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ABSTRACT

Educators must address the need for young people to be informed about both the scientific concepts and the reasons for controversy when dealing with controversial issues. Young people must be given the opportunity to form their own opinions when presented with evidence for conflicting arguments. Previous editions of "Nuclear Electricity" have provided helpful data and references about nuclear energy as well as the production of electrical energy from other sources. This book maintains the educational philosophy of previous editions while providing much more recent data and references. Most importantly it retains the challenge for everyone, especially young people, to be as open-minded and well-informed as possible. Chapters focus on energy use; electricity; nuclear power; the front and back end of the nuclear fuel cycle; environment, health, and safety issues; and avoiding weapons proliferation. (Contains 14 references.) (ASK)

nuclear electricity

5TH EDITION

Student Activities Included

Ian Hore-Lacy

Uranium Information Centre
Minerals Council of Australia
Canadian Nuclear Association

ABOUT THE AUTHOR(S)

Ian Hore-Lacy MSc FACE, a former biology teacher, became General Manager of the Uranium Information Centre in 1995. He has visited a number of nuclear reactors and fuel cycle facilities in several countries, including UK reprocessing plants, Sweden's waste facilities and French enrichment and mixed oxide fuel fabrication plants.

He joined the mining industry as an environmental scientist in 1974 and gained some acquaintance with uranium mining. From 1988-93 he was Manager, Education and Environment with CRA Limited and has written several books on environmental and mining topics. He has had continuing involvement with the Australian Science Teachers' Association and in 1992 he received an ASTA Distinguished Service award. Also in 1992 he was admitted as a Fellow of the Australian College of Education.

His particular interests range from the technical to the ethical and theological aspects of mineral resources and their use, especially nuclear power. He has four children.

Earlier editions of this book owed their substance to Ron Hubery as co-author. Ron is a chemical engineer, now retired, who spent eight years working with the Australian Atomic Energy Commission (now ANSTO) on nuclear fuel cycles and reprocessing. He also worked at the uranium production centres of Rum Jungle and Mary Kathleen in Australia.

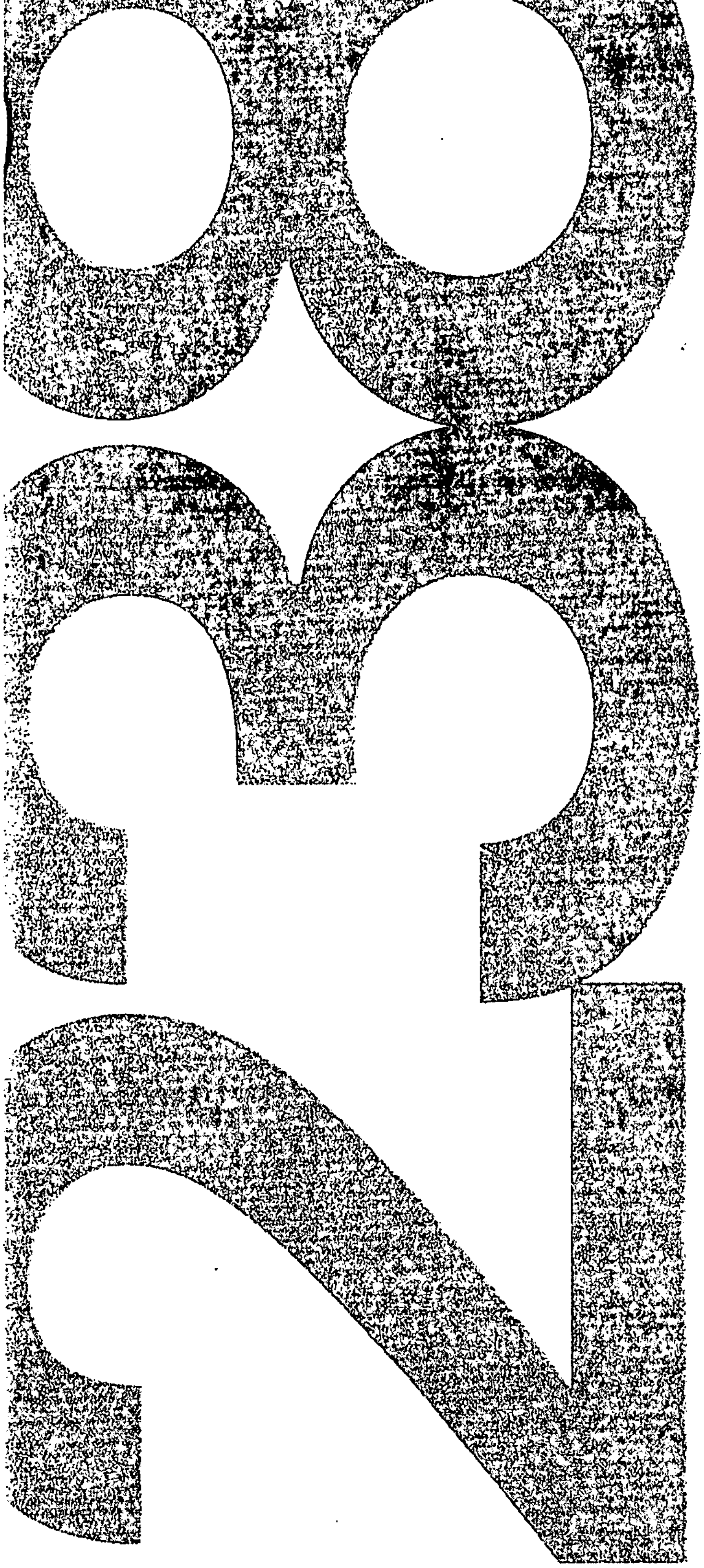
ACKNOWLEDGMENT

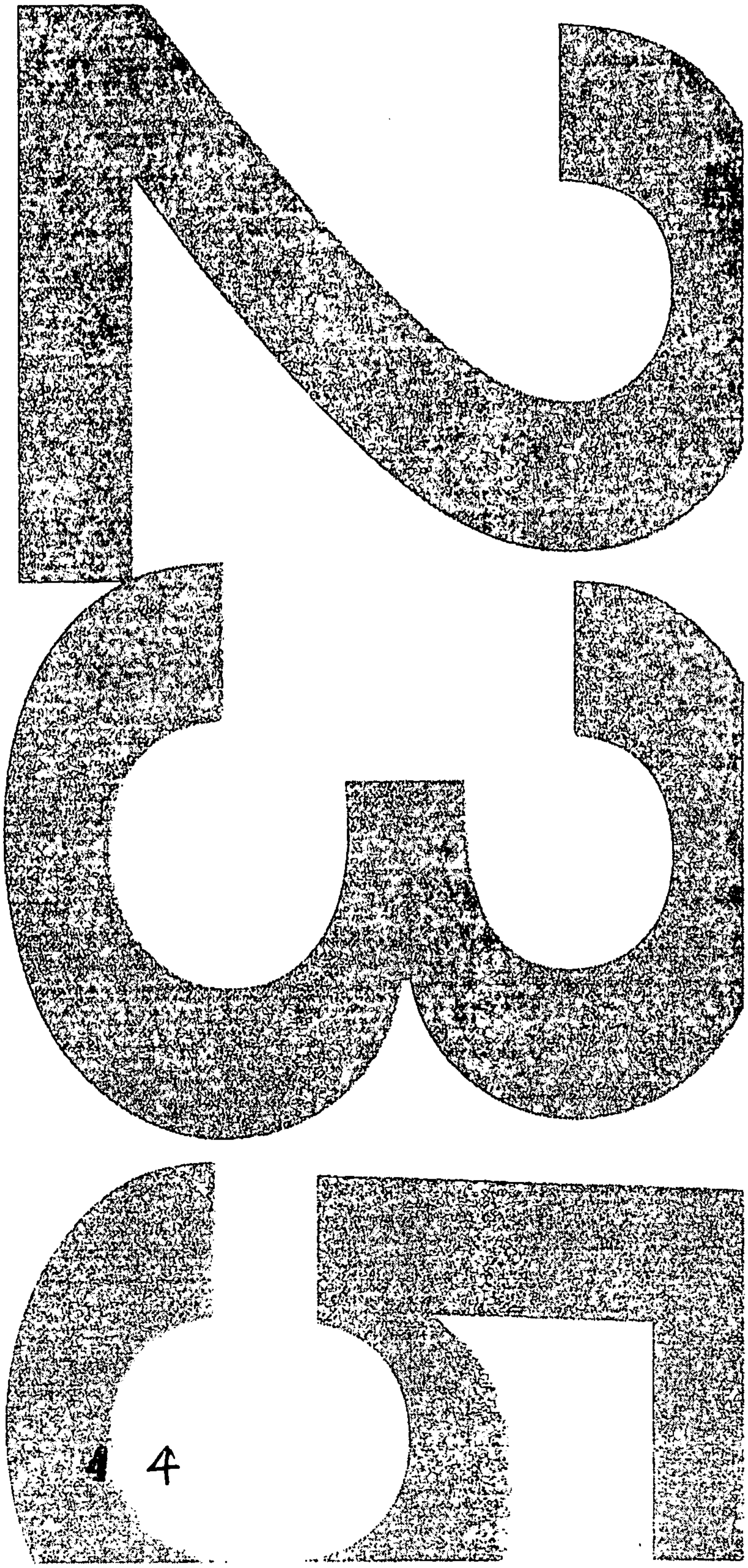
The 4th and 5th editions incorporate considerable input from staff at Atomic Energy of Canada Limited, who have greatly assisted the development of a broader perspective on the subject and in the rewriting of several chapters. Deborah Blackstone co-ordinated this AECL liaison. Many others have also helped check particular sections of the book, and have made a major contribution to ensuring its accuracy and completeness. I am very grateful for all such assistance both in relation to this text and, more broadly, in the functioning of the Uranium Information Centre.

Ian Hore-Lacy

nuclear electricity

5TH EDITION





Ian Hore-Lacy

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FOREWORD

NUCLEAR ELECTRICITY

AN AUSTRALIAN PERSPECTIVE

A hundred years ago the decisions that had to be made by responsible citizens were comparatively straightforward. Since then many factors, including the increased use of technology and the size of the world population, have made our lives much more complicated.

Decisions in relation to the production and use of energy need to be based on and to take into account the scientific facts and the social interactions and consequences which are more difficult to define or predict.

Educators must address the need for our young people to be informed about both the scientific concepts and reasons for controversy when dealing with controversial issues. They must be given the opportunity to form their own opinions when presented with evidence for conflicting arguments.

Previous editions of Nuclear Electricity have provided helpful data and references about nuclear energy, and also about the production of electrical energy from other sources. As we have become increasingly aware of the problems associated with producing electrical energy from alternative sources, we have been made much more conscious of the impact of all human activities on the environment.

Nuclear Electricity maintains the educational philosophy of previous editions as well as providing much more recent data and references. Most importantly it retains the challenge for everyone, especially young people, to be as open-minded and well informed as possible. It is only by taking on this challenge that future generations will be able to do a better job than past generations in looking after themselves and their environment.

Debra Smith
Past President
Australian Science Teachers' Association

INTRODUCTION

The context

Uranium's only substantial non-weapons use is to power nuclear reactors. There are some 1100 nuclear reactors operating today around the world. These include:

- about 280 small reactors, used for research and for producing isotopes for medicine and industry,*
- over 400 small reactors powering ships, mostly submarines,
- over 430 larger reactors generating electricity. Canada has 21 commercial power reactors which have supplied up to 18 percent of its electricity (some of these also produce cobalt-60 for medical and industrial use).

Practically all of the uranium produced today goes into electricity production, (though a significant small proportion is used for producing radioisotopes). In particular, uranium is generally used for base-load electricity. Here it competes with coal, and in recent years, natural gas.

Over the last 40 years nuclear energy has become a major source of the world's electricity. It now provides 17 percent of the world's total, equivalent to thirteen times Australia's total electricity production or five times that of Canada. It has the potential to contribute much more, especially if greenhouse concerns lead to a change in the relative economic advantage of nuclear electricity or its ethical desirability. Australian and Canadian uranium is needed to fuel some of this electricity generation.

> *The uranium debate is about options for producing electricity. None of those options are without some risk or side effects.*

Since the first edition of this book in 1978 many of the inflated expectations of alternative energy sources have been shown to be unrealistic, (as have some of those for nuclear energy). However, it is important that this return to reality does not lead to their neglect, such alternatives should continue to be investigated, and applied where they are appropriate. In particular a great deal can be achieved by matching the location, scale and thermodynamic character of energy sources to particular energy needs. Such action should be a higher priority than merely expanding capacity to supply high-grade electrical energy where for example only low-grade heat is required.

But when the question of utilising nuclear energy arises there are those who wish somehow to put the genie back in the bottle and to return to some pre-nuclear innocence. Such notions seem to achieve undue prominence in Australia because there is no actual utilisation of nuclear power. Australia is probably the only developed country where, when you switch on the light, you are not getting some nuclear electricity to help lighten your way.

To labour that point a little: France gets over 75 percent of its electricity from nuclear power. It is the world's largest electricity exporter, and gains some A$ 4.6 billion per year from those exports. Next door is Italy, a major industrial country without any operating nuclear power plants. It is the world's largest net importer of electricity, and most of that comes ultimately from France.

All Australian and Canadian uranium is sold for peaceful applications, predominantly electricity production, none goes into weapons; this is assured by comprehensive international safeguards arrangements.

I anticipate that my children's, or perhaps my grandchildren's generation will come to look upon weapons as simply an initial aberration of the nuclear age, rather than a major characteristic of it. Arguably the same is true of the bronze and iron ages.

The book

Considerable effort has been made to include as much up to date and pertinent information as possible on generating electricity from nuclear energy. The figures quoted are conservative, and generalisations are intended to withstand rigorous scrutiny. The reader will not see many of the frequently repeated assertions from supporters or opponents of nuclear energy. This book does not enter into debate on social issues.

Since the first edition, the intention has been to get behind the controversies and selective arguments to present facts about energy demand and how it is met.

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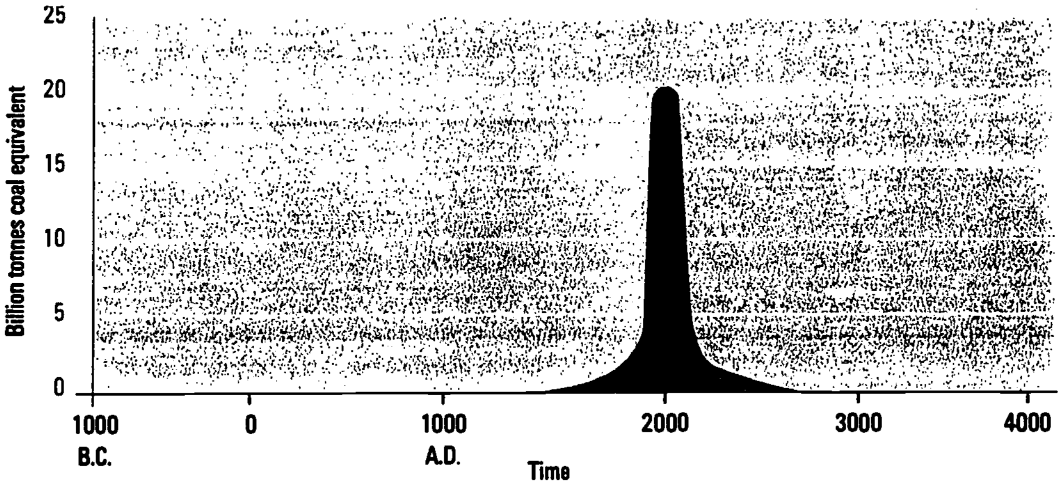
* Australia has only one research reactor operating and due to be replaced by 2005. Canada has several small research reactors at universities, as well as one large one. Canada also has two small reactors designed for isotope production under construction.

Consumption of fossil fuels



in part, by nuclear power. The text has been thoroughly checked by experts who carry public responsibility for their professional roles in their area of expertise.

Every form of energy production and conversion has an effect on the environment and carries risks. Nuclear energy has its challenges but these are frequently misunderstood and often overstated. Nuclear energy remains a safe, reliable, and economical source of electricity.

The fourth edition was published as a joint Australian and Canadian initiative for schools and the public. This 5th edition also comes out at a time when some environmental leaders are saying that it is time to have a fresh look at nuclear power. This desire is driven by increasing evidence of the contribution to global warming from burning fossil fuels, and is notwithstanding the 1986 Chernobyl disaster.

The introduction to the first edition of this book in the 1970s expressed the opinion that if more effort were put into improving the safety and effectiveness of commercial nuclear power, and correspondingly less into ideological battles with those who wished it had never been invented, then the world would be much better off. With Chernobyl behind us and the great improvements to safety in those plants which most needed it, plus the welcome recycling of military uranium into making electricity, it seems that we are now closer to that state of affairs.

Further information

All the matters covered in this book can be explored in more detail. One convenient way of doing so is by accessing the Uranium Information Centre's Web site: **http://www.uic.com.au**

In particular, this has a range of Briefing Papers on specific topics, as well as links to other Web sites with reliable information.

ENERGY USE

All energy is derived ultimately from the sun or from the elemental matter which comprises both the sun and the earth.

The sun warms our planet, and provides the light required for plants to grow. In past geological ages the sun provided the same kind of energy inputs. Its energy was incorporated into the particular plant and animal life from which were derived today's coal, oil and natural gas deposits - the all-important fossil fuels on which our civilisation depends.

The only other ultimate energy source is from the atoms of particular elements formed before the solar system itself and found today in the earth's crust*.

The amount of energy per unit mass of an atom is dependant on the size of the atom: The minimum amount of energy per unit mass is contained within the medium sized atoms (such as carbon and oxygen), while the greatest amount is contained in small atoms (such as hydrogen) or large atoms (such as uranium). Energy can therefore be released by combining small atoms to produce medium sized atoms (fusion) or by splitting large atoms to produce medium sized atoms (fission).

The tapping of this energy by nuclear fission or by nuclear fusion is one of the most important and contentious human achievements in history.

Much has been written since the early 1970s about the impending "world energy crisis", which was initially perceived as an oil supply crisis. The Figure opposite suggests the vital importance of conserving fossil fuel resources for future generations. While since the early 1970s the pressure has been to conserve crude oil supplies, in 50 years or so it will be to reduce burning of all fossil fuels and to conserve coal. In that time coal will have taken over some of the roles of oil today, especially as a chemical feedstock.

The importance of energy conservation is obvious, even in areas where so far fuels have been relatively cheap. The levelling-out of overall energy demand in developed countries over the last decade is a result of increased energy efficiency. However, in developing countries growth in energy demand from a low starting point continually increases the pressures on resources world-wide, despite conservation initiatives.

Many people in developing nations aspire to the standard of living, agricultural productivity and industrialisation characteristic of the developed countries. Fulfilling these hopes depends on the availability of abundant energy. Growth of the world's population from the 1996 level of slightly under 6 billion people to a projected 8 billion in 2020, mostly in today's developing nations, increases the challenge.

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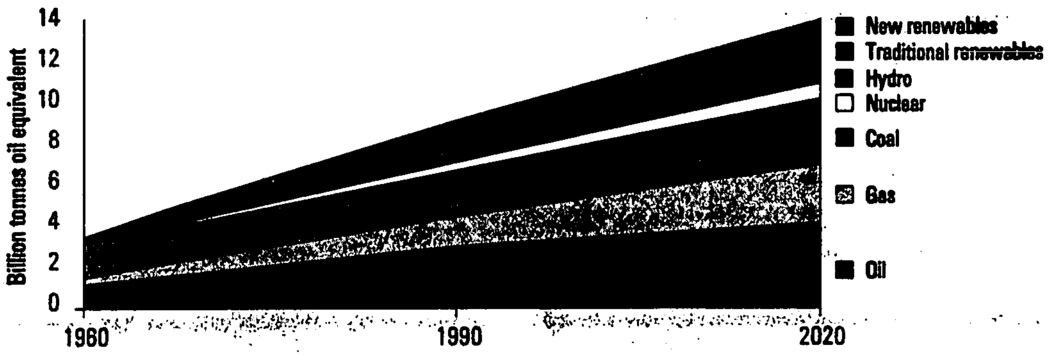
* Uranium appears to have been formed in super novae some 6.5 billion years ago, and though not common in the solar system has been concentrated in the earth's crust at an average of c1.4ppm. Heat from the radioactive decay of this uranium today drives the convection processes in the earth's mantle, and is thus vital to life.

Figure 1 World energy demand and mix



Source: World Energy Council 1993, projection to 2020 is Reference Case (total: 13.4 Gtoe, compared with Modified Reference 16.0 Gtoe, High Growth 17.2 Gtoe and Ecologically-driven 11.3 Gtoe cases)
See also Figure 5 re electricity for the Reference Case.

1.2 Energy demand

In industrialised countries energy demand comes from three major sectors:

- domestic and commerce
- industry and agriculture
- transport

In many countries these each account for about one third of the energy demand, although the size of domestic demand depends very much on climate. In Australia domestic demand is relatively small, whereas in Canada for example, it is relatively large because of the cold climate.

More specifically it is possible to identify demand for particular purposes within these sectors, eg

- low temperature heat (up to 110°C) for water and space heating in homes and industry.
- high temperature heat (over 110°C) for industrial processes.
- lighting.
- motive power for factories and appliances.
- mobile transport for public and private use.

For some of these purposes there is a significant demand for energy in the form of electricity. Worldwide, electricity demand is increasing very rapidly, and this is discussed further in section 2.1.

1.3 Energy supply

On the supply side, there are a number of primary energy sources available. These fall into three categories – renewable fuels, non-renewable fuels and renewable natural forces. The sources available in each category are:

Renewable fuels	Non-renewable fuels		Renewable natural forces
Wood and other fuel crops	Coal		Solar heat and light
(limited by availability of land	Gas	Fossil fuels	Wind
and by rate of growth)	Oil		Waves
e.g. for Ethanol/Methanol production	Uranium and thorium (fission)		Tides
	Deuterium-tritium (fusion)*		Rivers (hydro)
			Geothermal heating
			Ocean thermal gradients

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* Although deuterium (heavy hydrogen) would be consumed in a sustained fusion reaction the relatively vast quantities of this material available from sea water make it a virtually limitless resource. For practical purposes it could therefore be classified with the renewable resources. See also 2.4.

Derived from these primary sources are several secondary energy sources, though at this stage only electricity is of major importance. These include, for example:

Electricity can be generated from many primary sources

Hydrogen mainly from electrolysis of water

Alcohols from wood and other plant material

Oil and **gas** manufactured from coal.

Some types of energy demand can be met by more than one kind of energy supply. For instance low temperature heat can be produced from any of the fossil fuels directly, from electricity, or (as is increasingly realised) from the sun's radiant energy. Others such as mobile transport are most readily supplied by portable fuels such as those derived from oil or gas.

Both economic practicality and ethical considerations mean that versatile, easily portable energy sources such as oil and its derivatives are not usually squandered where other, more abundant fuels can be substituted.

Primary energy resources are set out for Australia in Table 2A and for Canada in Table 2B. Australia has large amounts of coal and uranium but apparently much less oil and gas. This situation is reflected in trade of energy resources – importing oil and exporting coal and uranium. Canada has large amounts of uranium, which provides an important export base, along with both coal and gas.

1.4 Changes in Energy Demand and Supply

The world distribution of energy resources means that as energy consumption rises, international trade in energy resources must increase. Energy-poor countries find themselves dependent on supplies from energy-rich countries. Because of the fundamental importance of energy in the industrial economy, these importing countries tend to feel vulnerable politically and economically.

The best illustration of this is the changing position of oil. Until the early 1970s, many countries had come to depend on oil because of its relatively low cost, and world oil production tripled between 1960 and 1973. But this suddenly changed as prices rose four-fold, and then there was a further "oil crisis" in 1979. As a result, world oil consumption in 1986 was the same as that in 1973, despite a substantial rise in total primary energy consumption. Forecasts in 1972 had generally predicted a doubling of oil use in ten years.

Japan for example, has little coal or oil of its own, only limited sunlight in relation to its population and little untapped hydro-electric potential. It suddenly found that escalating oil imports to supply three quarters of its total energy needs were not sustainable. Even the USA, originally self-sufficient in oil, found it difficult to pay for enough imported oil to offset declining domestic production.

Table 1 Electricity Production Terawatt Hours (GWh x1000, or billion kWh)

	1985	1995	10-year Increase
OECD			
North America	3174	4286	35%
Europe	2201	2700	18%
Pacific	820	1200	32%
former USSR	1544	1294	-16%
Africa	265	367	38%
Latin America	397	619	56%
Asia (exc. China)	494	1121	127%
China	411	1008	145%
Middle East	172	327	90%
World	**9831**	**13263**	**35%**

Source: OECD/IEA *Energy Statistics & Balances of non-OECD Countries 1994-95*, Paris 1997. See also Figure 1.

Table 2A Australia's energy situation (Petajoules - 10^{15} Joules)

	Economic Resources (thermal value)	Total Consumption 1995-6	Trade 1995-6
Black Coal	1 303 000	1 273	(plus 3 959 exported)
Brown Coal (Lignite)	399 000	522	
Oil	14 137	1 653	(including 515 net imports)
LPG	3 540	*	(plus 72 net exported)
Natural Gas	38 000	789	(plus 412 exported)
Uranium in light water reactor	335 000	-	(2 484 exported)
Hydro electric		55	
Wood, bagasse, other renewables		203	
	Total	**4 495**	(plus 6 412 net exports)

This excludes the vast amount of solar energy used domestically and industrially (not to mention agriculturally). For instance the Australian salt industry alone uses some 1000 PJ/yr in solar salt production, - equivalent to some two thirds of the nation's oil usage.

* 97 PJ, included in other figures. Thermal values calculated from tables 9 & 10 of ABARE report, except for uranium, Table 3 below.

Sources: *Australian Energy Consumption and Production, historical trends and projections*, ABARE Research Report 1997. Uranium reserves from 1997 OECD "red book", @ 440 GJ/kg.

Problems of oil prices and supply in the 1970s brought about rapid changes in the production and use of other primary energy resources:

- Coal production and international trade in coal increased to substitute for some oil use.
- Nuclear power for electricity generation was adopted or examined more closely by energy-deficient countries.
- All countries looked more closely at adopting measures to restrain energy consumption.
- Renewable energy sources were studied seriously (in some cases for the first time) to determine whether and where they could be used economically.

The thrust of these changes has continued into the 1990s, except that governments became disillusioned with the prospects of many of the renewable energy sources making a significant contribution. Throughout the world it was found possible to use significantly less energy per unit of economic activity. The use of oil for electricity production was greatly reduced and the use of natural gas increased.

Continuing a trend predating the oil crisis, the demand for primary energy per unit of Gross Domestic Product (ie "energy intensity") has shown a significant decline (1.3% per year) in OECD* countries and this is expected to be the case also in developing countries in the future. However, at the same time the electricity consumption per unit of Gross Domestic Product has been increasing steadily, reflecting a strong increase in the proportion of electricity used in all countries.

> ***The role of electricity is increasing because it is an extremely versatile energy source which can be generated from a wide range of fuels and can easily be reticulated to the point of use. At present electricity generation uses 40% of the world's total primary energy supply.***

Electricity is uniquely useful for driving machinery and for lighting in both industry and homes. However, it is also used for heating and in other ways for which alternatives are readily available. It can be argued that in view of the relatively low efficiency of energy conversion to electricity (often 30-35 percent) alternatives such as natural gas should be used wherever possible for heating (at double the efficiency)**. Conversely, it can be argued that uranium and coal resources are large relative to gas resources, that the most abundant primary fuel should be applied wherever possible, and that hence electricity use for heating (at almost 100 percent end use efficiency) is desirable despite a much higher consumption of primary fuel. Most people would agree that the sun is the world's most abundant energy source and would be delighted if it could be applied more widely to direct heating and even, eventually, for large scale generation

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* Organization for Economic Co-operation and Development

** Considering the whole sequence from production to end use, the efficiency of gas and oil for heating is often about 40-45%. For modern high efficiency gas furnaces, the value increases to about 70%, but overall depends on distance from the gas sources.

Table 2B Canada's energy situation (Petajoules - 10^{15} Joules)

		Economic Resources (thermal value)	Total Consumption 1997	Trade 1997
Coal: anthracite & bituminous		120 000	1 203	(690 net export)
Coal: sub-bituminous and lignite		76 000		
Petroleum (incl. Oil Sands)		53 200	3 892	(1 600 net export)
Natural Gas		74 400	2 776	(3 070 net export)
Uranium	in LWR	190 000		(4 500 net export)
	in CANDU	280 000	900	
Hydro electricity			1 123	(130 net export)
Other			587	
		Total	**10 481**	(9 990 net export)

Sources: Sources: NR Can 1998, *Energy Statistics Handbook*: AECL *1996 Summary of Energy, Electricity & Nuclear Data*. Uranium reserves from 1997 OECD "red book", @ 440 TJ/t LWR & 650 TJ/t Candu. Uranium export 10225t x 440 TJ/t.

of electricity. Questions concerned with the production of solar electricity are discussed in 2.4.

In the following chapters electricity demand, use and generation are the focus of discussion. In particular the booklet discusses the use of nuclear energy to generate electricity. The main nuclear fuel concerned is uranium, a metal which at present has virtually no other civil uses. However, before looking at these topics it is important to discuss some likely future trends in overall energy production and use in more detail.

1.5 Future energy demand and supply

Where will we obtain our future energy needs? There are a number of uncertainties:

- oil production peaked in 1979 and did not return to that level until 1994. Production costs have essentially remained unchanged since 1973. Prices depend largely on political factors,
- natural gas production, while increasing rapidly now, is likely to approach its peak in many countries in the next couple of decades,
- underground coal is costly to mine, and all coal use gives rise to concern about global warming,
- there is uncertainty over nuclear programs in many countries,
- there is limited practical experience in the utilisation of renewable energy resources,
- the further scope for energy conservation is limited without radical changes in lifestyle in developed countries, and is minimal in developing countries.

Until the early 1970s the world's energy supplies were easily and cheaply bolstered by oil and natural gas whenever consumption tended to exceed supply. After 1973 however, when serious doubt was thrown on continuing availability of affordable petroleum, many industrialised nations set out to develop other strategies including greater use of nuclear energy.

A solution to the future supply problem based on rapid development of renewable energy sources is impractical. Cost, the level of current technological development, and the diffuse and intermittent nature of these sources limit their potential.

In spite of all these uncertainties energy planners still have to provide for future needs. To do this they base their plans on projections of population growth, economic and social development, and availability of resources (which relates to their prices).

World energy consumption has been rising steadily for many decades. Even with the temporary effect of higher oil prices after 1973 and the resulting economic recession, the world continues to use more energy each year and can be expected to do so for some time to come. While the rate of increase is never again likely to be as high as prior to 1973, it is clear that economic growth occurs in most nations and that some increase in energy demand is an inescapable part of this growth. Also, growth of the world's population is expected to continue towards 8 billion by 2020, further increasing the demand for energy. There is also a rapidly increasing demand for potable water in many developing areas (for example, North Africa and the

Table 3 Energy conversion: The heat values and carbon coefficients of various fuels

	heat value		% carbon	CO_2
Crude Oil	45-46	MJ/kg	89	70-73 g/MJ
	37-39	MJ/L		
LPG	49	MJ/kg	81	59 g/MJ
Natural Gas	38-39	MJ/m^3	76	51 g/MJ
Black Coal				
(NSW & Qld)	21.5-30	MJ/kg	67	90 g/MJ
(SA & WA)	13.5-19.5	MJ/kg		
(Canadian bituminous)	27.0-30.5	MJ/kg		
(Canadian sub-bituminous)	18	MJ/kg		
Brown Coal				
(Vic. average)	9.7	MJ/kg	25	
(Loy Yang)	8.15	MJ/kg		1.25 kg/kWh
Firewood (dry)	16	MJ/kg	42	94 g/MJ
Natural uranium,				
in LWR	440	GJ/kg	-	-
in CANDU	650	GJ/kg	-	-
in FBR	24,000	GJ/kg	-	-
Uranium enriched to 3.5%				
in LWR	3456	GJ/kg	-	-

Source: *Australian Energy Consumption and Production, historical trends and projections,* ABARE Research Report 1997, except for uranium figures which are based on 40,000 MWD/t burnup of 3.5% enriched U in LWR, or 7500 MWD/t natural U in CANDU.

(MJ = 10^6 Joule, GJ = 10^9 J. % carbon is by mass, g/MJ=t/TJ, C to CO_2: x 3.667)
MJ to kWh @ 33% efficiency: x 0.0925

Arab Gulf States) that must be satisfied by desalinating facilities: this will further increase energy demand.

Taking these factors into account it seems that the future energy growth rate on a world-wide basis will be somewhere between that required to maintain per capita consumption (about 1.7% per year) and the 2.4 percent per year growth from 1971 to 1992. Achieving even two percent annual growth will require both some expansion of known supply and continuing efforts in energy conservation to increase the efficiency of energy use. Increased efficiency means making existing resources produce more useful work, light and heat than has hitherto been the case.

Since the 1970s economic factors have constrained energy demand and have resulted in unprecedented increases in energy efficiency in industry and transport, at least in the OECD countries, where primary energy consumption is forecast to increase by only 1.2 percent per year. On the other hand, energy consumption in developing countries is expected to grow much faster, that in east Asia is likely to be 5% per year, for instance.

In all cases, electricity demand is expected to grow much faster than overall energy demand.

In east Asia the projected growth in electricity demand is 7-8% per year to 2010. The World Energy Council projects a 23,000 TWh world demand in 2020, compared with 13,600 TWh in 1995, or a doubling from 1990, assuming much increased energy conservation and no increase in average primary energy use per capita.

Energy conservation is very difficult to project. To continue to be effective, it requires a present response to future prospects of high energy costs. It demands a national attitude with respect to energy use and lifestyle which is increasingly conservation-oriented, so that the rate of increase in overall energy consumption remains depressed after the initial easy fixes have been achieved. Despite popular acceptance of environmental ideas, there is little evidence of such an attitude emerging anywhere in the world.

ELECTRICITY TODAY AND TOMORROW

Electricity demand in an industrial society arises from a number of sources, including:

Industry

- some running on 24-hour basis.

- some working 8-10 hours per weekday.

Commerce

- most working 8-10 hours per weekday.

Public transport

- running during day and evening.

Homes

- heating or cooling mostly during day and evening.

- cooking morning and evening.

- off-peak water and space heating, especially during the night (in some systems).

It is clear from the above that electricity demand fluctuates throughout every 24-hour period as well as through the week, and also seasonally. It also varies from place to place and from country to country depending on the mix of demand, the climate, and other factors. A daily load curve for an electricity system is shown in Figure 2. From this it can be seen that there is a base load of about 60% of the maximum load for a typical weekday.

As well as these daily and weekly variations in demand there are gradual changes occurring in the pattern of electricity demand from year to year. In projecting demand patterns several decades into the future, planners must take note of such factors as:

- The changing pattern of seasonal peak demands; for example as summer air conditioning becomes more common.
- The impact of increased electrification of public transport and, possibly, of private transport as liquid fuels become more expensive.
- The effect on supply systems of increasing use of solar water heating with electrical boosting during periods of adverse weather.
- The effect of incentives to increase off-peak electricity demands for water and space heating.

- The practical effect of energy conservation measures such as insulation and more energy-efficient building design.
- The role of small-scale renewable energy sources providing electricity when they can.
- Industry needs and how they are changing.
- Improvements in the ability to transmit electricity long distances; e.g. fifty years ago 600 km was the maximum distance for efficient transmission, in the 1960s new technologies enabled transmission over 2000 km, and today it is greater still.

Some of these factors will affect total electricity consumption, while others will influence the relative importance of base-load demand. Production economics will require that as much of the electricity as possible is supplied from base-load generating plant, while allowing scope for occasional input from any renewable generating capacity linked to the system.

2.2 Electricity supply

Because of the large fluctuations in demand over the course of the day, it is normal to have several types of power stations broadly categorised as base-load, intermediate-load and peak-load stations.

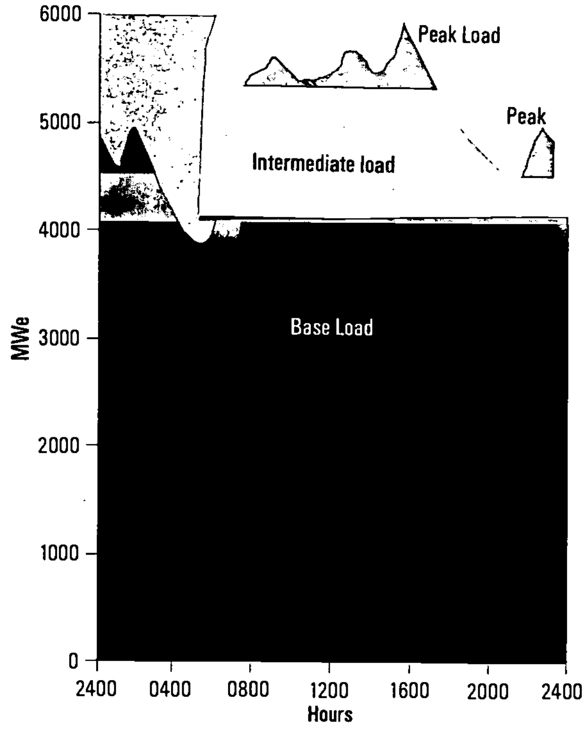
The base-load stations are usually steam driven and run more or less continuously at near rated power output. In Australia these plants are fossil fuelled, while in Canada a combination of nuclear power, hydro and fossil fuel is used.

Intermediate-load and peak-load stations must be capable of being brought on line and shut down quickly once or twice daily. A variety of techniques are used for intermediate and peak-load generation, including gas turbines, gas- and oil-fired steam boilers and hydro-electric generation.

Peak-load equipment tends to be characterised by low capital cost, and relatively high fuel cost is not a great problem. Base-load plant is designed to minimise fuel cost, and the relatively high capital cost can be written off over the large amounts of electricity produced continuously over many years.

The cost of building generating plant is an important part of the cost of electricity to the consumer (see also Table 4 and Figure 8). This capital cost component is determined by the total generating capacity required for both base- and peak-load (including intermediate-load) demands together. Lowest overall power costs to the consumer are obtained when the peak-load

Figure 2 Load curve of the Victorian electricity system

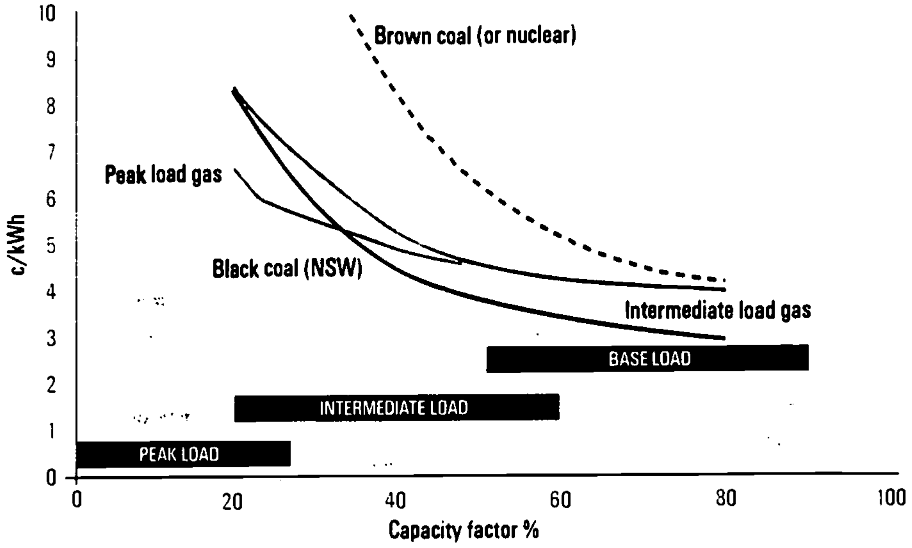


Load curve of the Victorian electricity system through one winter weekday in June 1996 showing the relative contributions of base, intermediate and peak-load plant duty. The shape of such a curve will vary markedly according to the kind of demand. Here, the peaks reflect domestic demand related to a normal working day, with household hot water systems evident overnight.

Note that the base-load here is about 4100 MWe, and while total capacity must allow for at least 50% more than this, most of the difference can be supplied by large intermediate-load gas-fired plant, or by adjusting the output of the base-load plant. The peak loads are typically supplied by hydro and gas turbines. Under the new wholesale electricity market, power stations bid into the market and compete for their energy to be despatched, so the economic factors evident from Figure 3 tend to determine the sources of supply at any particular moment.

Source: VPX.

Figure 3 Indicative Power Costs for Victoria in the late 1990s



Source: CRA Limited

increment is very small and a steady base-load utilises all of the available generating plant fairly constantly. Any practical system has to allow for some of the plant being idle for part of the time.

Base-load plants in Victoria, for example, make up over half of the system's total generating capacity, and produce more than 85 percent of the total electrical energy. Almost one third of the system's capacity can broadly be classified as intermediate-load plant, supplying power throughout the working day and evening. The balance is peak-load in the strict sense, supplying a short term energy reserve during high loading periods of the day or in emergencies. Victoria would be fairly typical of other systems in developed countries in these respects.

The capital cost of peak-load equipment such as gas turbines is about half that of base-load coal-fired plant, and in addition it can be installed much more quickly. However, partly due to low thermal efficiency, the fuel cost is relatively high compared with coal in a base-load station, per unit of power generated. Modern combined cycle gas turbine facilities, which have efficiencies around 25% greater than that of coal-fired plants, largely overcome this disadvantage.

Pumped water storage, using available base-load capacity overnight and on weekends, may be developed where topography permits, as an alternative to peak-load thermal power stations*. The capital cost may even be as low as oil- or gas-fired stations, and such installations will have the effect of increasing the extent to which base-load equipment can contribute to total load through the week.

A further means of increasing the utilisation of base-load plant is enabling it to follow the load to some extent, by varying the output.

Figure 3 shows how different kinds of plant are suited to different capacity factors for the Victorian system. Similar comparisons can be made for other locations in Australia or overseas and each would reflect the cost and availability of energy resources in the region considered.

A world-wide trend in electric plant is towards increased size of steam units, resulting in reduced capital cost per kilowatt capacity, especially for base-load equipment. This means that location is sometimes determined as much by the supply of cooling water as by the fuel source. However, large power station units require a large electrical transmission grid and overall generating system to enable them to be operated effectively. No single power station unit should be relatively so large that the whole generating system would be disabled or jeopardised by its sudden loss or by occasional maintenance outages.

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* See also later part of 2.4.

2.3 Fuels for electricity generation today

This book considers principally the question of electricity generation in the major industrialised and densely-populated areas of North America, east Asia and Europe. In these countries the fuelling of electricity generation constitutes at least one third of the primary energy supply (typically 33-45%).

Australia is fortunate in having large easily-mined deposits of coal close to the major urban centres in the eastern states. It has been possible to site the major power stations close to those coal deposits and thus eliminate much of the cost and inconvenience of moving large tonnages of a bulky material. Energy losses in electricity transmission are also relatively low.

Canada has ample hydro and/or fossil resources in most areas. However, these resources were largely exploited in the province of Ontario by the mid 1970s. Since that time nuclear power has been the main source of Ontario's electricity.

However, densely populated areas of the world such as Japan and many parts of Europe and North America are not as fortunate in the relative locations of coal supply and electricity demand. Also the high density of population and industrialisation has limited the attractiveness of coal not only from a cost but also an environmental point of view (see chapter 6).

Therefore the desirable criteria for a fuel for base-load electricity generation in highly populated and industrialised nations may be represented thus:

- It should be relatively **cheap**, giving low-cost power.
- Unless it can be supplied from a source very close to the power station it must be a **concentrated** source of energy, which can therefore be economically transported and readily stockpiled.
- It should have regard to the **scarcity of the resource** and alternative valued applications.
- Wastes should be manageable, so that they produce a minimum of **pollution** and environmental disturbance, including long-term global warming effect.
- It must be **safe** both in routine operation and regarding possible accident scenarios.

Of the two principal fuels available for base-load electricity generation, uranium often fits these criteria better overall than coal, especially if the coal must be transported very far.

National energy strategies will vary according to the indigenous resources of each country, the economics of importing fuels (or electricity), the amount of industrialisation and the security of supply.

An energy-rich country such as the USA has a variety of options. However, even in parts of the USA, transporting large quantities of coal long distances adds significantly to costs. Furthermore, the day when coal is in major demand for conversion to other fuels and materials is probably not more than a few decades away.

Japan lacks indigenous energy resources and relies almost entirely on imports. Oil was once the most convenient fuel import and the country depended on it for a large proportion of its energy needs, including electricity generation. Coal is increasingly being used for this purpose, but the cost of transport per unit of energy is much greater. Nuclear fuel has the advantage that so little is required and transport costs are negligible. Also, strategic stockpiles can easily be accumulated and variations in the price of the fuel have less impact than with coal.

Australia's situation varies across the country. The eastern mainland states have large reserves of coal. Western and South Australia have relatively less coal but plenty of gas and also lower demand for electricity. At present almost 60 percent of SA's electricity and half of Western Australia's is derived from burning gas. Development of Tasmania's large hydro-electric resources has put off the day when it needs any large thermal power stations, though this hydro potential is now almost fully utilised.

Canada is an energy-rich country where the use for electricity also varies from coast to coast. British Columbia, Manitoba and Quebec use large hydro electric resources to generate electricity, as does Ontario. Coal is used in the Prairie and Atlantic provinces, though to a lesser extent than in most developed countries. Ontario has made a major commitment to nuclear energy and depends on this for over 60% of its electricity. New Brunswick and Quebec also use nuclear electricity.

Figure 4 shows how electricity is produced in some of the countries considered including Australia and Canada. In all countries the demand for electric power is increasing steadily (mostly 3-4% p.a.). The diagram shows that coal provides a lot of the primary energy input for electricity in the USA and Europe, but much less in Japan and Canada. These countries have about one fifth to one third of their electrical power currently being generated from nuclear reactors. Of most significance from a world resources perspective is that a substantial amount of the fuel used in each country still consists of increasingly scarce and hence rather precious oil. This is most obvious and acute in Japan, though both it and Russia have markedly reduced their dependence on oil for electricity in the last 25 years, and both plan to increase the proportion of their electricity generated from nuclear energy.

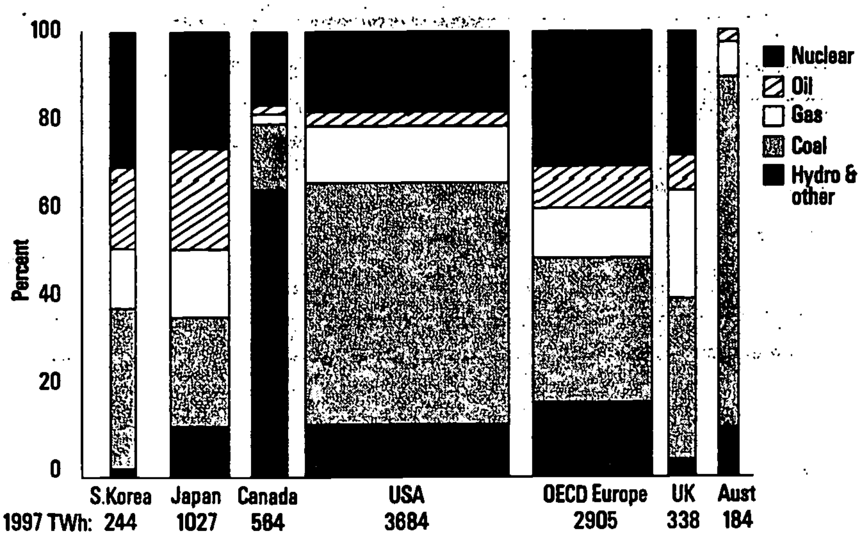
2.4 Provision for Future Base-Load Electricity

In considering the future beyond the year 2010 there are a couple of practical matters which cannot be overlooked. One is the **time scale**. A commitment today regarding a large base-load generating plant means that plant should be commissioned in five to ten years time. It can then be expected to have an operating life of up to 40 years, all of which adds up to something approaching one adult lifetime. Thus today's investment decisions regarding electric plant cannot change the overall pattern of a country's generating system for at least two or three decades - Britain's nuclear investments of the 1950s took two decades to achieve more than a mere ten percent of UK electric power being generated in this way.

Even combined cycle gas turbines (CCGT), which can be put into service in less than two years from date of order, and which are increasingly popular, cannot make a substantial short term change to the overall energy supply situation. If we are considering new technologies not yet commercially engineered, the lead time is longer, perhaps by another two of three decades. It also follows that much of the technology in use today will inevitably be in use for several more decades; it cannot be quickly abandoned.

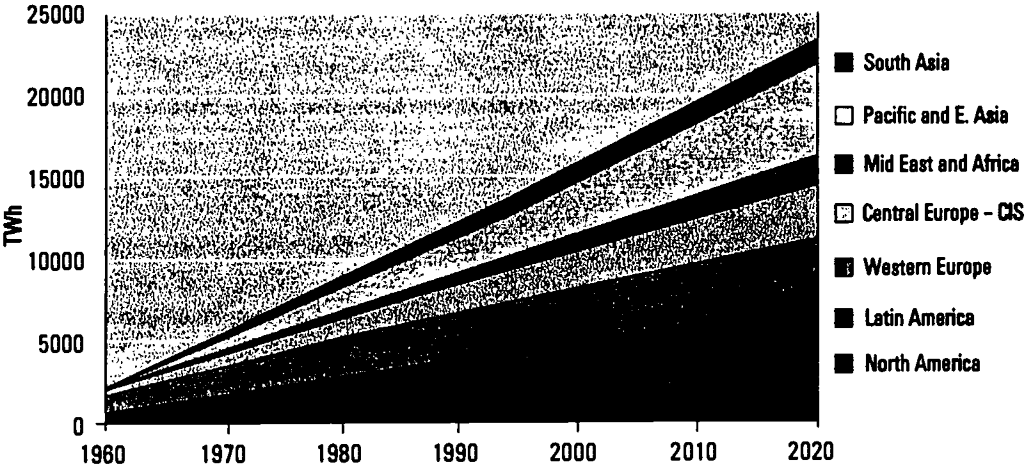
The other practical matter relates to **size**. In some things small is appropriate and, given low labour costs, also efficient. In mining fuels and generating electric power however, the economic constraints involved generally dictate that operations and plant be as large as practicable. Where the scale is reduced, the unit costs inexorably increase. With conventional types of plant, large scale installations are inevitable in urbanised and industrialised nations, where large electricity demands are concentrated in small areas of the country.

Figure 4 Fuel for electricity generation (%)



Width of each bar is indicative of actual amount of power generated (gross production).
Source: OECD/IAEA 1998: *Electricity Information 1997.*

Figure 5 World total electricity consumption, by region



Source: World Energy Council 1993. Projection to 2020 is Reference Case (total: 13.4 Gtoe, compared with Modified Reference 16.0 Gtoe, High Growth 17.2 Gtoe and Ecologically-driven 11.3 Gtoe cases). See also Figure 1 re total energy mix.

These practical matters of long lead-time and large-scale installations point to the need for careful assessment of future trends in electricity use to ensure that tomorrow's supply systems will effectively cope with tomorrow's electrical demand.

Furthermore, the technology used must be matched to the task. The big question facing planners is that of selecting the most appropriate means of generating base-load electricity for a particular region at a particular time in the future. What are the options?

Conservation

One possibility may be to use less energy by practising rigorous conservation, principally through increased energy efficiency in use. This approach can be "retrofitted" to many applications in developed countries, and can be applied to new installations in all countries. If the USA, the UK and Japan could each use less electricity such a strategy might, by itself, eventually eliminate the oil-fired component in two of these countries and markedly reduce it in the third. Energy conservation in general is discussed in 1.5. However, such conservation has a greater effect on total energy use than on actual electricity, and an increased proportion of electricity in the overall energy mix is often a prime means of conservation.

Oil

In 1994 oil provided 11% of all electricity and as noted above (and see Figure 4) a considerable amount of oil is still used today for large-scale base-load power generation in some countries. But oil is uniquely important as the source of very portable and energy-rich petroleum products used for mobile transport. Both oil and gas have important uses in the petrochemical industry as feedstock for the manufacture of plastics, fertilisers and pharmaceutical products. Burning oil for base-load electricity generation where other fuels are economically available is questionable. In Australia and Canada oil is used for power generation in areas remote from natural gas resources and coalfields, in relatively small installations.

Natural Gas

In Australia natural gas usage for electricity has increased markedly since the early 1970s, in Canada it has doubled since 1985, but still provides less than 3% of electricity. Elsewhere it plays a major role in power generation (14% of world electricity in 1994), and this share is increasing. It has the distinction of giving rise to less carbon dioxide than coal, and hence is favoured by some to displace coal for base-load power.

On the other hand, natural gas is easily and economically transported via pipe lines in may areas (for example, North America and Europe). It can then be reticulated to many points of use and is consequently of great value for direct heating purposes in homes and industry at moderate efficiency (up to 90% at end use, allowing for flue losses). Natural gas is liquefied for shipping overseas (for example as LNG to Japan and Korea), which significantly increases its cost. Its great value as a direct fuel suggests that its price is likely to rise in the medium-term future to the extent that it will be much less competitive for base-load electricity.

Coal

Of the other fuels for base-load electricity generation, coal is at present the most important.

Coal plays the major role in most countries and has done so for many years, currently providing 39% of the world's electricity. Modern coal-fired power stations are more efficient than in the past, and at extra cost some of the environmental effects of burning high-sulphur coals can be eliminated, even if the "greenhouse effect" due to the production of massive amounts of carbon dioxide cannot (see Chapter 6).

Coal from large open cut mines is fairly cheaply obtained, but the costs of transport over long distances can make it less attractive than alternatives. If millions of tonnes of coal are mined in one locality and shipped across a continent or overseas (for example, from Australia or Canada to Japan or Europe), its handling and transport imposes costs and involves the consumption of further energy.

Also, like oil and gas, coal has important uses other than as a fuel. Carbon, even in steaming coal, is needed in large quantities for metal smelting, for future conversion to gas and liquid fuels, and for other purposes. Although reserves are large, conservation will become increasingly important.

Uranium

The only other fuel which is a present option for base-load electricity is uranium. While large amounts of ore may be mined and treated, two or three 200-litre drums of uranium oxide (U_3O_8) concentrate leaving the mine contain enough energy to keep cities the size of Toronto or Sydney supplied with power for a day, so it is relatively very portable. It also has some environmental advantages (see Chapter 6). Its detractors sometimes emphasise that compared with coal, nuclear power still has too many unsolved problems. However, it is now forty years since the first commercial reactor came on line, and over half a century since nuclear fission (see Chapter 3) was first controlled.

In that time some 9000 reactor-years of operating experience have been acquired with commercial reactors, and about the same from similar (but smaller) reactors in naval use.

Today there are over 430 nuclear power reactors in operation in 32 countries, including several developing nations. They provide some 17% of the world's total electricity (Table 6).

More nuclear power stations are actively under construction. Electricity authorities in many countries are satisfied with the reliability, safety and economic performance of nuclear power relative to coal or oil (see also 2.5 and Chapter 6). Thus, in many countries at least one third of their electricity is generated by nuclear power. France is now generating three quarters of its electricity from nuclear power and is the world's largest electricity exporter. Table 5 gives an indication of the different kinds of nuclear power reactors currently being used for electricity generation.

CANDU nuclear power plants offer greater uranium resource utilisation than other available thermal nuclear reactors, and can operate on a variety of low fissile content fuels including spent fuel from other kinds of reactors. In the longer term fast neutron reactors (see 4.4) have the potential for vastly increasing the electric power yield from known uranium reserves.

Apart from military weapons and naval propulsion, uranium has no significant uses other than for electricity generation and for making medical and industrial isotopes. At least 95% of the world's uranium production today goes into electricity generation.

The potential of nuclear power for electricity generation, using uranium as a fuel, is principally applicable to developed nations which have large blocks of electricity demand. Today's nuclear power stations tend to be built in sizes from 500 megawatts electrical (MWe) to about 1300 MWe, anything smaller currently being less attractive economically. However, there are some developing nations which have moderate-sized electricity production and distribution systems and/or the need for co-generating (for example, electricity and potable water production). These are able economically to use reactors in the 100 MWe size range where expensive oil-fired generation is the main alternative.

Nuclear Fusion

Commercial nuclear fusion is still only a future hope. As well as looking for ways to harness incident sunlight, people have for a long time dreamed of taming the process which generates that light and heat – bringing the sun right down to earth. The process concerned is called nuclear fusion (as distinct from fission, see Chapter 3). The favoured method for achieving controlled fusion involves joining the nuclei of deuterium and tritium atoms (heavy isotopes of hydrogen) together at very high temperatures – about 100 million degrees Celsius. No method of sustaining such temperatures under stable conditions has yet been demonstrated. However, research continues, particularly in USA, Japan, Europe and Russia, and perhaps some time in the next half century heat from fusion will be harnessed to generate electricity. Fusion technology would be best suited to large-scale base-load applications such as supplying cities and industrial regions.

The deuterium fuel is relatively abundant in sea water, but tritium is derived either from lithium, or produced in heavy water-moderated reactors. Almost limitless energy would be available if the deuterium-deuterium reaction could be achieved, but this requires much higher temperatures than the deuterium-tritium process. Controlled fusion of ordinary hydrogen nuclei as occurs in the sun seems unlikely ever to be achieved on earth, as the conditions required are even more extreme. The big advantage of all these reactions is that only small quantities of radioactive wastes are expected. Disadvantages include projected high cost, the high radioactivity created in structural components of the plant and the cost of producing tritium gas.

Renewable energy sources

Technology to utilise the forces of nature for doing work to supply human needs is as old as the first sailing ship. There is a fundamental attractiveness about harnessing such forces in an age which is very conscious of the environmental effects of burning fossil fuels.

Sun, wind, waves, rivers, tides and the heat from radioactive decay in the earth's core as well as biomass are all abundant and ongoing, hence the term "renewables". Only one, the power of falling water in rivers, has been significantly tapped for electricity so far. Solar energy's main human application has been in agriculture and forestry, via photosynthesis, and increasingly it is harnessed for heat. Biomass (eg sugar cane residue) is burned where it can be utilised, and the use of corn to produce alcohol for transport fuel is increasing. The others are little used today.

There are immediate challenges in actually harnessing renewable energy sources for electricity. Apart from photovoltaic (PV) systems, the question is how to make them turn dynamos to generate the electricity. If it is heat which is harnessed, this is via a steam or other Renkin cycle generating system.

> *If the fundamental opportunity of renewables is their abundance and relatively widespread occurrence, the fundamental problem, especially for electricity supply, is their variable and diffuse nature*.*

This means either that there must be reliable duplicate sources of electricity, or some means of electricity storage on a large scale. Apart from pumped-storage hydro or compressed air systems (see below), no such means exist at present and nor are any in sight.

For a stand-alone system the energy storage problem remains paramount. If linking to a grid, the question of duplicate sources arises. For large-scale and especially base-load electricity generation there is little scope for harnessing energy from the sun.

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* The exception is geothermal, which is not widely accessible.

Solar energy

"Solar not nuclear" is a catch-cry of both anti-nuclear environmental groups and many technological optimists, particularly as advances in direct solar heating continued to be made. Certainly we can expect to see more roof area occupied by some kind of solar collectors in the future, as their price comes down and we adapt our energy usage to utilise better what is available from this source.

However, for electricity generation solar power has limited potential, as it is too diffuse* and too intermittent. First, solar input is interrupted by night and by cloud cover, which means that solar electric generation inevitably has a low capacity factor, typically less than 15%. Also, there is a low intensity of incoming radiation, and converting this to high-grade electricity is still relatively inefficient (12 – 16 percent), though this has been the subject of much research over several decades.

Two methods of converting the sun's radiant energy to electricity are the focus of attention. The better known method utilises sunlight acting on **photovoltaic cells** to produce electricity. This has application on satellites and for certain earthbound signalling and communication equipment, such as remote area telecommunications equipment in Australia and Canada. Sales of solar PV modules are increasing strongly as their efficiency increases and price falls (now c $4000/kW). But the cost per unit of electricity is still too high for ordinary use.

For a stand-alone system some means must be employed to store the collected energy during hours of darkness or cloud – either as electricity in batteries, or in some other form such as hydrogen (produced by electrolysis of water) or superconductors. In either case, an extra stage of energy conversion is involved with consequent energy losses, thus lowering overall net efficiency, and greatly increasing capital costs.

Several experimental PV power plants mostly of 300 – 500 kW capacity are connected to electricity grids in Europe and USA. Research continues into ways to make the actual solar collecting cells less expensive and more efficient. Other major research is investigating economic ways to store the energy which is collected from the sun's rays during the day.

A **solar thermal** power plant has a system of mirrors to concentrate the sunlight on to an absorber, the energy then being used to evaporate a liquid at pressure, and subsequently to drive turbines. The concentrator is usually a parabolic mirror trough oriented north-south, which tracks the sun's path through the day. The absorber is located at the focal point and converts the solar radiation to heat (about 400°C) which is transferred into a fluid such as synthetic oil. The fluid drives a conventional turbine and generator. Several such installations in modules of 80 MW are now operating. Each module requires about 50 hectares of land and needs very precise engineering and control. These plants are supplemented by a gas-fired boiler which generates about a quarter of the overall power output and keeps them warm overnight. Over 350 MWe capacity worldwide has supplied about 80% of the total solar electricity to the mid 1990s.

The main role of solar energy in the future will be that of **direct heating**. Much of our energy need is for heat below 60°C – eg. in hot water systems. A lot more, particularly in industry, is for heat in the range 60 – 110°C. Together these may account for a significant proportion of primary energy use in industrialised nations. The first need can readily be supplied by solar power much of the time in some places, and the second application commercially is probably not far off. Such uses will diminish to some extent the demand for electricity and the consumption of fossil fuels, particularly if coupled with energy conservation measures such as insulation.

With adequate insulation, heat pumps utilising the conventional refrigeration cycle can be used to warm and cool buildings, with very little energy input other than from the sun. Eventually, up to ten percent of total primary energy in industrialised countries may be supplied by direct solar thermal techniques, and to some extent this will substitute for base-load electrical energy.

Wind energy

Wind turbines have been used for household electricity generation in conjunction with battery storage over many decades in remote areas. Generator units of more than 1 MWe are now functioning in several countries. The power output is a function of the cube of the wind speed, so such turbines require a wind of about 7 – 20 metres/second (25 – 70 km/hr), and in practice

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* In Australia on a sunny day up to 1 kW/m^2 falls on a surface maintained at right angles to the sun's rays. In Canada much less than this is received through much of the year, for instance in winter most of Canada averages less than 1 kWh per day (on horizontal surface)

relatively few areas have such prevailing winds. Like solar, wind power requires alternative power sources or large-scale energy storage systems to cope with calmer periods.

However, there are now many thousands of wind turbines operating in various parts of the world, with a total capacity of over 5000 MWe. These are a valuable complement to large-scale base-load power stations. Denmark gets 3% of its electricity from wind. The most economical and practical size of commercial wind turbines seems to be 300 – 600 kWe grouped into wind farms of up to 6 MWe.

Rivers

Hydro-electric power, using the potential energy of rivers, now supplies 19% of world electricity (10% in Australia, 59% in Canada). Apart from a few countries with an abundance of it, hydro capacity is normally applied to peak-load demand, because it is so readily stopped and started and because water supply is often limited. It is not a major option for the future in the developed countries because most major sites in these countries having potential for harnessing gravity in this way are either being exploited already or are unavailable for other reasons such as environmental considerations. An advantage of many hydro systems is their capacity to handle seasonal (as well as daily) high peak loads. In practice the utilisation of stored water is sometimes complicated by demands for irrigation which may occur out of phase with peak electrical demands. In other situations, highly seasonal rainfall and/or topographical conditions limit the use of hydro power to the rainy season.

Geothermal

Where hot underground steam can be tapped and brought to the surface it may be used to generate electricity. Such geothermal sources have potential in certain parts of the world such as New Zealand, USA, Philippines, Iceland and Italy. Some 6000 MWe of capacity is operating. There are also prospects in certain other areas for pumping water underground to very hot regions of the earth's crust and using the steam thus produced for electricity generation.

Tides

Harnessing the tides in a bay or estuary has been achieved in France (since 1966) and Russia, and could be achieved in certain other areas where there is a large tidal range. In Canada the Bay of Fundy, between Nova Scotia and New Brunswick, is a prospective site. The tidal water can be used to turn turbines as it is released through the tidal barrage in either direction. Worldwide this technology appears to have little potential.

Waves

Harnessing power from wave motion is a possibility which might yield much more energy than tides. The feasibility of this has been investigated, particularly in the UK. Generators either coupled to floating devices or turned by air displaced by waves in a hollow concrete structure would produce electricity for delivery to shore. High cost and numerous practical problems have frustrated progress.

Relating renewables to base-load electricity demand

> ***Sun, wind, tides and waves cannot directly be applied as economic substitutes for coal, gas or nuclear power, however important they may become in particular areas.***

For the reasons discussed, they cannot be controlled to provide directly either continuous base-load power, or peak-load power when it is needed. In practical terms they are therefore limited to 10 – 20% of the capacity of an electricity grid, and cannot directly be applied as economic substitutes for coal, gas or nuclear power, however important they may become in particular areas with favourable conditions. Environmental objections to hundreds of very large wind turbines, extensive shaded areas or huge tidal barrages, not to mention new hydro-electric schemes, are another aspect. Nevertheless, such technologies will to some extent contribute to the world's energy future, even if they are unsuitable for carrying the main burden of supply.

If there were some way that large amounts of electricity from intermittent producers such as solar and wind could be stored efficiently, the contribution of these technologies to supplying base-load energy demand would be much greater. Already in some places pumped storage is used to even out the daily generating load by pumping water to a high storage dam during off-peak hours and weekends, using the excess base-load capacity from coal or nuclear sources. During peak hours this water can be used for hydro-electric generation. Relatively few places have scope for pumped storage dams close to where the power is needed, and overall efficiency is low. Compressed air storage in underground cavities has been used to a limited degree. Means of storing large amounts of electricity as such in giant batteries or by other means have not been developed.

There is some scope for reversing the whole way we look at power supply in developed countries, with its 24-hour, 7-day cycle, using peak load equipment simply to meet the daily peaks. Today's peak-load equipment could be used to some extent to provide infill capacity in a system relying heavily on renewables. The peak capacity would complement large-scale solar thermal and wind generation, providing power when they were unable to.

Any substantial use of solar or wind for electricity in a grid means that there must be allowance for 100% back-up with hydro or fossil fuel capacity. This gives rise to very high generating costs by present standards, but in some places it may be the shape of the future. This option is not available to developing countries with little or no base-load generating capacity.

Environmental aspects of renewables

Renewable energy sources have a completely different set of environmental costs and benefits relative to fossil fuel or nuclear generating capacity.

On the positive side they emit no carbon dioxide or other air pollutants (beyond some decay products from new hydro-electric reservoirs), but because they are harnessing relatively low-intensity energy, their 'footprint' – the area taken up by them – is necessarily much larger. In addition, the physical size of the equipment required to harness low-intensity energy sources is very great relative to that required for high intensity energy sources, and therefore requires large material and energy input during fabrication and construction.

Whether Australia would accept the environmental impact of another Snowy Mountains hydro scheme (providing some 3.5% of the country's electricity plus irrigation) is doubtful. Whether large areas near cities dedicated to solar collectors will be acceptable, if such proposals are ever made, remains to be seen. In Europe, wind turbines have not endeared themselves to neighbours on aesthetic, noise or nature conservation grounds. In some cases, large numbers of birds have been killed by the large rotating wind turbines.

However, environmental impact can be minimised in some cases. Fixed solar collectors can double as noise barriers along highways, roof-tops are readily available, and there are places where wind turbines would not obtrude unduly.

2.5 Coal and Uranium Compared

The only major fuel options for large-scale energy conversion to base-load electricity over the next several decades are coal and uranium.

Gas is an option in some places in the short term, but its great value as a direct fuel and the likelihood of significant price increases in the long term put the spotlight back on to coal and uranium. Choices between these alternatives will probably continue to depend principally on the final cost of electric power (including environmental costs), which varies significantly from site to site.

Some general comparisons between coal and uranium as the principal fuels for base-load electricity generation are discussed in this section. Other comparisons which are principally environmental or related to health are discussed in more detail in Chapter 6.

Different quantities of materials are involved with energy conversion to electricity, starting with coal and uranium. In either case the amount of electricity considered is 8000 kWh, the amount required by one person in Japan or northern Europe for one year.*

Using uranium as the fuel

Between 30 kg and 70 kg of uranium ore from a typical Australian or Canadian mine is needed to produce a handful (230 grams) of uranium oxide

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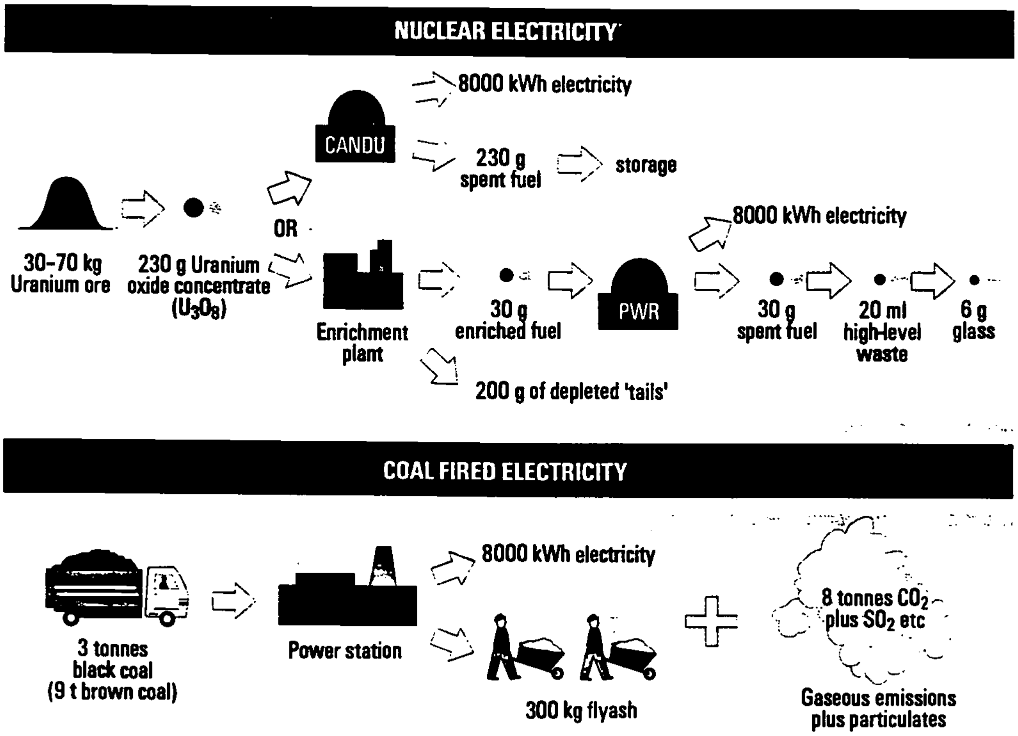
* Australian consumption is about 7500 kWh /person /year, after allowing for energy in aluminium and similar exports. Canadian consumption on the same basis is 15,500 kWh/person/year, and US electricity consumption is about 12,700 kWh /person /year.

Figure 6 Fuel and waste comparison



concentrate. The uranium in this concentrate, is referred to as "natural uranium" and contains about 0.7% U-235, the fissile isotope of uranium. Natural uranium is used to fuel CANDU reactors in Canada and around the world. In countries operating light water reactors (PWRs and BWRs) the natural uranium is enriched in its U-235 isotope to yield about 30 grams of enriched uranium fuel (3.5% U-235, see 4.2).

Irradiated fuel from CANDU reactors contains very little fissile material and is treated as waste. Irradiated fuel from light water reactors does contain a significant quantity of fissile material and, in some countries, it is reprocessed to recover this. When light water reactor fuel is reprocessed, about 20 ml of liquid high-level waste remains. This then can be incorporated into less than one cubic centimetre (6 g) of pyrex glass - about the size of a large coin, and highly radioactive. Other wastes are also produced, but they are of much less significance - see 5.1.

Using coal as the fuel

About three tonnes of high quality black coal (or 3.5 t of average black coal or 9 t of brown coal) can be fed into a power station to generate the same amount of electricity. This leaves a certain amount of ash, varying from a couple of barrow loads to half a tonne, depending on the particular coal used. Eight tonnes of carbon dioxide, which at atmospheric temperature and pressure would fill three full-sized Olympic pools (50m x 15m x 2m), is also produced. Depending on the coal, some sulfur dioxide (SO_2) is also produced. A common type of US coal might contain 2-3 percent sulfur, in which case possibly a hundred kilograms of sulfur dioxide would require costly removal, or would add to the acid rain problems well known in the northern hemisphere. The environmental effects of these gaseous by-products of coal-fired electricity generation are considered in more detail in 6.1 and 6.2, and the costs of SO_2 removal are mentioned below. (Australian and Canadian coal generally contains less than one percent sulfur).

Years ago, most coal-fired power plants emitted more radioactivity than any nuclear plants of similar size! This was due to trace quantities of radioactive materials (eg up to 17ppm U+Th in Australia and Canada) in the coal. With modern equipment this radioactivity is mostly retained with the fly ash.

Economic factors

As well as comparing the quantities of fuel and wastes involved, the relative costs of the two types of generating systems are important in considering options. Table 4 quotes some comparisons for the projected costs of electricity compiled by OECD and Figure 7 shows the actual costs over more than a decade in the USA, while Figure 8 shows the components of electricity cost for different means of generating it. A nuclear power station costs a lot more than a gas-fired station and somewhat more than a coal-fired station to build. But the nuclear fuel, including enrichment if needed, costs much less than oil, gas or coal. Hence the overall expected cost for energy conversion to electricity comes out much the same for nuclear as for coal-fired plants.

There are a number of US nuclear plants where capital costs blew out during construction and hence where any normal calculation of generating cost shows it to be very high. However, closing such plants would help neither owners nor customers, and in any case the criterion for running them is the cost of actual operation (O & M plus fuel - see Figure 7). On this basis they compare favourably with coal and are cheaper than gas. Regarding investment in new capacity, the capital costs are a major factor, and these are included in Table 4 and Figure 8.

In an earlier version of Table 4, OECD figures for plants starting operation in 2000 indicated the importance of having coal near its point of use and low in sulfur. Costs in the north eastern United States distinctly favoured nuclear, costs in the midwest marginally favoured nuclear, and in the west, coal was cheaper. Today, projected low gas prices are the main reason for nuclear being uncompetitive there. Having the location of electricity demand well removed from sources of cheap coal is the main reason for the steadily increasing use of nuclear power in many countries as compared with coal. **The major uncertainty in all the figures of Table 4 is the projected prices of coal and gas.**

Actual electricity production costs in the USA (excluding capital) are shown in Figure 7. These are average figures including a lot of old coal and nuclear plant, and should be read with Figure 8.

An important aspect of nuclear electricity is its relationship with a country's international balance of payments position. As noted above and in Figure 8, nuclear power is very capital-intensive compared with systems based on fossil fuels, where the fuel costs are relatively much more significant. Therefore where the choice for a country such as Japan or France lies between importing large quantities of fuel or spending a lot of capital at home, the decision may well be taken simply on foreign exchange grounds. This was a factor in Canada, where fossil fuel supplies are located in the west of the country. Eastern Canada, in the absence of nuclear, would rely heavily on imported coal. Development of nuclear power in such situations has the effect of stimulating local industries which build the plant and at the same time of minimising long-term commitments to buying fuels abroad. Overseas purchasing commitments for the life of a new coal-fired plant in Japan, for example, would be subject to price rises and could become a more serious drain on foreign currency reserves than with less costly uranium.

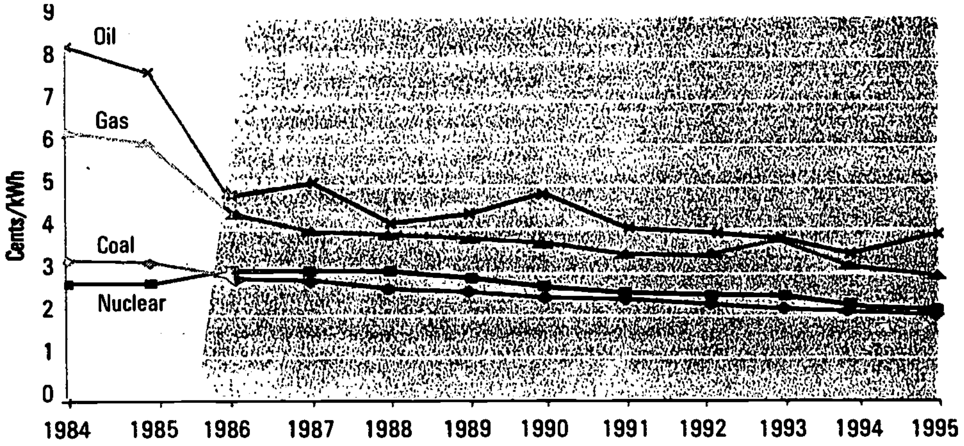
Table 4 Projected Costs

Some comparative electricity generating cost projections for year 2005-2010

	Nuclear	Coal	Gas
France	**3.22**	4.64	4.74
Russia	**2.69**	4.63	3.54
Japan	5.75	**5.58**	7.91
Korea	**3.07**	3.44	4.25
Spain	**4.10**	4.22	4.79
USA	3.33	2.48	**2.33**-2.71
Canada	**2.47**-2.96	2.92	3.00
China	**2.54**-3.08	3.18	-

US 1997 cents/kWh. Discount rate 5%, 30 year lifetime, 75% load factor.
Source: OECD/IEA NEA 1998, *Projected Costs of Generating Electricity.*

Figure 7 US Electricity production costs (O&M+fuel) in 1995 cents/kWh



Note: The above data refer to fuel plus operation end maintenance (O&M) costs only, they exclude capital since this varies greatly among utilities and states. Figures in Table 4 include capital.

Source: US Utility Data Institute

Uranium has the advantage of being a highly concentrated source of energy which is therefore easily and cheaply transportable, the quantities needed being very much less than for coal or oil. One kilogram of natural uranium yields about twenty thousand times as much energy as the same amount of coal (see Table 3). In addition the fuel cost contribution to the overall cost of electricity produced is relatively small, which means that even a large fuel price escalation will have relatively little effect*.

However as the long term global environmental consequences of consuming fossil fuels, especially coal, create additional concern, the environmental advantages of nuclear power are also receiving more attention (see 6.1).

Assigning carbon values, or imposing carbon taxes, on fossil fuel electricity generation changes the economic situation relative to nuclear energy. For instance, carbon values of $37 per tonne for typical coal, or $29 per tonne for brown coal will increase the electricity cost from those sources by one cent per kilowatt hour while leaving nuclear electricity costs unaffected.

It has already been noted that the capital cost of a nuclear power plant is higher than that of a coal plant. The "**energy cost**" may also be higher, that is, the amount of energy invested in materials and fuel preparation. This is particularly the case for light water reactors where the energy required to enrich the fuel is substantial. The energy capital used for construction and initial fuel charge of a light water reactor is equivalent to about 3 percent of a reactor's lifetime output, fuelling it accounts for less than one percent of its output (or up to 4% in a worst case scenario using least-efficient diffusion enrichment, see section 3.4).

Although coal and uranium appear to compete for base-load electricity generation, most developed nations fortunate enough to have the option see a role for both.

As a general rule countries without cheap coal tend to favour nuclear power as the lower cost option. In a few countries (such as Australia, where coal reserves and production potential far outweigh domestic needs) the use of coal for electricity generation is favoured over nuclear. However, in a world perspective, the need for both is evident, and as electricity demand increases along with concern regarding possible global warming, a corresponding increase in the priority of nuclear power for base-load electricity seems inevitable.

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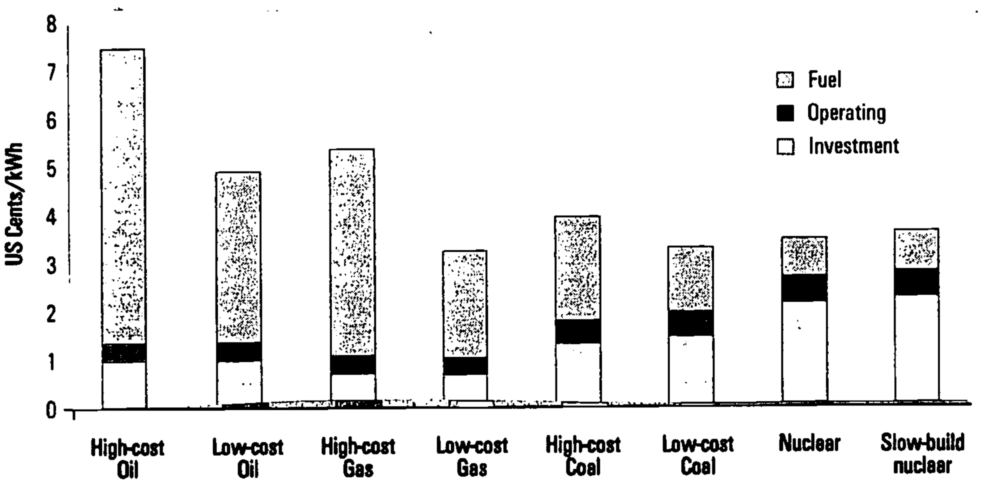
* A doubling of the 1997 U_3O_8 price would increase the fuel cost for a light water reactor 30% and the electricity cost about 7%.

Figure 8 Components of electricity costs



For different fuel costs (fossil fuels) or lead time (nuclear plants). Assumes 5% discount rate, 30 year life and 70% load factor.

Note: The key factor for fossil fuels is the high or low cost of fuels (top portion of bars), whereas nuclear power has a low proportion of fuel cost in total electricity cost and the key factor is the short or long lead time in planning and construction, hence investment cost (bottom portion of bars). Increasing the load factor thus benefits nuclear more than coal, and both these more than oil or gas.

Source: OECD 1992, Electricity Supply in OECD, annex 9.

Table 6 Nuclear power's role in electricity production

Country	Nuclear electricity generation 1997		Reactors operational end of 1998		Reactors building end of 1998		Uranium required 1997
	%	TWh	No.	MWe	No.	MWe	tonnes U
Argentina	11	7.5	2	935	1	692	127
Armenia	26	1.4	1	376	0	0	57
Belgium	60	45.1	7	5712	0	0	1064
Brazil	1.1	3.2	1	626	1	1245	72
Bulgaria	45	16.4	6	3538	0	0	506
Canada	14	77.9	18	12361	0	0	1780
China	0.8	11.4	3	2167	5	3735	381
Czech Republic	19	12.5	4	1648	2	1824	932
Finland	30	20.0	4	2656	0	0	500
France	78	376.0	58	61653	1	1450	11926
Germany	32	161.4	20	22326	0	0	3698
Hungary	40	14.0	4	1729	0	0	356
India	2.3	8.7	10	1695	4	808	260
Iran	0	0	0	0	1	950	0
Japan	35	318.1	53	43504	1	796	7183
Kazakhstan	0.6	0.3	1	70	0	0	0
Korea RO (South)	34	73.2	14	11370	4	3500	2260
Lithuania	81	10.9	2	2370	0	0	386
Mexico	6.5	10.5	2	1308	0	0	218
Netherlands	2.8	2.3	1	452	0	0	123
Pakistan	0.65	0.37	1	125	1	300	13
Romania	9.7	5.4	1	650	1	650	85
Russia	14	99.7	29	19843	3	2825	3827
Slovakia	44	10.8	5	2044	3	1252	328
Slovenia	40	4.8	1	632	0	0	130
South Africa	6.5	12.6	2	1842	0	0	298
Spain	29	53.1	9	7320	0	0	1399
Sweden	46	67.0	12	10047	0	0	1549
Switzerland	41	24.0	5	3077	0	0	610
Taiwan	35	34.9	6	4884	0	0	930
Ukraine	47	74.6	14	12120	2	1900	1769
United Kingdom	27	89.3	35	12928	0	0	2499
USA	20	629.4	104	97210	0	0	19226
World	**17**	**2276.5**	**435**	**349,350**	**30**	**21,927**	**64,492**

Sources: the nuclear power reactor data files of ANSTO, based on information to 6 January 1999.
Total includes 4 Canadian (Pickering A) reactors which are laid up, total 2060 MWe.
IAEA- for electricity production. Uranium Institute 1996: Global Nuclear Fuel Market (reference case) - for U

Note: 64,492 tU = 76,055 t U_3O_8

NUCLEAR ENERGY AND ITS FUELS

While people until relatively recently must have thought they were converting mass to energy when they burned wood to cook meals and to keep warm, any student today would be aware that this was not the case. One form of carbon compound (the solid wood) was simply being converted to another (a colourless gas) which blew away. The hydrogen involved with the original compound also dispersed as water vapour. No measurable mass was lost, although energy was released. However, during this century, as our understanding of nuclear physics developed, it was suggested that mass could in fact be turned into energy. This is what happens in a nuclear reactor, using atoms of particular metals such as uranium.

Uranium is 1.7 times more dense than lead, and is composed of atoms which have in their nucleus 92 protons (positively-charged) and about 140 neutrons (uncharged). One of the types of uranium atoms, or one of the uranium "isotopes" as they are called, has 143 neutrons. This uranium-235 (U-235) isotope is remarkable because when its nucleus is hit by a slow neutron (also known as a "thermal" neutron) the atom can split in two and release a lot of energy as heat. This is called nuclear "fission", and U-235 is thus a "fissile" isotope. In Einstein's terms some mass is lost and converted to energy. At the same time several fast neutrons are emitted from the split nucleus. If these are slowed by a moderator such as graphite or water they can cause other U-235 atoms to split, thus giving rise to a chain reaction. See also Figure 14.

The other main isotope of natural uranium, U-238 is not itself fissile in conventional reactors but each atom can capture a neutron, indirectly to become fissile plutonium-239. It is thus "fertile". Pu-239 behaves similarly to U-235 except that fast neutrons can also cause fission, hence a moderator is not necessary. Also its neutron yield is greater than U-235. About one third of the energy from a commercial nuclear reactor comes from fission of the plutonium produced in the reactor.

The reactor core is loaded with uranium oxide fuel. In CANDU reactors, natural uranium (0.7% U-235) is used, while for light water reactors it is enriched to 3-4% U-235 (see also Section 4.2). In both cases the uranium oxide is typically in the form of ceramic pellets of UO_2, assembled inside zircalloy or stainless steel tubes and surrounded by coolant and moderator (to slow down the fast neutrons from the nuclear fission chain reaction so that they are more likely to cause ongoing fission). The neutrons cause further fission in U-235 atoms. Each such fission typically releases about 170 MeV, or 2.7×10^{-11} Joule, (contrasting with 4 ev or 6.5×10^{-19} J per molecule of carbon dioxide released in the combustion of carbon).

Commercial nuclear power generation involves containing and controlling the fission reactions so that the heat can be used to make steam which in turn generates electricity. The nuclear fuel cycle is described in Section 4.2.

3.2 Nuclear Power Reactors

Figures 9A and 9B show two common types of reactors used for generating electricity. In the core the uranium undergoes fission and in the process a lot of heat is released. The control rods shown regulate the rate of the reaction, and therefore the heat yield, by absorbing some of the moving neutrons.

In the Pressurised Water Reactor (Figure 9A) the core is surrounded by water and is enclosed in a very thick steel pressure vessel. The water, under high pressure, serves as both coolant and moderator. It is circulated to a heat exchanger (steam generator) where water in a separate circuit is turned into steam.

Figure 9B shows the Canadian-designed and built CANDU reactor, which has been a major export success. Instead of being in a pressure vessel, the fuel is in a number of pressure tubes within a reactor vessel called a calandria. Pressurized heavy water flows through the tubes and conveys the heat to a steam generator. Heavy water under low pressure fills the calandria, surrounding the pressure tubes, and acts as moderator.

In both cases this all occurs in a big concrete or steel containment structure. The steam is fed to a turbine generator, much the same as those installed in oil or coal-fired power stations. The uranium-fuelled core of a nuclear power reactor simply takes the place of a boiler or furnace burning coal (or other fossil fuel) to generate the steam.

Nuclear electricity output is generally increasing.

In 1997 nuclear electricity generation was 2276 TWh, about the same level as all electricity generated worldwide in 1960, and an increase of 7% over the previous three years. The reasons for the overall growth are several: First, and most obviously, capacity is steadily increasing as **new reactors** come on line, as suggested by Table 6. At the end of 1998 there were 435 nuclear power reactors with a capacity of almost 350 GWe operating in 32 countries, with 30 power reactors (22 GWe) under construction in 14 countries.

Secondly, increased nuclear capacity in some countries is resulting from the uprating of existing plants. Power reactors in USA, Belgium, Sweden, Spain, Switzerland and Germany, for example, have had their generating **capacity increased**.

Thirdly, **capacity or load factors** are improving everywhere, so that more kilowatt hours come from the installed capacity. The average load factor for all plants outside Russia and Ukraine in the last few years has been over 75%, up from 67% in 1992. In 1998 Japanese plants came in at 82% load factor. There are six CANDU reactors in the world's top 20, based on lifetime performance, with capacity factors between 84% and 87%. US nuclear power plant performance, at around 75%, is about the world average. The 1995 improvement in US reactor performance was equivalent to putting three large new power station units on line.

Figure 9A Pressurized water reactor (PWR)

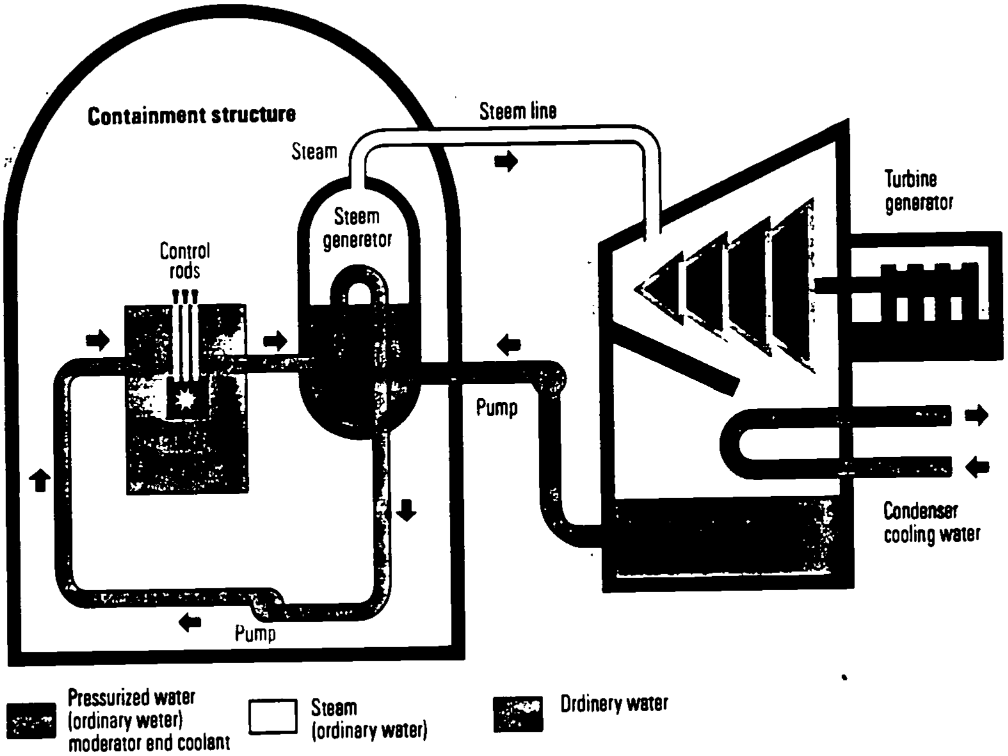


Figure 9B CANDU Pressurized heavy water reactor (PHWR)

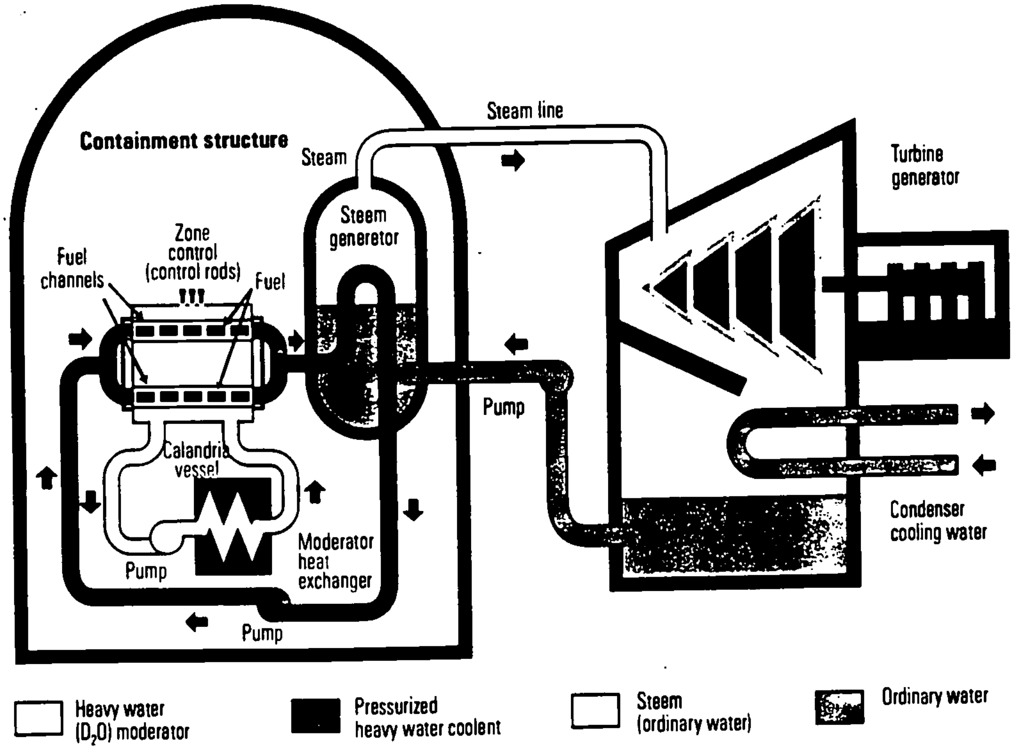


Table 5 Nuclear power plants in commercial operation

Reactor type	Main countries	Number	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia	251	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	95	enriched UO_2	water	water
Gas-cooled Reactor (Magnox & AGR)	UK	35	natural U, enriched UO_2	CO_2	graphite
Pressurised Heavy Water Reactor "CANDU" (PHWR)	Canada	34	natural UO_2	heavy water	heavy water
Light Water Graphite Reactor (RBMK)	Russia	14	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Japan, France, Russia	7	PuO_2 and UO_2	liquid sodium	none
other	Russia, Japan	12			
Total		**448**			

Fuels are oxide, except Magnox: metal. The FBRs are, strictly, prototypes

Source: *Nuclear Engineering International handbook 1997.*

Fourthly, **plant lives are being extended.** Most nuclear power plants originally had a nominal design lifetime of 30 to 40 years, but engineering assessments have established that many plants can operate longer. Extending reactor operating life by replacing major components is often an attractive and cost-effective option for utilities. In USA and Japan most reactors now have confirmed life-spans of over 40 years. When the oldest commercial nuclear power stations in the world, Calder Hall and Chapelcross in the UK, were built in the 1950s, it was assumed that they would have a useful lifetime of 20 years. They are now authorised to operate for 50 years.

New reactor start-ups seem likely to exceed the decommissioning of old reactors at least until early in the 21st century, though most of the new reactors will be in the Asian region.

Some typical concentrations of uranium are:

High-grade orebody	2% U,	20,000 ppm U
Low-grade orebody	0.1% U,	1,000 ppm U
Granite		4 ppm U
Sedimentary rock		2 ppm U
Average in earth's continental crust		1.4 ppm U
Seawater		0.003 ppm U

(ppm = parts per million)

3.3 Uranium availability

Uranium is ubiquitous on the earth.

It is a metal approximately as common as tin or zinc, and it is a constituent of most rocks and even of the sea.

An orebody is, by definition, an occurrence of mineralisation from which the metal is economically recoverable. It is therefore relative to both costs of extraction and market prices. At present neither the oceans nor any granites are orebodies, but conceivably either could become so if prices were to rise sufficiently.

Measured resources of uranium, the amount known to be economically recoverable from orebodies, are thus also relative to costs and prices. They are also dependent on the intensity of exploration effort. Changes in costs or prices, or further exploration, may alter measured resource figures markedly. Thus, any predictions of the future availability of any mineral, including uranium, which are based on current cost and price data and current geological knowledge are likely to be extremely conservative.

With those major qualifications Table 7 gives some idea of our present understanding of uranium resources. It can be seen that Australia has a substantial part (about 25 percent) of the world's low-cost uranium, and Canada 14 percent.

Present measured resources of uranium, are enough to last for well over 45 years.

Table 7 World Uranium Resources

Estimated Recoverable Resources of Uranium

	tonnes U_3O_8	percent of world
Australia	894,000	25%
Kazakhstan	681,000	19%
Canada	507,000	14%
South Africa	335,000	9%
Namibia	291,000	8%
Brazil	281,000	8%
Russian Fed.	195,000	5%
USA	130,000	4%
World total	**3,638,000**	

Reasonably Assured Resources plus Estimated Additional Resources - category 1, to US$ 80/kg U.

Brazil, Kazakhstan and Russian figures above are 91% of in situ totals.

Source: *Uranium: Resources, Production and Demand 1997*, OECD NEA & IAEA, May 1998.

The world's present measured resources of uranium, in the lower cost category and used only in conventional reactors, are enough to last for well over 45 years. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up. A doubling of price from present contract levels could be expected to create about a tenfold increase in measured resources.

Widespread use of the fast breeder reactor (see 4.2) could increase the utilisation of uranium sixty-fold or more. This type of reactor can be started up on plutonium derived from conventional reactors and operated in closed circuit with its reprocessing plant. Such a reactor supplied with natural uranium for its "fertile blanket", very quickly reaches the stage where each tonne of ore yields 60 times more energy than in a conventional reactor.

Reactor Fuel Requirements

The world's power reactors, with combined capacity of 350 GWe, require some 75,000 tonnes of uranium oxide concentrate from mines (or stockpiles) each year. While this capacity is being run more productively, with higher capacity factors and reactor power levels, the uranium fuel requirement is increasing but not necessarily at the same rate. The factors increasing fuel demand are offset by a trend for higher burnup of fuel and other efficiencies, so demand is steady. (Over the 18 years to 1993 the electricity generated by nuclear power increased 5.5-fold while uranium used increased only just over 3-fold.) It is likely that the annual uranium demand will grow only slightly in the next ten years to 2010.

Fuel burnup is measured in MW days per tonne U (MWd/t), and many countries are increasing the initial enrichment of their fuel (eg from 3.3 to 4.0% U-235) and then burning it longer or harder to leave only 0.5% U-235 in the fuel. This might mean that burnup is increased from 33,000 MWd/t to 45,000 MWd/t. On the other hand low uranium prices mean that enrichment plants are being operated so as to reduce energy requirements and leave more U-235 in the tails*.

Reprocessing of spent fuel from conventional light water reactors (see 5.2) also utilises present resources more efficiently, by a factor of up to 1.3 overall. At present only the (reactor-grade) plutonium arising from reprocessing is used in fresh mixed oxide fuel (MOX), with depleted uranium from enrichment plants. Another factor which may similarly affect uranium demand is a fuel cycle now being developed by Korea and Canada which allows spent light water reactor fuel to be used as CANDU fuel, without chemical reprocessing.

CANDU plants currently operate on natural uranium fuel (0.7% U-235) with burnup of some 7500 MWd/tonne. These plants can be fuelled with slightly enriched uranium fuel (up to 1.2% U-235), increasing burnup to above 20,000 MWd/tonne without significant physical modifications. This will be done as uranium prices significantly increase.

The net result from all this is a small reduction in the amount of uranium required ex-mine to fuel each kilowatt-hour produced.

3.4 Energy inputs to Nuclear Electricity

Any electricity generation requires some energy inputs in mining, concentrating and transporting the fuel, manufacturing and constructing the plant, and dealing with the wastes. No attempt is made to cover this comprehensively here, because figures are difficult to obtain. Energy use in mining and transport is closely

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* Increasing the tails assay from 0.25% to 0.30% U-235 for 3.5% enriched fuel means increasing the input from 7.0 to 7.8 kg per kilogram of enriched output.

related to quantities involved, and any comparison therefore favours uranium. On the other hand the capital-intensive nature of the nuclear fuel cycle is reflected in the plant, and the greater energy inputs to it..

The main energy input to the nuclear fuel cycle for reactors requiring enriched fuel is in enriching uranium (see 4.2), which is very energy-intensive. Considering a 1000 MWe reactor run at 80% and therefore generating 7000 GWh/yr, based on average world data for 1996 (table 6) this would require about 190 tonnes of natural uranium. This might be enriched to produce 24.5 tonnes of uranium fuel at 3.5% U-235, which would need 6.3 GWh of electricity to enrich it in a modern centrifuge plant or up to 250 GWh in an older diffusion plant*. Hence these, the major energy inputs to the nuclear fuel cycle, represent 0.1% or up to nearly 4% of the energy output respectively. Mining, at Ranger, uses energy equivalent to 0.03% of the mine's output in a light water reactor.

This energy input needs to be seen in the light of the contrasting energy outputs from coal and nuclear. Running the 1000 MWe power station for a year at 80% capacity, assuming 33% thermal efficiency and using the data in Table 3, would require 2.5 million tonnes of the best coal (3.1 million tonnes of average domestic Australian black coal) or 170 tonnes of natural uranium. Note the different basis of calculation from the above figures.

In the case of Canadian reactors, enrichment of the fuel is not required but heavy water has to be made, and this requires substantial energy input. In a sense, the water moderator and primary coolant are enriched rather than the fuel. However, this "enrichment" is required only once, and the heavy water stays in use indefinitely.

3.5 Nuclear Weapons as a source of fuel

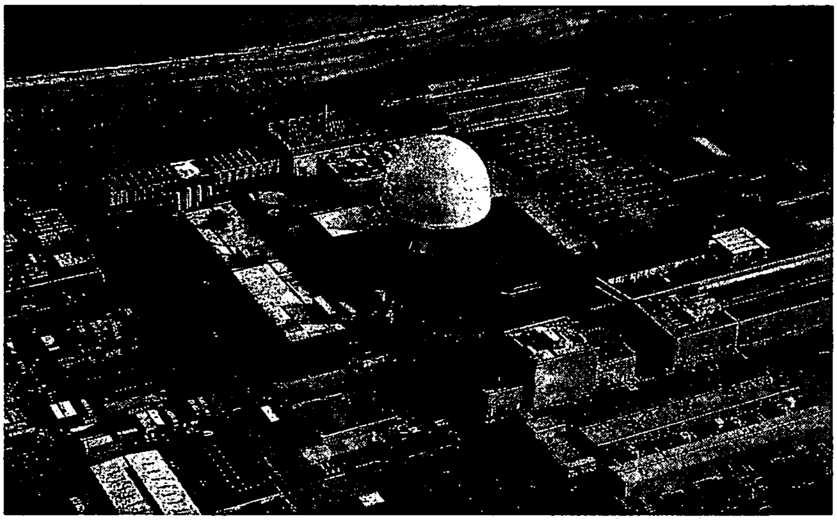
An increasingly important source of nuclear fuel is the world's nuclear weapons stockpiles.

Since 1987 the United States and countries of the former USSR have signed a series of disarmament treaties to reduce the nuclear arsenals of the signatory countries by approximately 80 percent by 2003.

The weapons contain a great deal of uranium enriched to over 90 percent U-235 (ie about 25 times the proportion in light water reactor fuel). Some weapons have plutonium-239, which can be used in diluted form in either conventional or fast breeder reactors.

Uranium

The surplus of weapons-grade highly enriched uranium (HEU) has led to an agreement between the US and Russia for the HEU from Russian warheads and military stockpiles to be diluted for delivery to the United States Enrichment Corporation and then used in civil nuclear reactors. Under the 'swords for ploughshares' deal signed in 1994, the US Government will purchase 500 tonnes of weapons-grade HEU over 20 years from Russia for dilution, for US$ 11.9 billion.



Sizewell B in England. See also Figure 9.

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* At a tails assay of 0.30% U-235 in the enrichment plant, 4.3 SWU per kg of 3.5% enriched product is required, @ 60 kWh/SWU for the modern centrifuge plant or up to 2400 kWh/SWU for the older gaseous diffusion plant. The 24.5 tonnes of enriched fuel would require input of 191 tonnes of natural uranium at this tails assay, or 172 tonnes at 0.25% U-235, which has been the norm. See also section 4.2

Weapons-grade HEU is enriched to over 90% U-235 while light water reactor fuel is usually enriched to about 3-4%. To be used in most commercial nuclear reactors, military HEU must therefore be diluted about 25:1 by blending with depleted uranium (mostly U-238), natural uranium (0.7% U-235), or partially enriched uranium. In CANDU reactors the U-235 concentration would have to be reduced to about 1.2% or less, by blending.

The contracted HEU is being blended down to 4.4% U-235 in Russia, using 1.5% U-235 for this (to minimise the levels of U-234 in the product). The 500 tonnes of weapons HEU will result in about 15 000 tonnes of low-enriched (4.4%) uranium over the 20 years. This is equivalent to about 152 000 tonnes of natural U, more than twice annual world demand.

The purchase and blending down will be done progressively. Up to 1999 it will be at the rate of 10 tonnes per year (equivalent to approximately 3 700 tonnes of uranium oxide production per year), and not less than 30 tonnes per year thereafter. From 2000 the dilution of 30 tonnes of military HEU will displace about 11 000 tonnes of uranium oxide mine production per year which will represent about 17% of the world's reactor requirements.

In addition, the US Government has declared 174 tonnes of highly-enriched uranium (of various enrichments) to be surplus from its military stockpiles, and this will be blended down to about 4300 tonnes of reactor fuel. In the short term the military uranium is likely to be blended down to 20% U-235, then stored. In this form it is not useable for weapons.

Plutonium

Disarmament will also give rise to some 150-200 tonnes of weapons-grade plutonium. Discussions are progressing as to what should be done with it. The present options for the disposal of weapons-grade plutonium are:

- Vitrification with high-level waste - treating plutonium as waste.
- Fabrication with uranium oxide as a mixed oxide (MOX) fuel for burning in existing reactors.
- Fuelling fast-neutron reactors.

The US Government has declared 38 tonnes of weapons-grade plutonium to be surplus, and is exploring the first two of these options for it. There is wide support for burning it as a mixed oxide fuel in conventional reactors, but the novelty of this for the US will mean regulatory and technical delays. Meanwhile the US is developing a "spent fuel standard", which means that plutonium should never be more accessible than if it is incorporated in spent fuel.

However, Europe has a well-developed MOX capacity and Japan is developing its use. This suggests that weapons plutonium could be disposed of relatively quickly. Input plutonium would need to be about half reactor grade and half weapons grade, but using such MOX as 30% of the fuel in one third of the world's reactor capacity would remove about 15 tonnes of warhead plutonium per year. This would amount to burning 3000 warheads per year to produce 110 billion kWh of electricity, - enough for two thirds of Australia's needs.

Over 35 reactors in Europe are licensed to use mixed oxide fuel, and 20 French reactors are using it or licensed to use it as 30% of their fuel. CANDU reactors are well suited to burn MOX fuel, and development of this is planned, using US-supplied MOX.

Russia intends to use its plutonium as a fuel, burning it in fast neutron reactors. If used in fast neutron reactors in conjunction with the depleted uranium from enrichment plant stockpiles,* there would be enough to run the world's commercial nuclear electricity programs for several decades without any further uranium mining.

3.6 Thorium as a nuclear fuel

Most of this book is concerned with uranium as a fuel for nuclear reactors. However, thorium can also be utilised as a fuel for CANDU reactors or in reactors specially designed for this purpose. The thorium fuel cycle has some attractive features, and is described further in Section 4.5.

Neutron efficient reactors, such as CANDU, are capable of operating on a thorium fuel cycle, once they are started using a fissile material such as U-235 or Pu-239. Then the thorium (Th-232) captures a neutron in the reactor to become fissile uranium (U-233), which continues the reaction.

* When uranium is enriched for a conventional reactor about seven times more depleted uranium is produced than the enriched product. If uranium is enriched to 93% U-235 for a weapons programme about 200 times more depleted uranium than enriched product is produced. All this, comprising a very large proportion of all uranium ever mined, is "fertile" material and thus potential fast breeder fuel.

Thorium is about three times as abundant in the earth's crust as uranium. Australian mineral sands, especially in Victoria and Western Australia, contain considerable quantities of thorium.

3.7 Research Reactors

Along with the electricity production focus of this booklet, it is relevant to note that in addition to over 470 commercial reactors operating or under construction, there are some 280 research and/or isotope production reactors operating in 54 countries. These are mostly much smaller than those used for electricity production, but they nevertheless need fuel and produce wastes. Apart from actual research, they are used to produce medical isotopes and other radioactive sources for industry.

3.8 Nuclear Powered Ships

Nuclear energy is particularly suitable for vessels which need to be at sea for long periods without refuelling, or for powerful and fast submarine propulsion. Following the end of the Cold War, there are still some 250 ships powered by more than 400 small nuclear reactors. Most of these are submarines, but they range from icebreakers to aircraft carriers. Their reactors are pressurised water types with special fuel and design which enables them to go at least ten years between refuelling.

The nuclear-powered submarines are able to maintain submerged speeds of up to 25 knots for weeks on end, which revolutionised their role. The navies of USA, Britain, France, Russia and China use nuclear-powered vessels.

Many nuclear-powered submarines have been decommissioned in the 1990s due both to obsolescence and arms reductions. In the USA, after defuelling the reactor compartments are simply cut away from the rest and are sent to low-level waste disposal sites (see chapter 5). In Russia however there are notorious problems apparently due to political and economic constraints. In the UK at this stage obsolete nuclear-powered vessels are simply defuelled.

3.9 Other applications of nuclear energy

Apart from marine propulsion and research reactors, few nuclear plants (totalling about 5 MW thermal) are being used for non-electric applications. However, the potential is great in areas such as desalination and the petroleum industry, for refining and for enhancing extraction of oil from the ground and from tar sands. Water cooled reactors can provide heat up to 300°C, and other experimental types such as the High Temperature Gas Reactor and Molten Salt Reactor, to more than 900°C. There is considerable experience in cogeneration, using heat as a by-product of electricity generation, in many countries.

3.10 Accelerator-driven systems

The essence of a conventional nuclear reactor is the controlled fission chain reaction of U-235 and Pu-239. This depends on having a surplus of neutrons to keep it going (a U-235 fission requires one neutron input and produces on average 2.43 neutrons). However, without such a surplus, a nuclear reaction can be sustained by input of neutrons produced by spallation from heavy element targets bombarded by protons in a high-energy accelerator.

If the spallation target is surrounded by a blanket assembly of nuclear fuel, such as fissile isotopes of uranium or plutonium (or thorium which can breed to U-233), there is a possibility of sustaining a fission reaction. This is described as an Accelerator-Driven System (ADS).

In such a subcritical nuclear reactor the neutrons produced by spallation would be used to cause fission in the fuel, assisted by further neutrons arising from that fission. One then has a nuclear reactor which could be turned off simply by stopping the proton beam, rather than needing to insert control rods to absorb neutrons and make the fuel assembly subcritical. The fuel may be mixed with long-lived wastes from conventional reactors.

The other role of a subcritical nuclear reactor or ADS is the destruction of heavy isotopes. In the case of atoms of odd-numbered isotopes heavier than thorium-232, they have a high probability of absorbing a neutron and subsequently undergoing nuclear fission, thereby producing some energy and contributing to the multiplication process. Even-numbered isotopes can capture a neutron, perhaps undergo beta decay, and then fission. This process of converting fertile isotopes to fissile ones is called breeding.

Therefore in principle, the subcritical nuclear reactor may be able to convert all long-lived transuranic elements into (generally) short-lived fission products and yield some energy in the process. But the main benefit would be in making the management and eventual disposal of high-level wastes from nuclear reactors easier and less expensive. However, much of the current interest is in the potential of ADS to burn weapons-grade plutonium, as an alternative to using it as mixed oxide fuel in conventional reactors.

THE "FRONT END" OF THE NUCLEAR FUEL CYCLE

Uranium minerals are always associated with other elements such as radium and radon in radioactive decay chains (see Appendix 2). Therefore, although uranium itself is barely radioactive, the ore which is mined must be regarded as potentially hazardous, especially if it is high-grade ore. The radiation hazards involved however are virtually all due to the associated elements and are similar to those in many mineral sands operations.

Australian uranium mines are mostly open cut and therefore naturally well ventilated. Ore grades at Ranger, as well as at the proposed Jabiluka and Kintyre mines, are less than 0.5% U_3O_8. The Olympic Dam underground mine, with ore grade less than 0.1% U_3O_8, is ventilated with powerful fans.

Canada's three existing mines at Cluff Lake, Key Lake and Rabbit Lake, as well as McClean Lake starting in 1997, are all open cut mines and well ventilated. The three new mines starting in 1999 and later are all underground operations. Two of them, McArthur River and Cigar Lake, are in very high-grade ore and will require special remote-control techniques for mining. There is some underground mining at Cluff Lake, and there will also be some at McClean Lake later.

The ore (i.e. rock containing economically recoverable concentrations of uranium) is crushed and ground. The resulting slurry is then leached, usually with sulphuric acid, to dissolve the uranium (together with some other metals). The solids remaining after the uranium is extracted are pumped as a slurry to the tailings dam, which is engineered to retain them securely. Tailings contain most of the radioactive material in the ore, such as radium.

The leach liquor then goes through a solvent extraction/ precipitation process to remove the uranium from solution as a bright yellow precipitate ("yellowcake"). After high-temperature drying, the uranium oxide (U_3O_8), now khaki in colour, is packed into 200-litre drums for shipment. The radiation level one metre from such a drum of freshly processed U_3O_8 is about half that (from cosmic rays) received by a person on a commercial jet flight.

In Australia, all these operations are undertaken under the Australian Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores.

In Canada, the Atomic Energy Control Board Regulations apply. These set strict health standards for gamma radiation and radon gas exposure* as well as for ingestion and inhalation of radioactive materials. These standards apply to both workers and members of the public.

The gamma radiation comes principally from isotopes of bismuth and lead. The radon gas emanates from the rock (or tailings) as radium decays.** It then decays itself to (solid) radon daughters, which are energetic alpha-emitters. Radon occurs in most rocks and traces of it are in the air we all breathe. However, at high concentrations it is a health hazard since its short half-life means that disintegrations giving off alpha particles are occurring relatively frequently. Alpha particles discharged in the lung can eventually give rise to lung cancer.

A number of precautions are taken at a uranium mine to protect the health of workers:

- Dust is controlled, so as to minimise inhalation of gamma or alpha-emitting minerals. In practice dust is the main source of radiation exposure in a uranium mine. At Ranger it typically contributes 4mSv/yr to a worker's annual dose (see also Table 13).
- Radiation exposure of workers in the mine, plant and tailings areas is limited. In practice radiation levels from the ore and tailings are usually so low that it would be difficult for a worker to come anywhere near the allowable annual dose.
- Radon daughter exposure is limited in an open cut mine because there is sufficient natural ventilation. At Ranger the radon level seldom exceeds one percent of the levels allowable for continuous occupational exposure. In an underground mine a good forced ventilation system is required to achieve the same result, – at Olympic Dam radiation doses are kept below 10 mSv/yr, with an average of about 5 mSv/yr. In Canada doses average about 3mSv/yr.
- Strict hygiene standards are imposed on workers handling the uranium oxide concentrate. If it is ingested it has a chemical toxicity similar to that of lead oxide.*** In effect, the same precautions are taken as in a lead smelter, with use of respiratory protection in particular areas identified by air monitoring.

Since the fifteenth century many miners who had worked underground in the mountains near the present border between East Germany and the Czech Republic contracted a mysterious illness, and many died prematurely. In the late 1800s the illness was diagnosed as lung cancer, but it was not until 1921 that radon gas was suggested as the possible cause. Although this was confirmed by 1939, between 1946 and 1959 much underground uranium mining took place in the USA without the precautions which might have become established as a result of the European experience. In the early 1960s a higher than expected incidence of lung cancer began to show up among miners who smoked. The cause was then recognised as the emission of alpha particles from radon and, more importantly, its solid daughter products of radioactive decay. The miners concerned had been exposed to high levels of radon 10–15 years earlier, accumulating radiation doses well in excess of present recommended levels.

The small unventilated uranium "gouging" operations in the USA which led to the greatest health risk are a thing of the past. In the last 35 years, individual mining operations have been larger, and efficient ventilation and other precautions now protect underground miners from these hazards. Open cut mining of uranium virtually eliminates the danger. There has been no known case of illness caused by radiation among uranium miners in Australia or Canada. While this may be partly due to the lack of detailed information on occupational health from operations in the 1950s, it is clear that no major occupational health effects have been experienced in either country.

After mining is complete most of the orebody, with virtually all of the radioactive radium, thorium and actinium materials, will end up in the tailings

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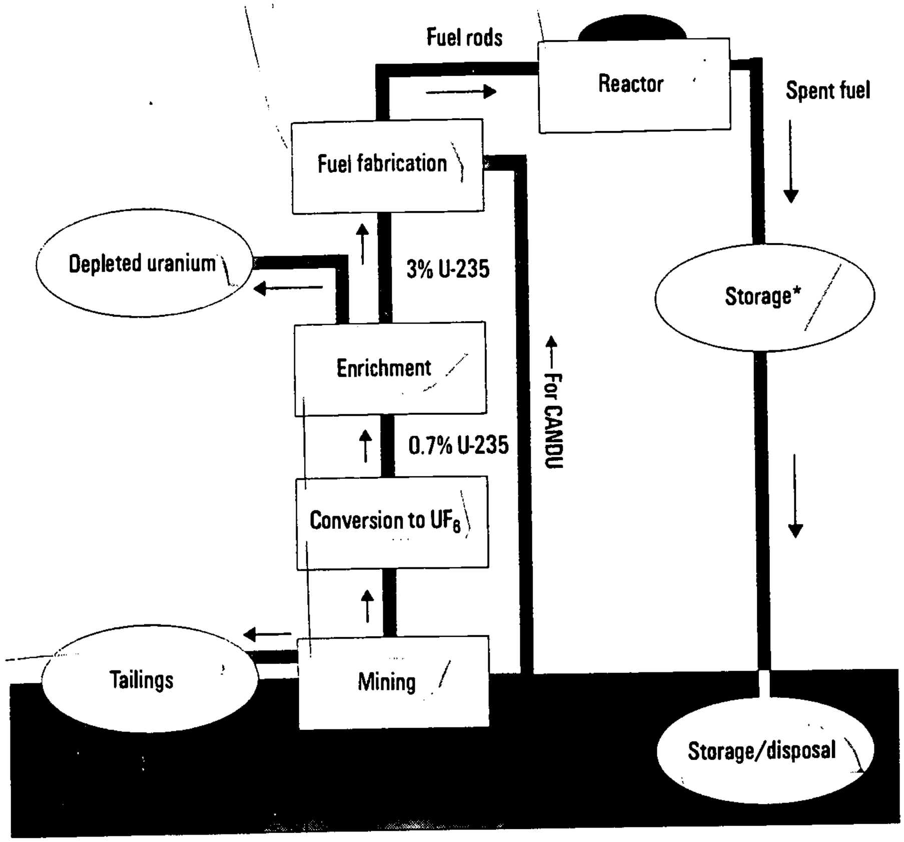
* 20 mSv/yr averaged over 5 years is the maximum allowable radiation dose rate for workers, including radon (and radon daughters) dose. This is in addition to natural background, and excludes medical exposure. See also Appendix 1 and glossary for definitions.

** "Radon" here normally refers to Rn-222. Another isotope, Rn-220 (known as "thoron"), is given off by thorium, which is a constituent of many Australian mineral sands. At Port Pirie in SA a rare earths treatment plant operating between 1968 and 1972 produced tailings containing thorium. These gave rise to minor Rn-220 emissions in addition to Rn-222 emanating from earlier Radium Hill uranium tailings at the same site. See also Appendix 2.

*** Both lead and uranium are toxic and affect the kidney. The body progressively eliminates most Pb or U, via the urine.

Figure 10 The open fuel cycle



dam*. Hence radiation levels and radon emissions from tailings will probably be significant. In the unlikely event of someone setting up camp on top of the material, they could eventually receive a radiation dose exceeding international standards, just as they could from outcropping orebodies. Therefore, the tailings need to be covered over with enough rock, clay and soil to reduce both gamma radiation levels and radon emanation rates to levels near those naturally occurring in the region. A vegetation cover can then be established.

Radon emanation from tailings during mining and before they are covered is sometimes seen as a general environmental hazard. However, traces of radon are emitted by minerals present in most rock and soil. Thus, apart from the local hazards mentioned above, the regional increase in radon release due to mining operations is infinitesimal. If all the Alligator Rivers area deposits in Australia were to be mined simultaneously radon emanations from the area would be increased by only about 2 percent. Considering the whole Northern Territory the increase would be only about 0.1 percent (see also notes on radiation in 6.3).

Process water discharged from the mill contains traces of radium and some other metals which would be undesirable in downstream biological systems. This water is retained and evaporated so that the contained metals are retained in safe storage, as in an orebody. In fact discharged process water is never released to natural waterways. It is treated with lime to precipitate heavy metals, then stored in the tailings dam and evaporated. At Ranger, rainfall run-off in excess of needs is retained, and if necessary it can be released during peak flood times – about one year in ten.**

The former Australian uranium mine at Rum Jungle is best known to some people as a source of water

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* About 95% of the radioactivity in the ore is from the U-238 decay series (see Appendix 2), totalling about 450 kBq/kg in ore with 0.3% U_3O_8 (eg from Ranger). The U-238 series has 14 radioactive isotopes in secular equilibrium, thus each represents about 32 kBq/kg (irrespective of the mass proportion). When the ore is processed, the U-238 and the very much smaller masses of U-234 (and U-235) are removed. The balance becomes tailings, and at this point has about 85% of its original intrinsic radioactivity. However, with the removal of most U-238, the following two short-lived decay products (Th-234 & Pa-234) soon disappear, leaving the tailings with a little over 70% of the radioactivity of the original ore after several months. The controlling long lived isotope then becomes Th-230 which decays with a half life of 77,000 years to radium-226 followed by radon-222. (Alex Zapantis, Supervising Scientist Group, Australia).

** Standards set take into account human consumption of both fish from the rivers and cattle from the flood plains downstream. Radionuclide levels are not to exceed drinking water standards.

pollution. Here the uranium ore was associated with a lot of sulphide mineralisation. In accordance with the low standards of the 1950s, few precautions were taken to prevent river pollution from the site either at the time or following mining*. Large heaps of both waste rock and low-grade ore in the monsoonal climate caused a large amount of acidic run-off, known as acid mine drainage.

4.2 The nuclear fuel cycle

Discussion of fuel cycles involves consideration of the way in which fuel gets to nuclear reactors and what happens to it when it comes out.

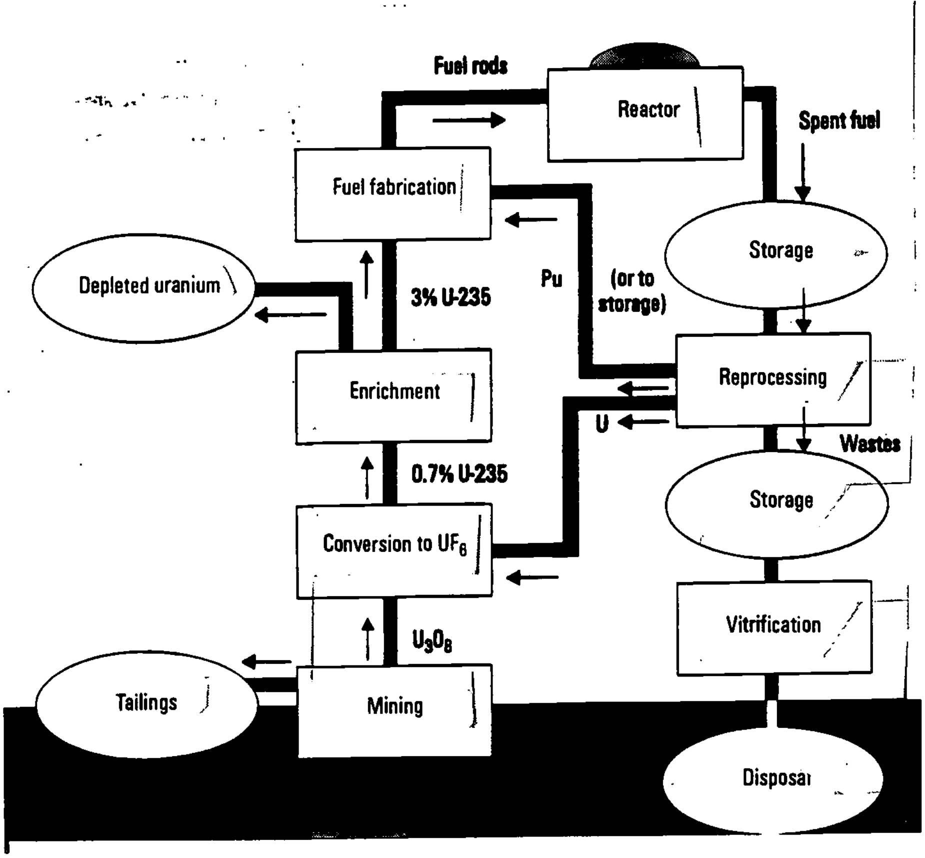
These aspects of nuclear technology together make up what is known as the fuel cycle. As the term suggests it has been the intention with nuclear power to recycle the unused part of the spent fuel so that it is incorporated into the fresh reactor fuel elements.

Unlike coal, uranium ore cannot be fed directly into a power station; it has to be purified, isotopically concentrated (usually) and made up into special fuel rods. Figure 10 shows the so-called "open fuel cycle" for nuclear power, which is the system as it stands today in most countries using the most common kinds of reactors.

Starting in **uranium mines** such as Olympic Dam or Ranger, in Australia, or the northern Saskatchewan mines in Canada, ore is mined and milled to produce uranium in the form of uranium oxide concentrate. It is a mixture of two oxides, commonly known as U_3O_8. This material, a khaki-coloured powder, is shipped to customers. It has the same isotopic ratio as the ore, where U-235 is present to the extent of about 0.7 percent. The rest is a heavier isotope of uranium – U-238 (with traces of U-234). Most reactors, including the common light water type (LWR), cannot run on natural uranium, so the proportion of U-235 must be increased to about 3.5 percent. This is called **enrichment**. (Canadian reactors use unenriched uranium – see below).

Enrichment is a fairly high-technology physical process which requires the uranium to be in the

Figure 11 The closed fuel cycle



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* Metal sulphides in contact with water and air in a warm climate tend to react readily, particularly in the presence of certain bacteria. Sulphuric acid is generated and toxic heavy metals such as copper then go into solution and may be carried downstream.

form of a gas. The simplest way to achieve this is to convert the uranium oxide to uranium hexafluoride, which is a gas at little more than room temperature. This form of uranium is commonly referred to as UF_6 or "hex". Hence the first destination of uranium oxide concentrate from a mine is a **conversion plant** where it is purified and converted to uranium hexafluoride.

The UF_6 is then fed to an **enrichment plant*** which increases the proportion of the fissile uranium-235 (U-235) isotope. In the process about 85% of the uranium feed is rejected as "depleted uranium" or "tails" (mainly U-238) which is stockpiled**. Thus, after enrichment about 15% of the original quantity is available as enriched uranium containing about 3.5 percent U-235.

The enrichment methods now in use are based on the slight difference in atomic mass of U-235 and U-238. Much of the installed capacity relies on the gaseous diffusion process, where the UF_6 gas is passed through a long series of membrane barriers which allow the lighter molecules with U-235 through faster than the U-238 ones. More modern plants use high-speed centrifuges to separate the molecules of the two isotopes.

Enriched uranium then goes on to a **fuel fabrication plant** where the reactor fuel elements are made. The UF_6 is converted to uranium dioxide, a ceramic material, and formed into small cylindrical pellets about 2cm long and 1.5cm in diameter. The pellets are loaded into zirconium alloy or stainless steel tubes about 4 metres long to form fuel rods. These are assembled into bundles about 30cm square to form reactor fuel assemblies. Fuel assemblies of this type are used to power the US-developed light water power reactor, currently the most popular design (see Table 5). A 1000 MWe reactor has about 75 tonnes of fuel in it.

Canadian CANDU (CANadian Deuterium Uranium) reactors have a different design, and run on natural (ie unenriched) uranium. Instead of a single large pressure vessel containing the core, they have multiple (eg 300-600) horizontal pressure tubes, each containing fuel and heavy water coolant. The pressure tubes extend through the reactor vessel, or calandria, which contains the heavy water moderator***. CANDU fuel bundles are only 10cm diameter and 50cm long.

Inside all kinds of operating **reactors** a fission chain reaction occurs in the fuel rods, as described in 3.1. Fast neutrons are slowed by the water or graphite moderator so that they can cause fission. Neutron-absorbing control rods are inserted or withdrawn to regulate the speed of the reaction. Heat from the fission reaction is conveyed from the reactor core and is used to make steam, which in turn is used to generate electricity.

In a light water reactor the fuel stays in the reactor for about three years, generating heat from fission of both the U-235 and also the fissile plutonium (eg Pu-239) which is formed there. After three years or so, the level of fission products and other neutron-absorbers has built up so that the reaction is slowing down, and the spent fuel assemblies are therefore removed. About one third of the fuel is changed each year. In a CANDU type, fuel stays in the reactor only 18 months or so.

When removed, spent fuel is hot and radioactive. It is therefore **stored** under water to remove the heat and to provide shielding from radiation, pending the next step. This may be reprocessing in the case of countries such as UK, France and Japan, which have chosen to close the fuel cycle, or final disposal in the case of countries such as USA and Sweden, which have chosen the "open fuel cycle". Storage is initially at the reactor site. It may then be transferred elsewhere, or to an engineered dry storage facility.

Earlier generations of reactors, such as are still operating in the UK, use uranium metal fuel instead of uranium oxide, and are gas-cooled. For these reactors reprocessing operations have been going on for some time, so that the fuel elements are not held very long in cooling ponds. This, and the corresponding arrangement for light water reactors, is illustrated by the more complicated diagram in Figure 11 which is known as the "closed fuel cycle" system.

In the closed fuel cycle for light water reactors fuel is supplied in exactly the same way as before. Starting with uranium mines and mills the uranium goes through conversion, enrichment, and fuel fabrication to the reactor.

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* Most enrichment has so far been undertaken using the expensive and energy intensive gaseous diffusion process. Newer plants are mostly based on very much more efficient gas centrifuge technology. The next generation of enrichment plants may use advanced laser technology.

** This material cannot be used in current types of reactors, its only significant use is as a feed for fast breeder reactors, or to dilute ex-military uranium, see sections 4.4 & 3.5. It is stored as UF_6 in steel cylinders. Usually less than 0.3% U-235 remains in it.

*** Heavy water, or deuterium oxide, contains deuterium, which is an isotope of hydrogen having a neutron in the nucleus.

But when removed from the reactor the fuel rods are put through a **reprocessing plant** where they are chopped up and dissolved in acid. Various chemical processes recover and separate the two valuable components: plutonium and unused uranium. This leaves about 3% of the fuel as a liquid high-level waste. After solidification it is reduced to a small volume of highly radioactive material suitable for permanent disposal. See also sections 5.2 - 5.3.

About 96% of the uranium which goes into the reactors emerges again in the spent fuel, albeit depleted to less than 1% U-235. As shown in Figure 14 some of the remainder is converted into heat and radioactive fission products and some into plutonium and other actinide elements. Hence reprocessing spent fuel may be economically attractive, to recover the unused uranium and the plutonium which has been generated and not burned in the reactor.

Plutonium comprises about 1% of the spent fuel. It is a very good nuclear fuel which needs no enrichment process, it can be mixed with natural uranium, made into fuel rods in a mixed oxide (MOX) fuel fabrication plant and put back into the reactor as fresh fuel (see 5.2). Alternatively it could be used to fuel future breeder reactors (see below).

The recovered uranium can go back into an enrichment plant and on into fresh fuel for a reactor. The closed fuel cycle is thus a more efficient system for making maximum use of the uranium dug out of the ground (by about 30%, in energy terms) and that is why the industry has favoured this approach. However, due largely to many years of low uranium prices (since about 1980), plans for widespread reprocessing of spent reactor fuel have not eventuated. France, Germany, UK, Russia and Japan are proceeding with the closed fuel cycle for oxide fuels, and across Europe over 35 reactors are licensed to load 20–50% of their core with MOX fuel containing up to 7% reactor-grade plutonium.

4.3 Advanced Reactors

Reactor suppliers in North America, Japan and Europe have nine new nuclear reactor designs at advanced stages of planning and others at a research and development stage.

These incorporate safety improvements including features which will allow operators more time to remedy safety problems and which will provide greater assurance regarding containment of radioactivity in all circumstances. New plants will also be simpler to operate, inspect, maintain and repair, thus increasing their overall reliability and economy.

The next generation reactors:

- have a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time
- are simpler and more rugged in design, easier to operate and less vulnerable to operational upsets
- have higher availability and longer operating life
- will be economically competitive in a range of sizes
- further reduce the possibility of core melt accidents and
- have higher burn-up to reduce fuel use and the amount of waste.

The greatest departure from current designs is that many new generation nuclear plants will have more 'passive' safety features which rely on gravity, natural convection, etc, requiring no active controls or operational intervention to avoid accidents in the event of malfunction.

The new designs fall into two broad categories: evolutionary and developmental. The evolutionary designs are those which are basically new models of existing, proven designs. The developmental designs depart more significantly from today's plants and require more testing and verification before large-scale deployment.

In USA, the Department of Energy (DOE) and the commercial nuclear industry have been developing three advanced reactor types. Two of the three are large (1300 MWe) "evolutionary" designs which build directly on the experience of operating light water reactors in the United States, Japan and Western Europe.

One is an advanced boiling water reactor (ABWR), two examples of which are in commercial operation in Japan. The other type is an advanced pressurised water reactor (System 80+), which is almost ready for commercialisation. Two System 80 reactors under construction in South Korea incorporate many of the design features of the System 80+.

The US Nuclear Regulatory Commission (NRC) gave final design certification for these designs in May 1997.

Table 8 Advanced thermal reactors

Country & developer	Reactor	Size MWe	Design progress	Main Features
US-Japan (GE-Hitachi-Toshiba)	ABWR	1300	Commenced commercial operation in Japan in 1996-7. In US: NRC design certification given in 1997, FOAKE.	• Evolutionary design • More efficient, less waste • Simplified construction (50 months) and operation
USA (ABB-Construction Eng)	System 80+ (PWR)	1300	NRC design certification given in 1997. Some elements in new S. Korean reactors.	• Evolutionary design • Increased reliability • Simplified construction and operation
USA (Westinghouse)	AP-600 (PWR)	600	NRC design approval given in 1998, FOAKE.	• Passive safety features • Simplified construction and operation
USA-Russia (General Atomics - Minatom)	GT-MHR	250-285	Under development by US-Russian-French-Japanese joint venture.	• Ceramic coated fuel particles • Operates at high temperature • High fuel efficiency • Passive safety features
Canada (AECL)	CANDU-9	925-1300	Undergoing regulatory review, prior to approval.	• Evolutionary design • Single stand-alone unit • Flexible fuel requirements • Passive safety features
Canada (AECL)	CANDU-3	480	Design 70% complete, on hold.	• Compact modular plant • 60-year plant life • Faster construction • Enhanced safety features
France-Germany (NPI)	EPR (PWR)	1525-1800	Confirmed as future French standard, final design stage.	• Evolutionary design standard, • Improved safety features
Russia (OKBM)	V-407 V-392 (PWR)	640 1000	construction of first three V-407 units started, two V-392 units planned.	• Passive safety features including double containment • 60-year plant life • Simplified construction and operation
Japan (Mitsubishi)	PWR-21	1400	Basic design in progress.	• Passive safety features • Simplified construction and operation

These are the first such generic certifications to be issued and will be valid for 15 years. Following an exhaustive public process, it means that safety issues within the scope of the certified designs have been fully resolved and hence will not be open to legal challenge during licensing for particular plants.

Another, more innovative US advanced reactor is smaller – about 600 megawatts – and has passive safety features. The AP-600 is being reviewed by the NRC and gained final design approval in 1998.

Separate from the NRC process and beyond its immediate requirements, the US nuclear industry has selected one standardised design in each category – the large ABWR and the medium-sized AP-600, for detailed first-of-a-kind engineering (FOAKE) work. The US$ 200 million program, half funded by DOE, is well advanced. It will give prospective buyers firm information on construction costs and schedules.

Another US design, the Gas Turbine – Modular Helium Reactor, developed from an earlier design, has its fuel as particles coated by ceramic to enable high temperature operation. It is cooled by helium which directly drives a gas turbine, and will be built as modules of 250-285 MWe each. The inert nature of the coolant and resistance of the fuel to melting make the concept attractive. It is being developed by an international partnership in Russia and may be used to burn ex-weapons plutonium.

In Japan, the first of the ABWRs has started operating, as noted above. In relation to PWRs, Mitsubishi has designed an advanced model which is simpler and combines active and passive cooling systems to greater effect. Design work on this 1400 MWe reactor continues and it will be the basis of the next generation of Japanese PWRs.

Canada has two designs under development which are advanced versions of its reliable CANDU-6 reactors. The CANDU-3 is smaller (480 MWe), with faster construction, longer (60-year) plant life and longer fuel life due to slight enrichment (0.9–1.2%) of fuel. However, with the design 70% complete, development effort was transferred to the larger CANDU-9, which is an evolutionary design.

The CANDU-9 (925–1300 MWe) is developed from an existing design but has flexible fuel requirements ranging from natural uranium through slightly-enriched uranium, recovered uranium from reprocessing spent PWR fuel, mixed oxide (U & Pu) fuel, direct use of spent PWR fuel, to thorium, and possibly burning military plutonium or actinides separated from reprocessed LWR waste. A two year regulatory review of the CANDU-9 design is under way.

Table 9 Fast Breeder Reactors

		Output		
		MW (electrical) gross	MW (thermal)	Full operation
USA	EBR 1	0.2		1951-63
	EBR 2	20		1963-94
	Fermi 1	66		1963-72
	SEFOR	20		1969-72
	Fast Flux Test Facility		400	1980-94
UK	Dounreay DFR	15		1959-77
	Dounreay PFR	270		1974-94
France	Rapsodie		40	1966-82
	Phenix *	250		1973-
	Superphenix 1	1240		1985-98
Germany	KNK 2	21		1977-91
India	FBTR		40	1985-
Japan	Joyo		100	1978-
	Monju	246		1994-96
Kazakhstan	BN 350*	135		1972-
Russia	BR5		5	1959-71
	BR 10		10	1971-
	BOR 60	12		1969-
	BN 600*	600		1980-

* Units in commercial operation

Source: OECD NEA 1997. Management of Separated Plutonium

In Europe, under a joint venture with French and German utilities, Nuclear Power International is developing a large (1450 MWe) European pressurized water reactor (EPR). This is an evolutionary design which was confirmed in mid 1995 as the new standard for France, meeting stringent new European safety criteria.

In Russia, several reactor designs, including small floating nuclear power plants, are under consideration. The largest of these is the VVER-1000 model V-392, an evolutionary PWR with passive safety features. A smaller version is the VVER-640 (V-407 type), with Western control systems. The first four of these are being built near St Petersberg and are expected to start up from 2002.

4.4 Fast neutron reactors

Fast neutron reactors are a different technology from those considered so far. They generate power from plutonium by using the uranium-238 in the reactor fuel assembly instead of needing just the fissile U-235 isotope used in most reactors. If they are designed to produce more plutonium than they consume, they are called Fast Breeder Reactors (FBR). If they are net consumers of plutonium they are sometimes called "burners". For many years the focus has been on the potential of this kind of reactor to produce more fuel than they consume, but today, with low uranium prices and the need to dispose of plutonium from military weapons stockpiles, the main interest is in their role as incinerators.

Several countries have research and development programs for Fast Breeder Reactors (FBR), which are, generically, Fast Neutron Reactors. Over 300 reactor-years of operating experience has been gained on this type of plant to mid 1996. See Table 9.

In the closed fuel cycle it can be seen that conventional reactors produce two "surplus" materials; plutonium (from neutron capture, separated in reprocessing) and depleted uranium (from enrichment). The fast neutron reactor uses plutonium as its basic fuel while at the same time converting depleted (or natural) uranium, basically U-238, comprising a "fertile blanket" around the core into fissile plutonium. In other words it "burns" and can "breed" plutonium*, as shown in Figure 13. Depending on the design, it is possible to recover from reprocessing the spent fuel enough fissile plutonium for its own needs, with some left over for future breeder reactors or for use in conventional reactors (see Figure 12).

Fast neutron reactors have a high thermal efficiency due to their high-temperature operation. Cooling is by liquid sodium. Although in many ways this is difficult to handle chemically, in some respects it is more benign overall than very high pressure water. Experiments on a 19 year old UK breeder reactor before it was decommissioned in 1977 showed that the liquid sodium cooling system made it less sensitive to coolant failures than the more conventional very high pressure water and steam systems in light water reactors. More recent operating experience with large French and UK prototypes has confirmed this.

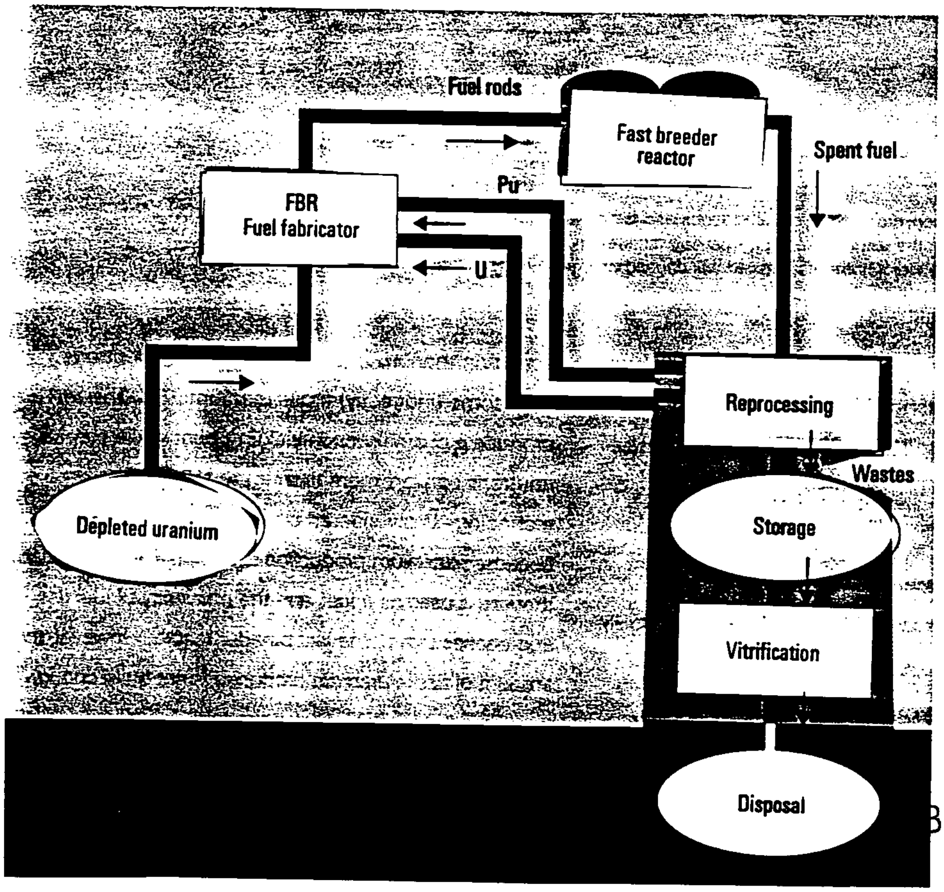
The fast breeder reactor has the potential for utilising virtually all of the uranium produced from mining operations.

As described in 3.2, overall about 60 times more energy can be extracted from the original uranium by the fast breeder cycle than can be produced by the current light water reactors operating in "open cycle". This extremely high energy efficiency makes the breeder an attractive energy conversion system. However, high capital costs and an abundance of low cost uranium means that they are unlikely to be competitive for several decades, probably not much before 2050.

For this reason design work on the 1450 MWe European FBR was phased out in 1994, although research at the 1250 MWe French Superphenix FBR continued after its re-start at the end of 1995. Research continues on the Indian FBRs, to pave the way to greater use of thorium as a fuel, and Japan's Monju prototype commercial FBR was connected to the grid in August 1995 (but was then shut down due to a major sodium leak).

The Russian BN-600 fast breeder reactor has been supplying electricity to the grid since 1980 and has the best operating and production record of all

Figure 12 The fast breeder fuel cycle



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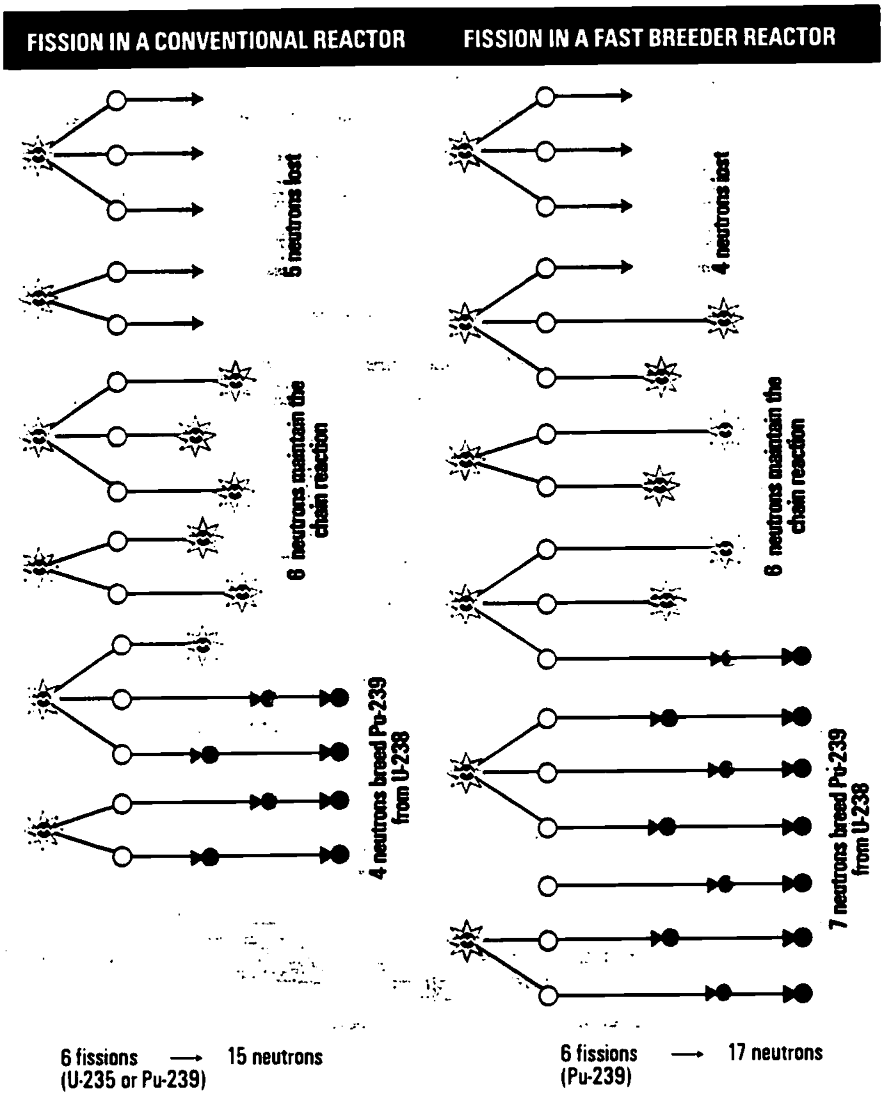
* Both U-238 and Pu-240 are "fertile" (materials), i.e. by capturing a neutron they become (directly or indirectly) fissile Pu-239 and Pu-241 respectively.

Figure 13 Contrast between thermal (eg PWR) and fast neutron reactors



Note: contrast between conventional ("thermal") reactor and fast-breeder reactor showing how typically more neutrons are produced in the fast breeder, thus enabling the system to breed more fissile material than is consumed if desired. The exact numbers involved will depend on design and operation.

Russia's nuclear power units. The BN-350 FBR has been operating in Kazakhstan for about 25 years and about half of its output is used for water desalination. Russia plans to build special fast neutron reactors to utilise the plutonium from its military stockpiles.

About 20 FBRs have already been operating, some since the 1950s, and some supply electricity commercially.

4.5 Thorium cycle

Near-breeder or thorium cycle reactors are similar to fast breeders in that a fertile material, naturally occurring thorium-232, will absorb slow neutrons to become (indirectly) fissile uranium-233. This will produce a chain reaction yielding heat while surplus neutrons convert more thorium to U-233. The technology is considered by some to be attractive because plutonium production is avoided, fairly abundant thorium is used as a fuel, and the efficiency of fuel use approaches that of the fast breeder reactor. However, the amount of fissile uranium produced is not quite enough to sustain the reaction, hence the term "near-breeder" is generally used. Though a focus of interest for 30 years, there are no commercial outcomes in sight.

THE "BACK END" OF THE NUCLEAR FUEL CYCLE

One of the most controversial aspects of the nuclear fuel cycle today is the question of handling and disposal of radioactive wastes.

The most difficult of these are the high-level wastes, and there are two alternative strategies for managing them: reprocessing spent fuel to separate them (followed by vitrification and disposal), or direct disposal of the spent fuel containing them.

The principal wastes remain locked up securely in the ceramic reactor fuel.

As outlined in chapters 3 and 4, "burning" the fuel of the reactor core produces fission products such as barium, strontium, caesium, iodine, krypton and xenon (Ba, Sr, Cs, I, Kr, and Xe). Many of the isotopes formed as fission products within the fuel are highly radioactive, and correspondingly short-lived.

As well as these smaller atoms formed from the fissile portion of the fuel, plutonium-239, Pu-240 and Pu-241, as well as other transuranic isotopes are formed from U-238 in the reactor core by neutron capture and subsequent beta decay. All are radioactive and apart from the fissile plutonium which is "burned", they remain within the spent fuel when it is removed from the reactor. (It is Pu-241 which decays to give us the Americium-241 used in household smoke detectors, for instance, though most transuranic isotopes form the long-lived portion of high-level waste.)

While the civil nuclear fuel cycle generates various wastes, these are not "pollution", since they are contained and managed, otherwise they would be dangerous. In fact, nuclear power is the only energy-producing industry which takes full responsibility for all its wastes and fully costs this into the product. Furthermore, the expertise developed in managing civil wastes is now starting to be applied to military wastes, which pose a real environmental problem in a few parts of the world.

***Radioactive wastes** comprise a variety of materials requiring different types of management to protect people and the environment.*

They are normally classified as low-level, intermediate-level or high-level wastes, according to the amount and types of radioactivity in them.

Another factor in managing wastes is the time that they are likely to remain hazardous. This depends on the kinds of radioactive isotopes in them, and particularly the half lives characteristic of each of those isotopes. The half life is the time it takes for a given radioactive isotope to lose half of its radioactivity. After four half lives the level of radioactivity is 1/16th of the original and after eight half lives 1/256th.

The various radioactive isotopes have half lives ranging from fractions of a second to minutes, hours or days, through to billions of years. Radioactivity decreases with time as these isotopes decay into stable, non-radioactive ones.

The rate of decay of an isotope is inversely proportional to its half life: a short half life means that it decays rapidly. Hence, for each kind of radiation, the higher the intensity of radioactivity in a given amount of material, the shorter the half lives involved.

Three general principles are employed in the management of radioactive wastes:

- concentrate-and-contain
- dilute-and-disperse
- delay-and-decay.

The first two are also used in the management of non-radioactive wastes. The waste is either concentrated and then isolated, or it is diluted to acceptable levels and then discharged to the environment. Delay-and-decay however is unique to radioactive waste management; it means that the waste is stored and its radioactivity is allowed to decrease naturally through decay of the radioisotopes in it.

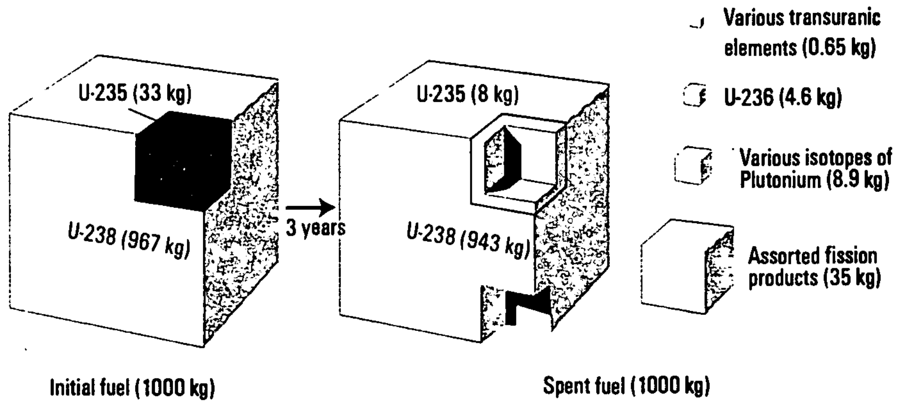
In the civil nuclear fuel cycle the main focus of attention is high-level waste containing the fission products and transuranic elements formed in the reactor core.

The **high-level waste** may be spent fuel itself, or the principal waste arising from reprocessing this. Either way, the volume is modest - about 25-30 tonnes of spent fuel or three cubic metres per year of vitrified waste for a typical large nuclear reactor (1000 MWe, light water type). This can be effectively and economically isolated. Its level of radioactivity falls rapidly. For instance, a newly-discharged light water reactor fuel assembly is so radioactive that it emits several hundred kilowatts of heat, but after a year this is down to 5kW and after five years, to one kilowatt.

If the spent fuel is reprocessed, the 3% of it which emerges as high-level waste is largely liquid, containing the "ash" from burning uranium. It consists of the highly-radioactive fission products and some heavy elements with long-lived radioactivity. It generates a considerable amount of heat and requires cooling. This is vitrified into borosilicate glass (similar to Pyrex) for encapsulation, interim storage, and eventual disposal deep underground. This is the policy adopted by UK, France, Germany and Japan. See sections 5.2 & 5.3 below.

On the other hand, if spent reactor fuel is not reprocessed, all the highly radioactive isotopes remain in it, and so the whole fuel assemblies are treated as high-level waste. The direct disposal option is being pursued by the USA and Sweden, see section 5.4 below.

Figure 14 What happens in a nuclear reactor over 3 years, mass balance



What happens to the fuel in a light water reactor over a three-year period: for every 1000 kg of uranium in the initial fuel load 25 kg of U-235 and 24 kg of U-238 are consumed or altered, reducing the enrichment of the remaining uranium to about 0.8%. The 35 kg of fission products and the 0.65 kg of transuranics other than plutonium become high-level waste. The 8.9 kg of plutonium is the nett amount produced, some undergoes fission. See also Figure 16.

Source: Scientific American, June 1977.

A number of countries, including Canada, have deferred choosing between reprocessing and direct disposal.

High-level wastes make up only 3% of the volume of all radioactive wastes worldwide, but they hold 95% of the total radioactivity in them.

In addition to the high-level wastes, all use of radioactivity generates what are termed **low-level wastes** (cleaning equipment, gloves, clothing, tools, etc.), which are not dangerous to handle but must be disposed of more carefully than normal garbage. Low-level wastes come from hospitals, universities and industry as well as the nuclear power industry. They may be incinerated. Ultimately they are usually buried in shallow landfill sites. Provided all highly toxic materials are first separated and included with high-level wastes, this has been shown to be an effective means of waste management for such relatively innocuous materials. Many countries have final repositories in operation for low level wastes. Low-level wastes have about the same level of radioactivity as a low-grade uranium orebody and amount to over fifty times the volume of the annual arisings of high-level wastes. Worldwide they make up 90% of the volume but have only 1% of the total radioactivity of all radioactive wastes.

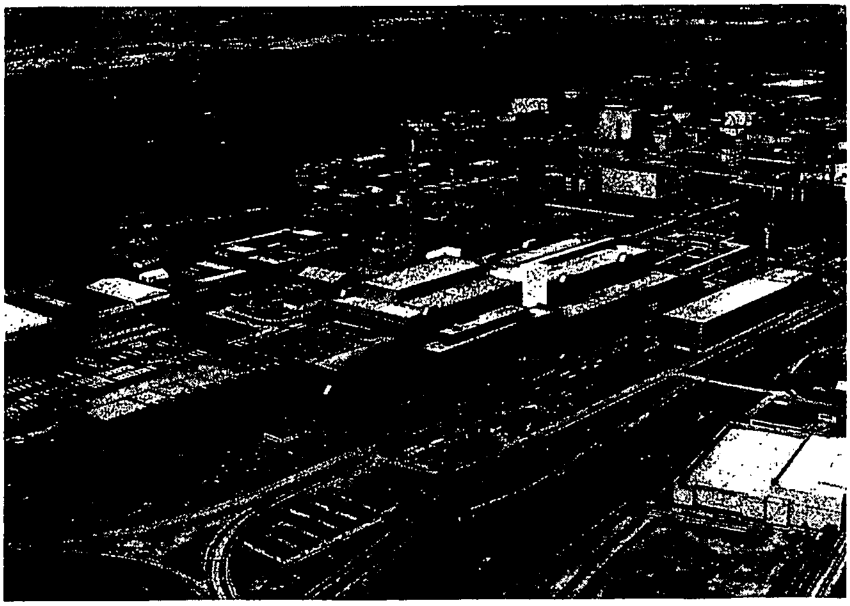
Intermediate-level wastes mostly come from the nuclear industry. They are more radioactive and are shielded from people before treatment and disposal. They typically comprise resins, chemical sludges and reactor components, as well as contaminated materials from reactor decommissioning. Mostly these wastes are embedded in concrete for disposal. Generally short-lived waste (mainly from reactors) is buried, but long-lived waste (from reprocessing nuclear fuel) will be disposed of deep underground. Worldwide it makes up 7% of the volume of radioactive wastes and has 4% of the radioactivity.

5.2 Reprocessing spent fuel

The principal reason for reprocessing is to recover unused uranium and plutonium in the spent fuel elements.

Reprocessing avoids the waste of a valuable resource because most of the spent fuel (uranium at less than 1% U-235 and a little plutonium) can be recycled as fresh fuel elements, saving some 20% of the natural uranium otherwise required. This mixed oxide fuel is an increasingly important resource. The remaining radioactive high-level wastes are then converted into compact, stable, insoluble solids for disposal, which is easier than disposing of the more bulky spent fuel assemblies.

Over the forty years to 1995, more than 55,000 tonnes of spent fuel from commercial power reactors was reprocessed, and annual capacity is now over 5000 tonnes per year.



Thermal Oxide Reprocessing Plant at Sellafield, UK. Photo: BNFL

Table 10 World Commercial Reprocessing Capacity

	tonnes per year
Light water reactor fuel	
France, La Hague	1600
UK, Sellafield (THORP)	1200
Russia, Kyshtym	400
Japan	90
Total	**3290**
Other nuclear fuels	
UK, Sellafield	1500
France, Marcoule	400
India	200
total	2100
Total civil capacity	**5400**

Sources: IAEA 1996 Yearbook, part C and OECD/NEA 1996 Nuclear Energy Data

Spent fuel assemblies removed from a reactor are very radioactive and generating heat. They are therefore put into large tanks or "ponds" of water which cool them and three metres of water over them shields the radiation. Here they remain, either at the reactor site or at the reprocessing plant, for a number of years as the level of radioactivity decreases considerably. For most types of fuel, reprocessing occurs about five years after reactor discharge.

A 1000 MWe light water reactor produces about 25 tonnes of spent fuel per year. This may be transported after initial cooling for six months to a year, using special shielded flasks which hold only a few tonnes of spent fuel but weigh about 80–100 tonnes. Transport of spent fuel and other high-level waste is tightly regulated.

Reprocessing of spent oxide fuel involves dissolving the fuel elements in nitric acid. Chemical separation of uranium and plutonium is then undertaken. The Pu and U are stored or can be returned to the input side of the fuel cycle – the uranium to the conversion plant prior to re-enrichment and the plutonium straight to fuel fabrication. Figure 11 shows reprocessing and fuel fabrication on opposite sides of the diagram – in fact for recycled fuel they are often on a single site.
The remaining liquid after Pu and U are removed is high-level waste, containing about 3% of the spent fuel. It is highly radioactive and continues to generate a lot of heat.

A great deal of reprocessing has been going on since the 1940s, mainly for military purposes, to recover plutonium for weapons. In the UK, metal fuel elements from the first generation gas-cooled commercial reactors have been reprocessed at Sellafield for about 40 years. The 1500 t/yr plant has been successfully developed to keep abreast of evolving safety, hygiene and other regulatory standards. From 1969 to 1973 oxide fuels were also reprocessed, using part of the plant modified for the purpose. A new 1200 t/yr thermal oxide reprocessing plant (THORP) was commissioned in 1994.

In the USA, there is a technical and political saga and no plants are now operating. Three plants for the reprocessing of civilian oxide fuels have been built in USA: the first, a 300 t/yr plant at West Valley, N.Y., was built and operated successfully from 1966–72. However, increasingly severe regulatory requirements meant plant modifications which were deemed uneconomic, and the plant was shut down. The second was a 300 t/yr plant built at Morris, Illinois, incorporating new technology which, although proven on a pilot-scale, failed to work successfully in the production plant. The third was a 1500 t/yr plant at Barnwell, South Carolina which was aborted due to a change in government policy which ruled out all US civilian reprocessing as one facet of US non-proliferation policy. In all, the USA has over 250 plant-years of reprocessing operational experience, the vast majority being at government-operated defence plants since the 1940s.

In France one 400 t/yr reprocessing plant is operating for metal fuels from gas-cooled reactors at Marcoule. At La Hague, reprocessing of oxide fuels has been

Table 11 World Mixed Oxide Fuel Fabrication Capacities

year	1996	2005
Belgium & France	170	205
Japan	10	25+
Russia	-	60
UK	8	120
Total for LWR	**188**	**410**

(tonnes per year)

New plant envisaged for 2005 is under construction, that in UK is due to start in 1998. IAEA projections put 2005 capacity at 430–610 t/yr.

Source: OECD/NEA 1996 Nuclear Energy Data done since 1976, and two 800 t/yr plants are now operating. India has a 150 t/yr oxide fuel plant operating at Tarapur, and Japan is building a major plant at Rokkasho while having most of its spent fuel reprocessed in Europe meanwhile. It has had a small (100 t/yr) plant operating. Russia has a 400 t/yr oxide fuel reprocessing plant at Chelyabinsk.

After reprocessing, the recovered uranium may be handled in a normal fuel fabrication plant (after re-enrichment), but the plutonium must be recycled via a dedicated mixed oxide (MOX) fuel fabrication plant, which will often be integrated with the reprocessing plant which separated it. In France the reprocessing output is coordinated with MOX plant input, to avoid building up stocks of plutonium. (If plutonium is stored for some years the level of Americium-241, the isotope used in household smoke detectors, will accumulate and make it difficult to handle through a MOX plant due to the elevated levels of radioactivity.)

5.3 High-level wastes from reprocessing

Despite the small quantities involved (see 5.1), high-level wastes from reprocessing require very great care in handling, storage and disposal because they contain fission products and transuranic elements which emit alpha, beta and gamma radiation at high levels, as well as a lot of heat. The heat arises mainly from the fission products. These are the materials popularly thought of as "nuclear wastes".

Based on an installed nuclear electricity capacity of one kilowatt per person, each of us in a Western society* would incur an annual waste commitment of about 20 ml of high-level waste from reprocessing. When solidified this would be reduced in volume to about one cubic centimetre. See also Figure 15.

It is worth noting that wastes from weapons programs will continue to dominate the scene in countries like USA and Russia until well into the next century, no matter how rapidly commercial nuclear power expands. The legacy of these, dating from the 1940s, in polluted land, leaking storage tanks and the prospect of very high clean-up costs remains with those countries which produced them.

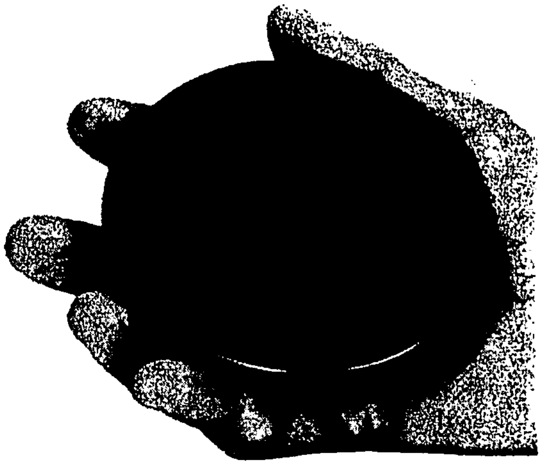
The liquid wastes generated in reprocessing plants are stored temporarily in cooled multiple-walled stainless steel tanks surrounded by reinforced concrete. While modern technology can cope quite safely with short term storage of liquid radioactive wastes, there appears to be universal acceptance of the need to change the potentially mobile liquids into compact, chemically inert solids before considering the question of permanent disposal.

The main method of achieving this is vitrification. The Australian Synroc (synthetic rock) is a more sophisticated way to immobilise such waste, but this has not yet been commercially developed.

Commercial vitrification plants are based on calcining of the wastes (evaporation to a dry powder), followed by incorporation in borosilicate glass. The final solid occupies less than one tenth of the volume of the liquid high-level waste. The molten glass is mixed with the dry wastes and poured into large stainless steel canisters, each holding 400kg. A lid is then welded on. A year's waste from a 1000 MWe reactor is contained in 5 tonnes of such glass, or about twelve canisters each 1.3 metres high and 0.4 metres diameter. In UK these are stored vertically in silos, ten deep.

Processes such as these have been developed and tested in pilot plants since the 1960s. In the UK at Harwell several tonnes of high-level wastes from reprocessed fuel were vitrified by 1966, but research was then set aside until there were enough high-level

Figure 15 Vitrified waste (simulated)



Borosilicate glass from the first waste vitrification plant in UK in the 1960s. This block contains material chemically identical to high-level waste from reprocessing spent fuel. A piece this size from a modern vitrification plant would contain the total high-level waste arising from nuclear electricity generation for one person throughout a lifetime.

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* See Fig 6 and associated footnote.

wastes to give the issue a higher priority. High temperature leaching tests on this glass showed that it has remained insoluble even where some physical breakdown of the glass had occurred. Similar results have been obtained on French wastes vitrified between 1969 and 1972.

Vitrification of civil high-level radioactive wastes first took place on an industrial scale in France in 1978. It is now carried out commercially at five facilities in Belgium, France and UK with capacity of 2500 canisters (1000 tonnes) per year.

In 1996 two vitrification plants were opened in USA. One, at West Valley, NY, was to treat 2.2 million litres of high-level waste from civil nuclear fuel reprocessed there 25 years earlier, and the other was at Savannah River, SC, to vitrify a larger quantity of military waste.

Vitrified wastes will be stored for some time before final disposal, to allow heat and radioactivity to diminish. In general the longer the material can be left before disposal the fewer problems are involved. Depending on the actual disposal methods adopted, there will be some 50 years between reactor and disposal.

All handling of such materials involves the use of protective shielding and procedures to ensure the safety of people involved. As in all situations where gamma radiation is involved, the simplest and cheapest protection is distance - ten times the distance reduces exposure to one percent.

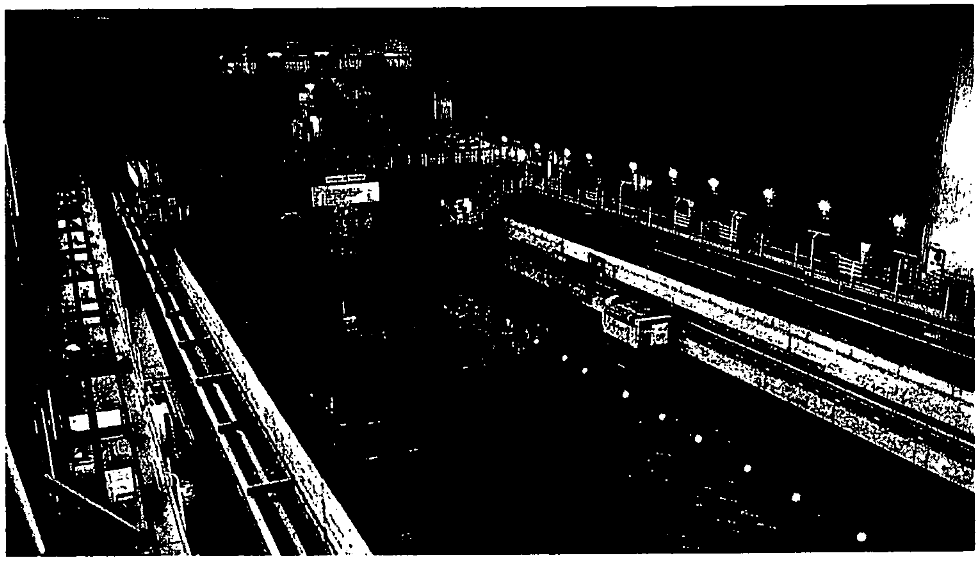
When separated high level wastes (or spent fuel assemblies) are moved from one place to another, robust shipping containers are used. These are designed to withstand all credible accident conditions without leakage or reduction in their radiation shielding effectiveness. Where such containers have been involved in serious accidents over the years they have created no radioactivity hazard at all. The high standards of integrity designed into these containers also makes them difficult to breach with explosives and therefore unattractive as an object for sabotage attempts.

5.4 Storage and disposal of spent fuel as "waste"

The direct disposal option is the US and Swedish policy, though in the latter case it will be recoverable. Sweden has had since 1988 a fully operational central long-term spent fuel storage facility (CLAB) with 5000 tonnes capacity, and fuel is sent to this after storage at the reactor site for only a year or so.

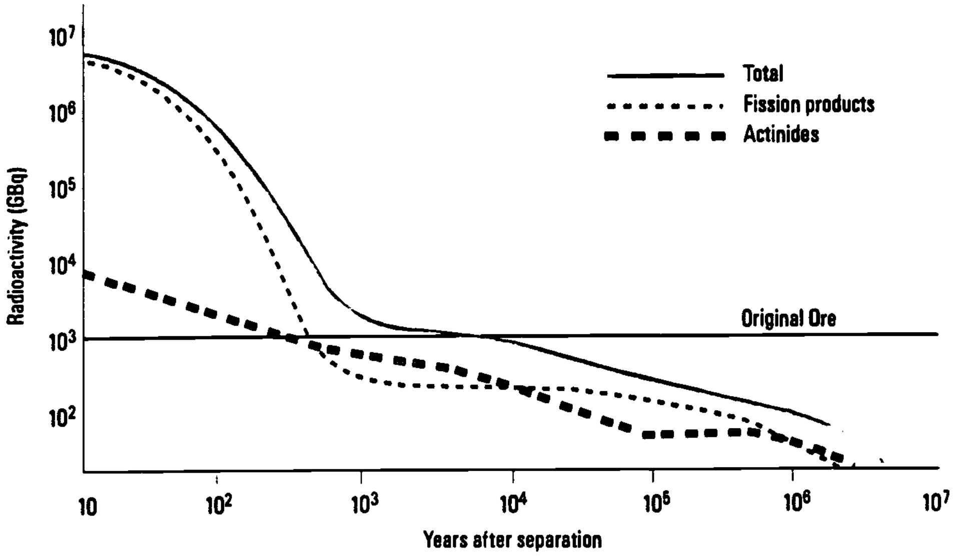
At CLAB the spent fuel is handled under water, for cooling and radiological shielding, and stored for some forty years. By 2020 this storage will be full and a final depository should be ready. Alternatively, some more storage pools can readily be built here.

While separated high-level wastes are vitrified to make them insoluble and physically stable, spent fuel



Storage pond for highly radioactive spent fuel. This is at the THORP plant in the UK, where it is held pending reprocessing. In Sweden a large central facility such as this holds spent fuel for some 40 years pending final disposal.
Photo: BNFL

Figure 16 Total Radioactivity of High-Level Wastes from one tonne of PWR fuel



Basis: compared with the quantity of ore from which that one tonne of fuel was derived.
Source: OECD NEA 1996.

destined for direct disposal is already in a very stable ceramic form as UO_2. In considering the spent fuel itself or the waste extracted from it, an important thing to note is the rate at which it cools and radioactivity decays. Forty years after removal from the reactor less than one thousanth of its initial radioactivity remains, and it is much easier to deal with. This feature sets nuclear waste apart from chemical wastes, which remain hazardous unless they are destroyed. The longer nuclear wastes are stored, the less hazardous they are and the more readily they can be handled.

In USA all spent fuel remains stored at reactor sites, by the utilities, and at present this is as far as the fuel cycle goes. It is intended that spent fuel should be transferred from the reactor site storage ponds or dry cask storage to federal interim storage facilities. Here it will await eventual disposal. Utility customers pay a fee of 0.1 cent per kilowatt hour for management and eventual disposal of their spent fuel. By the end of 1998 this amounted to US$15 billion.

5.5 Disposal of solidified wastes

Whether the final high-level waste is vitrified material from reprocessing or entire spent fuel assemblies, it needs eventually to be disposed of safely. In addition to concepts of safety applied elsewhere in the nuclear fuel cycle, this means that it should not require any ongoing management after disposal. While final disposal of high-level wastes will not take place for some years yet, preparations are being made at a rate appropriate to the nature and quantities of the wastes involved.

As part of an ongoing review of waste management strategies, the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency[*] reassessed the basis for the geological disposal of radioactive waste from an environmental and ethical perspective. Considerations of intergenerational equity were emphasised. In 1995 the Committee confirmed

"that the geological disposal strategy can be designed and implemented in a manner that is sensitive and responsive to fundamental ethical and environmental considerations", and concluded that:

"it is justified, both environmentally and ethically, to continue development of geological repositories for those long-lived radioactive wastes which should be isolated from the biosphere for more than a few hundred years", and that step-by-step "implementation of plans for geological disposal leaves open the possibility of adaptation, in the light of scientific progress and [developing] social acceptability over several decades, and does not exclude the possibility that other options could be developed at a later stage".

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[*] 'The Environmental and Ethical Basis of Geological Disposal of Long-Lived Radioactive Wastes'. OECD/NEA. 1995 (see Appendix 3)

The final disposal of high-level waste must be done with a very high degree of assurance. The question is how sure we can be before it has been undertaken on a large scale over many years? It is apparent that a high level of confidence can in fact be achieved by continuing the careful research and design which has been now going on for some time. The problems involved are neither very large nor exceptionally complicated.

> *First, the separated waste or spent fuel is in a stable and insoluble form. Secondly it is (or will be) encapsulated in heavy stainless steel flasks or in canisters which are corrosion-resistant (e.g. stainless steel and copper). Thirdly it will be geologically isolated.*

The degree of hazard involved is indicated by Figure 16, and the picture would be similar for spent fuel. Two important conclusions can readily be drawn from the changes shown. This first is that the radiological hazard falls by a factor of a thousand between ten and 1000 years, with relatively little change subsequently. This is because nearly all of the short half-life fission products from the chain reaction will have decayed to negligible levels.

This leaves behind small quantities of very heavy "transuranic" elements such as americium and neptunium which generally have much longer half lives. A thousand years is still a long time in human terms, but the object is to put it into stable geological formations where geological time becomes a more meaningful reference. Even the time needed for plutonium to decay to a low level is brief geologically.

The second important point from Figure 16 is that the relative radioactivity of the waste after 1000 years is much the same as that of the corresponding amount of uranium ore. Of course, toxic components of a uranium orebody which outcrops at the surface of the earth actually do find their way into the human food chain. Waste material in glass form buried up to a kilometre below the surface in a dry, stable geological structure will have virtually no conceivable chance of doing so. (However this is not to say that surface uranium deposits are dangerous, as the amounts which reach us are very small.)

Most countries with nuclear facilities planned or operational have active programs aimed at defining and testing suitable disposal sites. The aim of this work is to locate areas where multiple barriers can be established between the wastes and the human environment. Some of the barriers, both natural and artificial, being sought are:

- insoluble form of waste (glass, Synroc or UO_2), see 5.3 & 5.4
- seal in corrosion-resistant containers
- pack with bentonite clay to inhibit groundwater movement and insulate from minor earth movement
- locate deep underground (up to 1 km) in stable rock structure.

Two types of geological structures are being widely studied for this purpose – hard crystalline rocks and rock salt beds. Suitable locations have been defined in several countries and the sites are now undergoing detailed evaluation. Most approaches plan to utilise conventional mining techniques involving shaft-sinking and development of extensive drives and rooms. These will provide sufficient area for the canisters to be placed in suitably-spaced holes in the floor on each level, or some other arrangement.

The problems involved in carrying out this work are essentially technical. Conventional mining and engineering design techniques together with monitoring of rock temperatures and stresses will enable disposal operations to be carried out to a very high order of safety. The engineering and organisational tasks of maintaining effective isolation of hazardous materials are not new.

The question of geological stability of the rock structure is very important for the long term integrity of the waste depository. There are a number of rock structures which have been stable for much of the earth's 4500 million years, which suggest little likelihood of significant movement for isolation periods of 1000 years or more.

It is relevant to compare the toxicity of nuclear wastes with that of common industrial poisons and poisonous gases used every day by industry. Arsenic, of course, is routinely distributed to the environment as a herbicide and in treated timbers. Unlike nuclear wastes, it has an infinite life. Barium is not uncommon, and chlorine is in widespread use. Considering the quantities available, these are arguably more hazardous than nuclear wastes.

There is now little question that disposal of high-level waste, when it comes of age, will be safe. The wastes, though very toxic when first produced, are small in quantity and no more hazardous in total than other more familiar materials. Nevertheless, they have come to epitomise the 'not in my backyard' syndrome of modern society, where we find it easier to accept the benefits of technology and economic development while hoping someone else will grapple with any dirty or unpleasant aspects, however safe they may be.

While each country is responsible for disposing of its own wastes of all kinds, the possibility of an international nuclear waste repository is now being considered. Australia is one country with very suitable geology for such a venture.

A natural analogue: Oklo

Although highly active wastes from modern nuclear power have not yet been buried for long enough to observe the results, this process has in fact occurred naturally in at least one location. At Oklo in Gabon, West Africa, about 2 billion years ago, at least 17 natural nuclear reactors commenced operation in a rich deposit of uranium ore. Each operated at about 20 kW thermal. At that time the concentration of U-235 in all natural uranium was 3.7 percent instead of 0.7 percent as at present.*

These natural chain reactions, started spontaneously by the presence of water acting as a moderator, continued for about 2 million years before finally dying away. During this long reaction period about 5.4 tonnes of fission products as well as 1.5 tonnes of plutonium together with other transuranic elements were generated in the orebody.

The initial radioactive products have long since decayed into stable elements but close study of the amount and location of these has shown that there was little movement of radioactive wastes during and after the nuclear reactions. Plutonium and the other transuranics remained immobile. This is remarkable in view of the fact that ground water had ready access to the wastes and they were not in a chemically inert form (such as glass). However, waste materials do not necessarily move freely through the ground even in the presence of water because of their being adsorbed on to clays.**

Thus the only known "test" of underground nuclear waste disposal, at Oklo, was successful over a long period in spite of the characteristics of the site. Such a water-logged, sandstone/shale structure would not be considered for disposal of modern toxic wastes, nuclear or otherwise, although the clays and bitumen present played an important part in containing the wastes.

However, the Oklo example has prompted researchers to study the mobilisation of uranium dioxide in groundwaters associated with other orebodies (which have not undergone fission). This will assist in assessing the long-term safety of repositories for high-level wastes. One such international analogue study is taking place around the Koongarra deposit in Australia's Northern Territory.

Cost

Finally, the question of cost is important. The OECD has published estimates of waste disposal costs based on the known technology described above. These show that the cost of waste disposal is likely to be about 0.03 to 0.17 cents per kilowatt hour for vitrified high-level waste and 0.04 to 0.18 cents for spent fuel (1993 figures). In the USA, a 0.1 cent/kWh levy to finance the disposal of spent fuel had accumulated US$15 billion by late 1998. Canadian utilities collect a fee of about 0.1 cent/kWh to finance future disposal of spent fuel, and these funds amounted to over C$1.25 billion in 1997. In Sweden a levy of some 0.3 cents/kWh finances the country's smoothly functioning waste repository and research on disposal.

In summary, it is apparent that safe waste management is the norm, that disposal technology exists and that full scale demonstration at acceptable cost will be possible in several countries before long.

5.6 Decommissioning reactors

So far over 300 nuclear reactors have been decommissioned, including over 70 commercial power reactors.

Because it is only in recent years that any larger reactors have closed, only small and medium-sized reactors (up to 330 MWe) have been fully demolished

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* See also Appendix 2. U-235 decays much faster than U-238, whose half-life is about the same as the age of this planet.

** Leaks from the military waste tanks in the USA also demonstrated the ability of clay soils to retain fission products and transuranics.

at this stage, using remote control equipment. The broken-up pieces are buried along with other medium-level waste.

The International Atomic Energy Agency has defined three stages of decommissioning which have been internationally adopted:

Stage 1

This begins at shutdown. The spent fuel (and thus 99% of the radioactivity) is removed from the reactor, the liquid systems are drained, the operating systems are disconnected and the mechanical openings are securely sealed. The facility is kept under surveillance and inspections to ensure that it remains in a safe condition. Stage 1 takes about five years.

Stage 2

All equipment and buildings, outside the reactor core and its biological shielding are dismantled. With the reactor sealed and monitored ("safe storage"), the rest of the site can be released for re-use.

Stage 3

The reactor is completely dismantled and, unless the site, buildings or equipment are to be re-used for nuclear purposes, all materials still containing significant levels of radioactivity are removed and the site released for unrestricted use. No further inspection or monitoring is required - effectively returning the area to "green field" status.

The time taken between Stages 1 and 3 varies considerably between countries and projects. Some utilities have chosen to move immediately to Stage 3 decommissioning (an option called prompt dismantling or "Decon" in the United States), while others have chosen a lengthy period of storage (the US "Safstor" option). This period of storage also varies considerably. Because of this, total decommissioning times vary - from five to ten years maximum in Japan, where land is at a premium and long term storage not practical, to a planned 135 years for some reactors in the UK. In the United States, current regulations allow a period of 60 years for full decommissioning to stage 3.

In the case of nuclear reactors, about 99% of the radioactivity is associated with the fuel which is removed in stage 1. The remaining radioactivity comes from "activation products" such as steel components which have long been exposed to neutron irradiation. Their atoms are changed into different isotopes such as iron-55, cobalt-60, nickel-63 and carbon-14. The first two are highly radioactive, emitting gamma rays. However, their half life is such that after 50 years from closedown their radioactivity is much diminished. Overall, in 100 years after shutdown, the level of radioactivity falls by a factor of 100,000.

To decommission its retired gas-cooled reactors at the Chinon, Bugey and St Laurent nuclear power stations, Electricite de France chose partial dismantling to Stage 2 and postponed Stage 3 dismantling for 50 years. Although complete dismantling was technically possible, the utility preferred the delay, which will result in a significant reduction in residual radioactivity, thus reducing radiation hazard during the eventual dismantling. Improved mechanical techniques are also expected to be available then, again reducing hazards and also costs. As other reactors will continue to operate at those sites, monitoring and surveillance do not add to the cost.

Germany chose direct dismantling over safe enclosure for the closed Greifswald nuclear power station in the former East Germany, where five reactors had been operating. Similarly the site of the 100 MWe Niederaichbach nuclear power plant in Bavaria was declared fit for unrestricted agricultural use in mid 1995. Following removal of all nuclear systems, the radiation shield and some activated materials, the remainder of the plant was below accepted limits for radioactivity and the state government approved final demolition and clearance of the site.

Experience in the United States has varied. Rancho Seco (913 MWe, PWR), which was closed in 1989, will be in Safstor until 2008, when funds will be available for dismantling.

Immediate dismantling was the option chosen for Fort St Vrain, a 330 MWe high temperature gas-cooled reactor which was also closed in 1989. This took place on a fixed-price contract for US$195 million (hence costing less than 1 cent/kWh despite a short operating life) and the project has proceeded on schedule to clear the site and relinquish its licence early in 1997 - the first large US power reactor to achieve this.

A US Decon project was the 60 MWe Shippingport reactor, which operated commercially from 1957 to 1982. It was used to demonstrate the safe and cost-effective dismantling of a commercial scale nuclear power plant and the early release of the site. Defuelling was completed in two years, and five years later the site was released for use without any restrictions. Because of its size, the pressure vessel could be removed and disposed of intact. For larger units, such components will have to be cut up.

The total cost of decommissioning is dependent on the sequence and timing of the various stages of the program. Deferment of a stage tends to reduce its cost, due to decreasing radioactivity, but this is offset by increased storage and surveillance costs.

Even allowing for uncertainties in cost estimates and applicable discount rates, decommissioning contributes less than 5% to total electricity generation costs. For instance, in 1994 Scottish Nuclear made a record profit from operating two nuclear power stations (which supply half of Scotland's electricity) while decommissioning a third. Decommissioning cost was 0.07p/kWh, or 3.2% of the total generating cost of 2.2p/kWh. In the USA, decommissioning costs range from 0.1 to 0.2 cents per kWh.

Financing methods vary from country to country. Among the most common are:

- Prepayment, where money is deposited in a separate account to cover decommissioning costs even before the plant begins operation. This may be done in a number of ways but the funds cannot be withdrawn other than for decommissioning purposes.
- External sinking fund (Nuclear Power Levy): This is built up over the years from a percentage of the electricity rates charged to consumers. Proceeds are placed in a trust fund outside the utility's control. This is the main US system, where sufficient funds are set aside during the reactor's operating lifetime to cover the cost of decommissioning.
- Surety fund, letter of credit, or insurance purchased by the utility to guarantee that decommissioning costs will be covered even if the utility defaults.

ENVIRONMENT, HEALTH AND SAFETY ISSUES

The production of electricity from any form of primary energy has some environmental effect.

A balanced assessment of nuclear power requires comparison of its environmental effects with those of the principal alternative, coal-fired electricity generation.

At a uranium mine ordinary operating procedures normally ensure that there is no significant water or air pollution. The environmental effect of coal mining today is also small except that larger tracts may require subsequent rehabilitation. In certain areas acid drainage can be a problem. The effects of mining are discussed more fully in Section 4.1.

Small amounts of **radioactivity** are released to the atmosphere from both coal-fired and nuclear power stations. In the case of coal combustion small quantities of uranium, radium and thorium present in the coal cause the fly ash to be radioactive, the level varying considerably. Nuclear power stations and reprocessing plants release small quantities of radioactive gases (e.g. argon-41 and krypton-85) and iodine-129 which may also be detectable in the environment with sophisticated monitoring or analytical equipment. Steps are being taken to reduce further emissions of both fly ash from coal-fired power stations and radionuclides from nuclear power stations and other plants. At present neither constitutes a significant environmental problem.

As outlined in Sections 5.3 – 5.5, solid high-level waste from nuclear power stations is stored for 40–50 years while the radioactivity decays to less than one percent of its original level. Then it will be finally disposed of well away from the biosphere. Intermediate-level waste is placed in underground repositories. Low-level waste is generally buried more conventionally. Radioactive fly ash from coal-fired power stations has in the past had a much greater environmental impact largely because it was not perceived as a problem and appropriate action was not taken. Where it is dumped in dams, seepage and run-off needs to be controlled.

Waste heat produced due to the intrinsic inefficiency of energy conversion, and hence as a by-product of power generation, is much the same whether coal or uranium is the primary fuel. The thermal efficiency of coal-fired power stations ranges from about 20 percent to a possible 40 percent, with newer ones typically giving better than 32 percent. That of nuclear stations mostly ranges from 29–38 percent with the common light water reactor giving 32–34 percent. Early UK gas-cooled designs operate at a low temperature and are less efficient (24–28 percent). For a given level of electricity demand there is no reason for preferring one fuel over the other on account of waste heat. This is the case whether power station cooling is by water from a stream or estuary, or using atmospheric cooling towers. In any case this heat need not always be "waste". In colder climates district heating and agricultural uses are increasingly found. These decrease the extent to which local fogs result from the release of heat to the environment.

The main environmental matter relevant to power generation is the production of carbon dioxide (CO_2) and sulfur dioxide (SO_2) as a result of coal-fired electricity generation. When coal of say 2.5 percent sulfur is used to produce the electricity for one European or Japanese person for one year, then about 8 tonnes of CO_2 and 100 kg of SO_2 are produced (see Figure 6). CO_2 is also produced by the combustion of other fossil fuels such as oil and gas.

Sulfur dioxide in large quantities released to the atmosphere can cause (sulfuric) "acid rains" in areas downwind. In the northern hemisphere about 80 million tonnes of SO_2 is released annually from electricity generation, though such pollution is being reduced. The acid rain (rainwater having a pH of 4 and lower) in north-eastern USA and Scandinavia causes ecological changes and economic loss. In the UK and the USA electric power utilities at first sought to minimise this by increasing their use of oil with less sulfur, or natural gas. However, this strategy raises ethical issues due to the value of oil for transport and gas for reticulation to individual homes and industries.

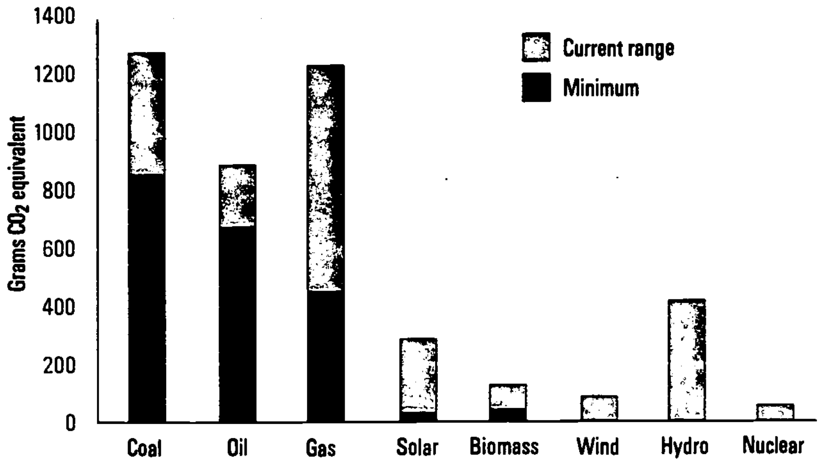
It is possible to remove a lot of the SO_2 from coal stack gases, but the cost is considerable. US power utilities however are spending many billions of dollars on this. On the other hand, between 1980 and 1986 French SO_2 emissions were halved by replacing fossil fuel power stations with nuclear. At the same time electricity production increased 40 percent and France became a significant exporter of electricity.

Oxides of nitrogen (NOx) from fossil fuel power stations are also an environmental problem. If high levels of hydrocarbons are present in the air, such as from motor vehicles, oil refineries and industries using solvents, nitrogen oxides react with these to form photochemical smog. Also, oxides of nitrogen have an adverse effect on the earth's ozone layer, thereby increasing the amount of ultra-violet light transmitted to the earth's surface.

6.2 The Greenhouse Effect

This term refers to the effect of certain trace gases in the earth's atmosphere so that long-wave radiation such as heat from the earth's surface is impeded. A build-up of "greenhouse gases", notably CO_2,

Figure 17 Greenhouse gas emission factors for electricity



Source: IAEA

appears to be causing a warming of the climate in many parts of the world, which if continued will cause changes in weather patterns and other profound changes. Much of the greenhouse effect is due to carbon dioxide.*

While our understanding of relevant processes is advancing, we do not know how much carbon dioxide the environment can absorb, nor how long-term global CO_2 balance is maintained. However, scientists are increasingly concerned about the slow worldwide build-up of CO_2 levels in the atmosphere. This is occurring as the world's carbon-based fossil fuels are being burned and rapidly converted to atmospheric CO_2 e.g. in motor vehicles, domestic and industrial furnaces, and electric power generation. Progressive clearing of the world's forests also contributes to the greenhouse effect, by diminishing the removal of atmospheric CO_2 by photosynthesis.

As early as 1977 a USA National Academy of Sciences report concluded that "the primary limiting factor on energy production from fossil fuels over the next few centuries may turn out to be the climatic effects of the release of carbon dioxide". Today this is conventional wisdom. The global climatic effect of increasing CO_2 levels is now a very significant factor in the comparison of coal and nuclear power, for producing electricity (see Figure 17).

Worldwide emissions of CO_2 from burning fossil fuels total about 25 billion tonnes per year. About 45% of this is from coal and about 40% from oil. Every 1000 MWe power station running on black coal means CO_2 emissions of about 7 million tonnes per year. If brown coal is used, the amount is much greater. If uranium is used in a nuclear reactor these emissions do not occur.

Every 25 tonnes of uranium (30t U_3O_8) used** saves about one million tonnes of CO_2 relative to coal.

There is now widespread agreement that we need resource strategies which will minimise CO_2 build-up. In respect to base load electricity generation, increased use of uranium as a fuel is the most obvious such strategy. Scope for energy conservation is unlikely to be as great in the next decade as since the mid 1970s, because most of the easy and cost-effective steps have already been taken.

6.3 Health effects and radiation

Once again, it is necessary, in relation to health effects and risks, to look not only at nuclear electric power but also the main alternative means of energy conversion: coal fired power plants. Both occupational and environmental health effects are considered, along with risks.

Traditionally **occupational health** risks have been measured in terms of immediate accident fatality rates. However, today, and particularly in relation to nuclear power, there is an increased emphasis on less obvious or delayed effects of exposure to cancer-inducing substances, radiation, etc.

Many occupational accident statistics have been generated over the last 40 years of nuclear reactor operations in USA and UK. These can be compared with those from coal-fired electricity generation. All show that nuclear is distinctly the safer means of electric power generation in this respect. Two simple sets of figures are quoted in Tables 12 and 12A.

Table 12 Comparison of accident statistics in primary energy production

Fuel	Immediate fatalities 1969-86	Who?	Normalised to deaths per Gwy* electricity
Coal	3600	workers	0.34
Natural gas	1440	workers & public	0.17
Oil (transport)	1620	workers & public	0.08
Hydro	3839	public	1.41
Nuclear	31	workers	0.03

* Basis: per 1000 MWe operating for one year, not including plant construction, based on historic data which is unlikely to represent current safety levels in any of the industries concerned.

Sources: Ball, Roberts & Simpson. Res. Report #20, Centre for Environmental and Risk Management, University of East Anglia, 1994.

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* CO_2 constitutes only 0.035% (350ppm) of the atmosphere. An increase from 280 to 350 ppm appears to have already occurred since the beginning of the Industrial Revolution.

** In a light water reactor.

Teble 12A The Hazerds of Using Energy: Some energy-related accidents since 1977

Place	year	number killed	comments
Mexico City	1984	500+	LPG explosion
Italy	1985	250	dam failure
Chernobyl, Ukraine	1986	31+	nuclear reactor accident
Piper Alpha, North Sea	1988	167	explosion of offshore oil platform
Asha-ufa, Siberia	1989	600	LPG pipeline leak and fire
Turkey	1992	270	coal mine methane explosion
Egypt	1994	460	fuel depot hit by lightning
Taegu, S.Korea	1995	100+	gas explosion
Henan, China	1996	84	coal mine methane explosion
Datong, China	1996	114	coal mine methane explosion
Henan, China	1997	89	coal mine methane explosion
Fushun, China	1997	68	coal mine methane explosion
Kuzbass, Siberia	1997	67	coal mine methane explosion
Donbass, Ukraine	1998	63	coal mine methane explosion
Warri, Nigeria	1998	500+	oil pipeline leak and fire
In Australia			
Appin, NSW	1979	14	coal mine methane explosion
Moura, Qld	1986	12	coal mine methane explosion
Moura, Qld	1994	11	coal mine methane explosion

Deaths per million tonnes of coal mined range from 0.1 per year in Australia and USA to 119 in Turkey.

China's total death toll from coal mining averages well over 1000 per year.

In Australia 281 coal miners have been killed in 18 major disasters since 1902, and there have been 112 deaths in NSW mines since 1979, though the Australian coal mining industry is considered the safest in the world.

Sources: media reports

A major reason for coal showing up unfavourably is the huge amount of it which must be mined and transported to supply even a single large power station. Mining and multiple handling of so much material of any kind involves hazards, and these are reflected in the statistics.

Health risks in uranium mining are largely discussed in Section 4.1. Past exposure of miners to radon gas, with a consequent higher incidence of lung cancer, is historically the most noteworthy aspect of this. However, exposure to high levels of radon has not been a feature of uranium (or other) mines for thirty years. Nevertheless, the presence of some radon around a uranium mining operation and some dust with radioactive decay products absorbed must be recognised and compared with the hazards of inhaled coal dust in a coal mine. In both cases, using the best current practice, the health hazards to miners are very small and certainly less than the risks of industrial accidents.

In the nuclear fuel cycle radiation hazards to workers are low, and industrial accidents are few. Certainly nuclear power generation is not completely free of hazards in the occupational sense, but it does appear to be far safer than other forms of energy conversion. Also, since cancer is a common disease in older people there have been, and will continue to be, cancer cases among radiation workers. It does not mean that they are radiation-induced. The occurrence of cancer is not uniform across the world population, and because of local differences it is not easy to see whether or not there is any association between low occupational radiation doses and possible excess cancers. However this question has been studied closely in a number of areas and work is continuing. So far no conclusive evidence has emerged to indicate that cancers are more frequent in radiation workers than in other people of similar ages, where cancer accounts for 15-25 percent of all deaths. At the low levels of exposure and dose rates involved in the nuclear industry, the effects are probabilistic rather than measurable, as described below.

Environmental (non occupational) **health effects** are qualitatively similar to those on workers in the industry: those from ionising radiation being rather better understood than those from air pollution, for example. Popular concern about ionising radiation has been promoted by the testing of nuclear weapons. This has mirrored the strong awareness of those in the nuclear power industry concerning radiation hazards. Fortunately radioactivity is readily measurable and its effects fairly well understood compared with those of other hazards with delayed effects, including virtually all chemical cancer-inducing substances.

The contrast between air quality effects from coal burning for electricity and increased radiation from nuclear power is very marked: a person living next to a nuclear power plant receives less radiation from it than from a few hours flying each year (see Table 13). On the other hand, anyone downwind of a coal-fired power plant can expect it to have an effect on the air quality, possibly even to the extent of affecting health. In some areas coal contains enough radium and thorium to cause coal-fired power stations to release far more radioactivity to the environment than a nuclear power station, though today this is mostly retained in fly ash.

Table 13 shows some typical levels and sources of **radiation exposure**. The contribution from the ground and buildings varies from place to place. Across Canada doses from the ground range from about 500 to 1100 microsieverts per year (µSv/yr). Around Sydney they vary from 160 to 900 µSv/yr, around Armidale, NSW, doses of 2500 µSv/yr are

Table 13 Ionising radiation

The earth is radioactive, though gradually becoming less so as particular isotopes decay. As they decay, ionising radiation is released. As well as the earth's radioactivity we are naturally subject to cosmic radiation from space. In addition to both these, we collect some radiation doses from artificial sources such as X-rays. We may also collect an increased cosmic radiation dose due to participating in high altitude activities such as flying or skiing. The average adult person contains about 13 mg of radioactive potassium-40 in body tissue - we therefore even irradiate one another at close quarters!

The relative importance of these various sources is indicated in the table below.
Types of radiation and units for measuring it are outlined in Appendix 1.

	Typical µSv/yr	Range
Natural		
Terrestrial + house: radon	700	300-100,000
Terrestrial + house: gamma	600	100-1000
Cosmic (at sea level)	300	
+20 for every 100m elevation		0-500
Food, drink & body tissue	300	100-1000
Total	**1900** (plus altitude adjustment)	
Artificial		
From nuclear weapons tests	3	
Medical (X-ray, CT, etc average)	370	up to 25,000
from nuclear energy	0.3	
From coal burning	0.1	
From household appliances	0.4	
Total	**375**	
Behavioural:		
Skiing holiday	8 per week	
Air travel in jet airliner	1.5-5 per hour	up to 5000/yr

The International Commission for Radiological Protection recommends, in addition to background, the following exposure limits:

- for general public 1,000 (ie 1 mSv)
- for nuclear worker 20,000 (ie 20 mSv) averaged over 5 consecutive years

Source: Australian Radiation Laboratory, National Radiation Protection Board (UK), Australian Nuclear Science and Technology Organisation, various common, and around Perth, Western Australia levels range from 20 to 3000 µSv/yr. Citizens of Cornwall, UK, receive an average of about 7000 µSv/yr. The cosmic radiation dose varies with altitude and latitude. Aircrew can receive up to about 5000 µSv/yr from their hours in the air, frequent flyers can score a similar increment. UK citizens receive about 0.3 µSv/yr from nuclear power generation. Appendix 1 gives further background to the topic of radiation and its measurement.

In practice, radiation protection is based on the understanding that small increases over natural levels of exposure are not likely to be harmful but should be kept to a minimum. To put this into practice the International Commission for Radiological Protection (ICRP) has established recommended standards of protection based on three basic principles:

- **Justification**

  No practice involving exposure to radiation should be adopted unless it produces a net benefit to those exposed or to society generally.
- **Optimisation**

  Radiation doses and risks should be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account.
- **Limitation**

  The exposure of individuals should be subject to dose or risk limits above which the radiation risk would be deemed unacceptable.

These principles apply to the potential for accidental exposures as well as predictable normal exposures.

Underlying these is the application of the "linear hypothesis" based on the idea that any level of radiation dose, no matter how low, involves the possibility of risk to human health. This assumption enables "risk factors" derived from studies of high radiation dose to populations (eg from Japanese bomb survivors) to be used in determining the risk to an individual from low doses*. However the weight of scientific evidence does not indicate any cancer risk or immediate effects at doses below 100 millisievert (mSv) per year.

Based on these conservative principles, ICRP recommends that the additional dose above natural background and excluding medical exposure should be limited to prescribed levels. These are: one millisievert per year for members of the public, and 20 mSv per year averaged over 5 years for radiation workers who are required to work under closely-monitored conditions (see Table 13).

The actual **level of individual risk** at the ICRP recommended limit for general public exposure is very small (it could result in about 1 fatal cancer per year in a population of 20,000 people) and impossible to measure directly. Nevertheless, the exposure of large populations to low level radiation is a continuing concern to radiation biologists and health physicists. In the Chernobyl accident (see 6.5), a large number of people were subject to significantly increased radiation exposure, the actual doses being approximately known. In due course this tragedy may result in a better understanding of the effects, if any, of exposure to various levels of radiation. At present most of our knowledge about the effect of radiation on people is derived from the survivors of the Hiroshima and Nagasaki bombings in 1945, where the doses received were difficult to estimate. Certainly there was a clear increase in certain types of leukaemia and lymphoma among the survivors, and of solid cancers as a class.

The body has defence mechanisms against damage induced by radiation as well as by chemical carcinogens. However, typically the body has to deal only with a relatively tiny amount of damage at any one time, as opposed to having to deal with a very large amount at once, as was the case for the bomb survivors. Some allowance has been made for this effect in setting occupational risk estimates and the values quoted incorporate these conservative factors. But the degree of protection for low-level radiation exposure may well be greater than these estimates cautiously allow.

Plutonium is a particular concern. It is separated from spent fuel by reprocessing, as discussed in Section 5.2. Plutonium has been called the most toxic element known to man and therefore represented as a hazard that we should do without. However it is pertinent to compare its toxicity with that of other materials with which we live. If swallowed, plutonium is much less toxic than cyanide or lead arsenate and about twice as toxic as the concentrate of caffeine from coffee. Its main danger comes if inhaled as a fine dust and absorbed through the lungs. This would increase the likelihood of cancer 15 or more years

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* ICRP Publication 60

afterwards, and there has been one documented fatality from plutonium-induced cancer. About seven tonnes of plutonium were dispersed in the upper atmosphere by nuclear weapons testing over the 30 years following World War II without discernible ill effects.

The health effects of exposure both to radiation and to chemical cancer-inducing agents or toxins must be considered in relation to time. We should be concerned not only about the effects on people presently living, but also about the cumulative effects of actions today over many generations. Some radioactive materials released into the environment will decay to safe levels within days, weeks or a few years, others continue their effect for a long time, as do some chemical cancer-inducing agents and toxins. Certainly this is true of the chemical toxicity of heavy metals such as mercury, cadmium and lead, these of course being a natural part of the human environment anyway, like radiation. The essential task for those involved with these in government and industry is to prevent excessive amounts harming people, now or in the future. Standards are set in the light of research on environmental pathways by which people might ultimately be affected.

6.4 Genetic effects

About sixty years ago it was discovered that ionising radiation such as that which continually forms part of our environment could induce genetic mutations in fruit flies. Intensive study since then has shown that radiation can similarly induce mutations in plants and test animals. However experimental evidence for genetic damage to humans from radiation, even as a result of the large doses received by atomic bomb survivors in Japan, indicates that **no such effects have arisen**.

In a plant or animal cell the material (DNA) which carries genetic information necessary to cell development, maintenance and division is the critical target for radiation. Much of the damage to DNA is repairable, but in a small proportion of cells the DNA is permanently altered. This may result in death of the cell or development of a cancer, or in the case of cells forming gonad tissue, alterations which continue as genetic changes in subsequent generations. Most such mutational changes are deleterious, very few can be expected to result in improvements.

The levels of radiation allowed for members of the public and for workers in the nuclear industry are such that any increase in genetic effects due to nuclear power will be imperceptible and probably non-existent. Radiation exposure levels are set so as to prevent tissue damage and minimise the risk of cancer. Experimental evidence indicates that these are more likely than genetic damage. Some 75 000 children born of parents who survived high radiation doses at Hiroshima and Nagasaki in 1945 have been the subject of intensive examination. This study confirms that an increased incidence of genetic abnormalities in human populations is most unlikely as a result of even quite high doses of radiation.

Life on earth commenced and developed when the environment was probably subject to several times as much radioactivity as it is now, so radiation is not a new phenomenon. If we ensure that there is no dramatic increase in people's general radiation exposure, it is most unlikely that genetic damage will suddenly become significant.

6.5 Reactor safety

There have been sophisticated statistical studies made to investigate reactor safety. However, for most people actual performance is more convincing than probability statistics.

> ***The situation to date is that in over 8300 reactor-years of civil operation there has been only one accident to a commercial reactor which was not substantially contained within the design and structure of the reactor.***

And only this one, exemplifying the "worst case" disaster scenario, has resulted in loss of life. This is remarkable for the first four decades of a complicated new technology which is being used in 32 countries, some reactors now operating having been built forty years ago. However, this does not give us grounds to rule out the possibility of another major disaster, even where normal engineering standards have been applied.

Most disaster scenarios involve primarily a loss of cooling. This may lead to the fuel in the reactor core

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overheating and releasing fission products. Hence the provision of emergency core cooling systems on standby. In case these should fail, a further protective barrier comes into play: the reactor core is normally enclosed in structures designed to prevent radioactive releases to the environment. As became evident in 1986, not all Soviet-designed reactors have the same "defence-in-depth" protection. About one quarter of the capital cost of reactors is normally due to engineering designed to enhance the safety of people - both operators and neighbours, if and when things go wrong. Table 14 shows the international scale for reporting nuclear accidents or incidents.

The 1979 accident at Three Mile Island in USA drew attention to the complex engineering involved in minimising the possibility of fuel meltdown and containing other effects of major malfunctions. The total radioactivity release from this accident was small, and the maximum dose to individuals living near the power plant was well below internationally-accepted limits, even though the reactor was written off. Containment works. Nevertheless, this accident had a pronounced psychological effect, was a severe blow to the US nuclear industry and had an adverse effect on the growth of nuclear capacity in USA and beyond.

The 1986 accident at **Chernobyl** in Ukraine was very serious and cost the lives of 31 staff and firefighters, 28 of them from acute radiation exposure. There have also been 800 cases of thyroid cancer in children, most of which were curable, though about ten have been fatal. No increase in leukaemia and other cancers had shown up in the first decade, but the World Health Organisation (WHO) expects some increase in cancers over the next decade, and the death toll from delayed health effects is certain to climb beyond the

Table 14 The International Nuclear Event Scale

For prompt communication of safety significance

Level, Descriptor	Off-Site Impact	On-Site Impact	Defence-in-Depth Degradation	Examples
7 - Major Accident	Major Release: Widespread health and environmental effects			Chernobyl, USSR, 1986
6 - Serious Accident	Significant Release: Full implementation of local emergency plans			
5 - Accident with Off-Site Risks	Limited Release: Partial implementation of local emergency plans	Severe core damage		Windscale, UK, 1957 Three Mile Island, USA, 1979
4 - Accident Mainly in Installation either of:	Minor Release: Public exposure of the order of prescribed limits	Partial core damage. Acute health effects to workers		Saint-Laurent, France, 1980 (fuel rupture)
3 - Serious Incident any of:	Very Small Release: Public exposure at a fraction of prescribed limits	Major contamination Overexposure of workers	Near Accident. Loss of Defence-in Depth provisions	Vandellos, Spain, 1989 (turbine fire, no radio-active contamination)
2 - Incident	nil	nil	Incidents with potential safety consequences	
1 - Anomaly	nil	nil	Deviations from authorised functional domains	
0 - Below Scale	nil	nil	No safety significance	

Source: International Atomic Energy Agency ten or so thyroid cancer victims. About 130,000 people received significant radiation doses (i.e. above ICRP limits), and are being closely monitored by WHO. Radioactive pollution drifted across a wide area of Europe and Scandinavia, causing disruption to agricultural production and some exposure (small doses) to a large population.*

The accident drew public attention to the lack of an adequate containment structure such as is standard on Western reactors. In addition, the RBMK design is such that coolant failure leads to strong increase in power output from the fission process. Under abnormal conditions all reactor types may experience power increases which, are controlled by the reactor shutdown system. Light water reactors, in which the coolant serves as moderator, automatically reduce power when the coolant/moderator is lost, and can then be shut down using the control rods. In CANDU reactors, with separate moderator and coolant, the same level of safety is assured by having two systems that are functionally and physically independent of each other. One is a shutdown system where solid shutoff rods drop from the top and in the other a liquid "poison" is injected into the moderator water. Both have the effect of stopping the chain reaction by absorbing the neutrons.

The Chernobyl accident resulted from a combination of design deficiencies, the violation of operating procedures and the absence of a safety culture. With assistance from the West, significant safety improvements have been made to the 15 RBMK reactors in operation in Russia, Ukraine and Lithuania and the one under construction in Russia. Russian reactor design has since been standardised on PWR types, with containment structures. The destroyed Chernobyl 4 reactor has been enclosed in a large concrete shed. The other three units on the site resumed operation, though two have since shut down.

An OECD expert report on it concluded that "the Chernobyl accident has not brought to light any new, previously unknown phenomena or safety issues that are not resolved or otherwise covered by current reactor safety programmes for commercial power reactors in OECD Member countries."

There have been a number of accidents in experimental reactors and in one military plutonium producing pile, but none of these has resulted in loss of life outside the actual plant, or long-term environmental contamination. The following table (Table 15) of serious reactor accidents includes those in which fatalities have occurred, together with the most serious commercial plant accidents. The list probably corresponds to incidents rating 4 or higher on today's International Nuclear Event Scale (Table 14). It should be emphasised that a commercial-type reactor simply cannot under any circumstances explode like a nuclear bomb.

In an uncontained reactor accident such as at Windscale in 1957 and Chernobyl in 1986, the principal health hazard is from volatile fission products such as iodine-131 and caesium-137. These are biologically active, so that if consumed in food, they tend to stay in organs of the body. I-131 has a half life of 8 days, so is a hazard for the first month or so, (and gave rise to the thyroid cancers after the Chernobyl accident). Cs-137 has a half life of 30 years, however, and is therefore potentially a long term contaminant of pastures and crops. As well as these there is caesium-134 which has a half life of about two years. While measures can be taken to limit human uptake of I-131, (evacuation of area for several weeks, iodine tablets), radioactive caesium can preclude food production from affected land for a long time. Other radioactive materials in a reactor core have been shown to be less of a problem because they are either not volatile (strontium, transuranic elements) or not biologically active (tellurium-132).

Despite the commercial nuclear power industry's impressive safety record and the thorough engineering of reactor structures and systems which make a catastrophic radioactive release from any Western reactor extremely unlikely, there are those who simply don't want to run any risk of this. This fear must then be weighed against the benefits of nuclear power, in the same way that some people's fear of having aeroplanes crash on top of them must be balanced against the utility of air transport for the rest of the population. Ultimately, balancing risks and benefits is not simply a scientific exercise.

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* See: Chernobyl Ten Years On, OECD NEA 1996.

Table 15 Serious reactor accidents

Serious accidents in military, research and commercial reactors. All except Browns Ferry and Vandellos involved damage to or malfunction of the reactor core. At Browns Ferry a fire damaged control cables and resulted in an 18-month shutdown for repairs, at Vandellos a turbine fire made the 17 year old plant uneconomic to repair.

Reactor	Date	Immediate Deaths	Environmental effect	Follow-up action
NRX, Canada (experimental, 40 MWt)	1952	Nil	Nil	Repaired (new core) closed 1992
Windscale-1, UK (military plutonium producing pile)	1957	Nil	Widespread contamination Farms affected (c 1.5 x 10^{15} Bq released)	Entombed (filled with concrete) Being demolished.
SL-1, USA (experimental, military, 3 MWt)	1961	3 operators	Very minor radioactive release	Decommissioned
Fermi-1 USA (experimental breeder, 66 MWe)	1966	Nil	Nil	Repaired, restarted 1972
Lucens, Switzerland (experimental, 7.5 MWe)	1969	Nil	Very minor radioactive release	Decommissioned
Browns Ferry, USA (commercial, 2 x 1080 MWe)	1975	Nil	Nil	Repaired
Three-Mile Island-2, USA (commercial, 880 MWe)	1979	Nil	Minor short-term radiation dose (within ICRP limits) to public	Clean-up program complete, in monitored storage stage of decommissioning
Saint Laurent-A2, France (commercial, 450 MWe)	1980	Nil	Minor radiation release (8 x 10^{10} Bq)	Repaired, (Decomm. 1992)
Chernobyl-4, Ukraine (commercial, 950 MWe)	1986	31 staff and fire-fighters	Major radiation release across Europe and Scandinavia (11 x 10^{18} Bq)	Entombed
Vandellos-1, Spain (commercial, 480 MWe)	1989	Nil	Nil	Decommissioned

AVOIDING WEAPONS PROLIFERATION

Like many other technological innovations, from the outset nuclear technology has been ambiguous. It has enabled humankind to access a virtually unlimited source of energy at a time when constraints are arising on the use of fossil fuels. But it remains also a threat, due to the possibility of military or terrorist use of the technology. The question which frames this chapter is: To what extent and in what ways does nuclear electric power generation contribute to or alleviate the risk from nuclear weapons?

Two nuclear bombs made from uranium-235 and plutonium-239 were dropped on Hiroshima and Nagasaki respectively in August 1945. These brought the long Second World War to a sudden end. The immense and previously unimaginable power of the atom had been demonstrated. There was a large death toll, and survivors have suffered from a slightly increased incidence of cancer.

Nuclear weapons are now in the possession of several nations,* and during the "Cold War" (1950s to 1980s) there was a massive build-up of nuclear armaments, particularly by the USA and the Soviet Union. In the last forty years there have been strenuous international efforts to dissuade other countries from joining the (now) five declared nuclear weapons states. These efforts have been central to the role of one particular body, the International Atomic Energy Agency (IAEA), set up in 1957 by unanimous resolution of the United Nations.

One of the main functions of the IAEA is "to establish and administer safeguards designed to ensure that special fissionable and other materials ... are not used in such a way as to further any military purpose." The IAEA endeavours to detect any diversion of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices. Further, it attempts to deter any such diversion by its capacity for early detection. The IAEA also advises its members on the use of nuclear materials in non-military areas such as agriculture, industry and medicine, and develops safety standards for nuclear power plants.

At the time the IAEA was being established, there was considerable concern that many countries would seek to develop or acquire nuclear weapons, just as they might upgrade their military forces with new equipment.

It was in this context that the cornerstone document governing the spread of nuclear weapons, the Treaty on the Non-proliferation of Nuclear Weapons (Non-Proliferation

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* Weapons states are USA, UK, Russia, France,and China. India, Pakistan and Israel are described as "threshold states", maintaining ambiguity about their nuclear status but generally considered to have nuclear weapons capability. South Africa voluntarily dismantled its weapons program.

Treaty or NPT), was negotiated. The NPT was essentially a deal between the nuclear weapons states and the other countries interested in nuclear technology. The deal was that assistance and cooperation would be traded for pledges, backed by international scrutiny, that no plant or material would be diverted to weapons use. Those who refused to be part of the deal would be excluded from international cooperation or trade involving nuclear technology. The NPT also represented a nuclear truce among non-weapons states, whereby they collectively resolved to turn away from the nuclear weapons option.

The first group of NPT signatories are non-nuclear weapon states. Each must agree not to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices. These states are obliged to conclude agreements with the IAEA for the application of safeguards on the full scope of their nuclear program (see 7.2).

The other NPT signatories are the so-called nuclear weapons states. This group includes those who had manufactured and exploded a nuclear weapon before 1967, and consists of the USA, the Soviet Union (now Russia), the United Kingdom, France and China*. These countries are not required to accept IAEA safeguards, although the NPT does contain certain obligations concerning disarmament which apply to them. All have, however, signed the NPT and accepted some safeguards on their peaceful nuclear activities.

The NPT entered into force in 1970 and was extended indefinitely in 1995. It is complemented by several regional treaties. Recently, other developments have helped to flesh out the non-proliferation regime. In September 1996, a Comprehensive Test Ban Treaty was opened for signature, aimed at the elimination of nuclear weapons testing. Negotiations are underway on a Cut-off convention, which would prohibit the further production of fissile nuclear weapons materials.

7.2 International nuclear safeguards

Over more than 25 years the IAEA's safeguards system under the NPT has been a conspicuous international success. It has involved cooperation in developing nuclear energy for electricity generation, while ensuring that civil uranium, plutonium and associated plant did not allow weapons proliferation to occur as a result of this.

It is important to realise that international nuclear safeguards are focused on the control of fissile materials only. They have nothing to do with engineering or organisational safety aspects of reactors, waste disposal, or transport. These are covered by other international arrangements and conventions. It is also important to understand that nuclear safeguards are a prime means of reassurance whereby non-nuclear weapons states demonstrate to others that they are fulfilling their peaceful commitments. They prevent nuclear proliferation in the same way that auditing procedures build confidence in proper conduct and prevent embezzlement. Their specific objective is to verify whether nuclear material is being used solely for peaceful purposes or not.

In other words, nuclear safeguards are intended to reveal whether a nation is adhering to its undertakings in relation to nuclear fuel materials. It is then up to the world community to bring pressure to bear on such a country if diversion of nuclear materials from its peaceful program is demonstrated. International nuclear safeguards are administered by the IAEA and were formally established under the NPT, which 185 parties plus Taiwan have signed. NPT safeguards require nations to:

- Report to the IAEA what nuclear materials they hold and their location.
- Accept visits by IAEA auditors and inspectors to verify their material reports and physically inspect the nuclear materials concerned to confirm physical inventories of them.
- Co-operate with IAEA in establishing security and surveillance procedures on nuclear materials as required. The IAEA will then monitor the actual surveillance measures.

The IAEA also administers specific safeguard procedures for some countries** that have not joined the NPT. The IAEA safeguards are the principal nuclear control procedures in the world today, and cover almost 900 nuclear facilities and other locations containing nuclear material in 57 non-nuclear-weapons countries. However, other safeguard systems also exist, eg between particular European nations (Euratom Safeguards)

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* France and The People's Republic of China did not ratify the NPT until 1992.

** India, Pakistan, Israel, Cuba and Brazil. The first three have significant nuclear activities which are not subject to IAEA safeguards, although they accept them for some facilities.

Table 16 Plutonium

Formation: U-238 + neutron => U-239 => Np-239 => Pu-239

23.5 min 2.35 day

Pu-239 + neutron => Pu-240
Pu-240 + neutron => Pu-241

One in four neutron absorptions by Pu-239 results in the formation of Pu-240 rather than in fission. Pu-241 and Pu-242 are formed by successive neutron capture in the reactor fuel. After fuel has been in the reactor a couple of years Pu-239 burns almost as fast as it forms, whereas Pu-240 accumulates steadily.

A very small amount of Pu-238 is formed from U-235 by neutron capture.

Amount: A 1,000 MWe reactor generates about 250 kg of plutonium (especially Pu-239) each year. It remains locked up in highly radioactive spent fuel unless reprocessed (see Figure 14). The amount of Pu-240 increases with the time that fuel elements remain in the reactor (see Figure 18). Pu-240 is not fissile in a thermal reactor, but can become fissile Pu-241 by further neutron capture.

Radioactivity: Pu-239 emits alpha particles to decay to U-235 (see appendix 2). Its half-life is 24 390 years, therefore it has a low level of radioactivity. Pu-240 emits alpha particles as it decays to U-236 (an isotope similar to U-238). Its half-life is 6600 years, therefore it has a higher level of radioactivity than Pu-239. It also emits neutrons from spontaneous fission disintegrations, as does Pu-238 (half-life 86 years). Providing protection from this alpha radioactivity involves sealing the plutonium from physical contact, e.g. in a plastic bag.

Uses: The decay heat of Pu-238 (0.56 W/g) enables its use as an energy source in the thermo-electric generators of some cardiac pacemakers, space satellites, navigation beacons, etc. Plutonium power enabled the Voyager spacecraft to send back pictures of distant planets. Pu-240 has been used in similar applications. The main peaceful use of Pu-239 is as nuclear reactor fuel.
Pu-241 (half-life 13 years) is the source, by beta decay, of Americium-241, the vital ingredient in most household smoke detectors.

Type	Composition	Origin	Use
Reactor-grade, from high-burnup fuel	55-60% Pu-239, >19% Pu-240, typically about 30% non-fissile	Comprises about 1% of spent fuel from normal operation of civil nuclear reactors used for electricity generation	As ingredient (c 5%) of MOX fuel for normal reactor, can also be used as fuel in fast neutron reactor
Weapons-grade	Pu-239 with <7% Pu-240	From military "production" reactors specifically designed and operated for production of low burn-up Pu.	Nuclear weapons (can be recycled as fuel in fast neutron reactor or as ingredient of MOX)

or between individual countries such as Australia and the USA, or Japan and USA (bilateral agreements).

These safeguard systems have been effective in preventing any diversion of materials actually covered by them. However, as nuclear power reactors, research reactors and fuel cycle components become more widespread the safeguards task becomes more complex. At the same time more than simply accounting and audit is now expected of the safeguards, and concerns are focused on countries and activities not so far covered by them. Revision and upgrading of safeguards procedures is a continuing process.

For instance, Iraq showed up shortcomings in detection when it mounted an ambitious and clandestine indigenous weapons program which was unrelated to civil nuclear power. This provided the impetus for a thorough reconsideration of what safeguards are expected to achieve, and how they should be implemented beyond the normal trade in civil nuclear materials and related activities. The enhanced safeguards system resulting from this will provide a credible assurance that any undeclared nuclear activities would be detected in NPT countries. The focus of concern and political attention would then be squarely on non-NPT countries, notably Israel, Pakistan and India.

An example of improving safeguards is the agreement reached among nuclear exporting nations in the late

1970s, concerning restriction on sale of sensitive fuel cycle technologies (enrichment, fuel fabrication and reprocessing). Even Iraq found this difficult to get around. Nuclear reactor exports are also placed under tight control by this agreement which stipulates the need for government assurances regarding peaceful use, together with acceptance by customer countries of full safeguards inspections on all present and future nuclear activities.

In May 1997 the IAEA adopted strengthened measures, known as Program 93+2, for use by Agency inspectors who verify states' compliance with their commitments not to produce nuclear weapons. This was in response to a widespread view that, having achieved so much in controlling trade in fissile materials, the IAEA could now look at any nuclear-related materials and technology as possible indicators of undeclared nuclear programs and hence undeclared nuclear materials. It is expected that most or all of the NPT's 186 signatories will eventually agree to these measures, which are detailed in a Protocol through which countries would accept stronger and more intrusive verification on their territory.

The new measures provide increased access for inspectors, both to information about current and planned nuclear programs and to more locations on the ground. Access will not be restricted to declared nuclear sites, but will extend almost anywhere, including high-tech industrial facilities. Inspection activity will include remote surveillance, environmental sampling and monitoring systems at key locations. States accepting the Protocol will need to remove restrictive requirements on inspectors so that they can visit anywhere at short notice.

Today many nations have the necessary trained scientists, experienced chemical technicians and the raw materials to attempt to carry out a moderate weapons production program, if they so desire, as Iraq demonstrated. Certainly the widespread use of nuclear power for electricity generation together with the large numbers of research reactors operating in over fifty countries has resulted in many people being trained and experienced in aspects of the nuclear fuel cycle.

The most important factor underpinning the safeguards regime is political pressure and how particular nations perceive their long term security interests in relation to their immediate neighbours. The solution to weapons proliferation is thus political more than technical, and it certainly goes beyond the question of uranium availability. International pressure not to acquire weapons is enough to deter most states from developing a weapons program. The major risk of nuclear weapons proliferation will always lie with countries which have not joined the NPT and which have significant unsafeguarded nuclear activities. India, Pakistan and Israel are in this category. While safeguards apply to some of their activities, others remain outside the safeguards scrutiny. Australia and Canada are in the forefront of international efforts to address this problem (see 7.5).

7.3 Fissile materials

Much popular concern about possible weapons proliferation arises from considering the fissile materials themselves. For instance, in relation to the plutonium contained in spent fuel discharged each year from the world's commercial nuclear power reactors, it is correctly but misleadingly asserted that "only a few kilograms of plutonium are required to make a bomb". Furthermore, no nation is without enough indigenous uranium to construct a few weapons (see 3.2).

Table 16 gives some of the important characteristics of plutonium and its use. Plutonium is a substance of varying properties depending on its source. It consists of several different isotopes, including Pu-238, Pu-239, Pu-240, and Pu-241. All of these are "plutonium" but not all are fissile – only Pu-239 and Pu-241 can undergo fission in a normal reactor. Plutonium-239 by itself is an excellent nuclear fuel. It has also been used extensively for nuclear weapons because it has a relatively low spontaneous fission rate and a low critical mass. Consequently plutonium-239, with only a few percent of the other isotopes present, is often called "weapons-grade" plutonium. This was used in the Nagasaki bomb in 1945, and in many of the bombs in world weapons stockpiles.

On the other hand, "commercial" or "reactor-grade" plutonium as routinely produced in all commercial nuclear power reactors, and which may be separated by reprocessing the spent fuel from them, is not the same thing at all. It contains a large proportion – up to 40 percent – of the heavier plutonium isotopes, especially Pu-240, due to it having remained in the reactor for a relatively long time - see Figure 18. This is not a particular problem for re-use of the plutonium in mixed oxide (MOX) fuel for reactors (see 4.2 and 5.2), but it seriously affects the suitability of the material for nuclear weapons. Due to spontaneous fission of Pu-240, only a very low level of it is tolerable in material for making weapons. Design and construction of nuclear explosives based on normal reactor-grade plutonium would be difficult and unreliable, and has not so far been done.* However, safeguards arrangements assume that both kinds of plutonium could conceivably be used for weapons.

It is worth noting that a nuclear reactor which uses mixed oxide input for one third of its fuel is not a net producer of plutonium, and that which emerges in the fuel is even less suitable for weapons use than what is in the fresh MOX fuel.

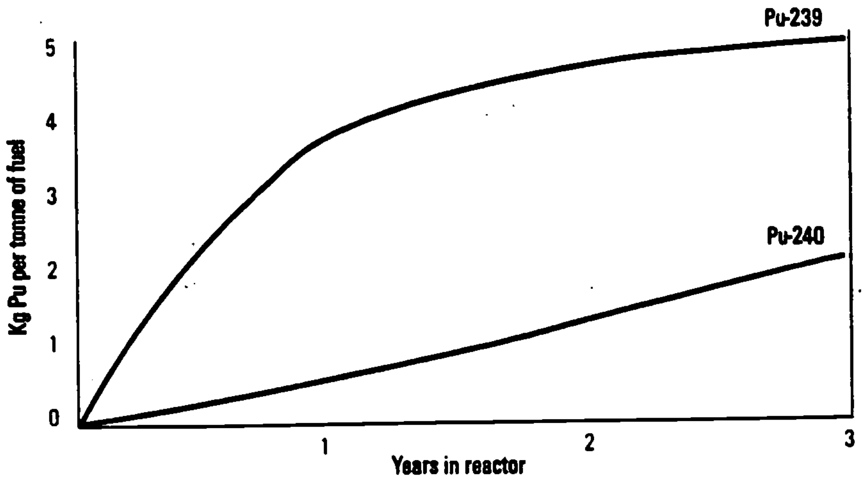
Commercial plutonium is therefore a much less attractive weapons material than plutonium produced in special "production reactors"** designed for producing Pu-239, and which are capable of frequent fuel changing. However, the development of laser enrichment technology may mean that it becomes feasible to enrich commercial plutonium to weapons-grade. Hence safeguards arrangements are set up accordingly to take seriously the proliferation possibilities even of reactor-grade plutonium. (Conventional enrichment cannot be used to separate Pu-239 from Pu-240 because the atomic mass is so similar.)

The plutonium-based fast breeder fuel cycle is seen as having features which might give rise to weapons proliferation problems. On the other hand conventional thermal reactors normally have a higher net yield of plutonium from the fuel cycle (see figures 13 and 14). This suggests that the fast neutron reactor should perhaps be seen more as a plutonium "incinerator" which is likely to mean less plutonium in storage or in spent fuel elements than otherwise.

There are two other fissile materials that could be used for weapons and both are isotopes of uranium. The most common, and the material used to make the 1945 Hiroshima bomb, is uranium-235. This material is produced by enriching natural uranium in an enrichment plant, not to 3 or 4 percent as required for light water reactor fuel, but to 93 percent U-235 or higher.

The other isotope of uranium suitable for use in explosives is U-233. This material is made from thorium-232 fuels in reactors in much the same way as plutonium is made from U-238 in uranium-fuelled reactors (see 4.2). However, the use of thorium-fuelled reactors (see 3.6) has not moved beyond the experimental stage and U-233 is not seen as a significant proliferation problem.

Figure 18 Plutonium in the Reactor Core



Build-up of Pu-239 and Pu-240 in the fuel assemblies of a light water reactor over the 3 years that fuel customarily remains in the core.

Source: Scientific American

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* In 1962 a nuclear device using low-burnup plutonium from a UK power reactor was detonated in USA. The isotopic composition of this plutonium has not been disclosed, but it was evidently about 90% Pu-239.

** or heavy water moderated research reactors, as in India.

Whilst the above materials can be used for explosives manufacture, they are not readily available in any practical sense, and international efforts are designed to make them even less accessible.

In recent years, the international community was challenged by the suspicions of an illicit nuclear weapons program in North Korea based on plutonium production in a research reactor and detected by safeguards inspections. The United Nations imposed a nuclear "freeze" on the country's reactors and facilities in 1994, and a Framework Agreement led to the country bowing to international pressure so that the IAEA could reassure the UN that all nuclear materials were safeguarded and be reasonably confident that nuclear materials were being used for peaceful purposes. The trade-off for North Korea was that an international consortium led by USA, South Korea and Japan is building two large modern nuclear reactors for the country to provide electricity untainted by military possibilities.

Even greater concern was generated by suspicions that Iraq had developed or was developing nuclear weapons; these fears were heightened during the Persian Gulf War. After the cease-fire in 1991, the United Nations was able to confirm that Iraq, though a signatory to the NPT, had been pursuing a clandestine weapons program apart from materials and facilities covered by IAEA inspections. This endeavour was based on indigenous uranium and its enrichment. As noted in 7.2, this situation led to the enhancement of the safeguards regime, through the IAEA's "Program 93+2".

Questions continue as to the nuclear intentions of India, Pakistan and Israel. None of these countries are bound by the NPT, and all are suspected of having or developing nuclear weapons programs. International efforts to encourage these states to abide by the NPT are ongoing.

7.4 Recycling Military Uranium and Plutonium for Electricity

International efforts aimed at nuclear disarmament have, ironically, led to some serious safety and security problems. Dismantling of nuclear warheads under US-Russia disarmament agreements (START 1 and START II) has resulted in an accumulation of weapons-grade material (plutonium and high-enriched uranium). Particularly following the break-up of the Soviet Union, concerns have arisen about the possibility that these fissile materials could be subject to theft, smuggling, trafficking, or could make their way into the hands of rogue states or terrorists. Inadequate control of nuclear materials inside Russia, the sheer size of Russian nuclear programs, and substandard security at nuclear installations are but a few of the factors that increase the likelihood of nuclear materials falling into the wrong hands.

The challenge of isolating and disposing of weapons-grade fissile material, particularly plutonium, that is no longer required for military purposes has therefore become a priority for the international community. The IAEA has been examining policy options concerning the management and use of stocks of military plutonium. The most pressing concern is its protection from theft and diversion, while determining the most appropriate means of disposition*.

The prospect of using weapons-grade plutonium (more than 93% Pu-239) in mixed oxide (MOX) fuel for civil reactors is receiving increased attention. It would be quite feasible to make MOX using a mixture of military and reactor-grade plutonium. This would be the only means of disposal which permanently removes military plutonium from circulation and effectively destroys it. Efforts are currently under way to "recycle" plutonium in this manner, and the so-called "Summit of the Eight", comprising the G-7 countries and Russia, is exploring this option further.

After three decades of concern regarding the possibility of uranium intended for commercial nuclear power finding its way into weapons, we are now seeing military uranium being directed into the civil nuclear fuel cycle for use in commercial nuclear power generation. The first such material from Soviet military warheads arrived in the USA in 1995, and a start has also been made on recycling US weapons-grade uranium for electricity. It is first diluted about 20:1 with depleted uranium left over from enrichment plants, or similar material (see also 3.5).

7.5 Australian and Canadian Nuclear Safeguards policies

Both countries are strong proponents of a robust international non-proliferation regime to enhance national and international security. Both are rigorous in seeking assurances that nuclear exports will only be used for legitimate and peaceful nuclear energy purposes.

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* The production of reactor-grade plutonium in spent fuel from civil reactors, at almost 100 tonnes per year, far exceeds that of weapons-grade plutonium.

Beyond that, Australia's main interest in international nuclear safeguards is in relation to the use of its uranium in overseas nuclear power programs. Canada's interest is broader, covering the whole domestic fuel cycle, plus the export of both uranium and reactor technology. In both countries, exports of uranium are controlled by the federal governments.

Following World War II, Canada pledged that it would not develop nuclear weapons, even though it had, at the time, the capability to do so. Both Canada and Australia participated in the drafting of the Statute of the IAEA, have been continuously represented on the IAEA's Board of Governors, and remain active in many of the various technical committees and advisory groups of the IAEA.

In Australia the Ranger Uranium Environmental Inquiry commissioners pointed out quite clearly in their first report (1976) the importance of adequate safeguard measures being applied to Australia's uranium. The Australian Government then decided on the basic principles of an Australian safeguards policy, and these were announced during 1977. Australia was involved in the International Nuclear Fuel Cycle Evaluation Program in the 1970s and continues to use its status as a uranium supplier to press for high safeguards standards to be applied. In so doing, Australia is allied with Canada, the Western world's largest uranium producer.

Table 17 sets out in summary the main elements of both countries' policies.

The Australian and Canadian policies as outlined are based on the requirements of the Nuclear Non-Proliferation Treaty (NPT) and the IAEA safeguards invoked under it. Superimposed on these are additional conditions which are required by bilateral agreement with customer countries[*] and implemented by the Australian Safeguards Office (ASO) or the Canadian Atomic Energy Control Board (AECB) respectively.

Both countries' legally-binding bilateral safeguard measures are directed towards preventing any unauthorised or clandestine use of exported uranium or any materials derived from it - "Australian-obligated nuclear materials" or the Canadian equivalent. The Canadian agreements cover nuclear material, heavy water, nuclear equipment and technology. The bilateral safeguards are designed to deter possible diversion of fissile material or misuse of equipment and technology more effectively than standard IAEA safeguards on their own.

The Canadian federal nuclear control agency is the Atomic Energy Control Board. The AECB is responsible

Table 17 Australian and Canadian nuclear safeguards policies

1. **Selected countries**
    - Non-weapon states must be party to NPT and must accept full-scope IAEA safeguards applying to all their nuclear-related activities.
    - Weapon states to give assurance of peaceful use, IAEA safeguards to cover the material.
2. **Bilateral agreements are required**
    - IAEA to monitor compliance with IAEA safeguards and Australian or Canadian requirements
    - Fallback safeguards (if NPT ceases to apply or IAEA cannot perform its safeguards functions)
    - Prior consent to transfer material or technology to another country
    - Prior consent to enrich above 20% U-235
    - Prior consent to reprocess
    - Control over storage of any separated plutonium
    - Adequate physical security
3. **Materials exported to be in a form attracting full IAEA safeguards.**
4. **Commercial contracts to be subject to conditions of bilateral agreements.**
5. **Australia and Canada will participate in international efforts to strengthen safeguards.**
6. **Australia and Canada recognise the need for constant review of standards and procedures.**

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[*] Australia has 14 bilateral safeguards agreements covering 24 countries (the Euratom agreement covering several); Canada has 20 agreements in force, including with Euratom.

for regulating domestic nuclear facilities and is charged with administering the agreement between Canada and the IAEA for the application of safeguards in Canada. The Board assists the IAEA by allowing access to Canadian nuclear facilities and arranging for the installation of safeguards equipment at the sites. It also reports regularly to the IAEA on nuclear materials held in Canada. The AECB also manages a program for research and development in support of IAEA safeguards, the Canadian Safeguards Support Program.

In Australia the Australian Safeguards Office performs a similar role. It administers the safeguards agreement with the IAEA, arranges IAEA access to Australian facilities, and reports to the IAEA on nuclear materials in Australia. The ASO also manages the Australian Safeguards Assistance Program.

AUSTRALIA AND CANADA

Note: In the following t = tonnes (metric tons). A$ approximately equal C$ in 1997.

In Australia uranium ores were mined in the 1930s at Radium Hill and Mount Painter, South Australia, to recover minute amounts of radium for medical purposes. Some uranium was also recovered and used as a bright yellow pigment in glass and ceramics.

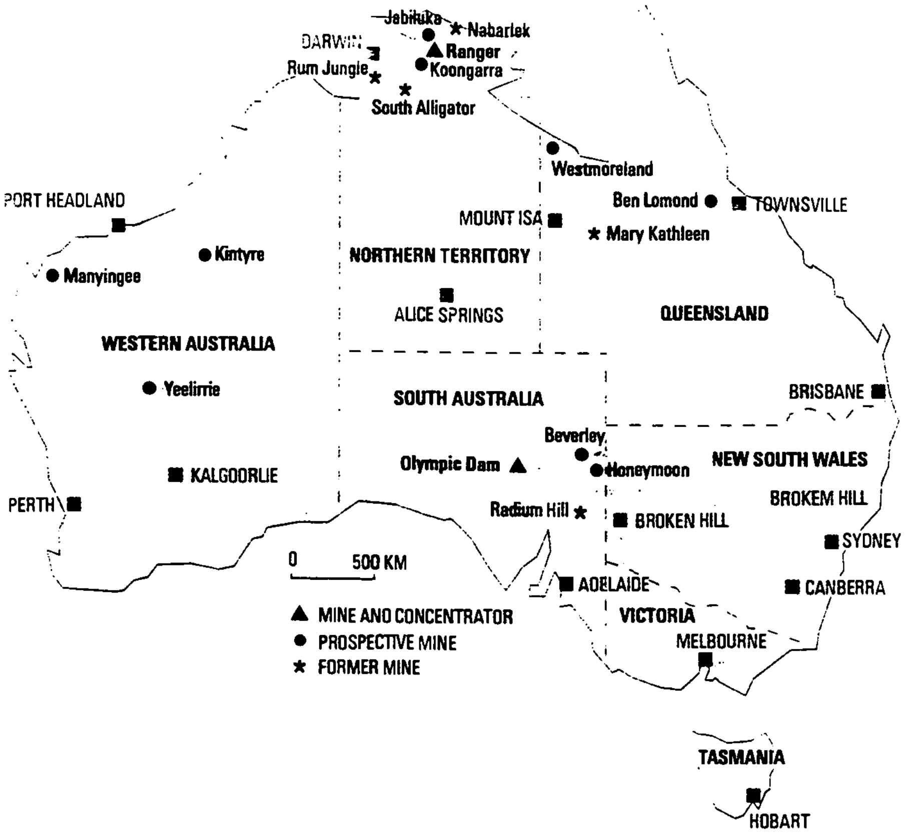
Following requests from the British and United States governments, systematic exploration for uranium began in 1944. In 1948 the Commonwealth Government offered tax-free rewards for the discovery of uranium orebodies. As a result, uranium was discovered at Rum Jungle in 1949, and in the South Alligator River region (1953) of the Northern Territory, then at Mary Kathleen (1954) and Westmoreland (1956) in north west Queensland.

In 1952 a decision was taken to mine Rum Jungle, NT and it opened in 1954 as a Commonwealth Government enterprise. Radium Hill, SA was reopened in 1954. Mining began at Mary Kathleen, Qld in 1958 and in the South Alligator region, NT in 1959. Production at most mines ceased by 1964, and Rum Jungle closed in 1971 either when ore reserves were exhausted or contracts were filled. Sales of some 7730 tonnes of uranium from these operations were to supply material primarily intended for USA and UK weapons programs at that time. However much of it was used in civil power production.

The development of nuclear power stimulated a second wave of exploration activity in the late 1960s. In the Northern Territory, Ranger was discovered in 1969, Nabarlek and Koongarra in 1970, and Jabiluka in 1971. New sales contracts (for electric power generation) were made by Mary Kathleen Uranium Ltd., Queensland Mines Ltd. (for Nabarlek), and Ranger Uranium Mines Pty. Ltd., in the years 1970-72.

Successive governments (both Liberal Coalition and Labor) approved these, and **Mary Kathleen** began recommissioning its mine and mill in 1974. Consideration by the Commonwealth Government of additional sales contracts was deferred pending the findings of the Ranger Uranium Environmental Inquiry, and its decision in the light of these. Mary Kathleen recommenced production of uranium oxide in 1976, after the Commonwealth Government had taken up a 42% share of the company.

The Government announced in 1977 that new uranium mining was to proceed, commencing with the **Ranger** project in the Northern Territory. In 1979 it decided



to sell its interest in Ranger, and as a result Energy Resources of Australia Ltd was set up to own and operate the mine. The mine opened in 1981, producing 2800 t/yr of uranium, sold to utilities in several countries. It has enough ore to maintain production for more than another decade, even at its 1997 production rate of 4300 t/yr of uranium.

In 1980, Queensland Mines opened **Nabarlek** in the same region of Northern Territory. The orebody was mined out in one dry season and the ore stockpiled for treatment. About 9160 tonnes of uranium were produced and sold to Japan, Finland and France, over 1981-88.

At the end of 1982 Mary Kathleen in Queensland had depleted its ore and finally closed down after 4070 tonnes of uranium had been produced in its second phase of operation. This then became the site of Australia's first major rehabilitation project on a uranium mine site, which was completed at the end of 1985. The Rum Jungle Rehabilitation project also took place in the 1980s.

In 1983 the Labor Government reviewed its uranium policy and decided upon allowing exports from three mines only: Ranger, Nabarlek and Olympic Dam. This policy persisted until 1996, despite the fact that Nabarlek ceased production by 1988.

During 1988 Western Mining Corporation's **Olympic Dam** project commenced operations. This is a large underground mine at Roxby Downs, South Australia, producing copper, uranium and gold. Annual production of uranium started at some 1300 tonnes, with sales to Sweden, UK, South Korea and Japan. Production will increase to 4600 tonnes uranium per year in 1999.

Both Ranger and Nabarlek mines are on aboriginal land in the Alligator Rivers region of the Northern Territory, close to the Kakadu National Park. In fact the Ranger and two other leases are surrounded by the National Park but were deliberately excluded from it when the park was established. Ranger is served by the township of Jabiru, constructed largely for that purpose. Nabarlek employees were based in Darwin and commuted by air.

The aboriginal people of the NT receive royalties on sales of uranium from NT mines. To mid 1998 these totalled A$ 145 million from Ranger alone.

The Olympic Dam mine is on formerly pastoral land in the middle of South Australia. A town to accommodate 3500 people was built at Roxby Downs to service the mine.

Meanwhile, in 1999 three other projects are under development. **Jabiluka**, NT, will be a conventional underground mine. **Honeymoon** and **Beverley** in SA will be small in situ leach mines, similar to those providing most US uranium. Further projects which may be brought forward include:

- Koongarra, NT
- Yeelirrie, WA
- Kintyre, WA
- Ben Lomond, Qld.

From 1981 to 1996, Australian uranium exports averaged about 3400 tonnes per year - less than ten percent of the world market, though Australia has nearly one third of the world's measured resources of uranium. By mid 1998 the rate of production and export had increased to 6000 tonnes uranium per year.

With the four new mines plus Ranger and the expansion of Olympic Dam, Australian uranium production is likely to reach 12,000 tonnes uranium per year by about 2002. This will be about 26% of projected world mine production then.

8.2 Canada's nuclear industry

Early Uranium Mining

In Canada, uranium ores first came to public attention in the early 1930s when the Eldorado Gold Mining Company began operations at Port Radium, Northwest Territories, to recover radium. A refinery to produce radium was built the following year at Port Hope, Ontario, some 5000 km away.

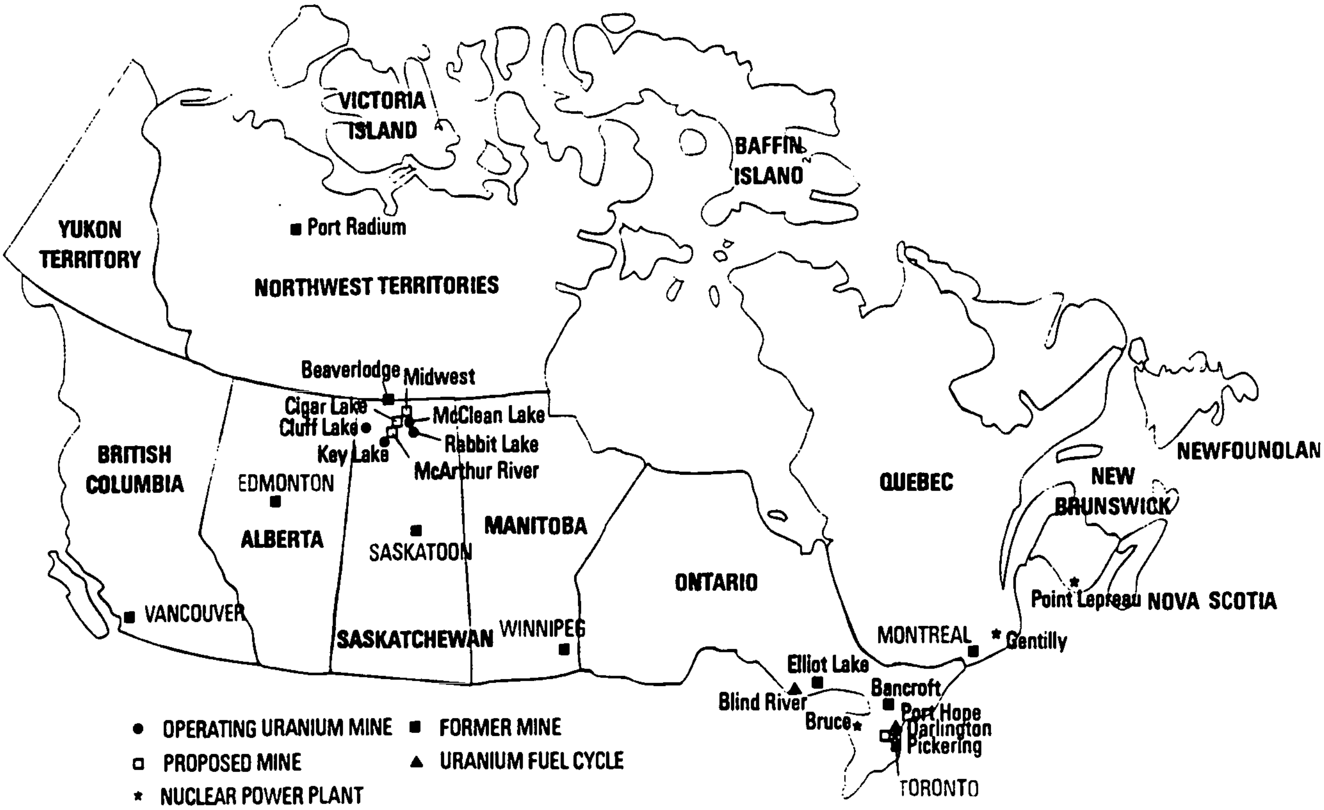
Exploration for uranium began in earnest in 1942, in response to a demand for defence purposes. The strategic nature of such material resulted in a ban on prospecting and mining of all radioactive materials across Canada. In 1944, the federal government took over the Eldorado company and formed a new Crown corporation which later became Eldorado Nuclear Ltd. Uranium exploration was restricted to the joint efforts of Eldorado and the Geological Survey of Canada.

Postwar, uranium exploration gathered pace when the ban on private prospecting was lifted in 1947. Deposits around the Bancroft, Ontario, area were discovered by the early 1950s, and the first discovery in Ontario's Elliot Lake region was in 1953. The northern Saskatchewan uranium province was also discovered in the 1950s and Eldorado Nuclear began mining at Beaverlodge in 1953.

By 1956 thousands of radioactive occurrences had been discovered. Several proved to be viable deposits, and by 1959, 23 mines with 19 treatment plants were in operation in five districts. Of these 19, about eleven in the Elliot Lake area, including the largest plants, would come to be operated by Rio Algom Ltd and Denison Mines Ltd. Three other plants were located near Bancroft, three in northern Saskatchewan and two in Northwest Territories.

This first phase of Canadian uranium production peaked in 1959 when more than 12,000 tonnes of uranium was produced. The uranium yielded C$330 million in export revenue, more than for any other mineral export from Canada that year. However, this period marked the end of cost-plus production for export, and over the next few years the number of mines declined to four. Uranium production in the Bancroft area and at Beaverlodge, Sk, ceased in 1982 and the last of the labour-intensive, lower-grade Elliot Lake mines closed in 1996.

The level of uranium exploration waned in the 1960s but recovered during the 1970s in response to world market conditions. During the 1960s the federal government supported the domestic uranium industry by initiating a stockpiling program which ended in 1974, after some 7000 tonnes of uranium was purchased at a cost of C$100 million. Uranium exploration was revived by expectations of nuclear power growth, and as a result several new uranium deposits were discovered in northern Saskatchewan's Athabasca Basin, starting in the late 1960s.



Recent Uranium Mining

In 1968 the Rabbit Lake deposit was discovered in northern Saskatchewan, and was brought into production in 1975. In that year Cluff Lake and Key Lake were discovered on the west and south of the same Athabasca Basin, and these started up in 1980 and 1983 respectively. Exploration expenditure in the region peaked at this time, resulting in the discoveries of Midwest, McClean Lake and Cigar Lake. Then in 1988 the newly-formed Cameco Corporation discovered the massive McArthur River deposit.

In the late 1970s the Saskatchewan Mining Development Corporation, a provincial crown corporation, had taken a 20% interest in the Cluff Lake development and a 50% interest in Key Lake. In 1988 this merged with Eldorado Nuclear Ltd to form Cameco Corporation, now the world's leading uranium producer. In 1991 Cameco made its first public share issue.

Canada's uranium production in 1997 was about 12,000 tonnes, one third of world mine output. In 1998 there were three Canadian mines in operation: Key Lake, Rabbit Lake (including Eagle Point) and Cluff Lake, all in northern Saskatchewan. Canada's uranium ore reserves are about 14% of world total.

Cameco's **Key Lake** is the world's largest high-grade uranium mine, supplying 15% of the world's uranium mine production in 1997. Cameco is also owner and operator of **Rabbit Lake**, another major producer.

The other uranium mine in operation is **Cluff Lake**, owned and operated by Cogema Resources Inc. Rio Algom's **Stanleigh** Mine, the last at Elliot Lake in Ontario, closed in mid 1996.

Four new uranium projects are planned for production by 2003. All are located in northern Saskatchewan.

The Canadian and Saskatchewan governments have adopted a policy of supporting uranium mining where it can be demonstrated to be environmentally acceptable. In 1991 a Joint Federal-Provincial Environmental Assessment and Review Panel was formed to study the health, safety, environmental and socio-economic impacts of five proposed uranium mining developments. A Federal Panel was formed to examine a sixth proposal.

Expansions at the Cluff Lake and Rabbit Lake operations were reviewed and approved in 1993, and are now in operation.

Of the four proposed new mines, three are expected to use a common treatment plant. The **McClean Lake** project was approved in 1993 and is expected to open in 1999. It will involve four open pits and later an underground mine, operated by Cogema. The high-grade **Cigar Lake** mine will be underground, utilising ground freezing and water jet boring, with remotely-operated equipment. Ore will be trucked 60 km for treatment at the Rabbit Lake and McClean Lake mills from 2001. The project will be operated by Cameco. Ore from Cogema's **Midwest** underground mine is also likely to be milled at McClean Lake nearby, from 2004.

Cameco's **McArthur River** deposit has enormous high-grade reserves and received final approvals in 1997. It will supply ore from its remotely-operated underground mine to the Key Lake mill, 80 km south, from 1999.

Thus by about 2003, Canadian output will substantially be concentrated at two mills: McClean Lake will produce some 7500 t and Key Lake 12,400 t uranium per year. Between them this will be about half of projected world mine production then.

Uranium Processing and Waste Disposal

Cameco operates Canada's only uranium refining and conversion facilities, located respectively at Blind River and Port Hope, Ontario. The refinery at Blind River takes uranium oxide concentrate (U_3O_8) from mines in Canada and abroad and refines it to UO_3, an intermediate product. The UO_3 is trucked to Port Hope, which has about one quarter of the Western world's uranium hexafluoride (UF_6) conversion capacity and provides the only commercial supply of fuel-grade natural (unenriched) uranium dioxide (UO_2).

The uranium hexafluoride is enriched outside Canada for use in light water reactors, while natural UO_2 is used to fabricate fuel bundles for CANDU reactors in Canada and abroad. About 80% of the UO_3 from Blind River is converted to UF_6, while the remainder is refined to UO_2. Two fuel fabrication plants in Ontario process some 1900 tonnes of uranium per year to UO_2 fuel pellets, mainly for domestic CANDU reactors. Between 15 and 20% of Canada's uranium production is consumed domestically.

Canada's Nuclear Fuel Waste Management Program has been a focus of attention in the mid 1990s. The concept proposed is burying nuclear waste 500 to 1000 metres deep in the stable rock of the Canadian Shield. This will be below the water table and with the containers packed in bentonite clay. The concept has been the subject of detailed scrutiny by the federal Environment Assessment Panel over three years, involving public hearings. The waste may consist of spent fuel bundles or the solidified high-level waste from reprocessing them, sealed in copper or titanium containers. (see also 5.5)

Canadian Reactors

In 1944, an engineering design team was brought together in Montreal, Quebec, to develop a heavy water moderated nuclear reactor. The National Research Experimental reactor (NRX) was built at Chalk River, Ontario, and started up in 1947. It provided the basis for Canada's development of the very successful CANDU series of power reactors, and served as one of the most valuable research reactors in the world.

The CANDU nuclear reactor system (see 3.2 & 4.2) has been developed since the 1950s by Atomic Energy of Canada Ltd (AECL) and Canadian industry. The key to the success of the system is its simplicity, its use of natural uranium (as UO_2) as a fuel, and the ability to refuel without shutting down. The reactors use heavy water under pressure as a coolant, as well as using heavy water as a moderator.

The use of heavy water means that an ancillary industry is needed to produce it, corresponding to the rather more capital-intensive enrichment services required by other reactor types. Canada produces all of its heavy water, now from a single D_2O production facility.

The major commercial utilisation of the CANDU system has been in Ontario, which has benefited from this electricity source since the early 1970s. In Ontario, 19 commercial nuclear reactors at three locations, have produced two thirds of the Province's electricity, though 7 of these are now laid up until 2000-2003. Three require new system generators, so may be retired permanently. Single unit CANDU reactors also operate in Quebec and New Brunswick. The total nuclear electricity generated has a value of about C$ 3.7 billion per year and helps Canada minimise emissions from electric power generation.

In addition, export sales of 12 CANDU units have been made to South Korea, Romania, India, Pakistan, Argentina and China, along with the engineering expertise to build and operate them. In 1996 total nuclear-related exports from Canada were over $1300 million.

The reactors at Darlington, Ontario provide the base design for the new CANDU 9 series of reactors of around 900 MWe. This design supplements the proven CANDU 6 of about 700 MWe, which has been such an export success.

The Canadian nuclear industry is responsible for providing 25 000 direct jobs and a further 10 000 indirect jobs. It involves over 125 companies in several provinces.

APPENDIX 1

Ionising radiation and how it is measured

The following are four kinds of nuclear radiation

Alpha particles
These are particles (atomic nuclei) consisting of 2 protons and 2 neutrons. They are intensely ionising but can be readily stopped by a few centimetres of air, a sheet of paper, or the human skin. They are only dangerous to people if they are released inside the body. Alpha-radioactive substances are safe if kept in any containers sealed to air.

Beta particles
These are either electrons or positrons (therefore of very low mass). They can be stopped by a thin piece of wood or plastic and are generally less dangerous to people than gamma radiation. Exposure produces an effect like sunburn, but which is slower to heal. Beta-radioactive substances are also safe if kept in appropriate sealed containers.

Gamma rays
These are high energy beams almost identical to x-rays and of shorter wavelength than ultraviolet radiation. They are very penetrating, and need substantial thicknesses of heavy materials such as lead, steel or concrete to shield them. They are the main hazard to people in dealing with sealed radioactive materials. Doses can be detected by the small badges worn by workers handling any radioactive materials. Gamma activity in a substance (e.g. rock) can be measured with a scintillometer or geiger counter.

Neutrons
These are mostly released by nuclear fission, and apart from a little cosmic radiation they are seldom encountered outside the core of a nuclear reactor. Fast neutrons are very penetrating as well as (indirectly) being strongly ionising and hence very destructive to human tissue. They can be slowed down (or "moderated") by wood, plastic, or (more commonly) by graphite or water.

Units

The amount of ionising radiation absorbed in tissue can be expressed in **grays**. 1 Gy = 1 J/kg. However, since neutrons and alpha particles cause more damage per gray than gamma or beta radiation, another unit, the sievert (Sv) is used in setting radiological protection standards. One gray of beta or gamma radiation has one **sievert** of biological effect, one gray of alpha particles has 20 Sv effect and one gray of neutrons is equivalent to around 10 Sv (depending on their energy).

Total dose is thus measured in sieverts (or millisieverts - mSv - one thousandth of a sievert, or microsieverts - µSv - one millionth of a sievert). The rate of dose is measured in milli or micro sieverts per hour or year. For instance, our natural dose is around 2 mSv/yr, and maximum annual dose allowed for a uranium miner is 20 mSv/yr, though that received in Australian and Canadian mining operations is typically less than half of this.

(These levels contrast with those which are harmful in a disaster scenario: with gamma radiation a short term dose of 1 Sv causes (temporary) radiation sickness, 5 Sv would kill about half the people receiving it in a month and a burst of 10 Sv would be fatal to all in a matter of days. The 28 radiation fatalities at Chernobyl appear to have received more than 5 Sv in a few days, those suffering acute radiation sickness averaged 3.4 Sv.)

The Becquerel (Bq) is a unit or measure of actual radioactivity in material (as distinct from the radiation it emits, or the human dose from that), with reference to the number of nuclear disintegrations per second (1 Bq = 1 disintegration/sec.). Quantities of radioactive material are commonly estimated by measuring the amount of intrinsic radioactivity in becquerels - one Bq of radioactive material is that amount which has an average of one disintegration per second, ie an activity of 1 Bq.

Older units of radiation measurement continue in use in some literature

1 gray = 100 rads

1 sievert = 100 rem

1 becquerel = 27 picocuries or 2.7×10^{-11} curies

One curie was originally the activity of one gram of radium-226, and represents 3.7×10^{10} disintegrations per second (Bq).

The Working Level Month (WLM) has been used as a measure of dose for exposure to radon and in particular, radon decay products (see Appendix 2). One "Working Level" is approximately equivalent to 3700 Bq/m^3 of Rn-222 in equilibrium with its decay products. Exposure to 0.4 WL was the maximum permissible for workers. Continuous exposure during working hours to 0.4 WL would result in a dose of 5 WLM over a full year, corresponding to about 50 mSv/yr whole body dose for a 40-hour week. In the underground mine at Olympic Dam, and at Ranger, individual workers' doses are kept below 1 WLM/yr (10 mSv/yr), and typically average half this.

Further information:

In Australia:
Uranium Information Centre, phone (03) 9629 7744 or
Australian Radiation Laboratory, Yallambie, Vic,
phone (03) 9433 2211 or e-mail <info@arl.oz.au>

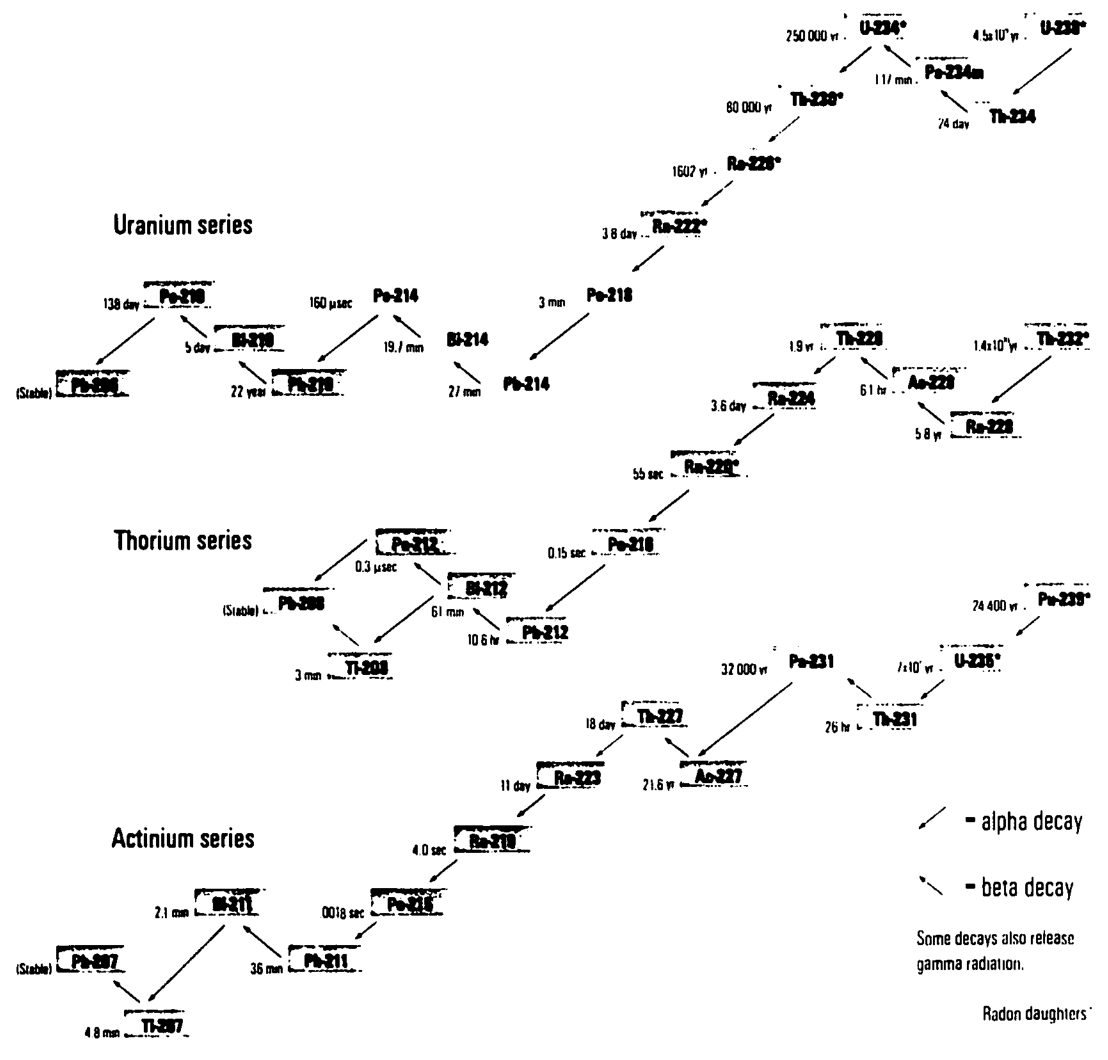
In Canada:
Canadian Nuclear Association, phone (416) 977 6152.

Some comparative radiation doses

2 mSv/year	Typical background radiation to Australian public.
3 mSv/year	Typical background radiation to North American public.
2.9 mSv/year	Average occupational dose to US nuclear industry employees.
5.0 mSv/year	Average occupational dose to Australian uranium miners.
1.5 mSv/year	Average incremental dose for aircrew.
10 mSv/year	Maximum actual dose to Australian uranium miners.
20 mSv/year	Current limit for nuclear industry employees (5 year average).
50 mSv/year	Former long-term limit for nuclear industry employees and U miners, current maximum limit in single year.
350 mSv in lifetime	Criterion for relocating people after Chernobyl accident.
1000 mSv	as short term dose: probably causes (temporary) radiation sickness.
5000 mSv	as short term dose: would kill about half those receiving it within a month.
10,000 mSv	as short term dose: fatal within days or weeks.

APPENDIX 2

Some radioactive decay series



Notes:

1. In a uranium orebody, the U-238 series represents almost 95% of the radioactivity.
2. The level of radioactivity of an isotope is inversely proportional to its half life. The shorter-lived each kind of radioisotope, the more radiation it emits per unit mass. Th-232, and U-238 are thus virtually stable.

* Specifically mentioned in text or footnote.

APPENDIX 3

Environmental and ethical aspects of radioactive waste management

These two statements were formulated and published in 1995 to confront the question of what are the best and most appropriate means of managing and disposing of radioactive wastes from the civil nuclear fuel cycle.

Fundamental Principles Of Radioactive Waste Management

International Atomic Energy Agency

1. **Protection of Human Health**
   Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.

2. **Protection of the environment**
   Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.

3. **Protection beyond national borders**
   Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.

4. **Protection of future generations**
   Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

5. **Burdens on future generations**
   Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.

6. **National legal framework**
   Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.

7. **Control of radioactive waste generation**
   Generation of radioactive waste shall be kept to the minimum practicable.

8. **Radioactive waste generation and management interdependencies**
   Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.

9. **Safety of facilities**
   The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

IAEA 1995

The Environmental and Ethical Basis of the Geological Disposal of Long-lived Radioactive Waste

OECD NEA Collective Opinion of the Radioactive Waste Management Committee

After a careful review of the environmental and ethical issues, the members of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency:

- **consider** that the ethical principles of intergenerational and intragenerational equity must be taken into account in assessing the acceptability of strategies for the long-term management of radioactive wastes;
- **consider** that from an ethical standpoint, including long-term safety considerations, our responsibilities to future generations are better discharged by a strategy of final disposal than by reliance on stores which require surveillance, bequeath long-term responsibilities of care, and may in due course be neglected by future societies whose structural stability should not be presumed;
- **note** that, after consideration of the options for achieving the required degree of isolation of such wastes from the biosphere, geological disposal is currently the most favoured strategy;
- **believe** that the strategy of geological disposal of long-lived radioactive wastes:
  - takes intergenerational equity issues into account, notably by applying the same standards of risk in the far future as it does to the present, and by limiting the liabilities bequeathed to future generations; and
  - takes intragenerational equity issues into account, notably by proposing implementation through an incremental process over several decades, considering the results of scientific progress; this process will allow consultation with interested parties, including the public, at all stages;
- **note** that the geological disposal concept does not require deliberate provision for retrieval of wastes from the repository, but that even after closure it would not be impossible to retrieve the wastes, albeit at a cost;
- **caution** that, in pursuing the reduction of risk from a geological disposal strategy for radioactive wastes, current generations should keep in perspective the resource deployment in other areas where there is potential for greater reduction of risks to humans or the environment, and consider whether resources may be used more effectively elsewhere;

Keeping these considerations in mind, the Committee members:

- **confirm** that the geological disposal strategy can be designed and implemented in a manner that is sensitive and responsive to fundamental ethical and environmental considerations;
- **conclude** that it is justified, both environmentally and ethically, to continue development of geological repositories for those long-lived radioactive wastes which should be isolated from the biosphere for more than a few hundred years; and
- **conclude** that stepwise implementation of plans for geological disposal leaves open the possibility of adaptation, in the light of scientific progress and social acceptability, over several decades, and does not exclude the possibility that other options could be developed at a later stage.

OECD NEA 1995

This opinion has been endorsed by the IAEA and the Commission of European Communities.

APPENDIX 4

Some Useful References

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GLOSSARY

The following is a list of terms which are commonly used in discussion of the uranium industry and the nuclear fuel cycle.

Activation product

A radioactive isotope of an element (eg in the steel of a reactor core) which has been created by neutron bombardment.

Alpha particle

A positively-charged particle from the nucleus of an atom, emitted during radioactive decay. Alpha particles are helium nuclei, with 2 protons and 2 neutrons.

Atom

A particle of matter which cannot be broken up by chemical means. Atoms have a nucleus consisting of positively-charged protons and uncharged neutrons of the same mass. The positive charges on the protons are balanced by a number of negatively-charged electrons in motion around the nucleus.

Beta particle

A particle emitted from an atom during radioactive decay. Beta particles may be electrons (with negative charge) or positrons.

Biological shield

A mass of absorbing material (eg thick concrete walls) placed around a reactor or radioactive material to reduce the radiation (especially neutrons and gamma rays respectively) to a level safe for humans.

Boiling water reactor (BWR)

A common type of light water reactor (LWR), where water is allowed to boil in the core thus generating steam directly in the reactor vessel.

Breed

To form fissile nuclei, usually as a result of neutron capture, possibly followed by radioactive decay.

Breeder reactor
see Fast Breeder Reactor and Fast Neutron Reactor.

Calandria (in a CANDU reactor)
A cylindrical reactor vessel which contains the heavy water moderator. It is penetrated from end to end by hundreds of calandria tubes which accommodate the pressure tubes containing the fuel and coolant.

CANDU
Canadian deuterium uranium reactor, moderated and cooled by heavy water.

Chain reaction
A reaction that stimulates its own repetition, in particular where the neutrons originating from nuclear fission cause an ongoing series of fission reactions.

Control rods
Devices to absorb neutrons so that the chain reaction in a reactor core may be slowed or stopped.

Conversion
Chemical process turning uranium oxide into uranium hexafluoride (UF_6) preparatory to enrichment.

Core
The central part of a nuclear reactor containing the fuel elements and any moderator.

Critical mass
The smallest mass of fissile material that will support a self-sustaining chain reaction under specified conditions.

Decay
Decrease in activity of a radioactive substance due to the disintegration of an atomic nucleus resulting in the release of alpha or beta particles or gamma radiation.

Decommissioning
Removal of a facility (eg reactor) from service, also the subsequent actions of safe storage, dismantling and making the site available for unrestricted use.

Depleted uranium
Uranium having less than the natural 0.7% U-235. As a by-product of enrichment in the fuel cycle it generally has 0.25-0.30% U-235, the rest being U-238. Can be blended with highly-enriched uranium (eg from weapons) to make reactor fuel.

Deuterium
"Heavy hydrogen", an isotope having one proton and one neutron in the nucleus. It occurs in nature as 1 atom to 6500 atoms of normal hydrogen, (Hydrogen atoms contain one proton and no neutrons).

Element
A chemical substance that cannot be divided into simple substances by chemical means; atomic species with same number of protons.

Enriched uranium
Uranium in which the proportion of U-235 (to U-238) has been increased above the natural 0.7%. Reactor-grade uranium is usually enriched to about 3.5% U-235, weapons-grade uranium is more than 90% U-235.

Enrichment
Physical process of increasing the proportion of U-235 to U238. See also 'SWU'.

Fast breeder reactor (FBR)
A fast neutron reactor (qv) configured to produce more fissile material than it consumes, using fertile material such as depleted uranium.

Fast neutron reactor
A reactor with little or no moderator and hence utilising fast neutrons and able to utilise fertile material such as depleted uranium.

Fertile (of an isotope)
Capable of becoming fissile, by capturing one or more neutrons, possibly followed by radioactive decay. U-238 and Th-232 are examples.

Fissile (of an isotope)
Capable of capturing a neutron and undergoing nuclear fission, e.g. U-235, Pu-239, U-233.

Fission
The splitting of a heavy nucleus into two, accompanied by the release of a relatively large amount of heat and generally one or more neutrons. It may be spontaneous but usually is due to a nucleus absorbing a neutron.

Fission products
Daughter nuclei resulting either from the fission of heavy elements such as uranium, or the radioactive decay of those primary daughters. Usually highly radioactive.

Fossil fuel

A fuel based on carbon presumed to be originally from living matter, eg coal, oil, gas. Burned with oxygen to yield energy.

Fuel fabrication

Making reactor fuel elements usually from UO_2.

Gamma rays

High energy electro-magnetic radiation, emitted by an atom undergoing radioactive decay

Genetic mutation

Sudden change in the chromosomal DNA of an individual gene. It may produce inherited changes in descendants. Mutation can be made more frequent by irradiation.

Graphite

A form of carbon used in very pure form as a moderator, principally in gas-cooled reactors, but also in Soviet-designed RBMK reactors.

Greenhouse gases

Radiative gases in the earth's atmosphere which absorb long-wave heat radiation from the earth's surface and re-radiate it, thereby warming the earth. Carbon dioxide and water vapour are the main ones.

Half-life

The period required for half of the atoms of a particular radioactive isotope to decay and become an isotope of another element.

Heavy water

Water containing an elevated concentration of molecules with deuterium ("heavy hydrogen") atoms.

Heavy water reactor

A reactor which uses heavy water as its moderator, eg Canadian CANDU (pressurised HWR or PHWR).

High-level wastes

Extremely radioactive fission products and transuranic elements (usually other than plutonium) in spent nuclear fuel. They may be separated by reprocessing the spent fuel, or the spent fuel containing them may be regarded as high-level waste.

Highly (or High)-enriched uranium (HEU)

Uranium enriched to at least 20% U-235.
That in weapons is about 90% U-235.

Ionising radiation

Radiation (including alpha particles) capable of breaking chemical bonds, thus causing ionisation of the matter through which it passes and damage to living tissue.

Isotope

An atomic form of an element having a particular number of neutrons. Different isotopes of an element have the same number of protons but different numbers of neutrons and hence different atomic masses, e.g. U-235, U-238.

Light water

Ordinary water (H_2O) as distinct from heavy water.

Light water reactor (LWR)

A common nuclear reactor cooled and usually moderated by ordinary water.

Low-enriched uranium (LEU)

Uranium enriched to less than 20% U-235.
That in reactors is typically about 3.5% U-235.

Megawatt (MW)

A unit of power, = 10^6 watts. MWe refers to electric output from a generator, MWt to thermal output from a reactor or heat source (eg the gross heat output of a reactor itself, typically three times the MWe figure).

Metal fuels

Natural uranium metal as used in a gas-cooled reactor.

Micro

One millionth of a unit (eg microsievert is 10^{-6}Sv).

Mixed oxide fuel (MOX)

Reactor fuel which consists of both uranium and plutonium oxides, usually about 5% Pu.

Moderator

A material such as light or heavy water or graphite used in a reactor to slow down fast neutrons so as to improve the likelihood of further fission.

Natural uranium

Uranium with an isotopic composition as found in nature, containing 99.3% U-238, 0.7% U-235 and a trace of U-234.

Neutron

An uncharged elementary particle found in the nucleus of every atom except hydrogen. Solitary mobile neutrons travelling at various speeds originate from fission reactions. Slow neutrons can in turn readily cause fission in atoms of some isotopes, e.g. U-235, and fast neutrons can readily cause fission in atoms of others, e.g. Pu-239. Sometimes atomic nuclei simply capture neutrons.

Nuclear reactor

A device in which a nuclear fission chain reaction occurs under controlled conditions so that the heat yield can be harnessed or the neutron beams utilised. All commercial reactors are thermal reactors, using a moderator to slow down the neutrons.

Oxide fuels

Enriched or natural uranium in the form of the oxide UO_2, used in many types of reactor.

Plutonium

A transuranic element, formed in a nuclear reactor by neutron capture. It has several isotopes, some of which are fissile and some of which undergo spontaneous fission, releasing neutrons. Weapons-grade plutonium is produced with >90% Pu-239, reactor-grade plutonium contains about 30% non-fissile isotopes.

Pressurised water reactor (PWR)

The most common type of light water reactor (LWR).

Radiation

The emission and propagation of energy by means of electromagnetic waves or particles.

Radioactivity

The spontaneous decay of an unstable atomic nucleus, giving rise to the emission of radiation.

Radionuclide

A radioactive isotope of an element.

Radiotoxicity

The adverse health effect of a radionuclide due to its radioactivity.

Radium

An element often found in uranium ore. It has several radioactive isotopes. Radium-226 decays to radon-222.

Radon (Rn)

A heavy radioactive gas given off by rocks containing radium (or thorium).

Radon daughters

Decay products of radon-222.

Reprocessing

Chemical treatment of spent reactor fuel to separate uranium and plutonium from the small quantity of fission products (and from each other), leaving a much reduced quantity of high-level waste.

Separative Work Unit (SWU)

This is a complex unit which is a function of the amount of uranium processed and the degree to which it is enriched, ie the extent of increase in the concentration of the U-235 isotope relative to the remainder. The unit is strictly: Kilogram Separative Work Unit, and it measures the quantity of separative work (indicative of energy used in enrichment) when feed and product quantities are expressed in kilograms.

For instance, to produce one kilogram of uranium enriched to 3.5% U-235 requires 4.3 SWU if the plant is operated at a tails assay 0.30%, or 4.8 SWU if the tails assay is 0.25% (thereby requiring only 7.0 kg instead of 7.8 kg of natural U feed).

About 100-120,000 SWU is required to enrich the annual fuel loading for a typical 1000 MWe light water reactor. Enrichment costs are related to electrical energy used. The gaseous diffusion process consumes some 2400 kWh per SWU, while gas centrifuge plants require only about 60 kWh/SWU.

Sievert (Sv)

Unit indicating the biological damage caused by radiation. One Joule of beta or gamma radiation absorbed per kilogram of tissue has 1 Sv of biological effect; 1 J/kg of alpha radiation has 20 Sv effect and 1 J/kg of neutrons has 10 Sv effect.

Stable

Incapable of spontaneous radioactive decay.

Tailings

Ground rock remaining after particular ore minerals (e.g. uranium oxides) are extracted.

Tails

Depleted uranium (cf. enriched uranium), with about 0.3% U-235.

Thermal reactor

A reactor in which the fission chain reaction is sustained primarily by slow neutrons (as distinct from Fast Neutron Reactor).

Transuranic element

A very heavy element formed artificially by neutron capture and subsequent beta decay(s). Has a higher atomic number than uranium (92). All are radioactive. Neptunium, plutonium and americium are the best-known.

Uranium

A mildly radioactive element with two isotopes which are fissile (U-235 and U-233) and two which are fertile (U-238 and U-234). Uranium is the basic raw material of nuclear energy.

Uranium hexafluoride (UF_6)

A compound of uranium with fluorine which is a gas above 56°C and is thus a suitable form in which to enrich the uranium.

Uranium oxide concentrate (U_3O_8)

The mixture of uranium oxides produced after milling uranium ore from a mine. Sometimes loosely called yellowcake. It is khaki in colour and is usually represented by the empirical formula U_3O_8. Uranium is exported from Australia in this form.

Vitrification

The incorporation of high-level wastes into borosilicate glass, to make up about 14% of the product by mass.

Waste

High-level waste (HLW) is highly radioactive material arising from nuclear fission. It can be recovered from reprocessing spent fuel, though some countries regard spent fuel itself as HLW and plan to dispose of it in that form. It requires very careful handling, storage and disposal.

Low-level waste is mildly radioactive or contaminated material, typically from medical or industrial applications of radioactivity, and usually disposed of by incineration and burial.

Yellowcake

Ammonium diuranate, the penultimate uranium compound in U_3O_8 production, but the form in which mine product was sold until about 1970. See also Uranium oxide.

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NUCLEAR ELECTRICITY IN SENIOR COURSES

Compiled by Peter Dodd, Senior Co-ordinator – Radford College, Canberra

Nuclear energy and its associated technologies have long been the subject of strong debate. The debate has not only taken place in scientific circles and in the general community, but also within schools.

People have looked for answers to questions such as:

- Should Australia mine uranium for other countries to use?
- How much should Australia mine, to whom should Australia sell it and what restrictions should Australia try to place on how it is used?
- Should Australia have its own new reactor or even a nuclear power plant? If so, where should it be built?
- What should Australia do with its nuclear waste?

The answers to these questions are still unresolved, and so the questions will continue to be asked. In fact, these questions and many like them concern important social issues which will have to be addressed by today's school students.

The trend in recent years has been for Physical Science curricula to expand away from straight mathematics, into topics which consider the implications of this mathematics. It has become common for senior students to study topics such as astronomy, the physics of sport or medicine, architecture ... and nuclear physics. Students are being asked to consider the social and ethical concerns surrounding these topics. Teachers and the courses they teach must attempt to give students a basis upon which to make informed decisions about these concerns.

Whatever your initial bias towards the topic of nuclear electricity, and whether you are a teacher or a student, this text adds much to the nuclear energy debate. It is unashamedly a text which supports the idea that there is a definite place for the nuclear industries in world electricity supply. It makes it clear why many countries utilise nuclear power and that this method of producing electrical power may even be the best environmental solution to steadily increasing power demands. The text explains this stance in clear terms, using up to date statistics. It provides excellent information and thus it provides a starting point for student research and classroom discussion.

There is little doubt that the nuclear energy debate will continue to rage for many years to come. The physical science students who have learnt how to research and inform themselves, and who have an interest in staying up to date, will be the people who form the cornerstone of the continuing debate.

QUESTIONS AND ACTIVITIES

Many of the Physics texts in common use in Australian schools include sections on nuclear physics which contain excellent problems: problems that test a student's knowledge of the factual base of nuclear physics and the interpretation of these facts. The questions which follow are of a more social/critical/opinion nature. Students should be encouraged to form and express opinions, but also to explain why they hold these opinions and to back their opinions up with facts. The facts can sometimes be obtained in this book, but often they will require additional research.

GROUP DISCUSSION AND BRAINSTORMING ACTIVITIES

1. Oil, gas, coal, nuclear fission, photovoltaic cells, wind and hydro' are all ways that are commonly used to generate electricity. Write these words onto separate slips of paper. Divide the class into small groups. For each small group, randomly draw two words and place them into one of the following questions.

   Place all of the words back in the middle and draw two more. Continue until every group has a completed question. The same, or a different question, can be used with each group. Allow the groups some time to work out an answer and then have each group give a short presentation.

   a. One clear advantage of (word 1) as a method of producing electrical power over (word 2) is.....?

   b. One clear disadvantage of (word 1) as a method of producing power over (word 2) is.....?

   c. What are the environmental problems associated with the production of electrical energy using (word 1) which would not occur using (word 2)?

   d. What are the engineering problems associated with the production of electrical energy using (word 1) which would not occur using (word 2)?

   Subsequent discussion should then be focused by the following questions:

   - Do other groups agree with the answers given?
   - Can other groups suggest different answers?
   - Which are the best answers?

2. In the early 1970's, oil production was expected to double within 10 years. However, the "oil crisis" in 1979 saw prices rise fourfold and oil consumption in 1986 was the same as in 1973.

   a. What possible major world events could cause a similar lowering of demand for energy in the late 90's or early next century?

   b. Are there some possible scenarios that could cause a drop in demand for all of oil, coal and uranium?

   c. Are there some possible scenarios that would cause a drop in demand for one (but only one) of oil, coal or uranium?

3. What could be some of the possible effects on:

   - the mining industry;
   - heavy manufacturing industries;
   - people in their homes;

   if electrical power supply was suddenly cut to half of its present level and electrical power to all users was rationed?

4. Conduct a survey of a particular group in your community about a nuclear energy issue. (Groups to survey could include senior school students, university students, people who have an age range of 20 to 30, 30 to 40 etc). You could use one of the following topics or make up your own.

   It may be best for different groups to use the same survey for different population groups and then for the class to compare results. How can you also determine the level of knowledge that people have to inform their opinion?

   a. Do you consider it likely that there will be a major uncontained nuclear accident, somewhere in the world, in the next ten years?

   b. Do you think that Australia or Canada should build a nuclear fuel enrichment plant? (or a spent nuclear fuel reprocessing plant?)

   c. Do you think Australia should build a nuclear power station within the next ten years? Should Canada build more of them?

RESEARCH AND ESSAY TOPICS

1. Which of the sources of electrical energy (oil, gas, coal, nuclear fission, photovoltaic cells, wind and hydro', geothermal, tides) are more suited to base load power supply and which to other, more specialist, purposes? Describe the specialist purposes and give reasons for your answers.

2. Show the steps by which thorium-232 can become uranium-233. As thorium is more common in many places in the earth's crust than uranium, why isn't a thorium fuel cycle in common use in the world today?

3. Show the steps by which uranium-238 can be turned into plutonium-239 in any nuclear power station. This reaction (harnessed in special breeder reactors) allows uranium to give up to sixty times its "usual" amount of energy. Why isn't this fast breeder fuel cycle in common use in the world today?

4. How much deuterium is there in a kilogram of water? How much is there in the oceans of the world? How much energy would be obtainable from this amount of deuterium if it becomes possible to harness nuclear fusion?

5. Air pollution does not respect international boundaries. For example, in northern Europe there have been major problems with acid rain and with nuclear fallout from the Chernobyl accident.

   Compare and contrast the sources and problems generated by these two differing forms of pollution. You should look for points concerning differences and similarities in the actual substances involved, in the ways of spreading, in the expected environmental hazards and in the methods used to clean up the problem.

6. Fly ash and other coal power station emissions have been associated with atmospheric radioactivity.

   What radioactive substances are released into the atmosphere when coal is burnt?

   Compare these with the radioactive substances which are released into the atmosphere during a nuclear accident such as at Chernobyl.

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