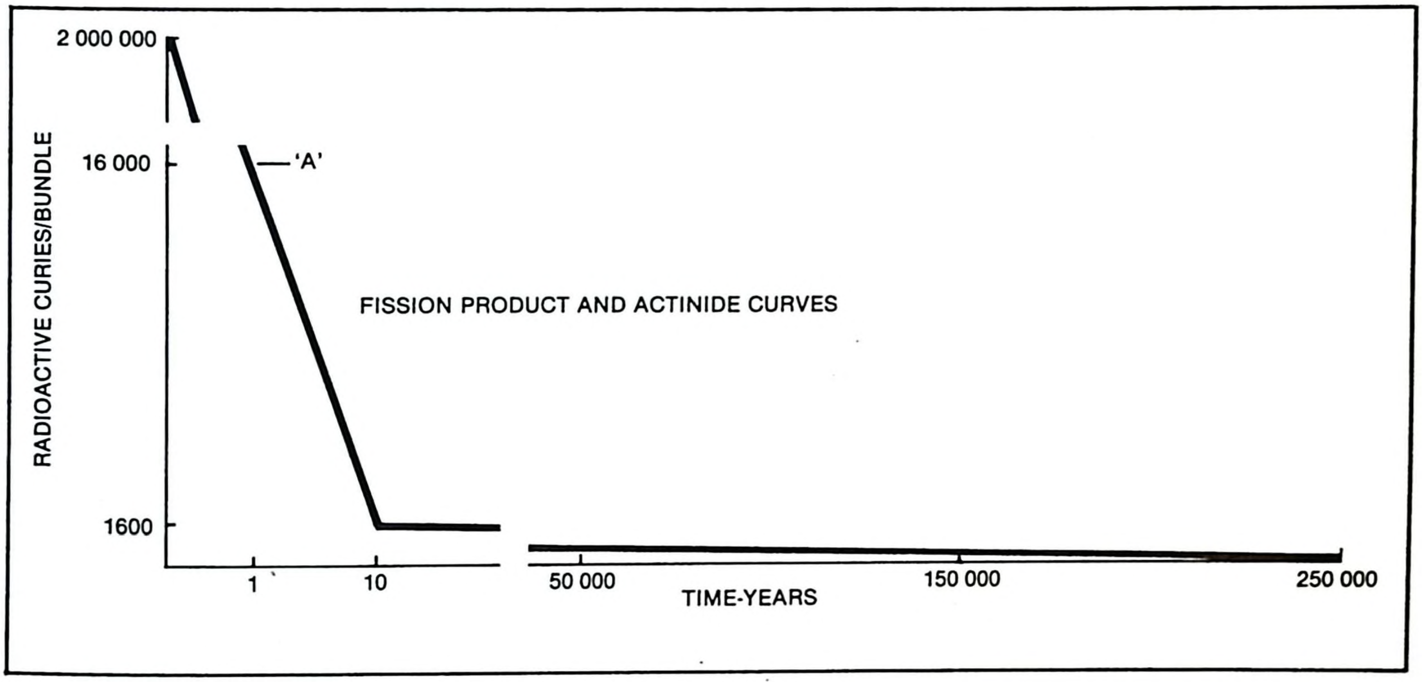


FIGURE 8-3 ILLUSTRATION OF THE CHANGING NATURE OF NUCLEAR WASTES

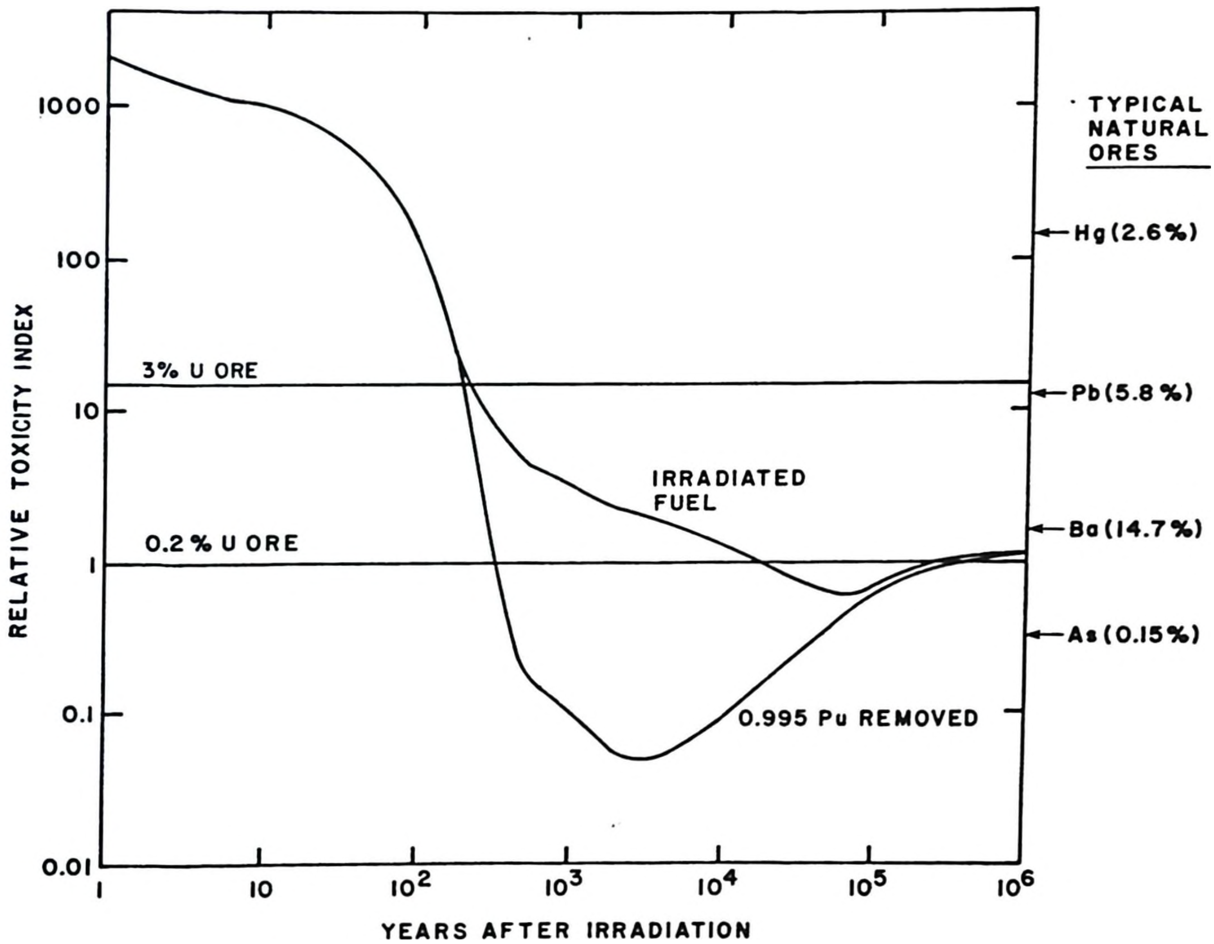


FIGURE 8-4 RELATIVE TOXICITY OF FUEL WASTE AND NATURAL ORES

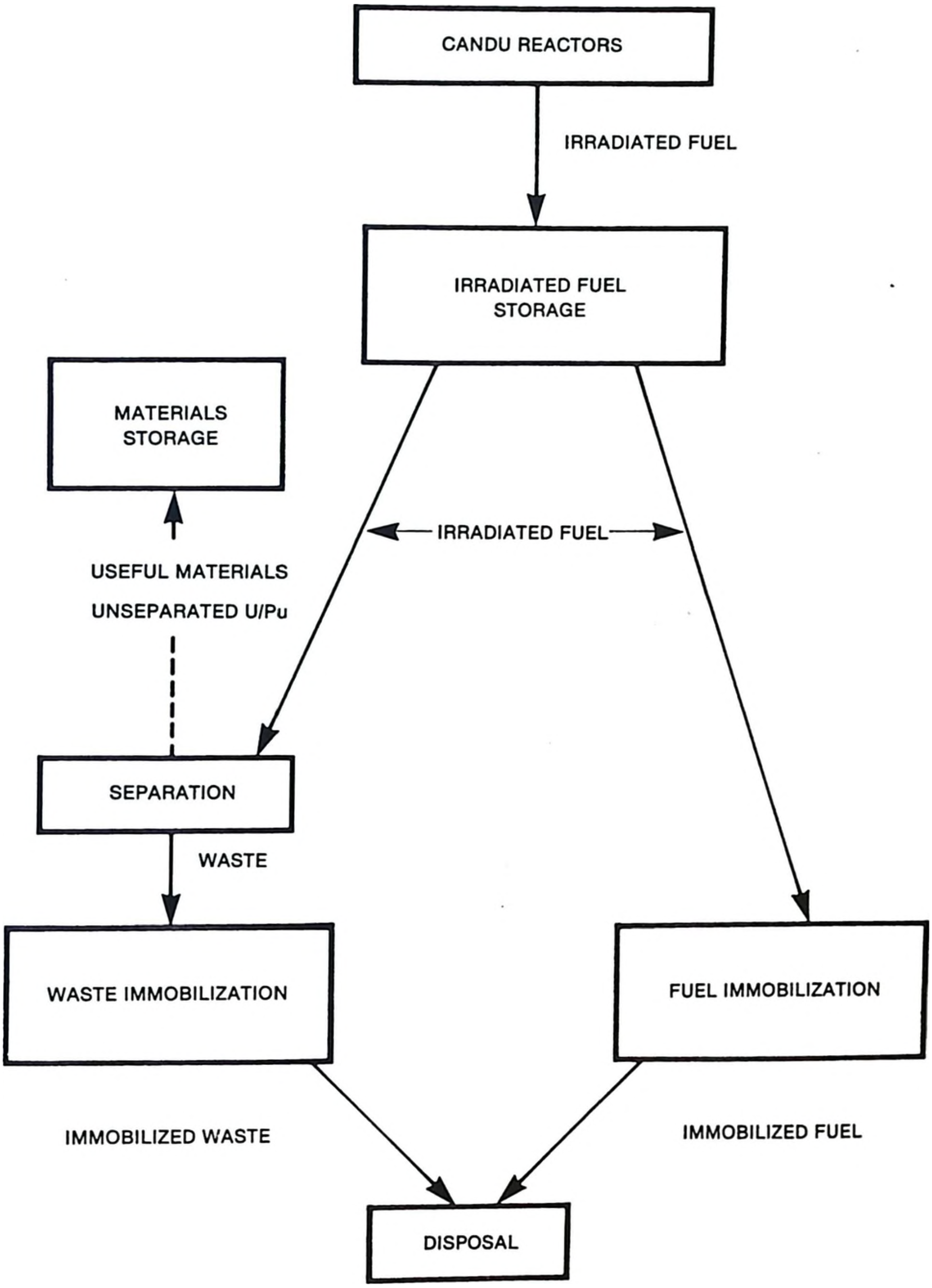


FIGURE 8-5 OPTIONS FOR CLOSING THE CANDU FUEL CYCLE

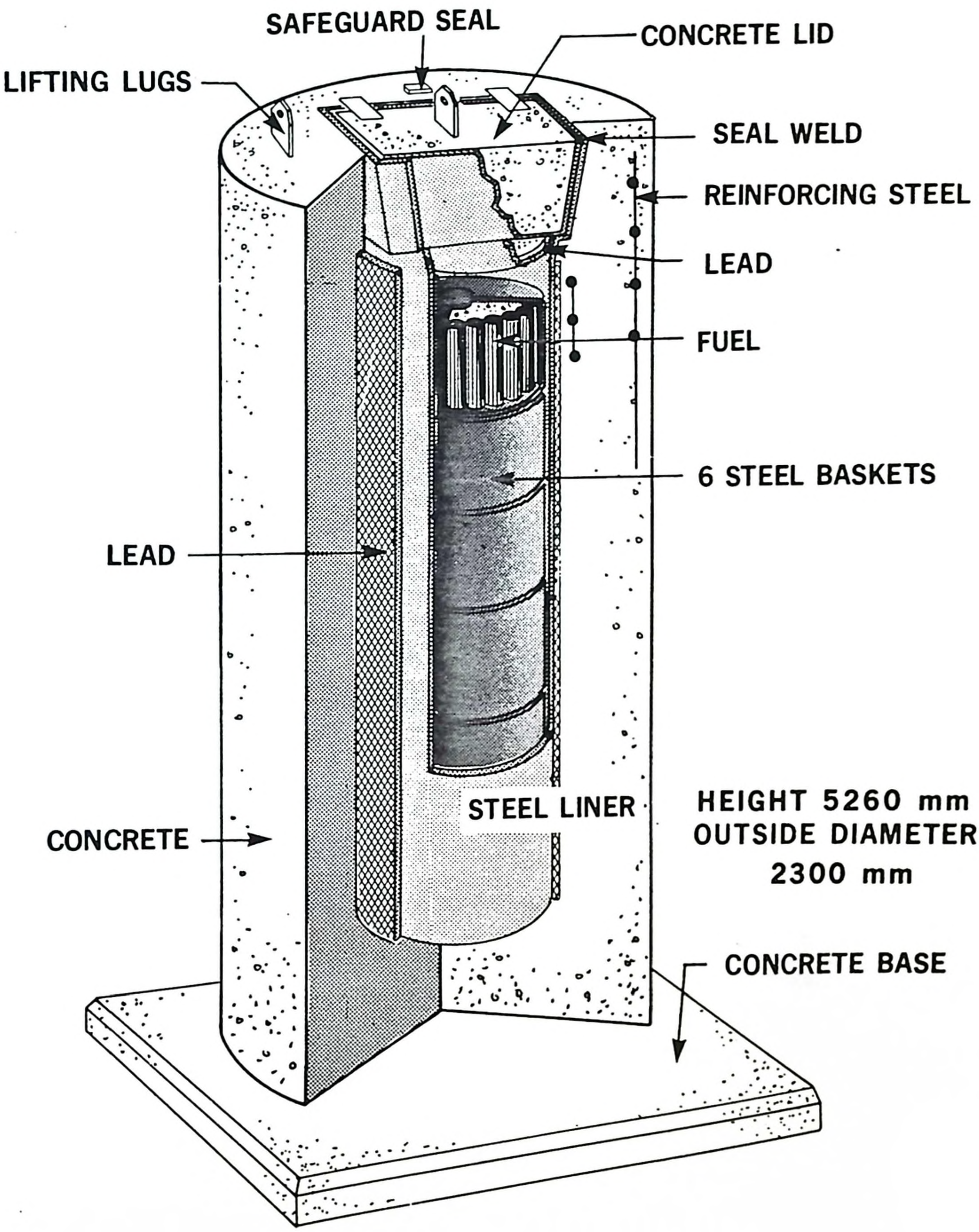


FIGURE 8-6 FUEL STORAGE CANISTER

9.0 THE PUBLIC PERCEPTION OF NUCLEAR POWER AND ITS ROLE IN MARKET DETERMINATION

Nuclear power faces three tests of viability[80]:

i) technical,

ii) economic, and

iii) political.

Today it is primarily for political reasons only that the nuclear power option is forgone, and coal or oil is used instead. Of all modern industries, nuclear power is perhaps the one that stirs the greatest passions between supporters and opponents. It is the industry about which governments of all western democracies are most sensitive. They are sensitive because the public is sensitive, and it is a government's job to create the society that its people want[126].

9.1 The Public Concern Over Nuclear Power

The scientists and engineers developing nuclear power for peaceful purposes must realize that their case has not been presented very well and there is still a degree of genuine concern by the public regarding the safety of nuclear power stations. This concern has virtually stopped the nuclear programs in the U.S.A. and Germany and has slowed development very significantly in most other countries[126]. It is unfortunate that the public fear which is based more on psychological factors rather than quantitative knowledge of the risks[20], should have such an impact on the nuclear industry. However little more can be expected of a society that is fed only sketchy explanations from somewhat less than authoritative sources.

Today the public receives most of its information regarding nuclear power production, from television, newspapers, and magazines. The discussion of many scientific matters is now out of the scientific literature where scientific accuracy and verification is paramount, and into the media where human interest and perhaps even shock value is paramount[107]. In the coverage of nuclear power the dominant issue is fear -- fear of "what if?"; of what "could have happened"; or what "almost happened". The three Mile Island Incident is a classic example of the media's perception of what constitutes news. The Three Mile Island story occupied only one month of the eleven years between 1968 and 1979, but it accounted for 42% of all the network news coverage of nuclear power over that eleven year period[127]. Even the slightest release of radioactivity or the smallest radiation exposure is a big story, even though no one has ever been injured in such minute exposures or is ever expected to suffer delayed health effects from them[89]. Even before the Three Mile Island accident, the New York Times data bank listed the following entries on the number of stories appearing each year[89]:

i) There were 120 motor vehicle accident reports per year, and 50,000 fatalies per year from such accidents in the U.S.A.

ii) There were 50 industrial accident reports per year, and 12,000 fatalities per year from such accidents in the U.S.A.

iii) There were 25 asphyxiation and suffocation reports per year, and 4500 fatalities per year from accidents in the U.S.A.

iv) There were one or two electrocution reports per year, and 1200 fatalities per year from such accidents in the U.S.A.

v) There were 200 reports per year on radiation leakage, though accidental releases of radiation caused much less than one fatality per year in the U.S.A.

The shear weight of the coverage of radiation hazards tends to build up fears in readers. But it is not soley the fault of the reporters. Again, the Three Mile Island accident provides a relevant example. It was not until the fifth day into the incident that a press room was set up. No technical resource personnel were available to interpret statements and provide reporters with a thorough understanding of the events[(126)]. Journalists were left with the impression that officials were attempting to cover up the truth.

The problem for reporters was that their own inherent fear of the unknown was all they had left to rely on. Nuclear power plants are remote from everyday experience precisely and ironically because of the interest in trying to protect the public from any possible health risk. This isolation prevents the contact and understanding needed to overcome the fear reaction[(127)]. The fact that nuclear power originated -- at least as far as the public is concerned -- with the atomic bomb, leaves the suspicion that vast damage could be caused if, in spite of what scientists say, the whole thing got somehow out of control[126]. The lack of communication and the complex nature of nuclear systems resulted in a great oversensationalization of the event that rapidly spread fear throughout the entire world. The ultimate social cost of this public affairs fiasco in terms of lost public confidence, scared politicians and cancelled or delayed nuclear projects will run into the many billions of dollars, far exceeding the costs of cleaning up the physical damage[128].

To gain political acceptance, nuclear programs will first have to gain public acceptance. Nuclear scientists must respect the arguments and feelings of the opposition. There is a definite need to end the polarization of "we" versus "they". The public needs to get involved in nuclear power in some direct and personal way. (Reactor tours go a long way towards accomplishing this[127].) The nuclear industry must be more articulate in speaking to the public, and must use a language the public understands, not seemingly unintelligible nuclear jargon. All statements made must be strictly accurate and truthful. (Inaccurate and careless statements can cause great trouble when they are brought to light, as is inevitable[126].) By making people aware of the true situation the case for nuclear power will become abundantly clear. And because people today are fearful of nuclear energy they can be recruited to learn. They care enough to pay attention[127].

9.2 CANDU: An International Competitor

While admittedly, there is no magic solution to obtain public acceptance of nuclear power, and though much more work and effort must go into defending the program, there is every indication that rational objective people will eventually realize that nuclear power programs are safe, and indeed the best way of obtaining the energy our world needs. The nuclear industry slowdown caused by the current public debate will soon end. The facts have been laid out. The good record of the nuclear industry in the areas of performance, safety and environmental considerations, all assist to create a climate that permits an accelerated nuclear power development program, and the CANDU-PHW reactor system will be a top contender, though the competition will be intense.

9.3 The World Market For CANDU Reactors

Offshore customers who are used to looking to countries other than Canada for industrial and technological leadership will have to come to realize that in the case of nuclear reactors, the situation is different. A significant part of the Canadian selling job must be concentrated on efforts to convince other countries that Canada possesses the technological capability and industrial depth to support a large program of major nuclear works[(129)].

Many nations today are under the impression that the commitment to Light Water Reactors is so large that they cannot fail to perform to predictions. This has been seized upon and exploited by suppliers[(129)]. But contrary to the impressions conveyed by the press and the Light Water Reactor manufacturers, there are many countries adopting Heavy Water

Reactor programs. Although Italy and Japan are buying Light Water Reactors at the moment, the only thermal reactor concept they are developing as national programs is the heavy water approach[49]. Romania, Korea, the United Kingdom, Germany, India, Pakistan and Argentina are all excercising the heavy water option[49], as well as Belgium, Holland, Sweden, Switzerland[69], and even the U.S.S.R.[130]. Countries such as Australia, Turkey, Yugoslavia[49], and Mexico, are also showing strong interest in the concept.

Canada, with its CANDU-PHW reactors, has a commercially proven heavy water system that can suit the needs of any developed or developing country.

The rapidly industrializing oil-depleted world is looking to the nuclear industry to temper its energy woes. Even major oil exporting nations such as Arabia and Mexico have shown interest in the CANDU-PHW system. These oil-exporting countries are looking seriously at nuclear power both as a vehicle through which to bolster and deepen their nations' industrial structure (through technology transfer), and as importantly perhaps, as a mechanism through which to put petroleum revenues to work to assure domestic and indigenous energy balances when the oil bonanza runs out[131].

In the CANDU reactor, Canada has a technically and economically competitive system which continues to demonstrate its capability. Other countries around the world, by purchasing CANDU reactors, can benefit from a reactor system that leads all others in its service record, no matter whose analyses one takes as the basis for such a claim[(7)].

There are many countries in the world with industrial capabilities similar to Canada's, and this is one of the reasons for the wide interest in the CANDU system for other national energy programs[(132)]. CANDU reactors are relatively uncomplicated, in that nuclear industries in different countries can readily assimilate the system concept[(7)]. A large proportion of the components required for reactor construction can be built in any country with a moderately equipped manufacturing capability requiring only a modest capital outlay for specialized manufacturing equipment[(39)].

Participation by national industries is essential in order to keep foreign exchange requirements as low as possible. The CANDU system and its design strategy are geared to handle the redesign requirements that may be necessary to ensure sufficient customer-country involvement without sacrificing performance or safety[(133)].

The first CANDU reactor purchased by a developing country would probably not have a very large fraction of its components built domestically. The first unit built by a developing country would require the country to purchase about 80% of the equipment from abroad[(134)]. As domestic development increases, sparked by the industrial involvement in the manufacture of the first reactor, the foreign exchange requirements for subsequent reactors will drop considerably[(134)], but probably not completely. Canada still imports about 15% of its reactor components[132].

Fuelling costs are a second, but just as important, foreign exchange requirement in reactor purchasing, that must be considered by a customer country. The natural uranium-dioxide CANDU fuel can be easily produced domestically using a country's indigenous uranium supplies. Alternatively the fuel can be purchased from abroad. Consider Tables 7-7 and 7-8. If a country is going to have to import fuel for electricity production, it would like to import fuel with the lowest cost per unit electricity output. This keeps foreign exchange requirements during operation down to a minimum, and it also would mean that once the production of electricity has begun, inflationary fuel price escalations will not be felt as severely by the operating country. From Tables 7-7 and 7-8 it can indeed be seen that CANDU-PHW reactors have the lowest Fuelling Unit Energy Costs and hence best suit the purchaser in this important economic aspect of reactor costing. The price of the final electrical output can be known quite accurately beforehand.

Light Water Reactors have distinct disadvantages to developing countries. They require the use of large high-strength pressure vessels which are beyond the industrial capability of most countries in the world. They also require the use of enriched fuel. Such enrichment facilities are very expensive and so customers are usually pressured economically into purchasing their fuel from abroad. And once the spent fuel is withdrawn from the reactor, expensive fuel reprocessing must be done. This too is often carried out by the same country that sells the reactors, but these selling countries are being pressured politically by public interest groups to refuse to accept spent fuel from abroad. If the pressures succeed in prohibiting the selling countries from accepting spent fuel from the purchasing countries, the purchasing countries would be forced to handle the nuclear wastes themselves. The fissile components of the wastes must be extracted from the LWR fuel in order to make the LWR system competitive. A country may not be prepared to engage in such activities.

Some nations are accepting Light Water Reactors as interim reactors as they await the coming of the Fast Breeder Reactor. Fast Breeder Reactors are, however, extremely high technology machines, and hence a developing country cannot expect to be involved in the manufacture of a significant portion of the components. Further, reprocessing of spent fuel is also required in such a technology. This could be somewhat dangerous for the workers involved, considering it has been suggested that FBRs will produce seven to ten times more long lived alpha-particle emitting nuclear wastes per unit energy than a thermal reactor does[135].

CANDU reactors are being developed and built as reactor systems in their own right. They shall advance and grow, exploiting modern technology and using diverse sources of fuel as economics and supply dictate.

Nuclear industries employing CANDU reactors can evolve along with the system without being forced into a convulsive change in technology that would indeed be necessary if they were to switch from

LWRs to FBRs. Hence a country can rely on its previous experience to increase the reliability of its new systems, and be confident in the knowledge that the CANDU system is open to a wide range of fuel cycles and hence fuel supply should not be a problem.

9.4 The Domestic Market For CANDU Reactors

Electricity, from hydro and nuclear sources, is the most appropriate form of energy for the two main energy concerns of the Canadian Government: energy self-sufficiency and Canadian ownership[132]. As the optimal hydro sources become fully utilized, Canada will turn more to nuclear power to meet its increasing energy demands. Each CANDU reactor under construction today in Canada is 85% Canadian made[132], and currently the Canadian nuclear industry directly and indirectly (including uranium mining) employs over 30,000 people[20].

Thirty-five per cent of the electricity used in Ontario comes from nuclear reactor sources. Quebec and New Brunswick are also entering into the nuclear energy business.

Studies have shown that steam from nuclear plants may be the most economical method of extracting the heavy oil from the Alberta tar-sands[136]. Precious fossil fuel resources can be saved for pharmaceutical and synthetic material production, and for use in transportation. Evenutally, too, electric vehicles with batteries charged by nuclear-generated electricity, and vehicles fuelled with hydrogen which was separated from water using nuclear-generated electricity, will revolutionize the transportation industry world-wide, further decreasing the world's economic dependence on oil. Nuclear generated process steam for industrial applications will also become important in Canada[41], with wide interest in its use in the pulp-and-paper industry[137]. The use of waste heat to warm green houses[138] will lead eventually to the use of fluids warmed by nuclear heat to provide district heating for entire cities[139]. This could save an average Canadian town of 70,000 people about two million barrels of oil each year[13]. (The advantage of sending heat rather than electricity is that it avoids the loss of about 70% of the energy, in the transfer of the heat into electricity by the generators.) In fact, since electricity will continue to be provided from the reactors, it will only be necessary to use the waste heat from the reactors for district heating purposes, thereby receiving the energy without burning additional uranium specifically for the purpose of heating. The hot fluid distribution costs, however, would be higher than electricity distribution costs, and a large scale operation would be required from the very beginning to ensure economic viability[139], but the process will undoubtedly open new markets for nuclear energy in the future.

9.5 Closing Remarks

The prospects for the future of the Canadian nuclear industry are indeed promising. The CANDU system has provided a proven, safe and efficient means of making a very needed contribution to electricity supply, while strengthening the economy through the deployment of indigenous resources and technology[20]. At home, and internationally, CANDU reactors will come to play ever-increasingly important roles. To quote the president of AECL, Mr. James Donnelly[7],

"We are fighting in a highly competitive environment, but with a product that is second to none, and a strong technical base to support it, we can achieve success."

Finally, energy resources are a measure of knowledge in all of its manifestations[4], and the good Lord willing, man shall continue to learn. For it is only with knowledge that peace will reign on Earth. And it is only in peace that man will have truly succeeded in his role in controlling his chosen destiny.

GLOSSARY

ACTINIDES: Heavy atoms in the range from those with atomic number 89 (actinium) to those with atomic number 103 (lawrencium). In the context of this report, "ACTINIDES" refers to those isotopes with atomic number larger than 92 (uranium). Most are long lived alpha-particle emitters.

AGR: Advanced Gas-Cooled Reactor (pressure vessel type).

ALPHA-PARTICLE: A positively charged helium-4 nucleus emitted in radioactive decay. Alpha-emitters are dangerous when taken internally.

BASE LOAD: Round-the-clock electrical demands that must be met by a utility. As opposed to peak demand which is an increase over base load that occurs at certain times during a day or season.

BETA-PARTICLE: An electron or position emitted in the decay of some radioactive nuclei.

BLW: Boiling Light Water Reactor (pressure tube type)

BWR:	Boiling Water Reactor (pressure vessel type).
CANDU-BLW:	A CANDU reactor with boiling light water coolant.
CANDU-OCR:	A CANDU reactor with an organic liquid coolant.
CAPABILITY FACTOR:	A way to determine reactor performance capability. It is equal to the amount of electricity that a reactor COULD actually deliver during a certain time period, divided by the amount that could be delivered during a perfect production period. NET CAPABILITY FACTOR refers to electrical output sent to the utility's electrical grid, while GROSS CAPABILITY FACTOR refers to electrical output sent to the grid plus electrical output used by the plant itself. The INCAPABILITY FACTOR is defined as [1 - (CAPABILITY FACTOR)].
CAPACITY FACTOR:	Similar to CAPABILITY FACTOR, except rather than considering the amount of energy that COULD be produced, the CAPACITY FACTOR is equal to the ACTUAL energy produced divided by the amount of energy that could be delivered during a perfect production period. NET and GROSS CAPACITY FACTORS are defined similarly.
ENRICHED URANIUM:	Uranium with an artifically boosted concentration of fissile uranium-235.

FBR: Fast Breeder Reactor.

FERTILE MATERIAL: Material that will become fissile upon the absorption of a neutron (eg. U-238, Th-232).

FISSILE MATERIAL: Material that will undergo fission upon the absorption of a neutron that has a very low speed (eg. U-235, U-233, Pu-239).

FISSION: The splitting of a nucleus either spontaneously or neutron-induced.

FISSION PRODUCTS: Atoms produced in fission. The "chunks" that are left once a heavy atom undergoes a fission event.

GAMMA RADIATION: High energy light rays emitted during the fission process and as a result of some radioactive decays.

HALF-LIFE: The time in which half the atoms of a material decay radioactively. This can range from millionths of a second to billions of years.

H.E.: Heavy Element. (Uranium, plutonium, thorium, etc.)

HEAVY WATER: Deuterium oxide. (D_2O where D is a proton-neutron pair.)

ISOTOPE:	Atoms of an element having the same number of protons and neutrons in its nucleus. Different isotopes of the same element cannot be separated chemically.
kWh:	Unit of energy derived from operating at one kilowatt for one hour.
LWR:	Light Water Reactor (pressure vessel type).
LIGHT WATER:	Ordinary water (with 0.0145% heavy water by weight)[(31)].
MW(e):	Unit of electrical power equal to one thousand kilowatts or one million Joules per second.
MW(e)-d:	Unit of electrical energy derived from a system operating at one megawatt for one day.
OCR:	Organically-Cooled Reactor (pressure tube type).
OM & A:	Operations, Maintenance, and Administration.
PHW:	Pressurize Heavy Water Reactor (pressure tube type).
PWR:	Pressurized Light Water Reactor (pressure vessel type).
RAD:	A unit of absorbed radiation energy dose per gram. 1 rad = 100 ergs per gram (1 Gray = 100 rads).

REACTIVITY: Net number of neutrons produced per neutron born in fission. Neutron absorbing materials such as stainless steel, boron and xenon cause the reactivity (and power) to fall in a reactor. REACTIVITY WORTH of a device is defined as the reactivity of the reactor after the device is inserted into the reactor, minus the reactivity before insertion and is often quote in units of milli-k, which is the reactivity multiplied by 1000.

REM: Rad times a quality factor. For each rem whole body radiation received, the average person (averaged over all ages and both sexes) increases his or her chances of receiving a fatal cancer by 1 in 10,000. The naturally occurring cancer rate is one in five. Hence a rem of whole body radiation is not very significant. (1 Sievert = 100 rems.)

TUEC: Total Unit Energy Cost. The cost that a utility incurs to produce its electrical output for public utilization.

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