Nuclear Development

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Nuclear Energy Today

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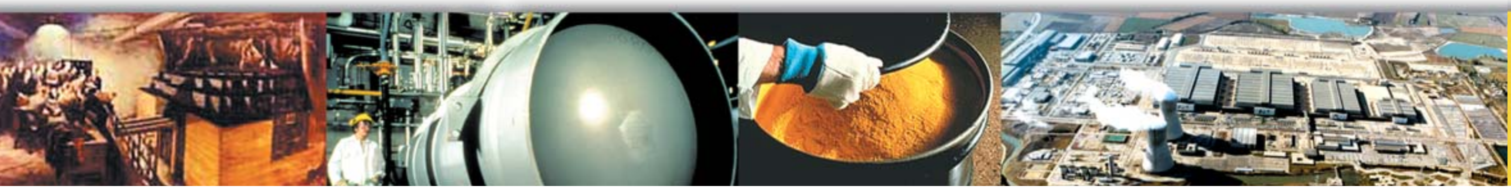
NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Foreword

All the forecasts of world energy demand for the next 50 years point towards very significant increases in consumption. A big share of this new demand will come from areas of the world where existing energy consumption is now relatively low in comparison with the OECD countries, and which are becoming increasingly integrated in the global economy. As energy demand grows, all societies worldwide will face a real challenge in providing the energy needed to feed economic growth and improve social development, while enhancing protection of the environment.

In this context, it is not difficult to conclude that it is the responsibility of policy makers to establish energy policies that meet that challenge while being robust enough to cope with the risks associated with the globalisation of the world economy. Diversification, security of supply, protection of the environment and technology development are key elements of any energy policy that tries to put into the markets enough energy at a reasonable price in a sustainable way.

Among the different energy sources that are contributing significantly to world supply none appears to policy makers as more complex than nuclear energy. The economic, technological and social implications of nuclear power makes any decision something that goes far beyond the normal actors of the market place.



The serious questions our societies are asking about nuclear energy include the safety of nuclear installations, the ultimate disposal of long-lived radioactive waste, nuclear energy's potential to help reduce greenhouse gas emissions, the economy of the whole fuel cycle, especially in liberalised electricity markets, and the non-proliferation of nuclear weapons.

The OECD Nuclear Energy Agency (NEA) has worked in many of these areas for more than 40 years. The NEA methodology calls for having most of the main world specialists in every field work together to provide a collective analysis in an objective way as a fundamental input for governments.

The work of the NEA is based on the scientific and technical analysis of the various components of the entire nuclear fuel cycle. This base of science and technology is the solid ground on which policy makers can establish nuclear and energy policies, once the social factors have been incorporated.

It is very difficult to describe in a short publication all the aspects that need to be considered to establish a robust nuclear policy. Yet, I think that this NEA publication can help policy makers in fulfilling their responsibilities, and other readers in better understanding what are the realities surrounding one of the most impressive technologies of the past 60 years; a technology that is based on something we cannot see, the internal forces that link together the basic physical entities, which form that smallest component of matter, the atom.

To the extent to which the atom can be mastered without unacceptable risk, the contribution of nuclear energy to the sustainable development of our societies is on the table.

Luis E. Echávarri
NEA Director-General

Introduction

This book addresses today's important questions about nuclear energy by providing an authoritative and factual introduction to the relevant issues. It is primarily intended for policy makers, but should also be useful to interested members of the public, industrial managers, academics and journalists.

Chapter 1 gives a brief overview. The rest of the book describes the fundamental issues important to a discussion of nuclear energy today. Chapters 2 and 3 provide an introduction to the basic sciences and technologies involved. Chapters 4 to 8 set out the facts and issues connected with radioactive waste management, nuclear safety, radiological protection, economics, and international law and non-proliferation. The ninth chapter assesses nuclear energy in the context of sustainable development. The last chapter looks to the future, and to the potential of new nuclear-based technologies.

The information throughout is necessarily brief but, at the end of each chapter, there is an annotated list that guides the reader to a fuller set of references at the end of the book that are appropriate for further study. Important principles and terms are normally briefly defined throughout the text with fuller definitions provided in the Glossary. Text in green indicates a definition can be found in the Glossary. If the term appears more than once in a chapter it will usually only be highlighted on its first usage.

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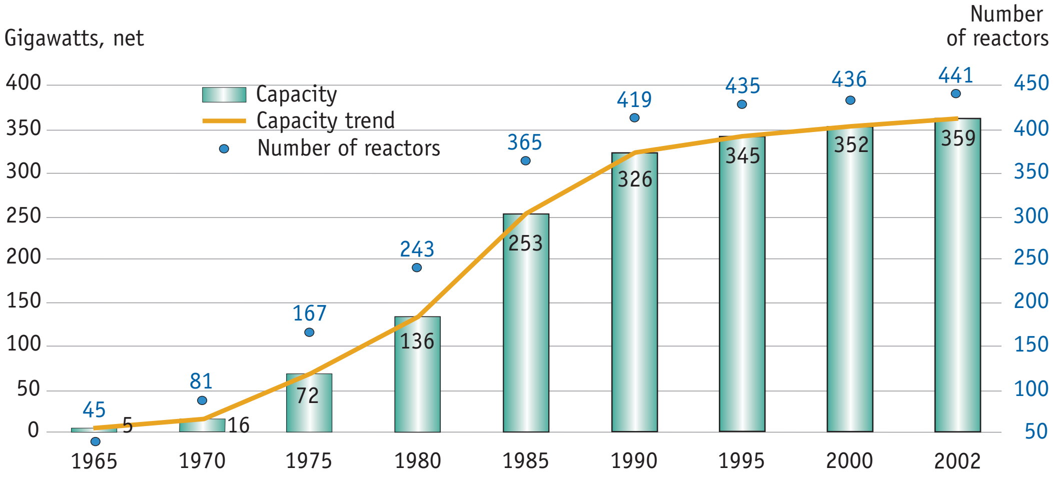
Overview of Nuclear Energy Today

Nuclear energy has grown continuously since its inception – demonstrating increased performance and efficiency – and today is a major source of energy, supplying about 17% of the world's electricity.

Stimulated by the urgency of the Second World War, nuclear science progressed rapidly from the discovery of the neutron by Sir James Chadwick in 1932. Out of this basic knowledge came the discovery in 1939 that when atoms fission (i.e. are split), energy is released. This led in turn to the first controlled chain reaction (1943), the first atomic weapon (1945), and the first production of electricity using nuclear energy (1951). Thus, within a span of twenty years, nuclear energy developed from first principles to practical demonstration.

Following its first application for generating electricity in the United States, nuclear energy began to be applied to the production of electricity in the United Kingdom (1953), Russia (1954), France (1956), and Germany (1961) – five countries within the first decade. Ten more countries began nuclear-based generation in the 1960s followed by another ten in the 1970s. The oil crisis of the early seventies provoked a surge in nuclear power plant orders and construction. Later that decade, the world economic slowdown combined with the declining price of fossil fuels curtailed the growth of nuclear energy demand. As this took effect, two accidents, at Three Mile Island in the United States (1979) and at Chernobyl in the former Soviet Union (1986), raised serious questions in the public mind about nuclear safety. The overall effect was a significant slowing of nuclear energy's growth in the nineties. Nevertheless, some countries continued to push ahead strongly with reactor construction, thus contributing to small increases in nuclear electricity production (see Figure 1.1).

Figure 1.1: Historical growth of nuclear energy (1965-2002)



Source: IAEA.

Sir James Chadwick discovered the neutron in 1932.

Altogether, 32 countries have so far produced electricity from nuclear reactors, amounting to over 10 000 reactor-years of operating experience and generating by the end of the first "nuclear century" over 40 000 Terawatt-hours (TWh) net of electricity. As of 1 January 2003, there were 441 commercially operating nuclear reactors (see Table 1.1) representing an installed generating capacity of about 357 Gigawatts (GWe) net supplying about 7% of the world's total energy and about 17% of the world's electricity (see Figures 1.2 and 1.3). Within the OECD area there were 356 nuclear reactors in commercial operation in 17 countries, representing an installed capacity of some 306 GWe net and producing about 11% of the energy supply (about 24% of the electricity supply). Additionally, 34 reactors were under construction worldwide that will add a further 27 GWe of net capacity.

Table 1.1
Operable reactors by country
(as of 1 January 2003)

Country	Number of reactors
United States	104
France	59
Japan	54
United Kingdom	33
Russian Federation	30
Germany	19
Republic of Korea	18
Canada	14
India	14
Ukraine	13
Rest of World	83
Total	441

Source: IAEA.

Figure 1.2: World primary energy supply by fuel, 2000
(in percentage)

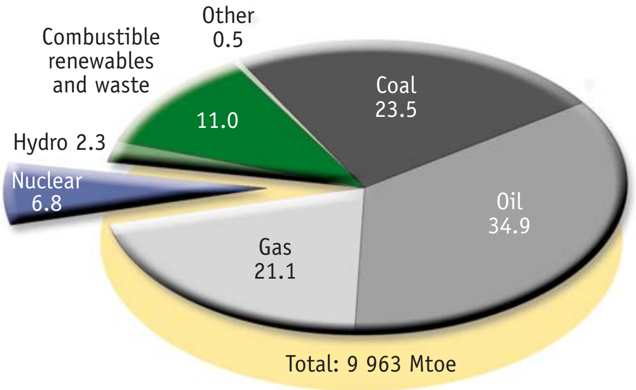
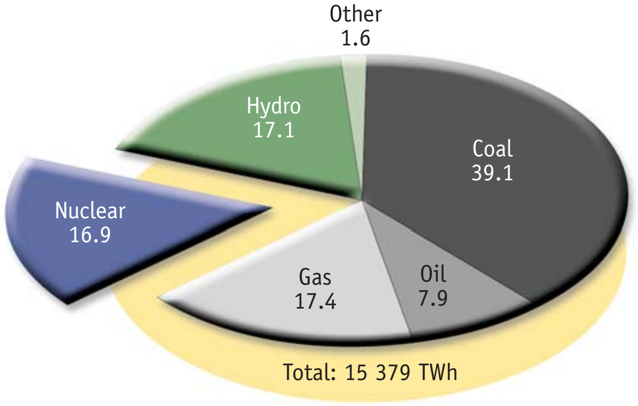


Figure 1.3: World electricity generation by fuel, 2000
(in percentage)



Source: International Energy Agency.

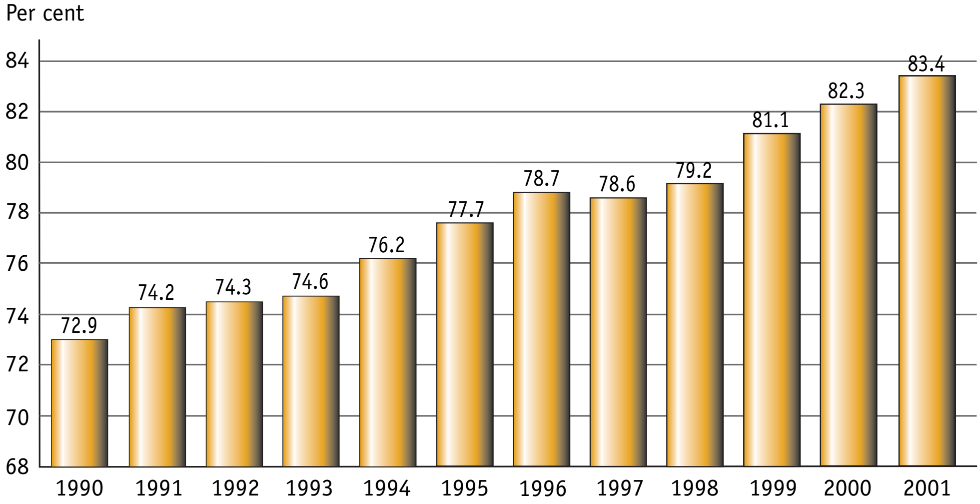
Figures 1.2 and 1.3 show the high worldwide reliance on fossil fuels in supplying primary energy and producing electricity. The consequent production of greenhouse gases, which cause changes in the world's climate, is a main cause of the growing emphasis on "decarbonising" the world's economies. Concern for the security of energy supply arising from the concentration of oil and natural gas resources among relatively few suppliers is also an element of reflection in national energy policies. Nuclear energy's lack of carbon emissions and the relatively uniform availability of fuel resources worldwide are focusing attention on its ability to meet these energy policy objectives.

Over the last decade, there has been a trend of improving nuclear plant performance measured by energy availability. This has led, in recent years, to many countries generating record amounts of electricity (see Figure 1.4). For example, the countries experiencing record generation performance during 2001 include Argentina, Brazil, Bulgaria, Finland, France, Germany, India, the Republic of Korea, Russia, Spain, Switzerland and the United States.

Yet despite its maturity, widespread usage and steady progress, compared with other energy sources, nuclear energy has a level of governmental involvement and public concern that makes it unique among energy sources. Many factors contribute to this, including its military origins and potential to be applied to weapons purposes, technical complexity, the long-term implications of nuclear waste, its complicated safety, legal and insurance requirements, the consequences associated with potential accidents, the health effects of exposure to ionising radiation and the large-scale investments required for its exploitation. Understanding these issues is important, then, to understanding nuclear energy today.

The first sustained atomic chain reaction occurred on 2 December 1942 in Chicago, Illinois, under the direction of **Dr. Enrico Fermi**.

Figure 1.4: Worldwide nuclear power plant energy availability factor (1990-2001)



Source: IAEA, Power Reactor Information System.

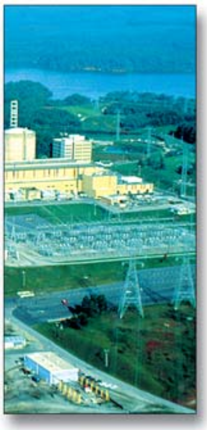
The energy availability factor is the percentage of maximum energy generation that a nuclear power plant is capable of supplying to the electricity grid and is a measure of operational performance.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- The numbers and types of reactors worldwide along with related information, updated annually, see 1.1 and 1.2.
- Estimates of energy supply and demand by region and fuel type, see 1.3, including projections of the near future, see 1.4.
- A general discussion of nuclear energy's role and related issues within the OECD, see 1.5.

Basic Principles of Nuclear Energy



Nuclear fission is a type of nuclear reaction that occurs in certain heavy atomic nuclei after collision with a neutron. When a nucleus undergoes fission it releases energy, most of which is convertible to heat. Fusion is another heat-producing nuclear reaction, not so far harnessed for energy production.

Nuclear reactors are machines for creating and controlling fission reactions to produce electricity and heat. There are many types of reactors in commercial operation, all possessing several components in common – fuel, moderator, coolant and control rods.

Currently, nearly 80% of nuclear reactors use ordinary water both as coolant and moderator. The main types are the pressurised water reactor (PWR) and the boiling water reactor (BWR). Their fuel is primarily uranium.

A nuclear reactor is, in essence, simply a way of producing heat to boil water, thereby creating steam to drive turbine generators for electricity production. This chapter explains the processes involved and introduces the basic technologies applied to harnessing the energy.

A nuclear reaction is one that occurs when the nucleus of any atom is changed as a result of collision with some other physical entity, which may be alpha particles, gamma rays, neutrons, protons or even other atoms. Of the many possible nuclear reactions, two – fission and fusion – are of particular interest because they can produce a great deal of energy. Of these two, only fission has so far been harnessed for electricity production.

Nuclear fission

Certain naturally occurring and man-made heavy elements, for example uranium and plutonium, are relatively unstable. When the nucleus of any such element is impacted by a neutron which it absorbs, it can fission, or split into two fragments, releasing at the same time two or three neutrons and energy (see Figure 2.1).

The fragments, of which many different combinations are possible, are called fission products. The total mass of the products of the reaction (fission products and neutrons) is minutely less than the original mass of the atom and impacting neutron, the difference having been converted into energy according to Einstein's famous formula $E = mc^2$.

Figure 2.2 gives the probabilities of isotopes of a given mass being formed by a fission reaction, in this case that of uranium-235 (^{235}U). In terms of abundance and radioactivity, the most important fission product isotopes resulting from the fission of ^{235}U are radioactive forms of bromine (Br), caesium (Cs), iodine (I), krypton (Kr), strontium (Sr) and xenon (Xe). Like any radioactive element, these daughter isotopes decay, each over a different period measured by and referred to as its half-life. Because of their abundance and radioactivity these daughter isotopes and their decay products form a significant part of nuclear waste (see Chapter 4).

As the fission fragments are ejected after the original impact, they begin to collide with nearby atoms and within a millimetre lose most of their motion energy, which is converted into heat

Lise Meitner (1878-1968) was one of the central persons in the discovery of nuclear fission. Born in Austria, she did her experimental work on transuranic elements in Germany. Forced to flee the Nazis, Meitner, a Jew, went to Sweden in 1938. While visiting her nephew Otto Frisch in Denmark, she and Frisch proved that a splitting of the uranium atom was feasible. In 1939, they described their discovery in a landmark paper, *Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction*, and in it coined the term fission.

energy. This heat is then used to generate electricity.

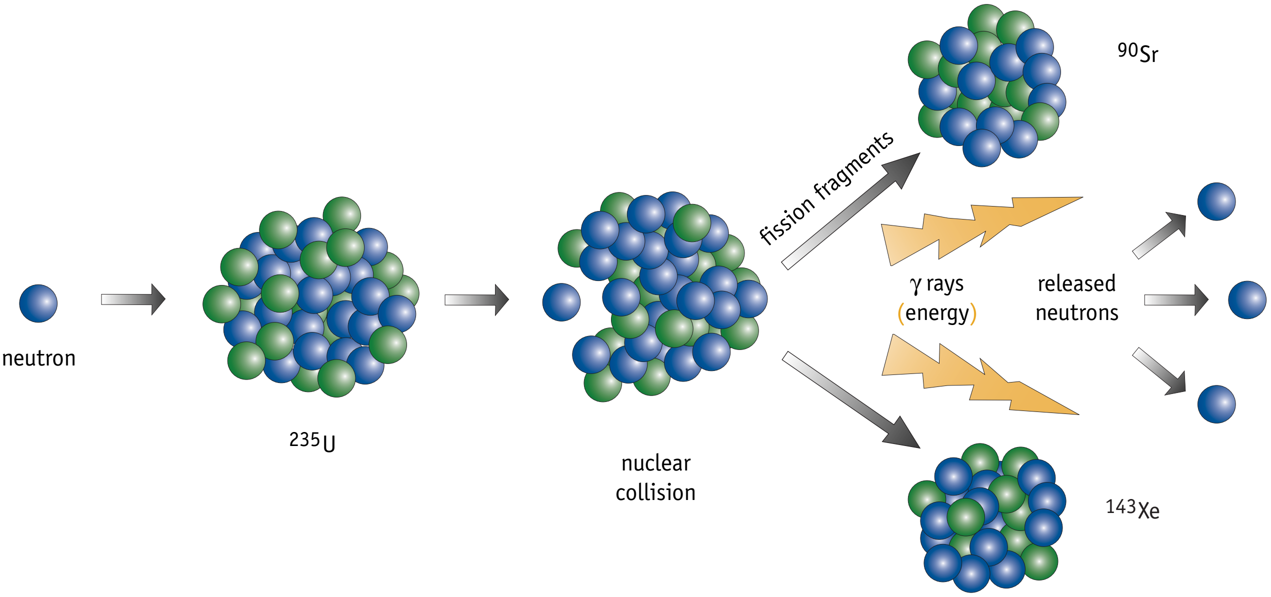
When the free neutrons, which are also released as a result of fission, are absorbed by other nearby fissionable atoms, those too can fission and release more neutrons – and so on in what is known as a chain reaction. Alternatively, they may bounce off a nucleus (scattering), escape without interaction (leakage) or simply be absorbed without causing fission (capture).

In a situation where enough free neutrons are being created to balance the number which are lost by leakage and capture, the fission process becomes self-sustaining, and the system is said at that point to have reached criticality. The critical mass is the minimum amount of fissionable material for a given set of conditions needed to maintain a chain reaction.

Neutrons with a relatively low kinetic energy [less than 0.1 electron volt (eV)] are known as thermal neutrons; these are the most efficient in causing fission in uranium or plutonium. Those with higher kinetic energy, typically in a range up to 10 million eV (MeV), are referred to as fast neutrons. All neutrons produced by a fission reaction are fast neutrons. Though fast neutrons are less efficient in producing fission in uranium, they can be effective for a wider range of isotopes. A moderator is used to slow the fast neutrons released during fission to the more efficient thermal energies needed in commercial nuclear power plants.

When the nucleus of an atom captures a neutron and does not fission, it may change into another element. In a nuclear reactor, this results in the creation of an important set of long-lived

Figure 2.1: A typical fission reaction



elements which either do not occur, or are very rare, in nature (see Table 2.1).

All the elements listed in Table 2.1 are radioactive, and some – particularly plutonium – are themselves capable of being used as nuclear fuel. Because of their long half-lives and high radiological and biological toxicity they are another important component in nuclear waste, and are the reason why some waste must be isolated for very long periods (see Chapter 4).

Nuclear fission is an extremely potent source of energy with a very high energy density, i.e. energy per mass of fuel. As compared to chemical reactions such as combustion of fossil fuels, fission reactions require a much smaller volume of basic material to produce an equivalent amount of energy. The energy released by the fission of 1 kilogram of uranium in a typical reactor is equivalent to that released by about 45 000 kg of wood, 22 000 kg of coal, 15 000 kg of oil and 14 000 kg of liquid natural gas (see Table 2.2).

Similarly, compared with non-combustion energy sources, like solar and wind, it requires a much smaller land area to generate an equivalent power. For example, in the current state of the relevant technologies, a 900 Megawatt electric (MWe) nuclear power station would produce as much electricity in a year as 70 square kilometres of solar panels, or a few thousand windmills taking into account efficiency and availability.

A **fissile material** is a material that is capable of fission after the impact of a thermal neutron. In practice, the most important fissile materials are ^{235}U and ^{239}Pu.
A **fissionable material** is a material that is capable of undergoing fission, normally differentiated from fissile in that these will fission if impacted by a fast neutron. An example of a fissionable material is ^{238}U.
A **fertile material** is one that is capable of becoming fissile through the capture of a neutron(s), possibly followed by radioactive decay. Important examples are ^{238}U, which is fissionable but can also transmute into fissile ^{239}Pu, and ^{232}Th, which can transmute into fissile ^{233}U.

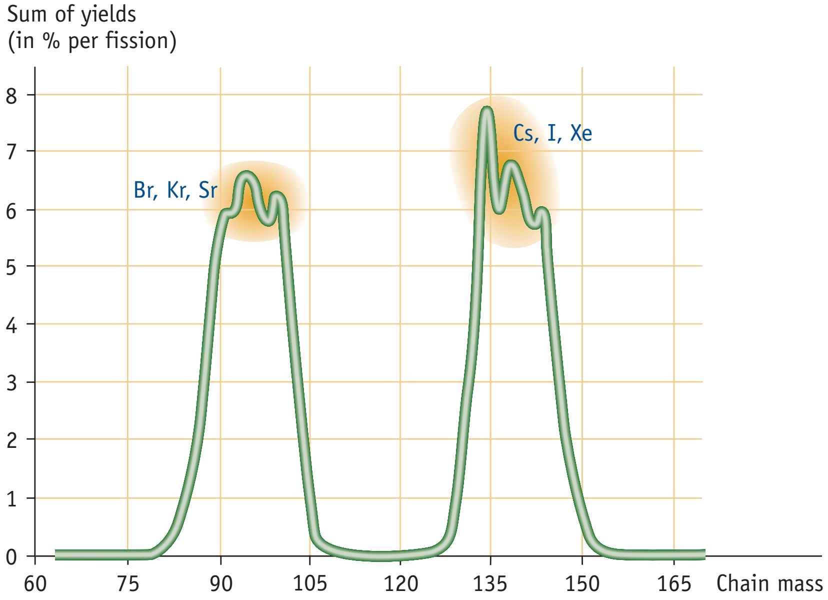
Table 2.1
Important isotopes formed
by neutron capture in a nuclear reactor

Element	Approximate half-life
Neptunium (^{237}Np)	210 000 years
Plutonium (^{239}Pu)	24 000 years
Americium (^{243}Am)	7 400 years

Table 2.2
Energy content of various fuels

Fuel	Approximate energy content in 1 tonne (GJ)
Wood	14
Coal	29
Oil	42
Natural gas (liquified)	46
Uranium (LWR, once-through)	630 000

Figure 2.2: Fission product yield for thermal fission of ^{235}U



Basic components of nuclear reactors

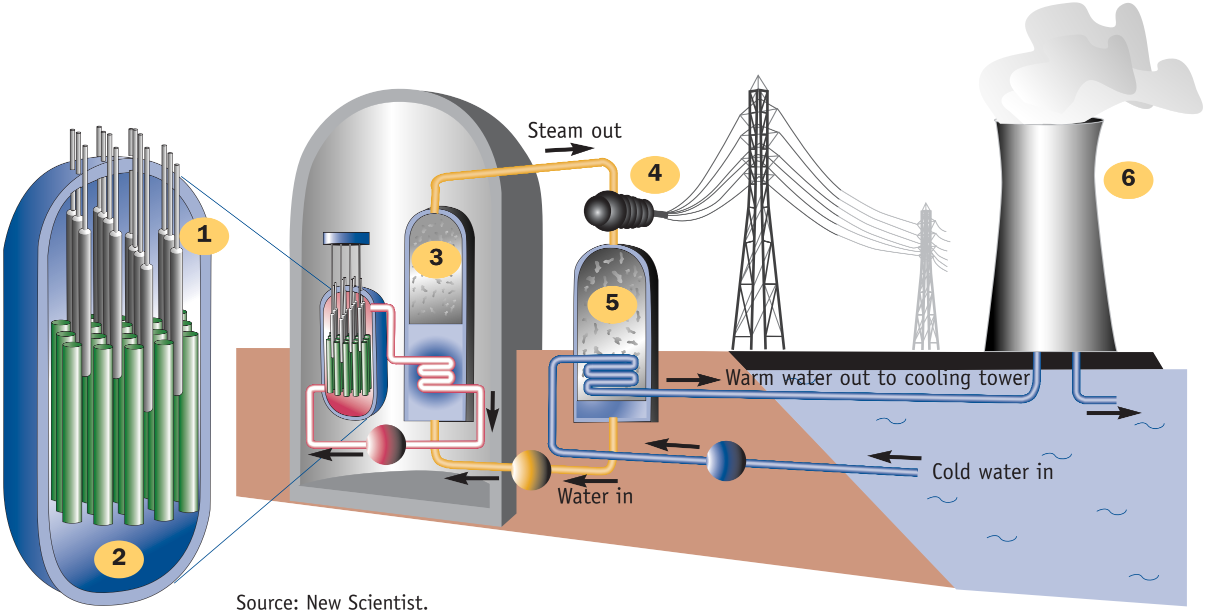
The basic technology used to harness the energy of nuclear fission is the nuclear reactor. Though there are many types of nuclear reactors, all have several components in common, viz fuel, moderator, coolant and control rods (see Figure 2.3).

Fuel

Uranium has two main isotopes: ^{235}U and ^{238}U. The former, ^{235}U, is the only fissile material found in nature, i.e. it can easily fission when hit either by thermal or fast neutrons. Thus, almost all reactors use uranium as fuel. Most fuels for commercial reactors are processed so as to contain a higher concentration of ^{235}U than occurs in nature, typically 2-5% compared with the 0.711% found in nature; the fuel is said to be enriched in ^{235}U.

The remainder of the fuel, typically ^{238}U, can fission only when hit by fast neutrons of certain energies; but when neutron capture occurs, it eventually transforms into plutonium-239 (^{239}Pu). This isotope of plutonium (one of many) is also able to fission under the impact of thermal or fast neutrons, and its contribution to the energy output of a light water reactor gradually grows until it represents almost 30% of the power that is generated. Some reactors use fuel in which plutonium is incorporated at the outset, called mixed-oxide fuel (or MOX). This is one way of using up stocks of plutonium extracted from spent fuels, and which could otherwise represent waste.

Figure 2.3: Basic components of a nuclear reactor (pressurised)



Source: New Scientist.

1 – Reactor: fuel (green) heats pressurised water. Control rods (grey) absorb neutrons to control or terminate fission.
2 – Coolant and moderator: fuel and control rods are surrounded by water that serves as coolant and moderator.
3 – Steam generator: hot water from the reactor is pumped through a heat exchanger to generate high-pressure steam.
4 – Turbine generator: steam drives electricity generator to produce electricity.
5 – Condenser: removes heat to convert steam back to water.
6 – Cooling tower: removes heat to return cooling water to near-ambient temperature.

Moderator

A moderator is necessary to slow the fast neutrons created during fission down to the thermal energy range so as to increase their efficiency in causing further fission. The moderator must be a light material that will allow the neutrons to slow down without being captured. Usually, ordinary water is used; alternatives in use are graphite, a form of carbon, and heavy water, water formed with the heavier deuterium isotope of hydrogen.

Coolant

A coolant is necessary to absorb and remove the heat produced by nuclear fission and maintain the temperature of the fuel within acceptable limits. It can then transfer the heat to drive electricity-generating turbines. If water is used as the coolant, the steam produced can be fed directly to the turbines. Alternatively, it can be passed through a heat-exchanger which will remove the heat and produce the necessary steam. Other possible coolants are heavy water, gases like carbon dioxide or helium, or molten metals such as sodium or lead and bismuth. A coolant can also be a moderator; water is used in this dual way in most modern reactors.

Control rods

Control rods are made of materials that absorb neutrons, for example, boron, silver, indium, cadmium and hafnium. They are introduced into the reactor to reduce the number of neutrons and thus stop the fission process when required, or, during operation, to control and regulate the level and spatial distribution of power in the reactor.

Other components

The fuel along with its mechanical structure that holds it in place forms the reactor core. Typically, a neutron reflector surrounds the core and serves to return as many neutrons as possible that have leaked out of the core and thus maximise the efficiency of their use. Often, the coolant and/or moderator serve as the reflector. The core and reflector are often housed in a thick steel container called the reactor pressure vessel. Radiation shielding is provided to reduce the high levels of radiation produced by the fission process (see Chapter 6). Numerous instruments are inserted into the core and support systems to permit the monitoring and control of the reactor, for example temperature, pressure, radiation and power level.

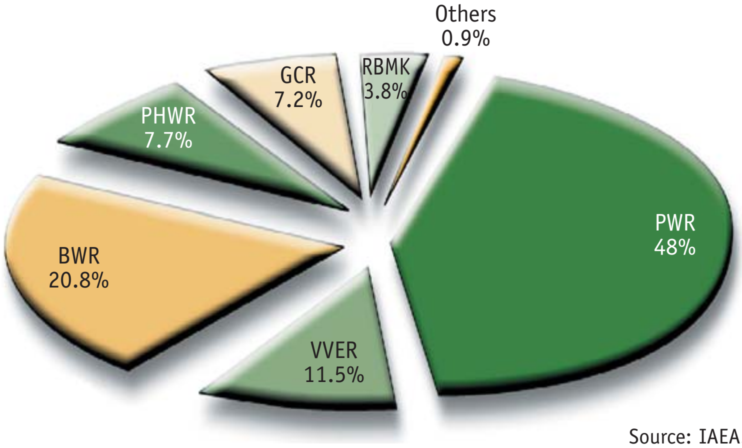
Reactor technologies

A popular and useful method of categorising reactors is according to the type of coolant used. About 80% of commercial reactors in use at the beginning of 2003 were cooled and moderated with ordinary water and are known as light water reactors (LWRs). Of these, two major types exist – pressurised water reactors (PWRs), which includes a Russian variant (VVER), and boiling water reactors (BWRs). The majority of the remaining 20% of reactors are cooled either by heavy water or gas. Figure 2.4 shows how the main types of commercial reactor are distributed worldwide.

Each of the main types of commercial reactor is briefly described below with data on the number of reactors current as of 1 January 2003.

Within each basic type there are different designs resulting from different national, manufacturer and customer requirements.

Figure 2.4: Reactor types in use worldwide (as of 1 January 2003)



Source: IAEA.

Pressurised water reactors (PWRs)

At the beginning of 2003, there were 212 PWRs worldwide, of which 150 were in France, Japan and the United States.

Ordinary water is used as both coolant and moderator. The coolant is kept at high pressure (about 15.5 MPa or 2 250 psi) to keep it liquid during operation, retained within a pressure boundary comprised mainly of the reactor pressure vessel and piping in the primary system. The coolant is circulated using powerful pumps so that the heat is transferred to boil water in a separate, secondary loop in a steam generator. The steam thus produced drives the electricity-producing turbine generators (see Figure 2.5).

Figure 2.5: A pressurised water reactor (PWR)

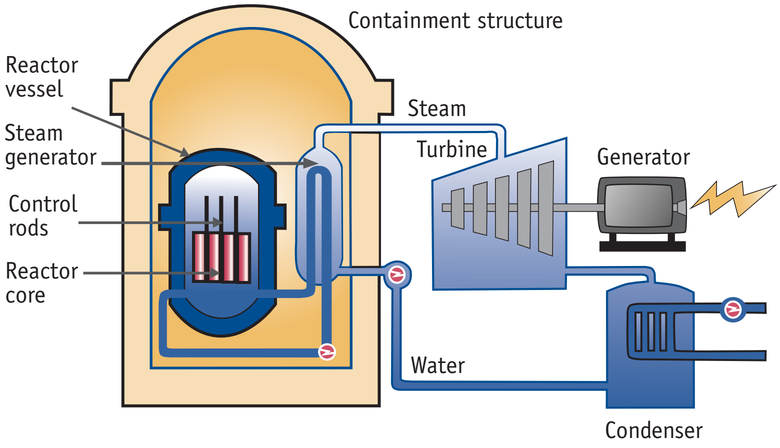
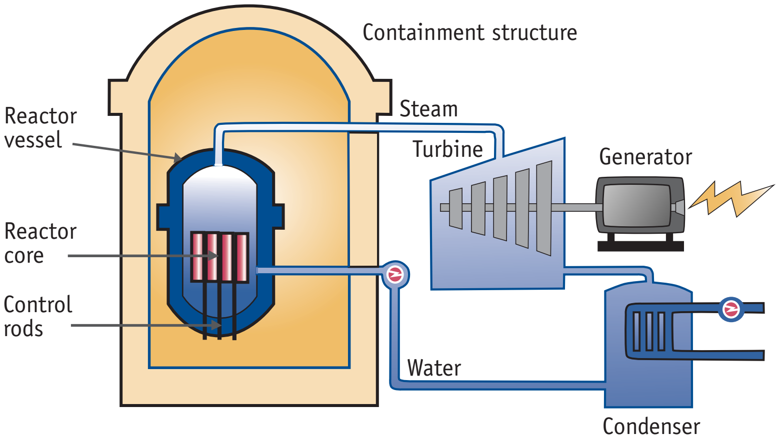


Figure 2.6: A boiling water reactor (BWR)



Source: Nuclear Energy Institute website.

VVERs

A total of 51 VVERs were in operation, of which 26 were in the Russian Federation and Ukraine. They are also operating in Armenia, Bulgaria, the Czech Republic, Finland, Hungary and the Slovak Republic. The name is a Russian acronym connoting a water-cooled, water-moderated energy reactor. VVERs are, in essence, Russian-designed PWRs.

First-generation VVER (type 440/230) reactors need expensive modifications because their original designs do not correspond to contemporary practices in nuclear safety. As a result, decisions have been taken to shut down some of these units, such as in Bulgaria and the Slovak Republic.

Boiling water reactors (BWRs)

There were 92 BWRs operating in nine countries, of which Japan and the United States account for 64. In a BWR, ordinary water acts as both coolant and moderator. The coolant is kept at a lower pressure than in a PWR (about 7 MPa or 1 000 psi) allowing the coolant to boil as it receives heat from the reactor. The resultant steam is passed directly to the turbine generators to produce electricity (see Figure 2.6). While the absence of a steam generator simplifies the design, as compared with PWRs, radioactivity contaminates the electricity generating turbine.

Pressurised heavy water reactors (PHWRs)

Thirty-four PHWRs were operating worldwide in six countries, of which 14 were in their country of origin, Canada, and the remainder in Argentina, India, Pakistan, the Republic of Korea and Romania. Known as CANDU reactors (short for Canadian deuterium uranium), they use heavy water (D_2O, water formed with the heavier deuterium isotope of hydrogen), as both coolant and moderator.

Heavy water allows natural uranium to be used as the fuel, thereby eliminating the need, and cost, to enrich the uranium. On the other hand, the production of heavy water requires a dedicated plant to separate the D_2O from ordinary water, raising the concentration of D_2O from its natural concentration of much less than 1% to the 99% used in a CANDU reactor. As in a PWR, the coolant is passed through a steam generator so as to boil ordinary water in a separate loop. An advantage of the CANDU design is that refuelling can take place during operation, whereas PWRs and BWRs must shut down in order to refuel. This feature allows high availability but also increases the complexity of operation.

Gas-cooled reactors (GCR)

As regards gas-cooled reactors, 33 were in commercial use only in the United Kingdom. There are two types, the Magnox (named from the magnesium alloy used to clad the fuel elements) and the advanced gas-cooled reactor (AGR). Both use carbon dioxide as the coolant and graphite as the moderator. The Magnox uses natural uranium as fuel and the AGR, enriched uranium. Like CANDU reactors, these designs can be refuelled on-line, with the same characteristics as stated above.

RBMK

Seventeen RBMK remain in operation of which 15 were in the Russian Federation and two in Lithuania. The name is a Russian acronym meaning large power boiling reactor.

Ordinary water is used as the coolant and graphite as the moderator. As with a BWR, the coolant boils as it passes through the reactor and the resultant steam is passed directly to turbine generators.

The RBMK, as an early design, was often built, and some are being operated, without safety characteristics and features required elsewhere. The well-known accident at Chernobyl (Ukraine) in 1986 happened to a reactor of this type.

Reactors of this type are the object of special safety concerns because they cannot be upgraded to correspond to contemporary safety practices at reasonable cost.

Fast breeder reactors

The reactor types described above are thermal reactors, most of the fission being caused by thermal neutrons. Fast reactors are designed so as to make use of fast neutrons with much higher kinetic energies. Fast reactors essentially create more neutrons per fission than thermal reactors and make better use of them because the probability of neutron capture decreases at higher neutron energies. These excess neutrons can be used to convert fertile materials, e.g. ^{238}U and ^{232}Th, into fissile materials through neutron capture. This newly created fissile material can in turn fuel the reactor. It is possible to design reactors to produce more fuel than they consume in breeder reactors. Typically, breeder reactors are fast reactors, though designs exist that could use thermal neutrons. Fast breeder reactors, by creating fuel from non-fissile isotopes and improving the efficiency of utilisation through recycling, can potentially increase available world nuclear fuel resources up to 50-fold and are thus a key element in the sustainability of nuclear energy in the very long term. Breeder reactors have been built and operated in a number of countries, though in 2002 they were operated only in France, India, Japan and the Russian Federation.

Reactor lifetimes

Some first-generation reactors, such as the Magnox reactors in the United Kingdom, are still in service, though after 35 years or more they are approaching the end of their operational lives. Many of today's reactors were built in the 1970s and 1980s and will approach lifetimes of 40 years beginning around 2015. However, studies based on operating and materials experience have revealed no major technological issues inhibiting longer operational lives for many reactors, particularly PWRs and BWRs. Careful monitoring of plant performance, analysis of operating experience, modernisation programmes and refurbishments offer good prospects for life extensions at many plants. For example, as of January 2003, the nuclear safety authorities in the United States had granted extensions to permit ten reactors to operate for 60 years, 20 years beyond the originally licensed operational life. Other countries such as the Russian Federation are also planning to extend the lifetimes of existing reactors. In many countries decisions on plant lifetimes are made through the periodic renewal of operating licenses, which involve comprehensive safety analyses using the latest methods, information and safety requirements.

A **breeder reactor** is one that generates as much, or more, fuel than it uses.

A **reactor's power rating** can be given in terms of either thermal or electrical power. The thermal power of a reactor represents the amount of heat generated per unit time and is usually given in megawatts thermal or MW_{th}. Most often the reactor's electrical power is given in terms of megawatts electric or MW_e. Because the efficiency of transforming the heat energy into electricity in light water reactor plant is around 33%, a power plant with a thermal power rating of around 3 300 MW_{th} would have an electrical power rating of 1 000 MW_e. A third form of power rating of a reactor is megawatts net, MW_{net}, which accounts for the electricity used within the site and not sold on the open market. Typically this represents a small percentage of the electrical output. For example, the latest French PWR at Civaux has an electrical rating of 1 516 MW_e and a net rating of 1 450 MW_{net}.

Nuclear fusion

Ten grams of deuterium, which can be extracted from 500 litres of ordinary water, and 15 grams of tritium, produced from just 30 grams of lithium, a plentiful naturally occurring element, would produce enough energy to supply the lifetime electricity needs of an average person in an industrialised country.

Whereas nuclear fission involves the splitting of a heavy atomic nucleus and a consequent release of energy, nuclear fusion is a process of combining light nuclei to form more massive nuclei with the release of energy. This process takes place continuously in the universe. In the core of the sun, at temperatures of 10-15 million °C, hydrogen is converted to helium, providing the energy that sustains life on earth.

The possibility of producing energy for commercial use by fusion has been researched for decades. One possible fusion reaction being investigated (the D-T fusion reaction) is illustrated in Figure 2.7. The nuclei of two isotopes of hydrogen, one (deuterium) having one neutron and one proton, and the other (tritium) having two neutrons and one proton, combine to form helium and a neutron, releasing energy in the process.

At the extremely high temperatures required for fusion reactions to take place, the fuel has changed its state from gas to plasma, a state of matter where all the electrons have been stripped from atoms, leaving only the nuclei. The understanding and control of plasma has been a major challenge in the development of fusion power.

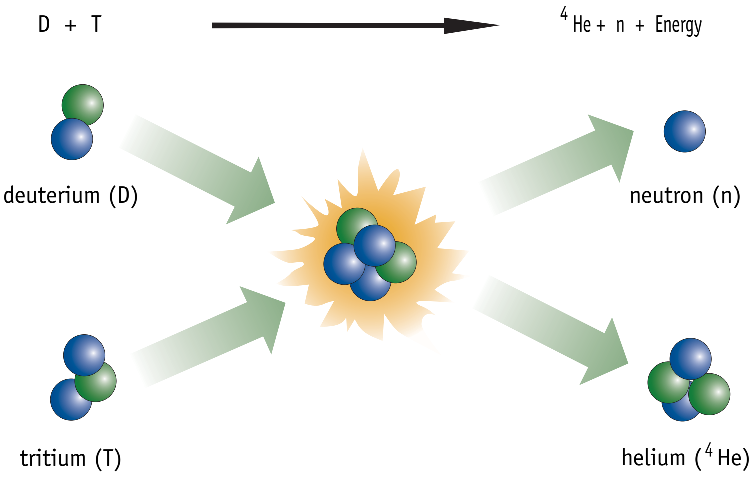
The design of a fusion reactor would differ considerably from that of a fission reactor. The principal problem is containment of the plasma fuel, which needs to be kept at very high temperatures to initiate and maintain the reaction. Research has focused on two different means of containment – magnetic and inertial. In the first, the plasma is held in a "bottle" or "torus" by magnetic fields. In the second, the mass of the fuel itself, under rapid compression, prevents escape of the plasma.

In either case, the plasma must be isolated from material surfaces to avoid cooling and the introduction of impurities from the surface that would contaminate the plasma. One of the most promising means for achieving this is a toroidal (ring-shaped) magnetic confinement system of which the Tokamak configuration is now the most generally favoured (see Figure 2.8).

If they become practicable, fusion reactors could potentially have certain beneficial nuclear characteristics. They could for example:

- have a more or less unlimited supply of fuel (hydrogen available from water and tritium produced from abundant lithium);

Figure 2.7: Typical fusion reaction

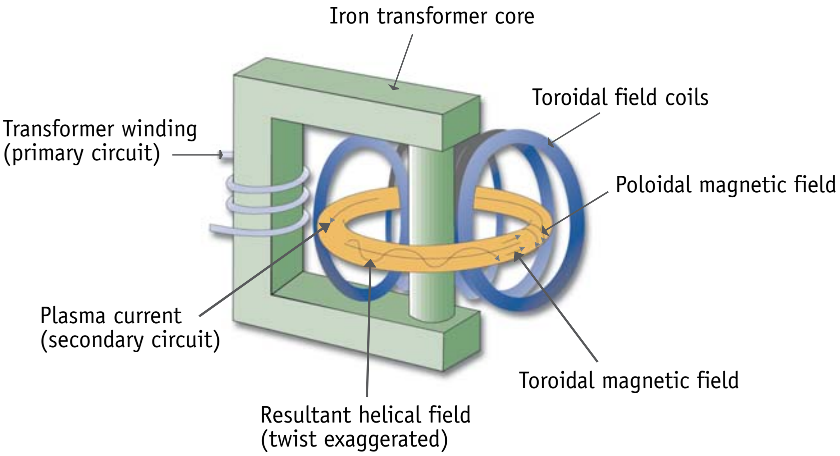


Source: Joint European Torus.

- be inherently safe (since the exposure of the plasma would instantly stop the fusion process);
- produce only small amounts of long-lived highly radioactive waste (though other types of radioactive waste would be produced with tritium being the most problematic);
- be unable to produce fissile materials that could be used for nuclear weapons.

Experiments in fusion are being conducted and test facilities exist in many parts of the world. Nevertheless, although progress has been considerable, many years of further research would be needed before a viable reactor could be available. Existing major facilities include the European Union's Joint European Torus (JET) located in the United Kingdom; the Princeton Plasma Physics Laboratory (United States), and the JT-60U Tokamak at the Japanese Atomic Energy Research Institute. Canada, China, the European Union, Japan, Russia and the United States are co-operating to build the next-generation fusion test reactor – the International Thermonuclear Experimental Reactor, or ITER.

Figure 2.8: Simple diagram of a Tokamak fusion reactor



Source: Joint European Torus.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- The visualisation and manipulation of basic nuclear data including fission cross-sections, radionuclide half-lives and fission product yields, see 2.1.
- Data on the numbers and types of reactors worldwide along with related information, updated annually, see 1.1, 1.2 and 1.3.
- The basics of nuclear fission and the different types of nuclear reactor, see 2.2 through 2.4.
- Nuclear fusion and the ITER, see 2.5.

Chapter 3

The Nuclear Fuel Cycle

The nuclear fuel cycle is a chain of processes, beginning with the mining of uranium, for manufacturing and managing nuclear fuel prior to and after its use in a reactor.

A once-through fuel cycle is usual, but several countries recycle spent fuel, mainly to make fuller use of the fuel and to minimise the long-term radiotoxicity of the waste.

The nuclear fuel cycle is the chain of processes whereby nuclear fuel is produced and managed before and after its use in a reactor; respectively, the front end and the back end of the fuel cycle. Here, the extraction of energy from the fuel while it is in the reactor is not regarded as part of the cycle.

Two major types of fuel cycle exist – once-through and closed – the difference being the way the spent nuclear fuel is managed. The major processes in the cycle are summarised in Figure 3.1. In the once-through fuel cycle, fuel removed from a reactor is set aside in storage areas pending its ultimate disposal. A closed fuel cycle, also known as a "recycling" fuel cycle, allows the unused fissile material of the spent fuel to be recovered and reused to produce energy as new fuel.

Figure 3.1: The nuclear fuel cycle

Most uranium is extracted using conventional mining techniques.

Uranium "yellowcake".

A UF_6 cylinder.

Table 3.1
Major uranium conversion facilities worldwide

Country	Site(s)
Canada	Blind River and Port Hope, Ontario
France	Malvési; Pierrelatte
Russian Federation	Angarsk; Ekaterinburg
United Kingdom	Springfields, Lancashire
United States	Metropolis, Illinois

The front end

Uranium mining and milling

The extraction of uranium ore from the earth is conducted in much the same manner as the recovery of other mineral resources, such as copper. Over 70% of uranium production is achieved by the extraction of ore using conventional open pit or underground mining methods. The remainder is mainly accounted for by *in situ* leaching (ISL), a method whereby a solvent solution is injected underground, dissolves the uranium into the solution and is recovered from wells for the extraction of the dissolved uranium.

Milling is the process through which mined uranium ore is physically reduced to a suitable size, then chemically treated to extract and purify the uranium. It also reduces the volume of material to be transported to the next stage of the fuel cycle. Reflecting its colour and consistency, the solid product of milling (U_3O_8) is known as "yellowcake", though it can also be grey in colour.

At the beginning of 2001, there were 21 uranium producing countries of which ten (Australia, Canada, Kazakhstan, Namibia, Niger, the Russian Federation, South Africa, Ukraine, the United States and Uzbekistan) produced 90% of the world's output. The dominant producers are Australia and Canada, who between them accounted for over 50% of world output in 2000.

Mining and milling of uranium ore produces waste of different types, all of which require appropriate management. Waste from open pit and underground mining are soils and/or waste rock. They may also include ore with sub-economic levels of uranium or excessively high levels of contaminants. Milling produces the largest volume of waste in the form of mill tailings, which are a mixture of finely ground rock and process liquid. Tailings pose particular problems because of their large volume and radiological and chemical contaminants. ISL produces no waste rock or mill tailings but it is suitable only in specific geological circumstances and it must be appropriately managed to protect groundwater.

The quantity of ore required to produce a tonne of product, whether it be copper or uranium, using open pit or underground mining depends primarily on the average grade of the ore and can range from 10 to 1 000 tonnes (average grades of 10% to 0.1%). Thus, the volume of tailings that results from milling this ore is large. For example, over its lifetime, the Shirley Basin mine in the United States produced 9 460 tonnes of uranium from ore with an average grade of 0.145%. This resulted in 7.1 million tonnes of tailings that cover an area of 106 ha.

The mining and milling processes are mature industries with competitive international markets.

Conversion

Conversion is the chemical process that transforms yellowcake into uranium hexafluoride (UF_6). It is conducted at only a few locations worldwide, mostly in OECD countries (see Table 3.1). Uranium hexafluoride is solid at room temperature but readily turns into a gas at a temperature below the boiling point of water, and in this form is very suitable for the enrichment process. It is usually stored and transported in large cylinders, nominally 122 cm in diameter and holding about 12 000 kg of UF_6. At this point the uranium still retains the same composition of isotopes as found in natural uranium.

Enrichment

Uranium enrichment involves the partial separation of uranium into its two main isotopes (^{235}U and ^{238}U), yielding two streams, the first enriched so as to contain more ^{235}U than its natural concentration (0.711%), and the second correspondingly depleted. Most commercial reactors require uranium enriched to less than 5% ^{235}U. Some research reactors use highly enriched uranium fuels, i.e. more than 20% ^{235}U, but there are programmes in place to move to low enriched uranium.

Two methods of enrichment are in commercial use, gaseous diffusion and centrifugation, both based on UF_6. Early plants used gaseous diffusion technology despite its high electricity requirement and the very large size of the plants, factors which account for their small number worldwide (see Table 3.2). For example, the gaseous diffusion plant at Tricastin in France is supplied by four nuclear reactors. More recently, advances in materials technology and fabrication methods have led to an increased use of centrifugation, resulting in lower enrichment costs, due mainly to a reduction in energy consumption by a factor of 50.

Uranium enrichment plant at Tricastin, France. This enrichment plant alone is large enough to more than meet the needs of all nuclear reactors in France.

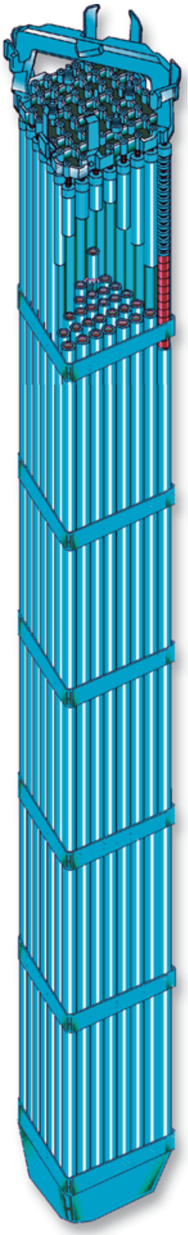
Cascade of centrifuges at Rokkasho-mura in Japan.

Table 3.2: Major uranium enrichment facilities worldwide

Country	Site(s)	Technology
China	Lanzhou	Centrifuge[1]
	Shaanxi	Centrifuge
France	Tricastin	Gaseous diffusion
Germany	Gronau	Centrifuge
Japan	Rokkasho-mura	Centrifuge
Netherlands	Almelo	Centrifuge
Russia	Angarsk	Centrifuge
	Ekaterinburg	Centrifuge
	Krasnoyarsk	Centrifuge
	Seversk	Centrifuge
United Kingdom	Capenhurst	Centrifuge
United States	Paducah	Gaseous diffusion

1. Under construction.

Typical fuel pellet.



Typical BWR fuel assembly: about 4 m tall and about 15 cm on each side; it weighs about 300 kg.

The enrichment process also produces depleted uranium, of which there existed, at the end of 1999, an estimated stock of over 1.2 million tonnes mainly produced using the gaseous diffusion process. The depleted uranium from the gaseous diffusion process often contains recoverable ^{235}U, normally around 0.3% ^{235}U (compared with the initial 0.711%).

Different countries have adopted different strategies for managing this material. Typically, the depleted uranium is stored in UF_6 form in large cylinders as in the United States and Russia. In this form, it can represent a potential chemical hazard if the cylinders leak. Other countries, France for example, are converting their stock into a stable oxide for long-term storage and possible eventual re-use as a fuel in fast breeder reactors. Depending on the economies and available centrifuge enrichment capacity, some countries, Russia for example, "re-enrich" to recover the remaining usable ^{235}U.

Enrichment is considered a mature service industry with competitive international markets.

Fuel fabrication

Most reactors use uranium dioxide as their fuel. Its production in fuel form involves the transformation of UF_6 into uranium dioxide (UO_2) powder, which is then pressed and heated at high temperatures (up to 1 400 °C) to produce dice-sized cylindrical pellets. These are loaded into hollow metal tubes (fuel rods) that are then bundled as fuel assemblies. The metal used is highly corrosion-resistant, typically stainless steel or zirconium alloy. Over 730 fuel assemblies, containing about 46 000 fuel rods would fuel a typical BWR reactor.

Less than 10% of reactors worldwide have been licensed to use mixed-oxide (MOX) fuel – a mixture of uranium dioxide and plutonium dioxide. The plutonium dioxide mainly results from the commercial recycling of spent fuel, though the Russian Federation and the United States are planning to use plutonium from surplus nuclear warheads. The production process for MOX is similar to that already described for uranium dioxide fuels, with additional precautions to protect workers from the increased radiation of this irradiated material and from inhalation of plutonium.

Although there are a large number of fuel fabricators worldwide, commercial competition between them is inhibited, largely due to the highly specific requirements, different national regulatory systems and variety of reactor types. Furthermore, the fuel management strategies pursued in different countries vary according to market circumstances.

Typical spent nuclear fuel storage pool.

Dry storage of spent fuel.

The back end

The back end of the fuel cycle starts when the irradiated or "spent" fuel is unloaded from the reactor and stored at the reactor site for an initial period, typically between five and ten years. This initial storage involves placing the spent fuel in water-filled "pools". The water both shields the high radiation of the recently discharged fuel and helps to cool it. After this initial period of cooling, during which the highest heat dissipation occurs, the fuel's temperature is much lower and it is then ready for longer-term storage or for reprocessing if a recycling strategy is being pursued.

Long-term storage of spent fuel may be under wet or dry conditions. If wet storage is chosen the spent fuel is transferred to another pool of water similar to that in which it has rested during the initial period of cooling. Alternatively, and nowadays increasingly, the fuel can be loaded into large, dry shielded casks in which natural air circulation maintains it at the required temperatures, in what is known as dry storage. These casks can be transported by truck or rail to other sites if necessary. Spent fuel can be maintained under either wet or dry conditions for over 30 to 50 years before packaging or repackaging becomes necessary, or before fuel disposal.

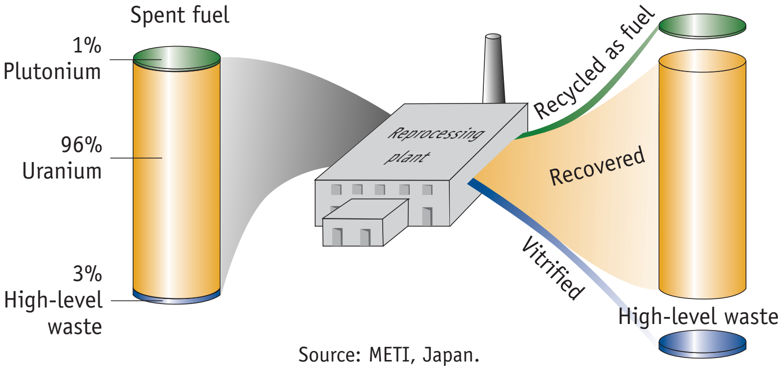
Reprocessing

Reprocessing is the operation by which the unused energy content of spent fuel is recovered with an intention of future re-use or, in some cases, to condition the fuel for disposal (see Figure 3.2). It also reduces the volume and long-term radiotoxicity of the waste that requires disposal. This approach to spent fuel management has been chosen by some European countries (Belgium, France, Germany and Switzerland), China, India, Japan and Russia, though not by the majority of the countries operating nuclear power plants.

Reprocessing can reduce by approximately 10-15% the requirements for natural uranium, mainly through the use of the plutonium created during the fission process, which is extracted from the spent fuel and recycled in MOX fuel. The separation of the uranium and plutonium from other isotopes is achieved commercially using a chemical process called PUREX (plutonium uranium extraction). The remnant of fission products and minor actinides are high-level waste (see Chapter 4). Another remnant is the non-dissolvable metallic structure of the fuel assemblies called hulls and end-pieces. Current reprocessing plants are large, complex and expensive facilities that have, for that reason, been built in only a few countries (see Table 3.3).

Between seven and ten tonnes of natural uranium are required to produce a tonne of enriched uranium used in a light-water reactor.

Figure 3.2: Composition and reprocessing of spent fuel



Source: METI, Japan.

Table 3.3: Commercial spent nuclear fuel reprocessing plants worldwide

Country	Facility/location	Year of commissioning	Fuel type
China	Diwopu (Ganzu)	2002	LWR
France	La Hague	1976	LWR
India	Kalpakkam	1998	PHWR
	Tarapur	1974	PHWR
Japan	Rokkasho-mura	2005 *(planned)*	LWR
	Tokai-mura	1977	LWR, ATR
Russian Federation	Tcheliabinsk-65 Mayak	1984	VVER
UK	B205/Sellafield	1964	Magnox GCR
	Thorp/Sellafield	1994	LWR, AGR

The number of plutonium recycles possible with current reprocessing and reactor technologies is limited by the build-up of plutonium isotopes that are not fissionable by the thermal neutrons found in light water reactors and by the build-up of undesirable elements, especially curium. After two to three cycles the fuel would have to be managed as a waste similar to the once-through cycle. This limitation on the number of recycles, however, does not apply if the recycled material is used in fast reactors.

The uranium recovered during reprocessing has been recycled into fuel in the past but currently it is not; rather it is stored for future reuse. This is because the recovered uranium is more radioactive than natural uranium due to its exposure to neutrons in a reactor and its recycle would contaminate the enrichment and fuel fabrication facilities, complicating their operation. To use it would require dedicated facilities, something not currently economical.

Decommissioning

When any nuclear plant closes permanently, whether it is a reactor, a uranium mine or a fuel cycle facility, it needs to be put into a state where it can do no harm to the public, workers or the environment. This process, known as decommissioning, usually consists of several stages.

As of January 2003, over 120 commercial reactors have been shut down and are in various stages of decommissioning.

Closeout

The spent fuel is recovered from the reactor and stored in the usual way, the liquid systems are drained, the operating systems are disconnected, and external apertures in the plant blocked or sealed. The atmosphere in the containment building is controlled and access is limited, with surveillance systems installed. Usually, closeout takes place very soon after shutdown.

Top biological shield being dismantled using a thermic lance process at the Windscale Advanced Gas-cooled Reactor Dismantling Project.

Decontamination and dismantling

All surfaces are washed with water or treated by mechanical, chemical or electrochemical means to remove radioactivity (decontamination). All working equipment and buildings connected with the process are then removed, monitored for any remaining radioactivity and either recycled or placed in interim storage, leaving only the core reactor parts, particularly the reactor vessel and its protective shielding. The non-nuclear parts of the establishment – offices, turbines, boilers, etc. are scrapped or put to other uses. An appropriate degree of surveillance of the remaining parts and the surrounding environment is then maintained. All of these activities may occur 10, 20 or more years after shutdown.

Demolition and site clearance

Eventually, and unless parts of the remaining facilities are to be used for some other purpose, all the plant and materials are removed and the site delicensed and made available for new uses. The timing of this final phase is determined in each country by economic, technical and regulatory factors; in some cases, it may not take place until a very long time, perhaps 100 years after shutdown. However, with the introduction of robotic and telemanipulation techniques, this phase of decommissioning is often being performed earlier.

The relatively long delays between completion of the three phases are to allow for the radioactivity to decay so as to protect the workers involved in the decommissioning process, as well as to facilitate storage and, ultimately, disposal of the radioactive materials.

Nuclear power plants have now reached quite advanced stages of decommissioning in the United States and several European countries (see Table 3.4). Decommissioning practices are maturing and experience is being exchanged to the point where the processes can now be considered a predictable part of the life cycle of a reactor.

Decommissioning waste

The decommissioning of a nuclear power plant or other nuclear installation generates a significant amount of radioactive waste, most of it low-level waste (see Chapter 4). The European Commission estimates that decommissioning of an "average" nuclear power plant produces up to 10 000 m^3 of radioactive waste. The bulk of radioactive waste, in terms of volume, is concrete or other building materials that contain only very small amounts of radioactivity.

The spent fuel in the reactor is the largest source of radioactivity and with its removal the total radioactivity inventory of the site is reduced by about 99%. Large components such as the reactor pressure vessel and the steam generators are also treated as radioactive waste though their size presents unique issues. They can be reduced by cutting them into more manageable sizes or can, as is commonly done, be removed and transported to low-level waste repositories intact.

One decommissioning issue currently under discussion is an internationally agreed-upon criterion below which slightly contaminated materials can be released from radiological regulatory control. On one side of this issue, free-release and recycling of large volumes of slightly contaminated concrete and metals from decommissioning would significantly reduce the costs of disposal of these materials and pose only very low radiological hazards. On the other side, the public assessment of what is a justifiable and acceptable risk has, in most cases, resulted in governments deciding against the free release of such decommissioning waste and, consequently, they are typically disposed of in low-level waste repositories.

Table 3.4: Selected reactors undergoing or having completed decommissioning

Reactor	Size (MWe)	Country	Comment
Niederaichbach	100	Germany	Gas-cooled reactor shut down in 1974. The plant was decommissioned and demolished with the site released for unrestricted agricultural use in 1995.
Shippingport	60	USA	Light water breeder reactor shut down in 1982. In 1989 the site was released for unrestricted use.
Trojan	1 180	USA	PWR shut down in 1993. The steam generators were removed and disposed of in 1995; the reactor vessel was removed and disposed of in 1999. The buildings are being decontaminated, but demolition is not planned until 2018.
Rancho Seco	913	USA	PWR shut down in 1989. The plant was placed in a safe storage condition and is planned to remain in this state until 2008 when funds are available to dismantle it.
Chinon	70 210 480	France	Three gas-cooled plants, the last of which was shut down in 1990. They were partially dismantled with final dismantling postponed for 50 years.
Berkeley	2 x 138	UK	Gas-cooled reactor shut down in 1989. Defuelling was completed in 1992. The plant is being prepared for an extended period of care and maintenance.

Source: World Nuclear Association.

Removal of the Belgian BR3 reactor pressure vessel for further dismantling.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- The typical uranium fuel cycle, see 3.1.
- The technologies and processes involved with the existing and potential advanced fuel cycles, see 3.2 and 3.3.
- The depleted uranium resulting from the enrichment process, see 3.4.
- Decommissioning, see 3.5 and 3.6.
- The environmental remediation of uranium production facilities, see 3.7.

Management of Radioactive Waste

Radioactive waste arises from numerous industrial and medical processes, of which nuclear energy production is the most important because of the volumes generated and its long-lived nature.

Radioactive waste is generally separated into three categories: low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW) depending on its level of radioactivity and the length of time it remains hazardous.

Disposal of LLW and most ILW is a mature practice. The disposal of HLW without harmful releases from its repository is accepted to be practicable by the scientific and technical community, but there is as yet little societal consensus for proceeding.

Radioactive waste results from any activity that makes use of nuclear materials, be it nuclear reactors or medical and industrial uses. Whatever its origin, it has to be managed safely and economically, as well as in an environmentally and publicly acceptable manner.

Radioactive waste types

Radioactive waste is normally classified into a small number of categories to facilitate regulation of handling, storage and disposal, based on the concentration of radioactive material they contain and the time for which they remain radioactive. The definitions of categories differ from country to country; however, in general, they can be addressed as low-level, intermediate-level and high-level waste.

Low-level waste (LLW) normally consists of items that have come into contact with small amounts of short-lived radioactivity, such as overalls, containers, syringes, etc. LLW can generally be handled using rubber gloves. Much of the waste generated during decommissioning of a nuclear power plant is managed as LLW.

Intermediate-level waste (ILW) is typically more industrial, e.g. equipment that has been used in conjunction with nuclear materials or spent ion-exchange resins used in the clean-up of radioactive liquids. It typically generates negligible heat, but emits radiation, which may be short or long-lived, and usually requires shielding to protect people. In the case of reprocessing, a waste is produced consisting of the non-dissolved metal structure of the fuel (called hulls and end-pieces) that is categorised as ILW.

High-level waste (HLW) consists mainly of highly radioactive and often long-lived remnants of the fission process. It must be heavily shielded and generally requires cooling. Within the HLW category, a distinction is made between spent nuclear fuel (SNF) that will not be reprocessed and the remnants of reprocessing. Though the two subsets are in many respects managed similarly, they are different in form and content, not least because the reprocessing remnants are most often initially in liquid form.

For the handling or transport of waste, the important factor is its radioactivity level. But for disposal, another important factor is the length of time that a waste must be kept isolated, as determined by the half-lives of the radioactive isotopes it contains. Some long-lived isotopes such as those found in HLW and SNF require isolation for thousands of years.

The half-life of a radioactive isotope is the time it takes for half of any given number of atoms to decay. This can vary from less than one second to infinity (i.e. stable) according to the isotope. Figure 4.1 shows that after five half-lives, the amount of a radioactive isotope remaining is about 3% of the original amount; after 10 half-lives, less than 0.1% remains. Table 4.1 shows some isotopes that are important in determining conditions for disposal of HLW and SNF. Caesium, strontium and technetium are fission products; the others result from neutron capture.

Figure 4.1: Decay of a radioactive element with a half-life of five days

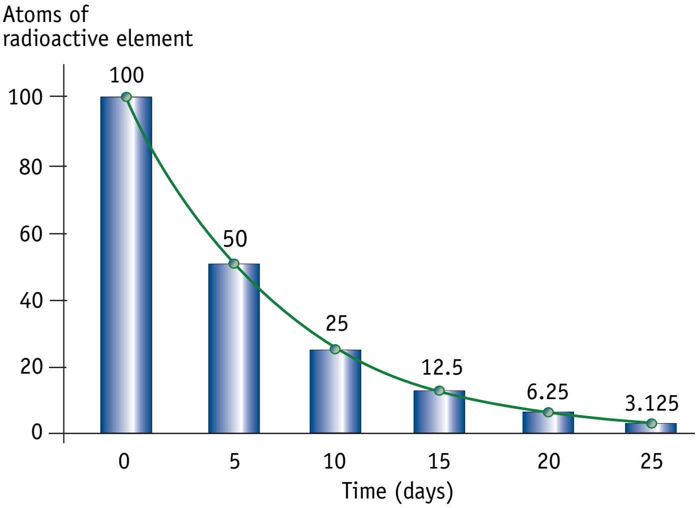


Table 4.1
Selected HLW isotopes

Isotope	Approximate half-life
Strontium-90	29 years
Caesium-137	30 years
Americium-241	430 years
Americium-243	7 400 years
Plutonium-239	24 000 years
Technetium-99	213 000 years

Radioactive waste volumes generated by nuclear energy

Because of its high energy density, nuclear energy generates a relatively low volume of waste per unit of energy generated. Different reactor and fuel cycles produce different amounts and types of waste. Table 4.2 nevertheless gives a general idea of the volumes of waste generated in producing nuclear energy.

Table 4.2
Indicative volumes of radioactive waste generated by a LWR of 1 000 MWe
(m^3 per annum)

Waste type	Once-through fuel-cycle	Recycling fuel-cycle
LLW/ILW	50-100	70-190
HLW	0	15-35
SNF	45-55	0

Source: European Commission, *Radioactive Waste Management in the European Union* (Brussels: EC, 1998).

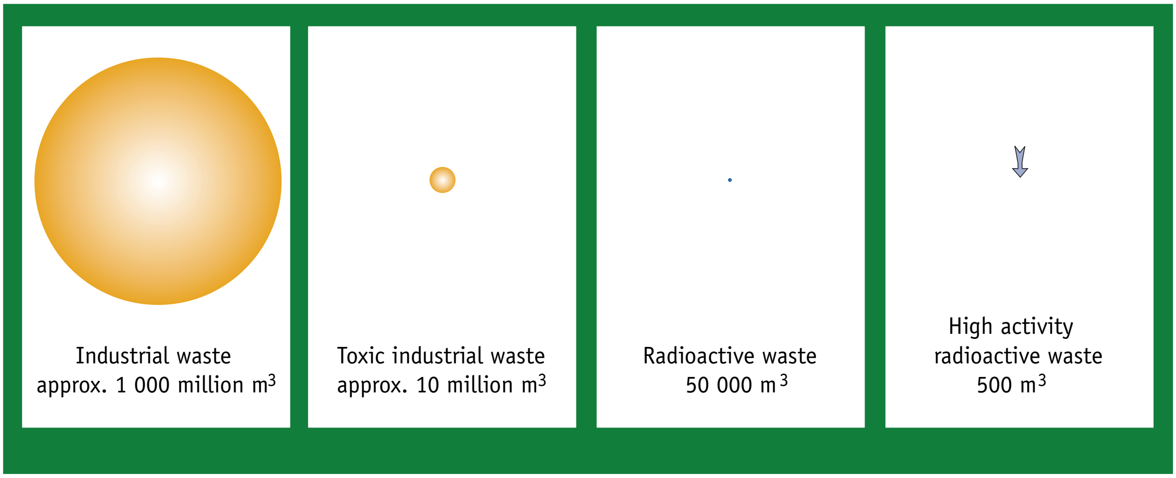
There has been a general trend towards a reduction in the volume of waste generated per unit of electricity through improved practices and technologies, in part, as a means to reduce operation and maintenance expenses.

To put these quantities into perspective, it should be borne in mind that large quantities of radioactive waste are also generated by factories, hospitals and cancer treatment centres, and that radioactive waste as a whole is only a small fraction of the toxic waste generated industrially each year, and a smaller fraction by far of society's total waste (see Figure 4.2).

Waste management principles

Managing and disposing of radioactive waste is everywhere regarded as a national responsibility. Although there are different national approaches to waste management, international co-operation has created a set of fundamental principles and obligations that form a common understanding; the IAEA *Principles of Radioactive Waste Management* are an example.

Figure 4.2: Waste generation comparison – yearly production of waste in the European Union



Source: *Nuclear and Renewable Energies* (Rome: Accademia Nazionale dei Lincei, 2000), updated with data from the European Commission, *Radioactive Waste Management in the European Union* (Brussels: EC, 1998).

In broad summary, the tenor of this document is that radioactive waste should be managed so as to ensure that:

- There is an acceptable level of protection for *human health* and for the *environment*, applying across *national boundaries*.
- The impact on *future generations* is no greater than that acceptable today, and that undue burdens on future generations are avoided.
- There is an appropriate *national, legal framework* with clear allocation of responsibilities and provision for *independent regulation*.
- *Generation of waste* is kept to the *minimum practicable*, with the interdependencies among the various necessary steps taken into account.
- The *safety of facilities* for management of waste is appropriately assured.

Waste management practice

The activities necessary for managing radioactive waste properly can be categorised as:

- minimising the amounts created;
- conditioning and packaging to permit safe handling and protection during transport;
- interim storage;
- final disposal.

Minimisation

Existing facilities can, with foresight and good practice, reduce the amount of waste created. New technologies and plant designs also aim for waste reduction through such means as simplifying maintenance requirements.

Conditioning and packaging

Solid LLW and ILW can be super-compacted into much smaller volumes. Since waste in liquid form cannot in practice be disposed of, it needs to be transformed into solids. The radioactive elements can be removed from the liquid by filtration or ion exchange and then dried, absorbed into a fixing medium, or solidified in concrete. After conditioning, ILW or LLW can be packaged for interim storage or disposal in steel drums or boxes. For example, the metallic remnants of

About 90% of the volume of radioactive waste generated in the world each year is LLW, though it contains only about 1% of the total radioactivity of all radioactive waste.
About 99% of the total radioactivity from nuclear fission is concentrated in the HLW.

Storage of conditioned radioactive waste in steel drums.

reprocessing are typically compacted, then cemented in steel drums for disposal.

HLW, which is a by-product of reprocessing, emerges as a liquid and needs to be transformed into a solid, normally by a process of vitrification (producing a special type of glass) – see photo below. Other waste forms using ceramics have also been tested. These waste forms share the characteristics of being extremely durable and suited to immobilise the waste for long periods. Spent nuclear fuel that has not been reprocessed requires little in the way of conditioning other than being placed in specialised containers for interim storage and/or disposal.

The amount of HLW that would be produced if nuclear energy were to supply the lifetime electricity needs of a person could fit into a person's hand. The high heat and radioactivity of HLW requires it to be heavily shielded.

Test glass produced by vitrification process.

Table 4.3: LLW and ILW disposal sites in OECD member countries

Country	Site(s)
Australia	Mt. Walton East
Czech Republic	Richard II
	Bratrstvi
	Dukovany
Finland	Loviisa
	Olkiluoto
France	Centre de l'Aube
Germany	Morsleben
Hungary	RHFT Puspokszilagy
Japan	Rokkasho
Mexico	Maquixco
Norway	Himdalen
Spain	El Cabril
Sweden	SFR
	Oskarshamn NPP
	Studsvik
	Forsmark
	Ringhals
United Kingdom	Dounreay; Drigg
United States	Barnwell, South Carolina
	Richland, Washington
	Envirocare, Utah

Interim storage

Storage differs from disposal in that there is an intent to retrieve the waste sometime in the future. Thus active monitoring, maintenance and institutional controls must be maintained for safety and security.

When a disposal site is available, ILW and LLW can be sent there directly at regular intervals. If not, interim storage in a structure above ground is necessary. For HLW and SNF, interim storage to permit decay of radiation and heat generation has always been recognised as necessary. Interim storage of waste may be required and can be safely accomplished for many decades.

Disposal

Disposal is the final step in radioactive waste management. Usually it is understood to mean putting waste away without any intention of retrieving it, and that long-term surveillance and monitoring will not be needed to keep it safely isolated from the public and the environment. Radioactive waste is disposed of in dedicated facilities, and is not mixed with non-radioactive waste.

Short-lived waste

Short-lived ILW and LLW are disposed of routinely at numerous sites in many countries (see Table 4.3); some sites have already been filled and closed. Most facilities are near-surface and usually equipped with simple engineered barriers to improve isolation – typically a lining of concrete or some other material in the disposal trenches. Spaces between waste packages are often filled with soil, clay or concrete. Low permeability covers are added to minimise water entry, and drainage systems divert water away from the disposal trenches or units.

These precautions extend the life of the waste packaging and are intended to prevent the possibility of migration of radioactivity from the site. Nevertheless it is expected that for a period of about 100 to 300 years following closure of an ILW/LLW disposal site active or passive controls will be applied, including groundwater monitoring, restrictions on access, periodic maintenance and restrictions on further land use. After this period the radioactive isotopes will have decayed to negligible levels.

Long-lived waste

Solutions for long-lived waste, either HLW and SNF, or long-lived ILW, have proved more elusive. No repository for SNF and HLW has yet been opened anywhere, though disposal of long-lived, defence-related waste in the United States does exist. Many countries (including Belgium, Canada, China, Finland, France, Germany, Japan, Russia, Spain, Switzerland, the United Kingdom and the United States) have set up programmes to develop disposal of long-lived waste.

Geological disposal of long-lived waste

The main disposal concept under active consideration for long-lived waste is burial deep underground, i.e. deep geological disposal, to ensure security and containment over long timescales (see Figure 4.3). The desired result is a long-lasting, passively safe system imposing no burden of care on future generations and ensuring that no significant radioactivity returns to the surface environment. The main issue of this approach is that the public lacks confidence that understanding geological processes and material properties is sufficient to guarantee containment over the long timescales being considered.

The geological barrier

Potential host geological formations are chosen for their long-term stability, as well as their ability to accommodate a facility of sufficient size and to prevent or severely attenuate any eventual release of radioactivity. A key feature is low groundwater flow, this potentially being the most likely pathway for migration to the human environment. The main types of formation studied so far are salt, sedimentary foundations such as clay and shale, crystalline formations such as granite, and volcanic formations such as basalt and tuff.

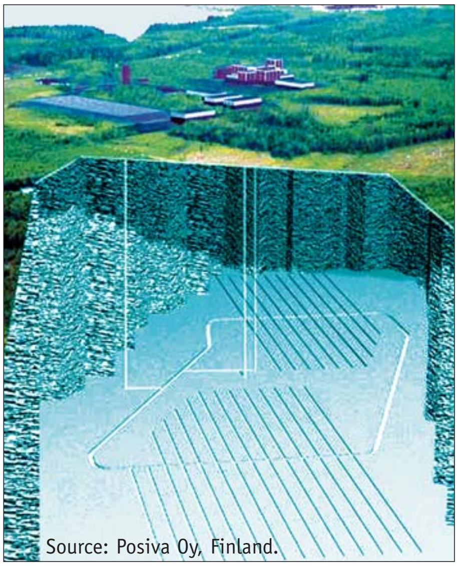
Engineered barriers

Engineered barriers are envisaged as complementing natural barriers by providing physical and chemical containment of the waste package (see Figure 4.4). The engineered barriers typically consist of:

- in the case of HLW, the glass matrix;
- in the case of SNF, the fuel pellets and cladding;
- in the case of other waste, the cement or other matrix material.

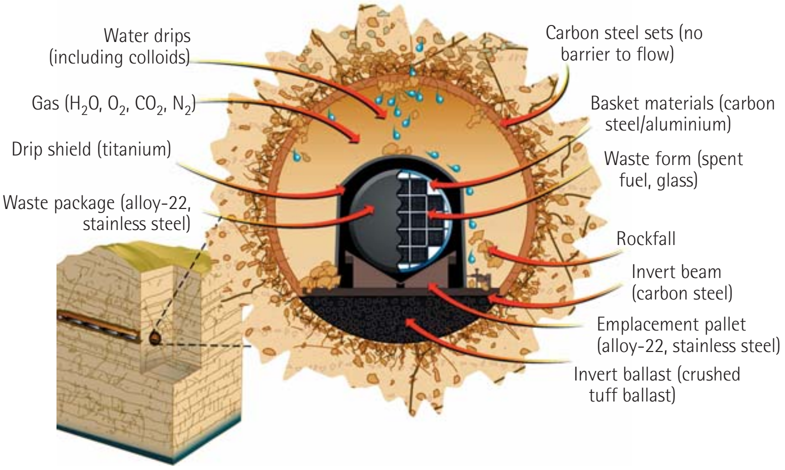
These engineered barriers are completed by the steel or concrete waste packaging and the backfill material placed around the containers in the repository.

Figure 4.3: Disposal concept
at Eurajoki, Finland



Source: Posiva Oy, Finland.

Figure 4.4: Engineered barrier design features
for the proposed repository in the United States at Yucca Mountain



Source: CRWMS, TDR-WIS-PA-000001 REV 00 ICN 01, Dec. 2000.

A number of container designs and materials have been proposed, depending on the geological environment and the specific safety function attributed to them. The engineered barriers are intended to delay access of groundwater. They can also provide chemical conditions that ensure that, in the unlikely event that any waste escapes the packaging, it would not readily dissolve and that any dissolved waste would become immobilised.

Performance assurance

Since the timeframes involved in geological disposal are well beyond recorded human experience and the chemical and physical interactions complex, demonstrating that a geological disposal site will remain safe over its existence is difficult. Defining appropriate models and obtaining the data necessary for performance assessment are major challenges.

The timescale over which a repository must be demonstrated to perform safely differs between countries – 10 000 years has been specified by some countries, though some require longer and others have specified no limit. Any prediction so many years into the future necessarily amounts more to a qualitative indication of safety than a precise prediction of the behaviour of the repository. However, even allowing for uncertainties of several orders of magnitude, calculated releases have been shown to be clearly within acceptable limits.

Technical confidence in the practicality of geological disposal stems from basic scientific knowledge of geology, hydrology, material sciences and geochemistry, reinforced by research underground. Laboratories, mostly established in used mines, have helped to obtain information on site-specific characteristics and to test the models used to assure performance (see Table 4.4). Confidence has also been given by studies of the behaviour of deposits of uranium and related radionuclides in their natural settings over very long timescales, that is, comparing these natural analogues with repository situations. Taken together, these studies confirm that geological disposal can be designed to prevent harmful releases. To achieve a potentially significant release, very unlikely events have to be assumed.

Current deep disposal activity

In 1999, the United States began disposal of waste containing long-lived, non-heat-emitting radioactive waste from defence-related activities at the Waste Isolation Pilot Plant (WIPP) in New Mexico, in caverns 650 metres below ground in a salt formation. In 2002, the United States officially proposed the Yucca Mountain site to serve as a national repository for HLW and SNF following a comprehensive investigation; but a decision to proceed will require a finding by the independent nuclear safety regulator that the facility is safe, and this will take several more years. In 2001, the Finnish Parliament took a decision in principle to proceed with implementation of a geological repository for SNF at Eurajoki, where the local community has agreed to host a national repository.

Table 4.4: Examples of underground laboratories

Country	Site(s)
Belgium	Mol/Dessel: specific research on site since 1984
Finland	Olkiluoto: specific research on site since 1992
France	Bure: construction of laboratory began in 2000
Germany	Asse: specific research on site since 1965 Gorleben: specific research on site since 1985
Japan	Mizunami: specific research on site since 2002 Horonobe: specific research on site since 2001
Switzerland	Grimsel: specific research on site since 1984 Mont Terri: specific research on site since 1995
United States	Yucca Mountain, Nevada: specific research on site since 1993

The natural reactors at Oklo, Gabon

In 1972, French physicist Francis Perrin found that naturally occurring nuclear chain reactions had taken place at the site of the Oklo uranium deposit in Gabon, Africa, about two billion years ago. They remain the world's best-known natural analogues. These natural reactors generated waste similar to those of modern nuclear power plants. Thus, the Oklo reactors are of special interest to geological disposal scientists because they can look at the behaviour of the long-lived waste over millions of years and better understand its behaviour in a geological repository. Geochemical observations of the Oklo site suggest that once the natural reactors burned themselves out, the highly radioactive waste they generated was held in place by the granite, sandstone and clays surrounding the reactors.

Transport

Because of the comparatively small volumes of radioactive waste and the need for long-term isolation, centralised storage and disposal is generally practised. This in turn necessitates transport to the chosen localities. Radioactive materials used in industrial and medical applications also require transport between the supplier and user.

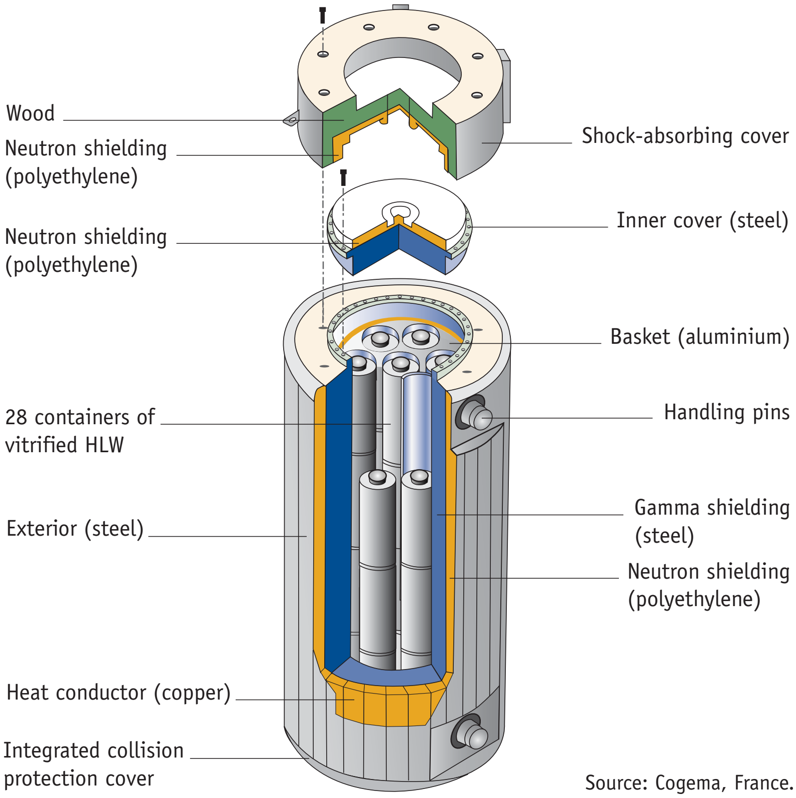
The safe transport of radioactive materials is primarily a national responsibility. Nevertheless, nearly 60 countries apply the IAEA *Regulations for the Safe Transport of Radioactive Material*, which serve to harmonise and standardise transport practices. Additionally, the International Civil Aviation Organisation (188 contracting parties) and the International Maritime Organisation (162 member states) incorporate these IAEA principles making their adherence mandatory in air and sea transport. These regulations embody the basic principle that safety is dependent on the packaging of the radioactive material, regardless of how it is transported. With traffic accidents being probable at some stage, this principle works to prevent any radiological consequences even if the package were to be involved in a severe accident.

The requirements and controls are proportioned to the hazard presented by the material. For example, some shipments of medical isotopes may be shipped in fairly unsophisticated cardboard packages, though the radioactive contents are strictly limited, there must be clear labelling, the packages must be certified for transport, and the shippers must have documentation to that effect. Spent nuclear fuel or high-level waste, on the other hand, must be shipped in high integrity containers designed to shield people and assure containment under extreme accident conditions (see Figure 4.5).

In the 1970s and 1980s, the United States conducted tests to determine the effects of subjecting nuclear fuel transport containers to real-world accident conditions. The tests included:

- running a truck loaded with a container directly into a reinforced concrete wall at about 130 km/h (see photos next page);

Figure 4.5: A typical HLW transport cask



Source: Cogema, France.

Finland moving forward

On 18 May 2001, the Finnish Parliament declared that construction of an underground repository for the disposal of spent nuclear fuel produced in Finnish nuclear power plants was in the overall interest of society. This decision in principle gives national political backing to the project and means that construction of underground research facilities and detailed site characterisation can begin at the Olkiluoto site near the city of Eurajoki. Construction and operating licenses will still need to be granted. Construction of the disposal facility would begin after 2010 and it is not expected to become operational before 2020.

Finnish parliamentary record 63/2001vp.

- hitting a container resting on a tractor-trailer broadside with a locomotive travelling at about 130 km/h;
- dropping a container from a height of about 600 metres onto compacted soil, the container moving at about 380 km/h on impact.

In all these tests, as in similar tests conducted in the United Kingdom in 1984, the container survived intact, and subsequent examinations demonstrated that there could have been no release of radioactivity.

Safety record

Numerous shipments of all forms of radioactive materials and waste take place worldwide each year and incidents are, in fact, extremely rare. For example, in France about 300 000 such movements take place annually, of which 15 000 relate to the nuclear fuel cycle and 750 contain fresh or spent fuel or HLW. During the period 1975-97 there was on average only one incident per annum with some possible local impact, e.g. contamination of the transport container. Worldwide, since 1971 there have been over 20 000 shipments of SNF and HLW using trains, trucks and ships, the material weighing in aggregate over 50 000 tonnes and travelling in total over 30 million kilometres. None have involved any accident that has breached a container or released radioactivity.

Societal and policy considerations

Radioactive waste management has sometimes been called the "Achilles heel" of nuclear energy because of the perceived absence of disposal facilities. There has been difficulty in achieving social and political confidence in strategies to protect present and future generations from any risk.

Technical experts have confidence that removing highly radioactive waste from the human environment by disposal in deep geological repositories is ethically and environmentally sound, and that the technology is both well developed and trustworthy.

However, many people do not share this confidence. Communicating with the public remains a key issue and a challenge to nuclear energy. However remote the risks to human populations from the disposal of long-lived radionuclides, a portion of public opinion feels that they represent a kind of burden on future generations that is ethically unsatisfactory. Others tend to regard risks of this low order, applying to generations whose physical environment and technical capabilities we cannot possibly envisage, as being negligible in the scale of the risks that future generations must bear. In any case, this conflict of philosophies is hindering the adoption

Testing of a nuclear fuel transport container.

of disposal solutions. Yet, the fact remains that this waste exists and solutions will need to be decided upon at some point.

Other aspects of waste disposal currently under debate include long-term storage while waiting for disposal; permitting the reversibility of disposal actions; and the desirability of repositories that would serve multiple countries.

Long-term storage

The near-term alternative to disposal of HLW and SNF is its long-term storage above ground. This is generally acknowledged to be technically feasible and indeed, represents existing practice. However, long-term storage has generally been regarded as a "second best" solution. The need to maintain security and environmental surveillance on the site increases costs. The unavoidable deterioration of the storage facilities and the waste packages they contain leaves to future generations the costs and risks of their periodic replacement and this option leaves open the question of the disposal of the waste should this eventually be decided upon. It remains, nonetheless, an attainable procedure either on a medium-term or on a semi-permanent basis.

Reversibility

Closely related to the concept of long-term storage, with many of the same issues of cost and risk is the provision for reversal of the disposal process by retrieving previously emplaced waste. This seems technically feasible, but could conflict with the aim of securing maximal isolation. Moreover, it may involve a later financial provision for a second stage of disposal. However, it would be technically possible to adopt a phased approach, progressing gradually towards a final configuration with all the waste in place and the repository sealed to provide maximum passive safety, postponing steps that would be difficult to reverse.

International repositories

The quantities of waste needing geological disposal are small enough to make the concept of one repository serving several countries attractive in principle, and particularly attractive to smaller countries for whom the fixed costs of developing a repository would be a large burden, or to those with difficult geological or environmental situations. Studies suggest that there are unlikely to be any significant technical or environmental objections to the development of an international repository. However the ethical and political problems associated with siting, and public disinclination to accept another country's waste, seem to pose major obstacles to progress, at least in the near future.

Repository for LLW and ILW in Sweden.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- The fundamental principles and obligations related to radioactive waste management, see 4.1 through 4.7.
- Biennial reports on the status of radioactive waste management programmes in NEA member countries, see 4.8.
- The technical aspects of geological disposal, see 4.9 through 4.12.
- The societal aspects of waste disposal, see 4.13 and 4.14.
- The issues of reversibility and retrievability, see 4.15.
- The Oklo natural nuclear reactors and other natural analogues, see 4.16 and 4.17.
- Transport of radioactive waste including information on real-life tests of radioactive material transport casks, see 4.18 and 4.19.

Nuclear Safety

The safety of a nuclear facility depends on the engineered protection built into it and on the organisation, training, procedures and attitudes of the operators.

The basic design philosophy underpinning the safety of nuclear facilities is defence in depth, a key aspect being the provision of several layers of protection against the release of radioactivity, each providing backup if another fails.

Nuclear energy has the potential to cause damage to people and to the environment through the accidental escape of harmful radioactive substances. Very high levels of safety have therefore always been considered essential to its deployment. There nevertheless remains some degree of risk, however slight, as with numerous other human endeavours.

Nuclear energy installations, whether they be nuclear power plants, reprocessing or waste conditioning plants or spent fuel storage facilities, typically involve large amounts of radioactivity whose release could produce radioactive contamination of the environment and be injurious to people's health. The primary purpose of all nuclear safety measures is thus to ensure that radioactivity remains in all circumstances contained or, if released, then only in amounts and under controls that ensure no significant harm is done.

In general terms, then, the safety of a nuclear installation can be understood as the ability of the installation's systems and its personnel to prevent accidents from occurring, or should one occur, to mitigate its consequences to a minimum. Ultimately, the radiological impact on people and the environment resulting from operating nuclear installations must be as small as possible for both normal operation and potential accidents. To achieve this objective, or in other words to ensure that the installation is considered sufficiently safe, technical and organisational measures are put in place at all stages of a nuclear facility's lifetime: starting with its siting and design; its manufacturing, construction and commissioning; during operation; and finally its decommissioning.

An accident at a nuclear power plant has a greater potential to do harm than accidents in other types of nuclear installation, since the fission process produces a major concentration of radioactivity. Additionally, large energies are involved, and the process liquids and gases could be agents in dispersing the radioactivity over wide areas. Much of the discussion that follows therefore relates primarily to nuclear power plants, but the same principles and approaches apply to other nuclear installations.

Basic elements of nuclear safety

Nuclear safety is achieved as a result of a number of complementary and overlapping factors (see Figure 5.1):

- detailed attention from the outset to all the factors that bear upon the safety of a planned installation, viz, its siting, its robust and proven design, high quality manufacturing and construction, and comprehensive testing prior to operation;

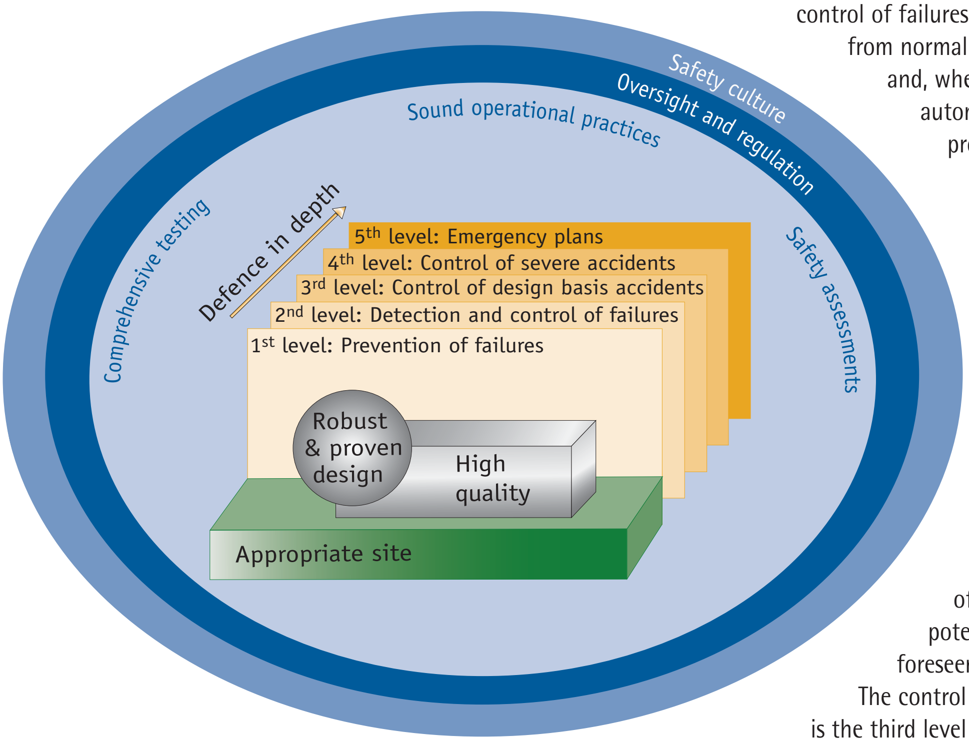
- ensuring that the probability of plant failures is low and considered in plant design, and that multiple protections are provided to prevent any particular fault or failure resulting in an accident (a concept known as defence in depth);
- close attention to the human element through sound operational practices and management systems that include performing periodic safety assessments and that foster the safety culture of the operating and regulatory organisations;
- monitoring and inspection by an independent regulatory authority with powers to suspend operations, or in the last resort to withdraw a licence.

These concepts lead to the practical arrangements summarised below.

Siting

The selection of a site for a nuclear power station (or for any nuclear facility) is governed by national legislation and requires safety regulator approval. The safety factors taken into account include a potential site's hydrological, geological, meteorological, seismic and demographic characteristics. The objects are minimising the human and environmental exposure to any release of radioactivity and ensuring that safety-related structures and systems are able to withstand the strongest foreseeable natural or human-induced event, e.g. an earthquake. For these reasons nuclear power stations are, to the extent possible, generally sited away from large population centres. Re-evaluation of a site may occur as understanding or methods to assess possible natural or man-made hazards improve.

Figure 5.1: Elements of nuclear safety



Robust and proven design

The basic design philosophy of nuclear facilities is one of defence in depth, that is, providing several levels of protection against the release of radioactive substances. The first level of defence is the prevention of failures. Thus nuclear designs strive to ensure reliable, stable and easily manageable operation. The use of high-quality technology with allowance for considerable safety margins in the strength and capacity of safety-critical components are vital elements in achieving this. These factors also work to maximise potential productivity and favour safety.

The second level of defence, the detection and control of failures, is to ensure that any deviation from normal operation is quickly detectable and, where possible, is corrected automatically by process control and protection systems, without interfering with normal operation. In case such systems fail due to some abnormal operational occurrence, engineered safety systems (see below) are built in to automatically place the reactor into a safe condition and to contain the radioactive materials. These systems are designed to withstand the so-called design basis accidents, a set of abnormal occurrences and potential accidents that have been foreseen and provided for in the design. The control of these design basis accidents is the third level of defence.

The design characteristics summarised above represent the first, second and third level of protection in depth against a nuclear accident. The fourth and fifth levels consist respectively in the control of severe accidents with an aim to limit consequences and prevent an external release of radioactivity (if necessary, at the sacrifice of the future operability of the plant), and the mitigation of radiological consequences if in fact a serious release occurs through off-site emergency planning (see Chapter 6 for additional information on accident response).

Engineered safety systems

In a nuclear power plant, systems are put in place to ensure that (1) radioactive material is at all times contained, that (2) the fission process can at all times be shut down almost instantaneously if any abnormality persists so as to terminate the generation of all but residual heat and radioactivity, and that (3) residual heat is removed after shutdown in order to protect the integrity of the barriers against a radioactive release.

Taking these concerns in order, multiple barriers are provided to prevent the release of radioactivity. The primary containment barriers against a release of radioactivity are the fuel matrix and its hermetic container – the fuel cladding. Next is the robust reactor pressure boundary within which the coolant circulates during normal operation, particularly the pressure vessel that contains the reactor core itself. Normally, the ultimate barrier is the containment building, typically a large reinforced concrete structure designed both to retain the products of an unconfined radioactive release and to protect the structures that constitute the pressure boundary from external hazards such as missiles, fires or explosions (see Figure 5.2). In the Three Mile Island accident in 1979, one of two very serious accidents to have occurred in commercial nuclear power stations, the reactor pressure vessel and containment building successfully prevented any injury to the public, though serious core damage had occurred releasing both intense heat and radioactivity.

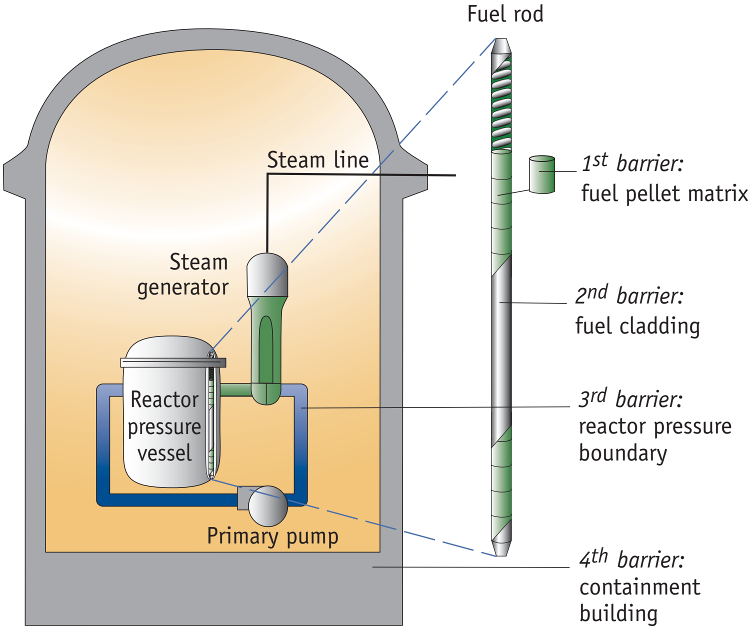
The fission process can be shut down by means of neutron-absorbing control rods (see Chapter 2). These rods can be inserted in a controlled fashion to shut down a reactor slowly or rapidly inserted to almost instantly stop the fission reaction in what is known as a scram. In addition, a secondary means of shutdown is always provided, e.g. by the injection of neutron-absorbing liquids to ensure long-term reactor shutdown.

Heat is normally removed from a reactor by the ordinary operation of the coolant, e.g. for a LWR that means creating steam to drive the electricity-producing turbine generators. Should this fail, separate engineered systems are in place to assure that residual heat (heat generated in the reactor after shutdown) is removed. The power for these and other needed systems is, if necessary, provided by onsite emergency backup generators, typically diesel-fuelled.

The continuous availability and reliable operation of the engineered systems are key elements of defence in depth, and their operation is regularly tested. Design of these systems must ensure that the failure of any single safety component would not cause loss of function (single failure criterion).

Moreover, the safety systems are designed by applying the principles of redundancy, i.e. providing additional backups or greater strength than is needed based on already pessimistic assumptions; diversity, i.e. the avoidance of

Figure 5.2: Typical barriers confining radioactive materials



common cause failure by the provision of several pathways to operation; and the physical separation of safety systems from plant process systems. Underlying all this is conservatism in all assumptions about risks of failure, the practice of basing design safety on a "what if?" approach and the close analysis of previous component and materials performance.

High-quality manufacturing and construction

High-quality equipment is a prerequisite for reliable operation. Thus quality assurance is a vital component of nuclear safety. A special set of codes and standards has been developed for the equipment and components used in any nuclear facility. These demand rigorous testing to confirm that quality standards are met, and their criteria ensure that only well-proven and established technologies are employed. National regulatory authorities oversee the implementation of these quality assurance and control programmes, whose extra cost accounts for a significant part of the high cost of constructing and maintaining a nuclear facility.

Comprehensive testing

Commissioning is an important stage in the completion of a nuclear power plant. The reactor power is gradually increased to specified levels and the as-built operating characteristics of the process and safety systems are determined, documented and checked against pre-defined success criteria. A large number of specific tests are conducted to verify the functioning of components and systems and the overall behaviour of the plant; weaknesses are corrected, and the tests repeated until satisfactorily completed.

Extensive testing is also conducted after major maintenance operations or the replacement or upgrading of components.

The current practice in most OECD countries requires basic and refresher training of plant operators in a wide variety of operational and emergency situations using full scale replicas of control rooms.

Safety assessments

The safety of any nuclear installation must be assessed through a systematic analysis of a defined set of potential failures and their interaction with safety barriers, known as the deterministic safety approach. In the deterministic approach, conservative assumptions are used to demonstrate that the response of the plant and its safety systems to a set of design basis accidents, e.g. a loss of coolant, is within the prescribed regulatory limits and requirements. This approach does not account for the probability of their occurrence and it assumes that all designed safety systems will be available to perform their designed safety function.

Such an assessment is conducted before a design is finalised, so as to confirm the plant's ability to operate easily within prescribed operating and regulatory limits given the characteristics of the proposed site. These assessments are documented in "safety analysis reports" or "safety cases". These are critically reviewed by regulatory authorities prior to licensing; afterwards they constitute the baseline point of reference for the safe operation of the plant.

National regulations also frequently require that systematic safety assessments be made periodically throughout the lifetime of any nuclear plant, together with self-assessments by operators, to ensure that plants can continue to operate in accordance with their safety cases and other operating requirements.

It has been common practice since the 1980s to complement the deterministic analysis using a type of analysis called probabilistic safety assessments (PSA). In a PSA, all types of circumstances, including equipment failures and human errors that can lead to an accident, are analysed. The combinations of events and failures that can potentially lead to severe accidents are also identified and their probability of occurrence estimated. The results of these studies are used for a variety of purposes, such as prioritising plant safety improvements, training operators and setting inspection priorities.

Sound operational practices

Experience has shown that safe operation depends on adherence to certain principles, including:

- laying the prime responsibility for safety on the operator, with management principles giving the necessary priority to safety;
- a strong organisation ensuring among other things an adequate number and deployment of qualified and experienced personnel;
- establishing conservative limits and conditions that define the safe boundaries for operation;

- approved procedures for all operations including tests, maintenance and non-standard operations that include self-checking and independent verification processes;
- extensive quality-assurance programmes for all operations, inspections, testing and maintenance;
- training programmes for all activities having a direct impact on nuclear safety;
- necessary engineering and technical support throughout the lifetime of the installation;
- timely reporting of all incidents to the appropriate regulatory body;
- the establishment of programmes for collecting and analysing operational experience, and for sharing it with international bodies, regulatory authorities and other operating organisations, and for its incorporation in training programmes;
- the preparation before start-up of emergency procedures and plans, and thereafter their regular rehearsal, so as to harmonise the responses of the various organisations that would be involved in mitigating the consequences of any accident;
- careful consideration of human factors engineering principles in the design and layout of the control room, alarm and indicating systems.

Safety culture

Experience has shown that a weak "safety culture" is in many cases a root cause of declining safety performance. Despite all the systems-based safeguards, it is the people involved who are the ultimate guarantors of the safety of any nuclear plant. The existence of a good safety culture, which strongly influences the attitudes and states of mind of all the individuals whose actions can impact on safety, is a key nuclear safety principle. The attributes of a good safety culture include a strong sense of responsibility, self-discipline and respect for regulatory requirements on the part of individuals, but management style is also an essential component. Safety culture is not inherent and as it is linked to national habits and attitudes, it cannot be acquired in a short period of time or "installed" like a piece of hardware. It must be transmitted continuously and unmistakably from the top, and permeate the whole of the operating and regulatory organisations.

Oversight and regulation

The responsibility for nuclear safety is foremost a national one with each country responsible for the safety of the nuclear power plants that it has permitted to be constructed and operated within its borders. The prime responsibility for safety is most often assigned to plant operators who are the license-holders. However, international

Periodic refresher training in simulators is one of the sound operational practices through which nuclear safety is achieved.

Safety culture means that "assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance".
IAEA Report, Safety Culture, 1991.

A set of internationally accepted nuclear safety principles has been defined in the *Convention on Nuclear Safety* deposited with the IAEA. This incentive agreement entered into force in October 1996 and as of April 2002 there were 54 parties and 65 signatories including all states with operating nuclear power plants. The Convention addresses establishing a legislative and regulatory framework; facility siting, design, construction and operation; the availability of adequate financial and human resources; the assessment and verification of safety; quality assurance; and emergency preparedness.

co-operation including organisations such as the OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) has always made a fundamental contribution to the development of relevant concepts and the spreading of good practice (see also Chapter 8).

For example, the *Convention on Nuclear Safety*, to which all States operating nuclear power plants are now signatory, defines a set of internationally accepted principles and a set of obligations relating to the basic elements of safety assurance.

Although the responsibility for nuclear safety is the operator's, regulatory review and control are essential. In all countries with a nuclear programme there exists a nuclear regulatory organisation responsible for licensing nuclear installations and for enforcing the relevant regulations.

These regulatory organisations:

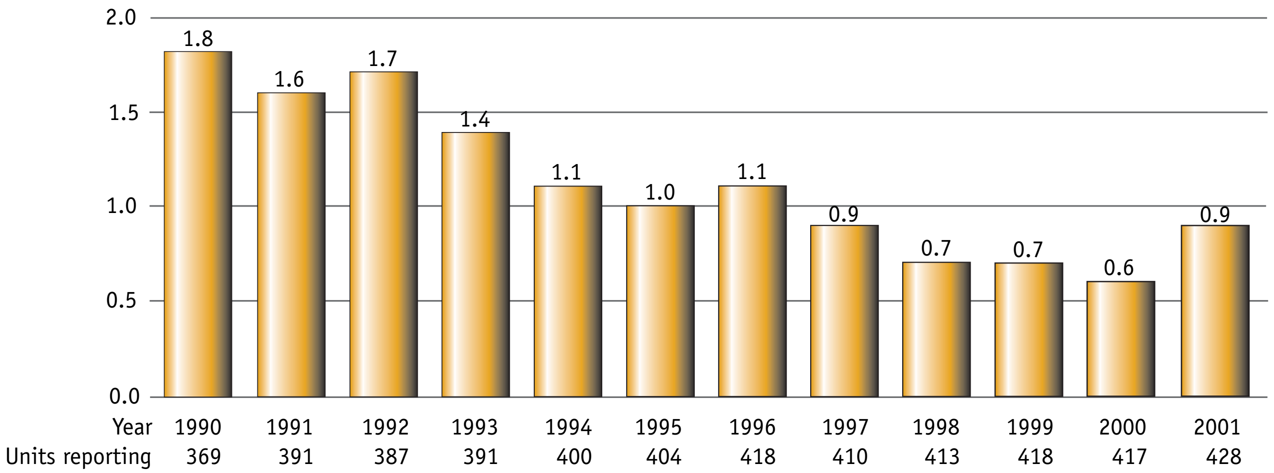
- develop and enact appropriate regulatory requirements, safety standards or regulations;
- issue licences following their assessment of plant safety;
- inspect, monitor and review the safety performance of licensees;
- verify compliance with regulatory requirements or regulations and impose corrections in case of malpractice or departure from prescribed standards.

An important principle reflected in the *Nuclear Safety Convention* is the effective separation between the regulatory organisation and other groups involved in promoting or using nuclear energy, so that the safety authority and its decision-making process are protected from undue external pressure.

Operating experience

A great deal of information and many lessons have been gathered from over 10 000 reactor-years of operating experience worldwide. These lessons are routinely shared through such means as databases and reports by international organisations, journals and conferences. A significant result has been a steady improvement in the operating safety performance of nuclear plants, particularly in recent years. For example, the number of unplanned automatic scrams has been decreasing over the past decade, indicating a widespread improvement in plant operation (see Figure 5.3).

Figure 5.3: Worldwide unplanned automatic shutdown rate (number per 7 000 hours)



The unplanned automatic scrams per 7 000 hours critical indicator tracks the mean scram (automatic shutdown) rate for approximately one year (7 000 hours) of operation. Unplanned automatic scrams result in thermal and hydraulic transients that affect plant systems.

Source: WANO, 2001 Performance Indicators.

The overall good safety record of commercial nuclear power plants is marred by two severe accidents – those at Three Mile Island (TMI) in the United States in 1979 and at Chernobyl in Ukraine (former Soviet Union) in 1986. The TMI accident resulted in serious damage to the reactor core but the reactor pressure vessel and containment building prevented all but trace amounts of radioactive gases from being released and caused no effect on the population. It was subsequently rated 5 on the INES scale. The Chernobyl accident was on any reckoning a disaster and the only event ever rated above 5 (at 7). At Chernobyl, there was a meltdown of the nuclear fuel that combined with a steam explosion, and the lack of a complete containment building resulted in large amounts of solid and gaseous radioactive materials being widely distributed over Europe.

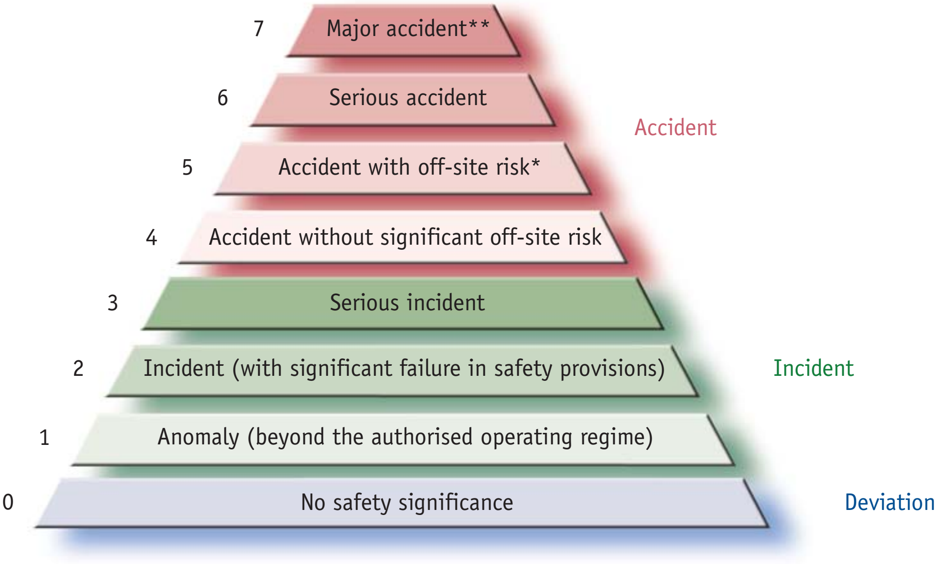
These two accidents provided important lessons. The TMI accident emphasised the need for greater attention to the human factors, including improved operator qualification and training and better emergency procedures and public communication. The Chernobyl accident, as well as publicising weaknesses in the RBMK reactor design (not present in OECD countries), led to the recognition of the importance of safety culture. It showed that a weak safety culture not only among operators, but also stemming from weak management and distracting external influences, could lead to operational behaviour breaching every element of defence in depth.

Impact of market deregulation on safety

There has been a growing recent trend towards opening electricity markets to competitive supply and pricing. While there are few doubts that economic deregulation will improve the overall economic effectiveness of electricity production, its impact on nuclear safety is a matter for discussion. Early indications are that regulatory compliance and competitive economic performance are not in conflict, though an independent and vigilant oversight is necessary to ensure that this remains so. Regulatory bodies may need to develop and adapt their regulations and staff to meet the changing market circumstances in order to ensure that effective oversight is maintained while not unnecessarily impacting on an operator's ability to compete in an open market.

A tool that allows the prompt and consistent communication of the safety significance of a nuclear event is the International Nuclear Event Scale (INES – see Figure 5.4).

Figure 5.4: The international nuclear event scale (INES)



* Three Mile Island, USA, 1979 ** Chernobyl, Ukraine, 1986

Safety aspects of future reactors

Over the next few decades new reactor designs may be introduced to compete with other sources of electricity. These advanced designs will be faced with the challenge of cutting generating costs while maintaining or improving safety levels. Various concepts of the next generation of nuclear power reactors have been proposed and are being studied (see Chapter 10). Some safety-related features can be characterised as follows:

- explicit consideration of severe accidents as a part of the design basis;
- effective elimination of some severe accident sequences by use of inherent safety features;
- significant reduction or elimination of large radioactive release even should a severe accident occur;
- improved operability and maintainability by extensive use of digital technology;
- reduction in system complexity and potential for human error.

All of these, if successfully implemented, could result in the reduction of on-site and off-site protective measures, such as evacuation plans for the public and would represent improvements over the current safety posture.

For further information

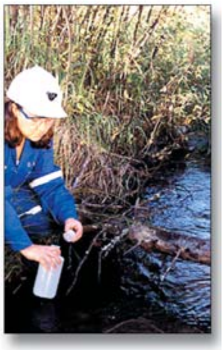
See the references listed below provided in the "For Further Information" section for more in-depth information on:

- Basic nuclear safety principles, see 5.1 and 5.3.
- Nuclear safety culture, see 5.4 and 5.5.
- The International Nuclear Event Scale, see 5.6.
- The causes of the Chernobyl accident and its radiological and health impacts, see 5.7 and 6.1.
- Operational experience and lessons learned, see 5.8.
- The impacts of market deregulation, see 5.9 and 5.10.
- The safety aspects of future nuclear reactors, see 5.11.

Radiological Protection

Radiation is everywhere and it has been found useful for medical and industrial purposes. It is one of the most studied risks to health and these risks are increasingly well understood. There are many types of radiation, some more harmful than others, and many ways of assuring the safe, beneficial use of radiation and radiation-generating processes.

Radiological protection of the public, environment and workers is a prime safety objective for the nuclear power industry. Systematic approaches to radiation protection are based on three principles: the justification of practices, the optimisation of protection and the limitation of exposures.



The universe is awash with radiation, as is the earth and the living creatures on it. Since man's discovery of their existence in the late 1800s, many uses for radiation and radioactivity have been discovered and exploited.

Medical science was among the first to make use of the penetrating properties of radiation; the use of X-rays revolutionised the study and treatment of the human body. But very early on, it was discovered that along with the benefits came risks, and thus the need to protect people from radiation. Ever since, the use of radiation has been a matter of balancing benefits and risks. To assist this balancing, the theory, policy, regulation and practice of radiological protection has been developed, always alongside an evolving understanding of the sources, uses and effects of radiation.

Scientific and medical background

Types of radiation

Radiation is energy travelling through space or matter in the form of sub-atomic particles or electromagnetic waves. Radioactivity is the spontaneous change in the nucleus of an unstable atom that results in the emission of radiation. This process of change is often referred to as the "decay" of atoms. Radioactive atoms are often called "radionuclides" or "radioactive isotopes" of the relevant chemical element.

When radiation, either particles or electromagnetic waves, has enough energy to remove the electrons of atoms with which it interacts, it causes the atoms to become charged, or "ionised", and it is called ionising radiation. The ions resulting from the interaction are capable of causing chemical changes damaging to human cells. If radiation, either particles or electromagnetic waves, has insufficient energy to ionise atoms, it is known as non-ionising radiation.

Ionising radiation occurs in several forms – as alpha particles, beta particles or neutrons, or in the form of electromagnetic radiation (gamma rays and X-rays). Each type of ionising radiation interacts differently with matter, including the human body, and each can be effectively stopped by different types of material (see Figure 6.1).

Alpha particles are emitted from the nucleus of an atom and consist of two protons and two neutrons. They are identical to the nucleus of a helium atom and have a double positive charge. Because they are heavy and doubly charged, they lose their energy very quickly in matter. A sheet of

Cosmogenic radionuclides are radioactive isotopes produced by interaction of cosmic radiation with the nucleus of an atom. They can be in the earth's atmosphere, on the solid surface of the earth, or produced in meteorites and other extraterrestrial materials, which then fall to earth. Examples include tritium (^{3}H), hydrogen with two extra neutrons (12.3-year half-life) and carbon-14 (5 730-year half-life), both of which exist in small amounts in every living thing.

Primordial radionuclides are left over from when the earth and universe were created. They are typically long-lived, with half-lives often on the order of hundreds of millions of years. Important examples are uranium-238 (4 470 million-year half-life), thorium-232 (14 100 million-year half-life), and potassium-40 (1 280 million-year half-life).

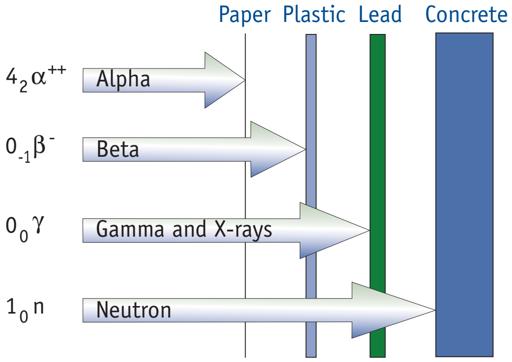
paper or a person's surface layer of dead skin will stop them. Alpha particles are only considered hazardous to a person's health if they are ingested or inhaled and thus come into contact with sensitive cells.

Beta particles are electrons emitted from the nucleus of an atom. They have only one negative charge, which causes them to interact less with matter than alpha particles and thus penetrate further. They will be stopped by thin layers of plastic or metal, and again, are considered hazardous mainly if a beta-emitter is ingested or inhaled. They can, however, cause radiation damage to the skin if the exposure is large enough.

Neutrons are contained in the nucleus of an atom, from which they may be expelled by collision, or fission. They are electrically neutral particles with approximately the same mass as a proton, and, being neutral, interact only weakly with matter and are thus very penetrating – not easy to stop. They are best shielded by thick layers of concrete, or by materials rich in hydrogen atoms, such as water or oil.

Gamma rays and X-rays are both electromagnetic waves, the one being emitted from the nucleus of an atom, the other by energy changes in an atom's electrons. Both are forms of high-energy electromagnetic radiation that interact lightly with matter. They are best stopped by thick layers of lead or other dense materials, and are hazardous to people even when their emitters are external to the body.

Figure 6.1: Penetrating distances for different radiation types



Source: University of Michigan, United States.

Sources of radiation

There are two primary categories of radiation sources to which we are exposed: natural sources and man-made sources.

Natural radiation

Natural radiation, which may be either ionising or non-ionising, can be characterised either as "cosmic" or "terrestrial". Cosmic radiation comes from the heavens and is generated through various processes including the birth and death of stars. The biggest emitter of cosmic radiation, so far as we on earth are concerned, is the sun. Terrestrial radiation comes from the earth itself, and is produced by the decay of primordial and cosmogenic radionuclides embedded in the earth's crust. Two common elements, uranium and thorium, emit ionising radiation as they gradually decay over millions of years, eventually becoming lead – which is stable and therefore emits no radiation.

One of the members of the uranium decay chain is radon, a gas that enters the atmosphere if it is "born" near the surface of the earth. So radiation is not only emitted directly from its sources in the earth, but forms part of the atmosphere we breathe, in greater or lesser quantity according to the amounts and types of radioactive materials in the part of the earth where we happen to be.

Even our food is naturally radioactive, since plants and animals absorb radioactive materials from the environment. As a result, our own bodies and particularly our bones contain small amounts of radioactive elements like carbon-14, potassium-40 and radium-226. Potassium is an important nutritive mineral; bananas, for example are a rich source of potassium, including the radioactive isotope potassium-40. Tritium, a naturally occurring and man-made radioactive isotope of hydrogen that forms part of all water on earth, is also found in small amounts in our bodies, mostly in the soft tissues and bloodstream.

Man-made radiation

The development of nuclear energy and science has created various new sources of radiation, *man-made radiation*. Nuclear weapons tests, initially conducted above ground, resulted in large quantities of radioactive material being thrown into the upper atmosphere where it encircled the globe. Most of the population of the Northern Hemisphere and some of the Southern was, and continues to be, exposed to radiation from this material.

The development of nuclear power since the 1950s has also led to releases of radioactivity into the atmosphere and into water from various stages of the fuel cycle, largely from the reprocessing of spent fuel and to a lesser extent from fuel manufacture and power production.

Radiation has been extensively used in medicine since its discovery. The use of X-rays involves a very significant exposure to ionising radiation; a recent development is the use of real-time television X-ray images in the operating room to help guide the surgeon in positioning surgical instruments. Other sophisticated medical uses of gamma rays include computerised tomography (CT) and positron emission tomography (PET).

Radiation is also used in therapy, precisely because it can kill cells – such as tumour cells. Radiation sources can be surgically implanted in tumours, and liquid radiation sources can be injected into the bloodstream and concentrate in target cells – a practice used to cure thyroid cancer. All these procedures are sources of ionising radiation both to the patient and to medical staff.

Levels of radiation exposure

To what levels of radiation are humans typically exposed, and what are the most important sources? The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has gathered this information since 1955 and produces a report about every four years summarising the average exposures from all sources. Figure 6.2 summarises the results of the latest such report, UNSCEAR 2000.

Our exposure to these various natural and man-made sources of radiation may of course be either voluntary or involuntary.

Effects of radiation exposure

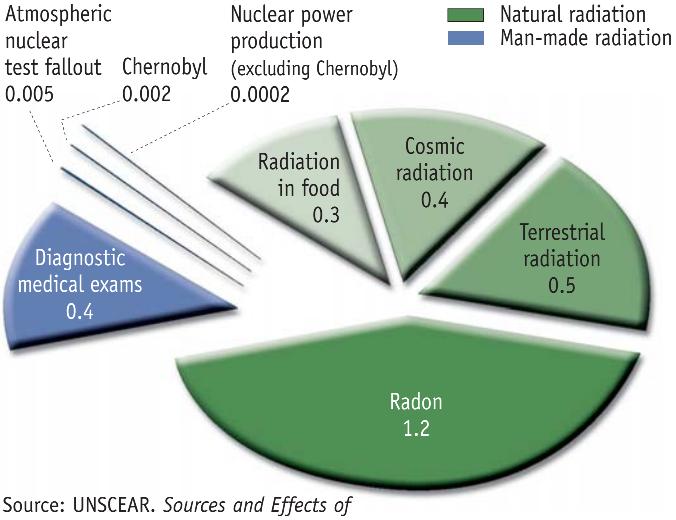
The principal result of radiation passing through something – such as human tissue – is the deposition of energy. Radiation loses energy as it interacts with matter and the matter gains this energy. So the unit used to measure radiation exposure is based on the amount of energy absorbed. Nowadays, radiation exposure (also referred to as "dose") is measured in grays (Gy). One gray is defined as an absorption of radiation which deposits one joule of energy in one kilogram of material.

Some types of ionising radiation are more damaging than others. For example, alpha particles, because of their large mass and electrical charge tend to deposit lots of energy over very short distances, and they can thus cause significant damage if they travel through sensitive biological tissue. Neutrons, on the other hand, interact very infrequently with atoms but when they do, the effects can be significant. For these physical reasons, the different types of radiation have been given different weighting factors that are used to relate their physically deposited energy to the biological significance of the damage they cause.

The unit used to measure this biological significance is the sievert (Sv). The sievert is equal to the amount of energy deposited, in grays, multiplied by the relevant weighting factor; the higher the factor, the greater the reckoned damage. For alpha particles the factor is 20; for neutrons it is in the 5-20 range varying with their energy; for gamma rays, beta rays and X-rays, the factor is 1.

In estimating damage, account also has to be taken of whether the whole body is exposed or

Figure 6.2: Typical sources of public radiation exposure (in mSv per year)



Source: UNSCEAR. *Sources and Effects of Ionizing Radiation*, Vol. 1 (New York: UN, 2000).

One joule is the energy that is required to raise the temperature of one gram of water by 0.24°C.

The terms dose and exposure are, in general, equivalent and interchangeable; both are commonly used.

People routinely encounter electromagnetic radiation that is not ionising. It makes up our visible light, radio and television signals, emanates from our computer screens and heats our food in microwave ovens. Yet, because of their low energy, all of these examples are classified as non-ionising radiation.

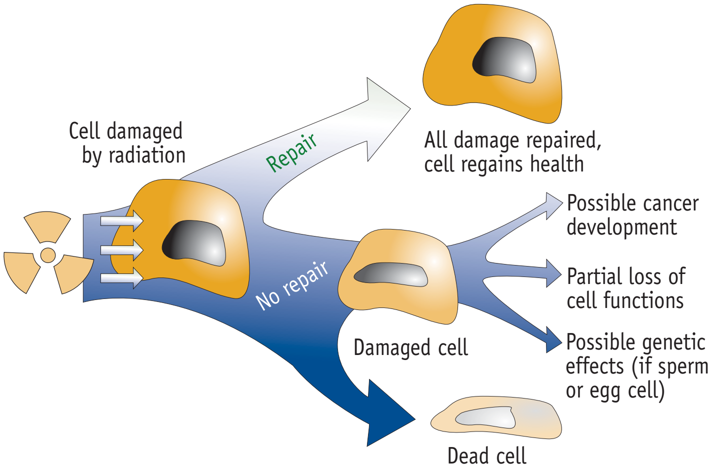
Radionuclides that enter the body can remain for some time, being eliminated through biological functions and through radioactive decay. To account for the doses caused by these radionuclides and to ensure that associated risks are not underestimated, it is assumed for regulatory purposes that the exposure that would accrue over the 50 years after the intake occurs in the single year of the intake. This calculated internal exposure is known as “committed” dose.

only a part, and if so, which part. Different tissues (e.g. lungs, liver, bones) have different sensitivities to radiation damage. For example, the most biologically significant radiation emitted by uranium are alpha particles. These cannot even penetrate a person's skin, so exposure to uranium dust on the skin is generally not hazardous. But if the same dust is inhaled and ends up next to sensitive lung tissue it can be very damaging to the cells exposed. In this case, primarily one tissue is exposed and the deposited energy is limited to it alone. To allow this exposure to be equated to others, researchers have developed tissue-weighting factors. This allows for the comparison and summation of the biological significance of an exposure to one type of radiation affecting the whole body with exposure of another type that has affected only a particular organ. This makes it possible to represent the biological significance of different exposures to radiation on a single scale.

Biological effects of radiation exposure

Radiation is one of the most studied of all toxic agents. Although it cannot be touched, tasted or smelled, it happens – unlike, for example, cancer-causing chemicals – to be very easy to identify and quantify. The physics of radiation passing through matter is also very well understood, and this makes it scientifically possible to study the effects that different amounts of radiation exposure can have on humans.

Figure 6.3: Potential biological results after radiation damages a cell



However, the physics of radiation are just the beginning of the story. Looking at it more closely, the energy from ionising radiation is transferred to the atoms of the substance through which it passes. Water is the most abundant molecule in our bodies, and is quite often ionised, i.e. made abnormally chemically reactive by radiation. If the water molecule in question happens to be located next to a molecule of deoxyribonucleic acid (DNA) within a human tissue cell, it might damage it – and DNA is the cell's engine of reproduction. It follows that there can be three principal results to a body cell that is damaged by radiation (see Figure 6.3):

- It repairs itself successfully.
- It fails to repair itself and dies.
- It cannot repair itself, but does not die.

The potential for long-term effects lies in the third case; the damage may cause the cell to become cancerous. Additionally, if the damaged cell is a human reproductive cell – an egg or a sperm cell – the damage to the DNA could potentially result in a genetic mutation. It is these two potential effects that are the principal concern of radiation health scientists.

When people are exposed to ionising radiation, the possible effects on their health can be categorised as follows:

- Immediate effects, occurring as soon as an exposure to radiation has taken place – called deterministic effects.
- Delayed effects, perhaps revealing themselves only many years later - called stochastic effects.

For humans, the threshold level of radiation exposure that results in deterministic effects is around 0.25 sievert (250 mSv). Depending on the amount of the dose above this threshold, different types of biological reaction will occur, the effects increasing in severity as the dose increases (see Figure 6.4).

Fortunately, accidents involving such high radiation exposures are very rare, and the medical treatments for highly exposed people have advanced greatly and continue to do so.

Stochastic effects are not certain to occur, but their chance of occurrence increases with increasing exposure. The important types of stochastic effects are cancers, including leukaemia. Should reproductive cells be exposed, genetic modifications can theoretically occur, though none have ever been observed in any studied human population, including the survivors of Hiroshima, Nagasaki and Chernobyl.

Risks at high doses

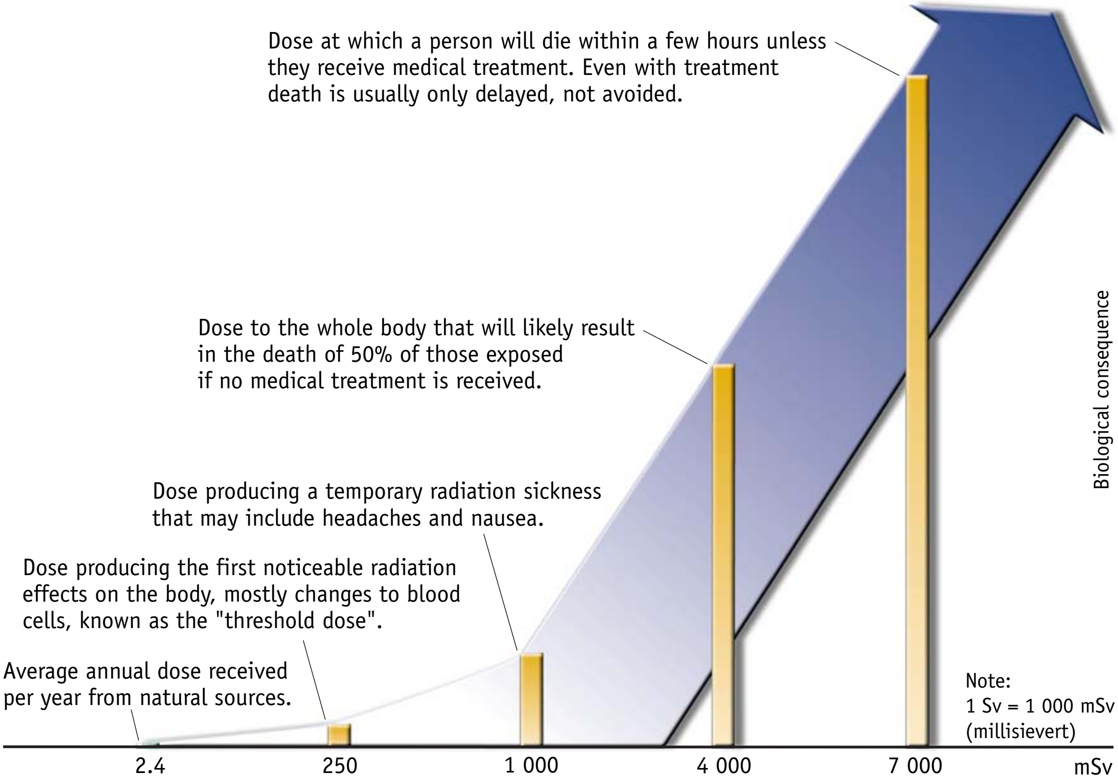
A fair amount is known about the effects of large radiation doses received instantaneously. Over the 55 years or more since the atomic bombing of Japan, the 100 000 exposed survivors have been medically monitored. About 20% of the deaths in this population have been due to some form of cancer – approximately the same percentage of deaths from cancer as is average for any group of similar composition in any Western society. However, when the comparison is made with similar Japanese populations that were not exposed to the bombing, it has been concluded that about 400 of the cancer deaths in the group of atomic bomb survivors can be attributed to radiation received in the bomb blasts.

Using the information gathered from high-dose accidents, including the Japan bombings, it has been possible to develop a dose-response curve, a graph that correlates the predicted number of cancer deaths to calculated individual exposures. This curve has been used to predict and describe the excess risk of cancer death associated with any given level of exposure. For every sievert of exposure, the risk above the "normal" 20% chance of dying from cancer is an additional 5%, that is, the total lifetime risk from cancer raises from 20% to 25% for every sievert of exposure received.

Risks at low doses

As with scientific study in general, there are things that are known and things that are not known about the biological effects of radiation. The statistics so far considered are based on relatively high doses and it is known how much increased cancer risk can be attributed to high radiation exposures. What is not known is whether similar significant effects can result from low doses of radiation such as we all naturally receive

Figure 6.4: Deterministic effects of radiation at high doses



from background radiation, or that certain workers may receive as part of their jobs.

The data from the high-dose groups show a definite link between the amount of the dose and an increased risk of cancer starting from about 100 mSv above natural background levels. For exposures below this level studies to date have not demonstrated any statistical evidence of harm. In the many studies of populations that have received radiation doses below 100 mSv, no increases of cancer have been observed compared to similar populations not exposed to this "extra" radiation.

However, because it is known that radiation can cause cancer at the higher doses, and because our understanding of the relevant biological mechanisms is incomplete, we cannot reasonably assume that cancer *cannot* be caused by low doses of radiation. So it has always been deemed prudent to assume that every dose received, no matter how small, carries a certain risk proportionate to the dose. It is, in other words, assumed that there is no threshold of safety; that is, that there is no dose, however small, at which there is no risk.

These two assumptions, that any radiation dose carries some risk and that the risk is proportionate to the dose, are known as the linear no-threshold hypothesis (LNT). This hypothesis forms an important basis for the regulation and application of radiological protection and is conservative in nature. In the absence of conclusive scientific evidence either for or against the existence of cancer risks at low doses, a prudent, precautionary approach has been taken.

The radiological protection system and its regulatory basis

The objective of radiological protection is to protect people from potentially harmful effects of radiation while allowing beneficial exposure-causing activity to take place.

The radiological protection system applied worldwide has developed since its origins in 1928 – with the creation of the International Commission on Radiological Protection (ICRP) at the International Congress of Radiology, through applying the knowledge gained by numerous studies of exposed populations such as those mentioned above, and through studies of the effects of radiation on plants, insects and animals. This worldwide system is now based on three basic principles:

- justification of practices causing exposure;
- optimisation of protection;
- limitation of the exposure of individuals.

This approach, as codified in the Recommendations of the International Commission on Radiological Protection (ICRP), has been implemented in virtually all national regulatory arrangements. The ICRP meets annually and publishes recommendations as needed to respond to new developments. The current system of radiological protection is evolving and is expected to undergo major revision with a new set of ICRP recommendations by 2005. Among other improvements, the radiological protection of non-human species will be specifically addressed.

ICRP Recommendations are also reflected in international standards, such as the IAEA's Basic Safety Standards (BSS) and regional agreements such as European Union directives (e.g. 96/29/EURATOM).

Justification

The principle is that no practice should be allowed unless it is justified. In such a matter, decision criteria cannot rest on scientific considerations alone, but necessarily include social, economic and ethical factors. The scientific community can assess and inform about the risks, but ultimately it is society, through its consensus-building processes that has to decide whether a risk-causing practice is justified, and the process is essentially judgemental. The principle is applied on a case-by-case basis, the important point being that those who take decisions to expose people must be prepared to advance their reasons, as well as to accept that these may be challenged.

To take a general case, the medical use of X-rays is routinely taken to be justifiable, but medical staff are expected to consider the value of each exposure before they apply it. They must weigh the very slight increased risk of causing a cancer against the benefit they expect from a precise diagnosis. Similarly, in many countries, the benefit of using nuclear energy to produce electricity in the light of its risks has been challenged and public policy decisions taken.

Optimisation

The principle of optimising protection applies only for practices that have been judged to be justified. It requires that all resulting exposures be kept as low as reasonably achievable (ALARA). Practically speaking, the ALARA principle resolves itself into the questions "Has enough been done to reduce exposure in this particular case? Might it be possible and reasonable to reduce exposure further?" It should be noted that the objective of optimisation, or ALARA, is not to reduce exposures to zero, but to ensure that the risks are reduced to an acceptable level in the circumstances of each case. What is acceptable is a matter of scientific and social judgement.

Various means can be employed to do this, such as minimising the size of the radiation source, limiting the time a person is exposed, maximising the distance between people and radiation sources, using shielding, etc. The number of people exposed in any operation and the geographic distribution of doses (e.g. exposure of the public to radiation over any particular geographic area) are also important considerations of the optimisation process.

Limitation

Over and above the principle that doses must be optimised using the ALARA test, individuals must not be exposed above stipulated dose limits. Exposure limits for members of the public have been fixed nationally and internationally at 1 mSv per year. For radiation workers the international limit is a total of 100 mSv over any five-year period, without exceeding 50 mSv in any one year. Some national regulators have implemented a stricter limit for workers of 20 mSv per annum. In practice, the rigorous application of the ALARA principle and such things as the limitation of gaseous and liquid discharges have ensured that actual and average doses are normally far lower than these limits.

As with highway speed limits, the dose limit is not a boundary above which dire consequences will occur, or below which they certainly will not. It simply represents a level above which societies and their national governments prefer not to go in routine circumstances. As with many other radiological decisions, it involves the best attainable scientific understanding of the risks but is ultimately judgemental.

In summary, for any justified practice, radiological protection must be optimised such that all individual exposures are as low as reasonably achievable, but must also be below any relevant regulatory limits.

Radiological protection in the nuclear industry

Because uranium and its daughter isotopes naturally emit radiation and because nuclear fission emits radiation and creates waste that emits radiation, radiological protection is a central safety issue in the nuclear industry. However, the various sectors of the nuclear fuel cycle face different radiological protection issues.

For example, the mining of uranium results in workers being exposed to dust containing uranium and its daughter products. These can be hazardous to the lungs from alpha-emitting radionuclides that may be inhaled, thus requiring adequate mine ventilation and worker respiratory protection. These same alpha-emitting radionuclides are also the main source of potential hazard during the front-end fuel cycle processes.

Continuous monitoring of the environment is mandatory for all nuclear installations.

In nuclear power plants, radiation exposure of workers generally comes from more penetrating gamma-emitting radionuclides such as cobalt-60. Such radiation is limited, within the plants, to the piping and systems directly associated with cooling the reactor core. These generally only represent a hazard for workers during maintenance of these systems. During normal operation these systems are shielded and workers are excluded from the hazardous areas. Worker protection is afforded during maintenance through the use of shielding and by appropriately selecting work tasks and managing work to minimise worker time in proximity to radiation-emitting sources.

Exposure hazards from waste management operations, including spent fuel handling, results largely from gamma-emitting radionuclides. With LLW and ILW, cobalt-60 is a significant source of radiation. Fission products, e.g. caesium-137 and strontium-90, are the significant source of radiation connected with high-level waste and spent nuclear fuel. Radiation exposure associated with waste management is minimised through the use of specially designed facilities, equipment and procedures that keeps the radiation remote from the workers.

Several parts of the nuclear fuel cycle release small quantities of radioactivity into the environment. These emissions come mostly from spent nuclear fuel reprocessing, but also from nuclear power plants during normal operation. As such, there is a need to minimise and measure these effluents in order to protect the public and environment. Filtering and purification of air and water effluents minimise these releases and extensive environmental monitoring around all nuclear installations verify that these are working appropriately.

Accident response

There is no such thing as zero risk for any human activity. Despite the very high levels of safety maintained in all radiological activity, accidents involving the exposure of workers and of the public can occur, and can possibly (like Chernobyl) have international scope. The international community has therefore developed detailed programmes and approaches for nuclear emergency preparedness and nuclear accident management.

The main objective of these programmes and approaches is to minimise the consequences of any relevant event. Nuclear accident preparedness involves developing plans and procedures that can be put rapidly into action. This involves imagining and studying numerous "accident scenarios", and then developing, in consultation with all the necessary services, a basic organisational structure and a set of planned responses variable according to circumstances. These flexible plans are then kept on "hot stand-by" and rehearsed.

The organisational structures developed under preparedness programmes include: command and communications systems, the careful definition of the responsibilities of the various authorities and services likely to be involved, and the training of personnel. All nuclear installations around the world maintain such plans and structures in conjunction with local and national authorities. Those who would be involved in decision making during an incident train regularly with technical experts and with each other. In many countries, the public in the vicinity of nuclear plants is also kept informed and is involved in training exercises.

Emergency response is the application of these measures according to the nature of the nuclear facility and of the accident (e.g. fire, unplanned criticality or radioactive release). Large nuclear installations, particularly power plants, are equipped with many barriers to halt the progression of an accident (see Chapter 5), and severe accidents, necessarily involving the successive failure of these systems, would be likely to develop over a considerable period before the public was directly threatened. There would usually be hours, even days, to warn of the need to take protective measures.

There are three types of countermeasure that can be taken during the early stages of a nuclear or radiological emergency as follows:

- **Sheltering** the affected population. Simple measures can be effective. A very easy way to greatly reduce the impact of a cloud of released radioactivity is to ask people to move indoors, close all windows and turn off ventilation systems pending the dispersal of the cloud by wind and weather.
- **Evacuation** of the population. This measure would be taken if an expected release was estimated to be sufficiently high. Clearly, evacuation is most effective if it takes place

before a release and after the requisite meteorological judgements have been made about its likely direction and speed of dispersal.

- Administration of **iodine tablets** containing a non-radioactive, stable form of iodine. Taking stable iodine can greatly reduce the uptake of radioactive iodine that is produced by the fission process and would be an important part of any release resulting from a severe accident from a nuclear power plant. Iodine is used by the body for many purposes, and stored in the thyroid gland. So any radioactive iodine that enters the body concentrates in the thyroid, causing it a large dose that could lead to thyroid cancer, especially in children. Similarly, radioactive iodine deposited on the ground could enter the milk or other food supplies with similar results. The answer therefore is to "fill up" the thyroid gland with non-radioactive, stable iodine by taking iodine tablets; any surplus that then entered the body would be quickly eliminated, mostly in sweat and urine.

In most countries, steps are now taken to ensure the speedy availability of iodine tablets to populations vulnerable to any significant release of fission products. The administration of iodine is, however, seen only as a measure additional to sheltering or evacuation.

Accident recovery

Once an emergency situation is brought under control and the population protected, the longer-term work of recovery must begin. This would generally first involve establishing the levels of contamination deposited in the environment, assessing the doses that will have been received by individuals, and developing appropriate clean-up and medical follow-up programmes. The clean-up of contaminated land, particularly land used for food production, would be an important part of these programmes. Fortunately, the fact that radioactivity can be readily detected assists greatly in applying the many relevant clean-up techniques that exist.

In the case of very severe contamination, as for example in the area surrounding the damaged Chernobyl reactor, a return to pre-accident levels and exposures might only be achievable through extreme measures such as the removal of all topsoil and vegetation or the voluntary curbing of consumption of local products.

Chernobyl Health Effects 15 Years On

The health impact of the Chernobyl accident can be described in terms of acute health effects and late health effects.

The **acute health effects** occurred among the plant personnel and the persons who intervened in the emergency phase to fight fires, provide medical aid and help with immediate clean-up operations. A total of 31 persons died as a direct consequence of the accident and about 140 persons suffered various degrees of radiation sickness and health impairment. No members of the general public suffered these kinds of effects.

In terms of **late health effects**, there was a real and significant increase of carcinomas of the thyroid among the children living in the contaminated regions of the former Soviet Union, which should be attributed to the accident until proved otherwise. For example, for the eight years prior to the accident, only five cases of childhood thyroid cancer (0-14 years old) were seen in Minsk, the main Belarussian centre for childhood thyroid cancer diagnosis and treatment. By the end of 1998 the total number of thyroid cancers in children had reached over 600 in Belarus. Similarly, the Ukraine saw 402 cases of thyroid cancer develop between 1986 and 1998. Of these cases, three of these children have died, while the rest have been successfully treated. There might also be some increase of thyroid cancers among the adults living in those regions. From the observed trend of this increase of thyroid cancers it is expected that the peak has not yet been reached and that this kind of cancer will continue for some time to show an excess above its natural rate in the area.

On the other hand, scientific and medical observation of the population to date has not revealed any increase above "natural" levels in other cancers, or in leukaemia, congenital abnormalities, adverse pregnancy outcomes or any other radiation-induced disease that could be attributed to the accident.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

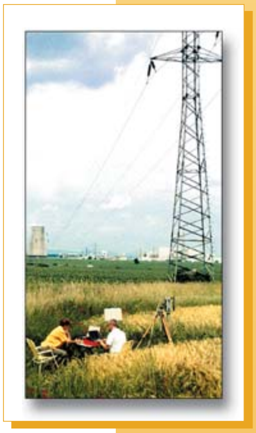
- Sources of radiation and summaries of average exposures, see 6.1.
- The basics of radiological protection, see 6.2 through 6.5.
- Recent developments in radiological protection, see 6.6 through 6.8.
- The emergency response system, see 6.9.

The Economics of Nuclear Energy

Nuclear energy is characterised by low production costs, high capital costs, insensitivity to variations in fuel prices, long operational life and significant regulatory costs.

Existing nuclear power plants are generally competitive even in deregulated markets and particularly when initial investment costs have been amortised. Mainly because of high capital costs, decisions to build new nuclear power plants may depend significantly on public policy factors.

A difference between nuclear energy and other forms of electricity production is that some costs that are mainly external to other energy sources are internalised in the case of nuclear.



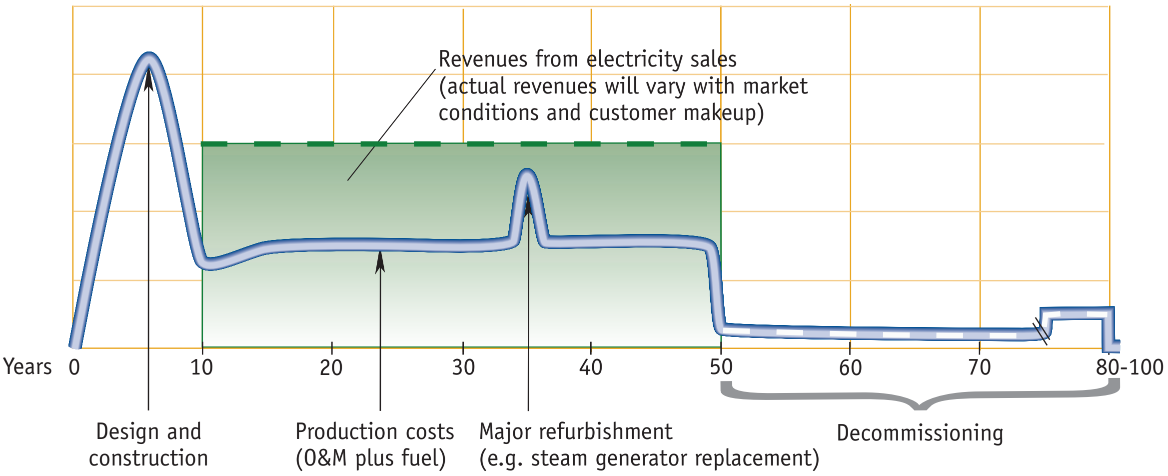
Costs, risks and liabilities

Factors influencing the economics of nuclear energy

Figure 7.1 shows the life cycle revenues and costs for a typical nuclear power plant. It demonstrates the factors that characterise the economics of nuclear energy, viz:

- high capital investment costs;
- long planning horizons and operational life;
- low fuel, operating and maintenance (O&M) costs;
- significant costs incurred after cessation of power generation (notably management and disposal of radioactive waste and decommissioning).

Figure 7.1: Illustrative life cycle cash flow for a nuclear power plant



Investment costs include those of construction, major refurbishment during the life of the plant and decommissioning.

Operations and maintenance costs include those for operating staff, training, security, health, safety and the costs for management of low- and intermediate-level operational waste. In fact, this category includes all costs that are not considered investment or fuel costs.

Fuel costs include all those related to the fuel cycle. They include the cost of the uranium, its conversion and enrichment, fuel fabrication, spent fuel conditioning and disposal or recycling, as well as disposal of the waste of reprocessing.

Elements of nuclear generating costs

The costs of generating electricity are usually broken down into three major categories, the costs of investment (capital); operation and maintenance; and fuel.

Investment costs include those of design and construction, major refurbishing, and decommissioning. The last comprises all the costs incurred from the shutdown of the plant until the site is released in accordance with national policy and includes the costs to manage the radioactive and other waste generated during decommissioning until they are disposed of. To these costs are added those associated with securing regulatory approval to proceed with construction and operation.

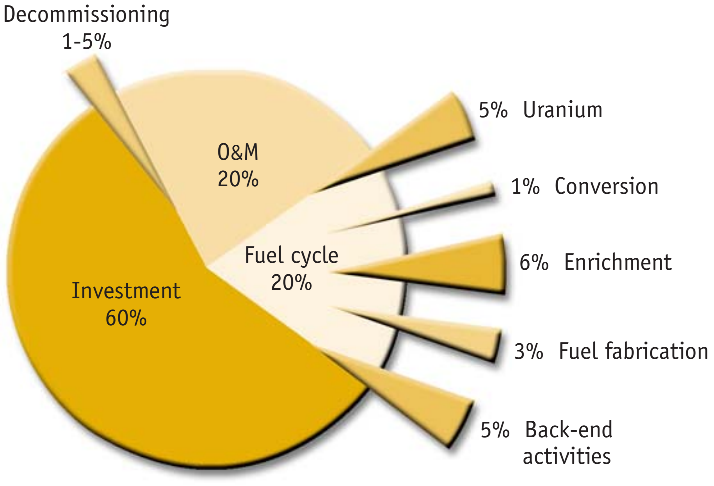
Investment costs must be financed, and they thus incur interest charges. These are amortised over some set period, perhaps on the order of 20-25 years, and the debt service becomes part of the costs of electricity generation. Provisions are also required to be set aside or paid by plant operators for decommissioning and disposal of its associated waste – processes that can take many decades.

Operation and maintenance (O&M) costs include all costs that are not considered investment or fuel costs, the main elements being the costs of operating and support staff, training, security, health and safety, and management and disposal of operational waste. The costs of day-to-day and periodic maintenance and inspection (during which plants usually have to be taken off-line) are also included. Because investment costs are essentially fixed after construction, O&M costs represent a major opportunity for cost-reduction in an existing power plant.

Fuel costs include costs related to the fuel cycle, including the costs of purchasing, converting and enriching uranium, fuel fabrication, spent fuel conditioning, reprocessing, disposal of the spent fuel or the high-level waste resulting from reprocessing and transport. Fuel costs make up only about 20% of the costs of nuclear-generated electricity, which is therefore relatively insensitive to fuel price fluctuations – in contrast to the position of fossil fuels.

Although generating costs are country-specific, Figure 7.2 shows the relative importance of the components in the cost of nuclear generation of electricity.

Figure 7.2: Typical nuclear electricity generation cost breakdown



Long-term financial risks and liabilities

A decision to build or to continue to operate a nuclear power plant represents a greater commercial risk than is normally associated with alternative energy sources, for several reasons:

- The long planning timescale and operational life provides greater potential for long-term changes in the market to impact revenues negatively or positively.
- The high fixed-cost element, due largely to the high investment costs, produces greater vulnerability to short-term fluctuations in market conditions.
- The strong regulatory framework reduces operational flexibility and introduces the possibility of changes in regulatory requirements that could impact adversely on costs (and historically have done so).
- Uncertainties associated with the costs of decommissioning and long-lived waste disposal, including the time periods involved.
- Whereas non-nuclear plants can trade or sell much of their cost base under negative economic conditions, this is in practice largely

ruled out for nuclear power plants (e.g. a gas-fired power plant can sell its gas supply on the open market).

Although decommissioning costs and the costs of managing its associated waste are high, they are a relatively small component of total life-cycle costs, not least because the long time periods involved produce considerable discounting. Uncertainties in the accuracy of predicted future costs are possible given the long service lives of reactors and the potential for changing and usually strengthening regulatory requirements. Therefore, allowances for uncertainty are made a part of the provisions to cover decommissioning costs.

If these costs are provided for based on projected income over the expected life of a plant, there is a risk of shortfall should economic conditions force early closure or should the plant produce revenues below projected levels. In practice, however, these funds have been collected over projected lifetimes considerably shorter than those actually achieved. The potential also exists for advances in the relevant technologies to reduce costs below those envisaged.

Competitive aspects

Comparative costs of generating electricity

Figure 7.3 gives a comparison of the representative generating costs of electricity from nuclear and some fossil fuel sources.

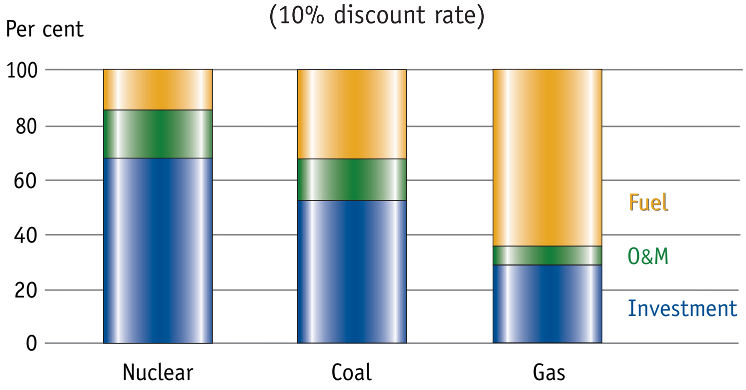
Compared with nuclear energy, natural gas-fired plants are characterised by low capital investment costs and significant fuel costs. Coal-fired plants are characterised by mid-range investment and fuel costs. In general, fuel costs represent a relatively large proportion of fossil-fuel-based generating costs that are, as a result, sensitive to fuel price variations. Renewable sources of energy, e.g. wind and hydropower, are similar to nuclear power in having high investment and low production costs per unit of power produced.

Existing plants

Given the relatively low cost of nuclear fuel, the recent advances in improving efficiency, and the fact that in many cases original investment costs are now substantially amortised, existing nuclear power plants have mainly proved to be competitive worldwide.

Data from the European Commission on electricity production costs (investment, O&M and fuel costs included) show nuclear energy to be competitive even accounting for its large investment costs (see Table 7.1).

Figure 7.3: Breakdown of representative generation costs (10% discount rate)



Source: NEA. *Projected Costs of Generating Electricity* (Paris: OECD, 1998). Average of values for Canada, France, Japan, Spain and the United States.

Table 7.1: Electricity production costs for 7 000 hours of production (1990 Euro cents/kWh)

	Coal	Oil & lignite	Gas	Nuclear	Biomass	Photovoltaic	Wind
Minimum	3.2	4.9	2.6	3.4	3.4	51.2	6.7
Maximum	5.0	5.2	3.5	5.9	34.5	85.3	7.2

Source: European Commission. *Green Paper: Towards a European Strategy for Energy Supply* (Brussels: EC, 2000), Annex 2, Table 1 without excise taxes and subsidies.

External costs are costs that are imposed on society and the environment that are not accounted for in the cost to producers and consumers of energy, and omitted when calculating the market price.

Data from the United States on energy operating costs (only O&M plus fuel costs) show a similar result. In 1999, operating expenses were reported as US 1.92 cents/kWh for nuclear, US 2.02 cents/kWh for fossil fuel sources, US 0.68 cents/kWh for hydro and US 3.87 cents/kWh for gas turbine, photoelectric and wind.

The outlook for existing plants on economic grounds is therefore one of continuing use of these facilities, particularly as the costs for lifetime extension or capacity upgrade are typically much lower than those for building new plant.

Nuclear energy in deregulated markets

An OECD/NEA study on *Nuclear Power in Competitive Electricity Markets*, published in 2000, found that nuclear power plants in Finland, Germany, the Netherlands, Spain, Sweden, the United States and the United Kingdom had been competitive in their respective deregulated markets.

Generally, the response to market deregulation had been an improvement in operating efficiency and profitability. The pressure to manage a plant properly to meet stringent nuclear safety regulations appears to provide a sound basis for competitive performance.

Construction of units 6 and 7 at the Kashiwazaki-Kariwa nuclear power station in Japan was accomplished in under six years.

New plants

The 1998 OECD/NEA study on *Projected Costs of Generating Electricity* compares the levelised costs of electricity for various fuel types. The results showed that the attractiveness of building new plants is dependent on country-specific factors including the prevailing discount rate. For example, according to the study, nuclear power is cheapest in 5 of 12 countries at a 5% per year rate while at 10% per year it is cheapest in none.

The relatively large investment cost for new nuclear plants is a main factor. To make construction of new plants commercially more attractive under competitive conditions, investment costs must be reduced. New more cost-effective designs, improved construction methods, standardisation and series construction and multiple unit construction are all means to reduce the investment costs of nuclear power plants. Improvement is possible. For example, in Japan during the 1990s, use of a standardised advanced design together with duplication of construction on a single site enabled the construction of new plants to be completed in under 6 years as compared with a previous range of 7-10 years, the construction of two advanced boiling water reactors (ABWR) at Kashiwazaki-Kariwa having been accomplished (from start to commercialisation) in 62 and 65 months.

However, the high levels of financial commitment and risk in a competitive market can make it difficult for the private sector alone to finance new nuclear power plants, even given the potential time and cost savings. Historically, the exploitation of nuclear energy on a highly innovative basis has been driven by public-private sector relationships. The question now is whether this relationship can or should exist under deregulated conditions.

External costs

A difference between nuclear energy and other forms of electricity production is that nuclear energy bears some costs that are not included in (are external to) the costs of other sources of electricity. Some of the costs associated with nuclear electricity generation included in the prices at which the resulting electricity is sold on the open market include radioactive waste management and disposal. Fossil fuel energy bears certain costs for reducing its emissions to air and water, as does nuclear, but a considerable part of the waste is disposed of to the atmosphere, imposing costs on the community that are not reflected in the price of its electricity. Table 7.2 represents the outcome of a major study by the European Commission on the external costs of electricity production by fuel source, including not only the costs of waste deposition but also the impacts on public health, together with certain other detriments whose costs are generally borne by society rather than the consumer.

The economic competitiveness of nuclear power might be dramatically shifted if the external costs of fossil fuel generation were to be internalised. For example, if the external costs for carbon emissions alone were internalised through the imposition of a "carbon tax", the effect on levelised generation costs would be significant (see Figure 7.4).

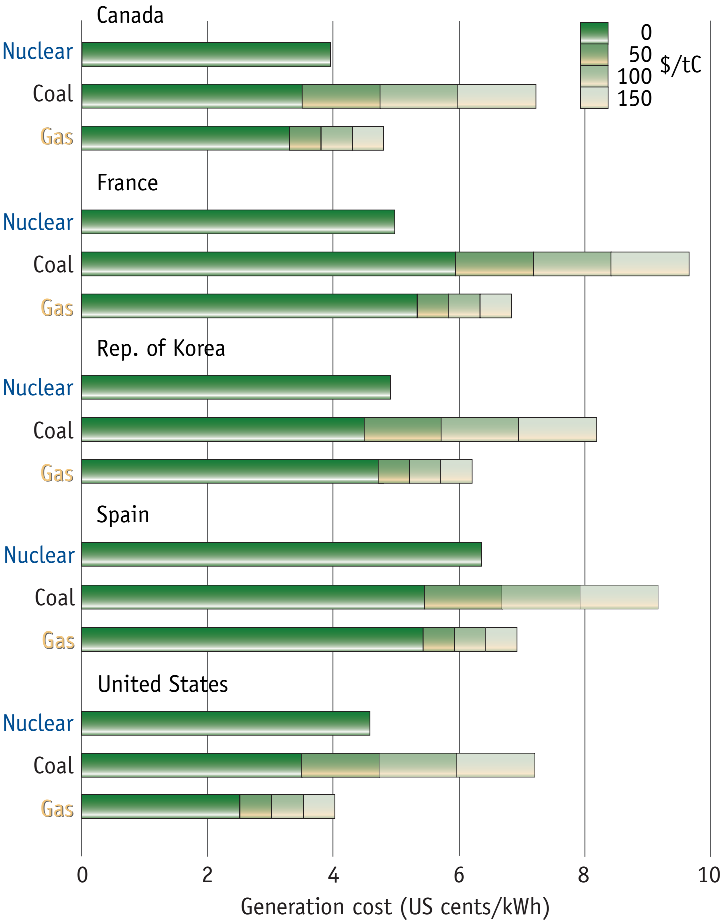
Unless there is a steep reduction in nuclear energy capital costs, a significant and sustained rise in fossil fuel costs or political decisions to internalise some of the external costs associated with fossil fuels, private sector investment in new nuclear power plants may be lacking. Until then, decisions to build new nuclear power plants are likely to be significantly influenced by public policy factors, such as security of supply. Whether and how these governmental concerns may be addressed in competitive markets is an open question and outside the purview of the private sector.

Table 7.2
External costs for electricity production in the European Union (Euro cents/kWh)

Coal and lignite	1.8 - 15.0
Oil	2.6 - 10.9
Gas	0.5 - 3.5
Hydro	0.04 - 0.7
Photovoltaic	0.1 - 0.3
Biomass (includes peat)	0.1 - 5.2
Wind	0.05 - 0.25
Nuclear	0.3 - 0.7

Source: European Commission, *ExternE – Externalities of Energy*, Vol. 10: National Implementation (Luxembourg: EC, 1999), p. 6.

Figure 7.4: Effect of carbon tax on levelised generation cost in different countries (10% discount rate)



Source: NEA. *Nuclear Energy and the Kyoto Protocol* (Paris: OECD, 2002).

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- The economics of the nuclear fuel cycle, see 7.1.
- An in-depth analysis of the cost of generating electricity by the various technologies in current use, including nuclear, see 7.2.
- Additional information on the economics of nuclear energy, see 7.2, 7.3 and 7.4.
- Nuclear energy in competitive electricity markets, see 7.3 through 7.5.
- External costs of generating energy, see 7.6 through 7.8.

International Nuclear Law and Non-proliferation

Virtually all aspects of the use of nuclear energy are governed by a framework of national laws, frequently based on principles that have been agreed to internationally and which are often reflected in international agreements or other instruments.

Those agreements and instruments that deal with non-proliferation, are a particularly important strand in these arrangements, responding to widely held public concerns regarding the spread of nuclear weapons. The Nuclear Non-proliferation Treaty of 1968 is the fundamental legal basis for the international nuclear non-proliferation regime.

This chapter does not attempt to deal comprehensively with the extensive web of agreements, conventions, laws, regulations, standards and institutions that govern nuclear matters. Rather, it concentrates on two particularly important aspects of nuclear energy use – its legal framework and the non-proliferation of nuclear weapons.

International nuclear law

Responsible regulation of nuclear energy has always been indispensable for public confidence in its exploitation. Achieving that confidence requires the existence of a comprehensive and effective legal framework whose goal is the protection of the health, safety and security of the public and the integrity of the natural environment.

Public confidence also requires trust in the involved institutions, both in the regulator and the regulated. This, in turn, requires among other things transparency and pro-active communication.

An effective legal framework depends on strong requirements, as well as enforcement measures to ensure compliance with those requirements. At the same time, the framework needs to be flexible enough to keep pace with changes in technology and public concerns. Finally, because the consequences of nuclear energy's use may not be confined within national borders, the framework should be international in character.

National requirements

All OECD countries using nuclear energy have established (1) general legislative requirements for the conduct of civil nuclear activities and (2) a public authority empowered to enforce compliance with these requirements.

Most countries have established a mandatory licensing system, a form of regulation under which specific activities can only be lawfully carried out in accordance with terms and conditions specified in a licence issued by a public authority. In the vast majority of cases, compliance is verified through systematic inspection by the licensing authority, and by reporting requirements imposed on the licensee. Non-compliance with license conditions can result in the suspension or revocation of the license, the imposition of fines, or even imprisonment of the licensee or other responsible entity, depending on the severity of the violation.

With the rapid development of nuclear science and technology over the past decades, The OECD Nuclear Energy Agency was established in 1958 and as of January 2003 had 28 member countries. The European Commission takes part in the work of the Agency. The NEA also works in close collaboration with the IAEA as well as with other international organisations in the nuclear field. Specific areas of competence include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

governments have had to ensure that legislative requirements kept pace with the utilisation of new technologies and with new uses for existing technologies. In so doing, national legislation has steadily extended its scope with the intention of protecting the public and the environment from the risks associated with these new developments. As a result, today's national legislative requirements cover an extremely wide range of activities, including:

- uranium mining and milling;
- use of nuclear substances and radiation in research and medicine;
- packaging and transport of radioactive materials including nuclear fuel;
- nuclear safety for all stages in the life of nuclear installations, from power plants to radiation therapy units, and from design to decommissioning;
- physical protection (security) of nuclear materials and nuclear installations;
- international trade in nuclear materials, equipment and technology;
- management of spent fuel and radioactive waste;
- non-proliferation and safeguards obligations;
- radiological emergency preparedness and incident response measures;
- liability and compensation for damage suffered as a result of accidents.

Many of these legislative requirements derive from, or are based on, internationally accepted principles and standards. Most industrialised countries, for example, follow the Recommendations of the International Commission on Radiological Protection with regard to dose rates (see Chapter 6), though some apply still stricter requirements. Similarly, they follow the International Atomic Energy Agency (IAEA) *Basic Safety Standards for Protection Against Ionising Radiation and for the Safety of Radioactive Sources* as well as its *Regulations for the Safe Transport of Radioactive Material*. These international instruments flow from the co-operation and advice of national governments and experts.

International framework

There are a variety of international conventions in the nuclear field, to which most OECD countries are party, dealing with such matters as non-proliferation of nuclear weapons, physical protection of nuclear materials, co-operation and mutual assistance in the event of a nuclear accident, nuclear safety and radioactive waste management. The most important of these are:

- the *Treaty on Non-proliferation of Nuclear Weapons* (in force since 1970), that works to prevent the spread of nuclear weapons and weapons technology and to foster the peaceful uses of nuclear energy;
- the *Convention on the Physical Protection of Nuclear Materials* (entered into force in 1987), which imposes obligations on contracting States in relation to the protection of nuclear materials within their territory or in the course of international transport;[1]
- The *Convention on Early Notification of a Nuclear Accident* (entered into force in 1986), that establishes a system for notifying the IAEA and neighbouring States in the event of a nuclear accident which could have transnational consequences;
- the *Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency* (in force since 1987), which establishes an international framework to facilitate prompt assistance and support in the event of nuclear accidents or radiological emergencies (see Chapter 6 for more information on nuclear accident response);
- the *Convention on Nuclear Safety* (entered into force in 1996), an incentive convention[2] that aims to maintain a high level of safety at operating nuclear power plants by setting

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1. A revision of this convention is currently being negotiated. While the existing convention covers the physical protection of nuclear materials in the course of international transit only, it is anticipated that its scope will be expanded to cover such materials while in domestic use, storage or transit, as well as the sabotage of such materials.
2. An incentive convention is designed to obtain compliance through voluntary co-operation rather than by means of controls and sanctions.

international benchmarks for nuclear safety practices and regulation (see Chapter 5 for more information on nuclear safety);

- the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* (entered into force in 2001), an incentive convention that aims to achieve and maintain a high level of safety through the enhancement of national measures and international co-operation (see Chapters 3 and 4 for more information on radioactive waste management).

In addition to these conventions, a considerable number of multilateral agreements have been entered into, often by neighbouring countries, as for example the 1998 agreement for co-operation in the transport of nuclear materials between the Czech Republic, the Russian Federation, the Slovak Republic and Ukraine. There are also bilateral agreements on co-operation on such matters as the exchange of technical information and specialists; the provision of materials and equipment for experiments; and the carrying out of joint research and similar agreements dealing with aspects of safety and radiological protection.

Finally, there is the routine activity of supranational bodies such as the European Union and international organisations such as the IAEA and the OECD/NEA, in the setting of guidelines and standards and in providing fora for international discussion and mutual assistance. In the case of the European Union this extends to a variety of Council Regulations, Directives and other instruments with binding force on its members.

A special regime for liability and compensation

Most OECD countries have adopted special liability and compensation legislation to ensure that those who suffer damage as a result of a nuclear accident have recourse to adequate compensation. These special regimes are unique, deviating as they do from the normal legal principles that determine liability for damages resulting from a hazardous activity.

Under these regimes, the operator of a nuclear installation[3] is both *strictly* and *exclusively* liable for nuclear damage suffered by third parties as a result of a nuclear accident occurring at its installation or involving nuclear substances coming from that installation. However, a limit is usually placed upon the amount of that liability as well as upon the time within which claims for damages must be brought. Within the OECD, the operator of a nuclear installation is required to maintain financial security covering the amount of its liability to ensure that funds will be available to compensate the damage suffered. Although this financial security may be obtained through a variety of means, e.g. a bank guarantee, a pledge of assets, a State guarantee or through a form of State insurance, in practice, private insurance is the most common form of financial security.

Given the risks involved and the large amounts of coverage required, it is impossible for individual insurance companies to insure this risk on their own. As a result, within each country private nuclear insurance is provided by a "pool", a group of insurance companies who have joined together on a co-insurance basis.[4] Since their creation in the mid-1950s, the capacity of these pools has increased many times over – not only because more companies join but because with increasing experience, they are able to assume more risk. Nevertheless, even with this pooling of resources, their total financial capacity is still usually less than the amount of financial security required of the operator of a nuclear power plant. Consequently, the national pools work with other national pools to obtain coverage for the balance. Generally, the sponsoring national pool commits itself to provide the full amount of insurance to the policyholder and then reinsures[5] most of that amount through re-insurance contracts with another pool.

As a result of the 1979 nuclear accident at Three Mile Island in the United States, the insurance paid or on reserve to be paid is USD 100 million for settlement of damage claims.

Strict liability means that the operator of a nuclear installation is liable for injuries or damage suffered by third parties as a result of a nuclear accident occurring at its installation, without the need to prove that the operator was negligent or at fault.

Exclusive liability means that only the operator of the nuclear installation where the accident occurs can be held liable for injuries or damage suffered by third parties.

Third parties, in this context, are anyone who is neither the operator of the nuclear installation nor a supplier of goods, services or technology to that operator.

It may be noted that in most OECD countries, the required financial security may only be used as compensation for victims and not for the payment of interest or costs.

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[3] While the definition of *nuclear installation* may vary somewhat from country to country, it generally includes nuclear reactors, nuclear fuel fabrication and processing plants, isotope separation plants, irradiated nuclear fuel reprocessing plants, and facilities for the storage or disposal of nuclear fuel or radioactive products or waste.

[4] Co-insurance means that a number of insurers collectively insure a certain risk, the sum of their individual shares totalling 100%.

[5] Re-insurance is where an insurer or co-insurer cedes part of the risk it has assumed to another insurer for which it pays a premium, essentially insuring the risk it has itself insured.

International agreements are an important element of the co-ordination of nuclear energy worldwide.

It is acknowledged that the operator liability amounts may not be sufficient to cover the consequences of a catastrophic nuclear accident. Therefore, supplementing these financial security requirements, most OECD member countries have mechanisms or policies in place to provide additional financial assistance or compensation out of public funds in the event that the operator's financial security is not adequate to compensate for the damages incurred. Specific measures and amounts vary from country to country.

In addition to these national compensation regimes, many countries are signatory or party to one or another of the several international conventions that establish liability and compensation regimes to manage the complicated process of claiming compensation for a nuclear accident with transnational effects. These conventions include:

- the 1960 *Paris Convention on Third Party Liability in the Field of Nuclear Energy* (Paris Convention);
- the 1963 *Brussels Convention Supplementary to the Paris Convention* (Brussels Supplementary Convention, BSC);
- the 1963 *Vienna Convention on Civil Liability for Nuclear Damage* (Vienna Convention);
- the 1988 *Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention* (1988 Joint Protocol);
- the 1997 *Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage* (Vienna Amending Protocol);[6]
- the 1997 *Convention on Supplementary Compensation for Nuclear Damage* (CSC).[7]

Under the Paris Convention an operator of a nuclear installation is not relieved of liability for damage caused by a nuclear incident directly due to a terrorist act.

The Paris and Vienna Conventions as well as the Vienna Amending Protocol contain the same basic principles:

- strict and exclusive liability of the operator for third party nuclear damage;
- the operator's obligation to secure this liability financially;
- limitation on the amount of operator liability and a time limit within which victims must bring their claims;
- non-discrimination among victims on grounds of nationality, domicile or residence;
- unity of jurisdiction, meaning that one single court determines all claims for compensation resulting from a particular accident.

The 1988 Joint Protocol acts as a geographical link between the Paris and Vienna Conventions. The Brussels Supplementary Convention provides for compensation supplementary to that called for under the Paris Convention. The CSC is designed to provide for compensation supplementary to that called for under either the Paris Convention, the Vienna Convention or the legislation of an Annex State as defined in that Convention.

As for the amounts of liability that are imposed upon nuclear operators under these conventions:

- the Vienna Convention imposes a minimum liability amount of USD 5 million;[8]
- the Paris Convention imposes a maximum liability amount of 15 million SDR[9] (about EUR 22 million) although most contracting parties have imposed higher amounts on nuclear operators pursuant to national

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[6] It should be noted that the 1997 *Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage* had not yet come into force as of 1 January 2003.

[7] It may be noted that the 1997 *Convention on Supplementary Compensation for Nuclear Damage* had not yet come into force as of 1 January 2003.

[8] This amount is defined by reference to its value in gold on 29 April 1963. That value is USD 35 per one troy ounce of fine gold, and is generally considered as having a value of approximately USD 60 million today.

[9] SDR stands for *special drawing right*, a unit of account defined by the International Monetary Fund. It is calculated daily on the basis of a basket of currencies consisting as of 1 January 2003 of the euro, the yen, the US dollar and the pound sterling. As of 20 February 2003 an SDR was equivalent to Euro 1.48 and USD 1.37.

Table 8.1: International liability and compensation conventions and coverage for OECD member countries[i]

	Paris Conv.	BSC	Vienna Conv.	Joint Protocol	Approximate operator liability amounts imposed under national legislation (unless otherwise indicated the financial security limit is equal to the liability amount)[ii]
Australia					No specific legislation.
Austria					Unlimited liability though a maximum financial security limit is set at about EUR 400 million.
Belgium	✓	✓			EUR 300 million.
Canada					Financial security limit of CAD 75 million.
Czech Republic			✓	✓	CZK 6 000 million.
Denmark	✓	✓		✓	SDR 60 million (about EUR 90 million).
Finland	✓	✓		✓	SDR 175 million (about EUR 260 million).
France	✓	✓			EUR 91.5 million.
Germany	✓	✓		✓	Unlimited liability though a financial security limit is set at about EUR 2 500 million.
Greece	✓			✓	No specific legislation.
Hungary			✓	✓	SDR 100 million (about EUR 150 million).
Iceland					No specific legislation.
Ireland					No specific legislation.
Italy	✓	✓		✓	EUR 4 million.
Japan					Unlimited liability though a maximum financial security limit is set at JPY 60 000 million for reactors over 10 000 kW.[iii]
Luxembourg					No specific legislation.
Mexico			✓		MXP 100 million.
Netherlands	✓	✓		✓	EUR 340 million.
New Zealand					No specific legislation.
Norway	✓	✓		✓	SDR 60 million (about EUR 90 million).
Poland			✓	✓	SDR 150 million (about EUR 225 million).
Portugal	✓				No specific legislation.
Republic of Korea					SDR 300 million (about EUR 450 million).
Slovak Republic			✓	✓	SKK 2 000 million.
Spain	✓	✓			EUR 150 million.
Sweden	✓	✓		✓	SDR 300 million (about EUR 450 million).
Switzerland					Unlimited liability though a financial security limit is set at about CHF 1 000 million.
Turkey	✓				No specific legislation.
United Kingdom	✓	✓			GBP 140 million.
United States					USD 9 700 million though a financial security limit is set at USD 200 million.

i. Based upon unofficial statistics of the OECD Nuclear Energy Agency as of October 2002.
ii. SDR converted to euros at 1.48 euro per SDR (20 February 2003, IMF SDR valuation).
iii. Reactors of less than 10 000 kW have a security limit of JPY 12 000 million and other nuclear facilities, JPY 2 000 million.

legislation, usually in the range of 150 million SDR (about EUR 220 million);

- the Brussels Supplementary Convention provides for a maximum of 300 million SDR (about EUR 450 million) to be made available through the liable operator's financial security, public funds provided by the State in which the liable operator's installation is located, and public funds provided by all contracting parties together;

The International Atomic Energy Agency (IAEA) founded in 1957, is an independent, intergovernmental organisation in the United Nations family that serves as a forum for scientific and technical co-operation in the peaceful use of nuclear technology. Key aspects of its responsibilities include developing internationally accepted nuclear safety standards and verifying that States use nuclear materials and facilities only for peaceful purposes. As of May 2003, 136 States were members of the IAEA.

- the Vienna Amending Protocol will impose a minimum liability amount of 300 million SDR (about EUR 450 million) (of which one-half may be provided by the State in whose territory its installation is situated);
- the CSC will provide for approximately 600 million SDR (about EUR 900 million) to be made available, it being understood that the "supplementary" portion of the fund under this Convention will amount to approximately 300 million SDR (about EUR 450 million).

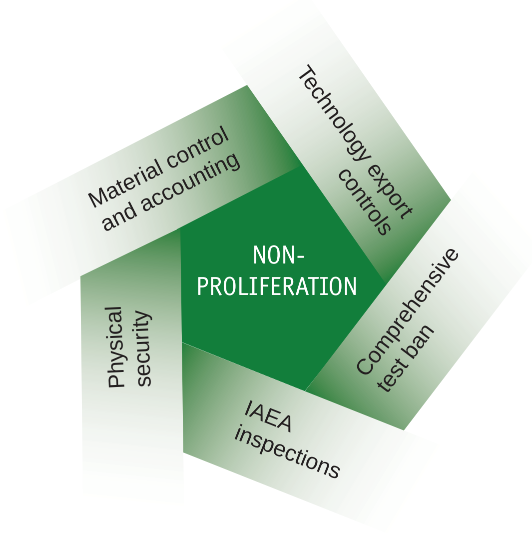
Both the Paris and Brussels Supplementary Conventions are currently in the process of revision. Once these revisions come into force, the liability limits imposed upon Paris Convention parties cannot be set at less than EUR 700 million, while the total amount of compensation to be made available under the combined Paris-Brussels regime will increase to a maximum of EUR 1.5 billion.

A summary of the international liability and compensation conventions to which OECD member countries are party is given in Table 8.1. The table indicates the liability amounts imposed on nuclear operators under national legislation, which may differ from the amounts applicable under the conventions that the State is party to. Where the limits differ the higher amount is applicable. Nuclear installation operators must maintain financial security equal to the liability amount. Some countries, though, have imposed very high or even unlimited amounts of liability. In these cases, lower financial security limits have been established in order to permit the operators to obtain insurance and are indicated in the table.

As can be seen, many countries that generate significant amounts of nuclear power are not party to these conventions, e.g. Canada, China, Japan, the Republic of Korea, the Russian Federation, Switzerland and the United States, although most of them have adopted identical principles in their national legislation.

As in the past, nuclear law will continue to evolve at both the national and international levels. This evolution will reflect not only the need to properly manage scientific and technological developments in the nuclear field, but also the need to ensure that maximum benefits are derived from the peaceful use of nuclear energy while protecting public health and safety, and the environment.

Figure 8.1: The elements of non-proliferation



Non-proliferation

The incredible destructive potential of nuclear weapons has driven the international community to prevent their proliferation, or to "keep the genie in the bottle". Yet, the peaceful uses of nuclear energy are seen to provide much benefit. Because a good deal of knowledge relevant to nuclear weapons is intrinsically acquired in the course of the preparation for and actual use of nuclear energy and/or nuclear research facilities, preventing weapons proliferation while allowing civil nuclear development to go on is a difficult task. Consequently, the risk of weapons proliferation will remain an issue for nuclear energy as long as the public has concerns that the link between civilian and military use of nuclear energy cannot be effectively and permanently cut.

Obtaining nuclear weapons is a complex undertaking requiring not just specialised fissile material, but also the necessary knowledge and technology to be able to design, build, handle and deliver them. Physical testing of a nuclear weapon may also be sought to ensure its reliability and effectiveness.

Beginning in 1946, the international community targeted each of these "essentials" with the object of preventing access to the materials and critical technologies, preventing testing and also seeking to control access to the technologies needed to deliver a weapon (see Figure 8.1). These efforts culminated in a series of treaties, notably the *Treaty on Non-proliferation of Nuclear Weapons* (NPT) and the *Comprehensive Nuclear-Test-Ban Treaty* (CTBT), which continue to form the basis of all efforts to prevent proliferation.

The NPT divides the world into two groups – States that had nuclear weapons when the Treaty came into place, or the "Nuclear Weapons States" which included China, France, Russia, the United Kingdom and the United States; and the remainder of the signatories called the "Non-nuclear Weapons States". As of the beginning of 2003 there were 188 signatories of the treaty the most recent being Cuba, which acceded to the treaty in November 2002. Each Nuclear Weapons State pledged not to transfer nuclear weapons, not to assist any Non-nuclear Weapons State to develop nuclear weapons and to work to achieve nuclear disarmament. India, Israel and Pakistan have so far refused to sign the NPT.

Controls on nuclear materials

IAEA safeguards are the key means of detecting and deterring the diversion of nuclear material by a State. All Non-nuclear Weapons States party to the NPT must agree to the application of IAEA safeguards to all of their nuclear material. Such comprehensive or full-scope safeguards agreements are intended to provide confidence that a Non-nuclear Weapons State is complying with its commitment not to manufacture nuclear weapons. Furthermore, while not obligated to do so, each of the Nuclear Weapons States has concluded safeguards agreements (so-called voluntary offers) that permit the IAEA to verify some or all of its civil nuclear activities. IAEA safeguards are also applied in States that have not signed the NPT (Cuba, India, Israel and Pakistan), but only on selected facilities when required by the suppliers of the facilities or the nuclear material involved. In 1997, an additional safeguards protocol, which includes measures to improve the capability to detect possibly undeclared nuclear activities, was agreed and is now in the ratification process.

The essence of safeguards is a State declaration about its nuclear material, facilities and activities coupled with IAEA inspection or access to verify this information. Inspections are usually conducted on a random, yet pre-announced basis at least annually. In the most sensitive facilities physical inspections may even be performed continuously. IAEA inspection activities can include verification that the design of nuclear facilities is as declared, examination of operating records, measurement and sampling of the nuclear material itself, and the use of surveillance equipment and sealing devices to maintain knowledge of the material. The additional safeguards protocol requires that States provide even more wide-ranging information on their nuclear activities (extending to those that do not necessarily involve nuclear material) and allow the IAEA access to all the locations concerned on a surprise or challenge basis.

"Not achieving a nuclear test ban would have to be classed as the greatest disappointment of any administration, of any decade, of any time and of any party."
Dwight D. Eisenhower, 1961.

IAEA safeguards are complemented by other regional arrangements such as the Euratom safeguards programme and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials. In addition, national security measures are used to prevent theft or diversion of nuclear materials and technologies as well as to prevent sabotage. These security measures consist largely of physical security controls such as secure facilities, armed guards, special locks and access codes and cameras, but include also organisational controls such as limiting access to sensitive information and the security clearance of individuals.

Controls on key technologies

Certain key materials and technologies are subject to very strict international *export controls* because it is considered very important to ensure that they are not diverted to military purposes. The Nuclear Suppliers Group (NSG) has a series of nuclear suppliers guidelines governing the transfer of key materials and technologies. The Guidelines for Nuclear Transfers concern the transfer of nuclear material, equipment, technology, components and facilities defined in an export trigger list. Members of the NSG have agreed not to transfer trigger list items to a Non-nuclear Weapons State that does not have a full-scope safeguards agreement with the IAEA. The NSG also has guidelines relating to the transfer of certain "dual-use" items or technologies that can have

The Nuclear Suppliers Group (NSG) is a group of nuclear supplier countries, 39 as of October 2002, which work together to prevent the proliferation of nuclear weapons. These countries pursue the aims of the NSG through adherence to consensus guidelines concerning nuclear and nuclear-related exports and through the exchange of information.

non-nuclear use in addition to a nuclear-related use, such as high-speed computers.

Similarly, most parties to the NPT already co-operate to control missile technologies that can deliver nuclear weapons through the *Missile Technology Control Regime*. Actions are also being taken to stop smuggling of nuclear materials, most prominently the G-8 illicit trafficking programme and its IAEA follow-up. Less formally, many governments share information on suspected illegal exports and imports of nuclear technology and materials and may well apply sanctions in the case of suspected or actual actions of proliferation.

Controls on testing of nuclear weapons

Negotiations for a "comprehensive test ban" were initiated in January 1994 and the CTBT was concluded in September 1996, although it will not enter into force until all of the 44 States with nuclear power or research reactors have ratified it. It prohibits all nuclear explosions, either for military or civilian purposes. Its signatories (numbering 166 countries by October 2002) agree to prohibit or prevent nuclear explosions at any place within their jurisdiction or control, and not to encourage in any way participation in any nuclear explosion. The treaty establishes a comprehensive verification regime including the conduct of on-site inspections, provisions for consultation and clarification, and mutual confidence-building measures.

Nuclear terrorism

Recent events have renewed concerns about the use of radioactive or nuclear materials for terrorist purposes. The potential to use conventional explosives to disperse radioactive material, a so-called "dirty bomb", reinforces the importance of national and international controls of these materials. For example, the IAEA is working to establish an international framework to improve the security of radioactive sources.

So far, national and international controls on nuclear materials, testing and key technologies have succeeded in slowing the proliferation of nuclear weapons. The challenges posed by India, Iran, North Korea and Pakistan are proving that continued efforts and vigilance are needed to ensure that the genie gets no further out of the bottle.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

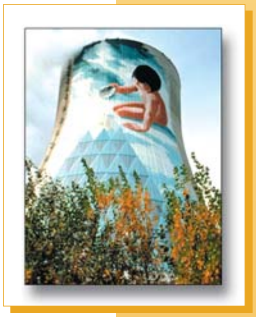
- Nuclear law, see 8.1 through 8.6.
- Third party liability and compensation for nuclear accidents, see 8.7 through 8.9.
- The conventions and agreements under IAEA auspices, see 8.10.
- Safeguards and non-proliferation, see 8.11 through 8.13.
- Specific international safeguards regimes, see 8.14 through 8.16.
- Nuclear Suppliers Guidelines, see 8.17.
- Comprehensive Nuclear-Test-Ban Treaty, see 8.18.

Chapter 9

Nuclear Energy and Sustainable Development

World energy demand is likely to grow rapidly against a background of increasing public concern about the environmental implications of competing sources of energy supply.

The question of the sustainability of different energy sources is likely to assume greater significance, and in this context, nuclear energy has certain advantages in its carbon-free generation of electricity and heat, as well as in security of supply.



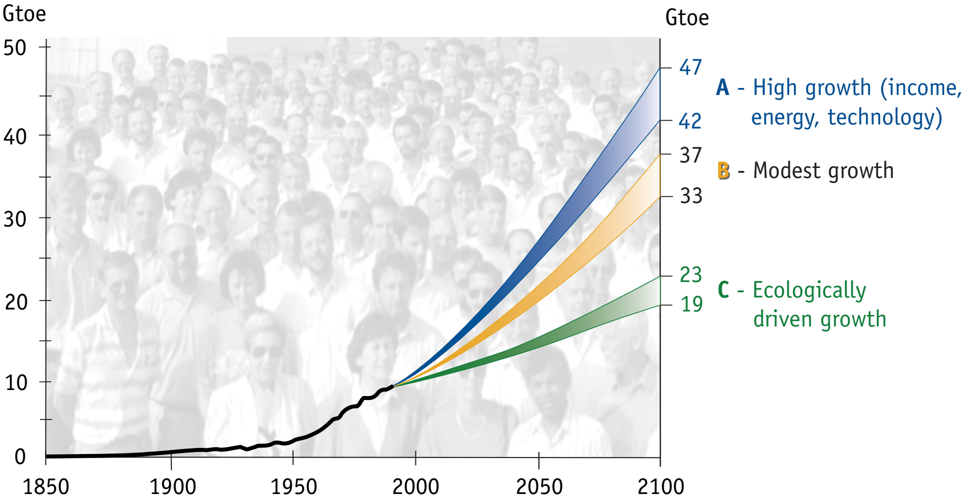
This chapter considers the future of nuclear energy in the broader context of the world's supply of and demand for energy.

Energy demand

The world's demand for energy will continue to increase as a result of economic development and population growth (see Figure 9.1). The overwhelming share of this growth is likely to take place in the developing countries, as they strive to raise the living standards of their growing populations. In 1998, the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council concluded that by 2050, global energy demand would probably grow by a factor between 1.5 and 3.0 with demand for electricity at least doubling. The British Royal Society and Royal Academy of Engineering concluded in 1999 that the consumption of energy would:

> *...at least double in the next 50 years and... grow by a factor of up to five in the next 100 years as the world population increases and as people seek to improve their standard of living.*

Figure 9.1: Projected energy demand to 2100



Source: IIASA. *Global Energy Perspectives* (Cambridge: Cambridge University Press, 1998).

Worldwide, 2 billion people are without access to electricity and an equal number continue to use traditional solid fuels for cooking. *World Energy Assessment, United Nations Development Program, 2000.*

Sustainable development – development that meets the needs of the present without compromising the ability of future generations to meet their own needs. *Brundtland Commission, 1987.*

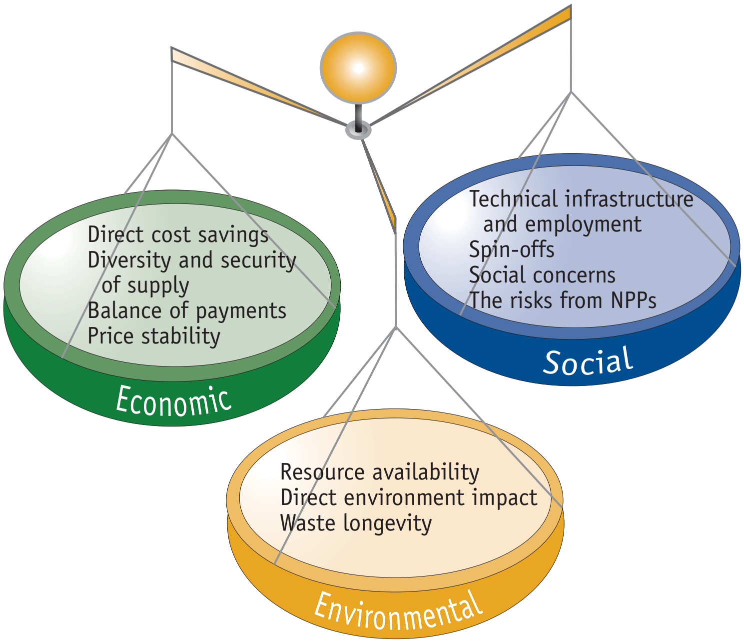
The challenge will be one of responding to these demands in a way that supports society's growing desire to meet current needs without unduly impacting on future generations.

Nuclear energy and sustainable development

Energy is an important component of any policy for sustainable development because it is vital to human activity and economic growth. The fact that current technologies for providing energy are now increasingly viewed as unsustainable provides both opportunity and challenge. The extent to which nuclear energy can be shown to be sustainable will to a significant extent determine its place in the energy supply spectrum.

The sustainability of any development is customarily discussed under three dimensions – *economic*, *environmental* and *social* (see Figure 9.2).

Figure 9.2: Elements of sustainable development applicable to nuclear energy



Economic aspects

The microeconomic aspects of nuclear energy were discussed in Chapter 7. The following paragraphs concentrate on macroeconomic elements.

Direct cost savings

The ability to provide reliable, low-cost electricity is an important aspect of sustainable development. As shown in Chapter 7, nuclear energy can become cost-competitive with other major forms of electricity generation in the long term, possibly supplemented by political action to internalise environmental costs, engender social acceptance and ensure security of fuel supplies. In the shorter run, its competitiveness is different in each country, depending primarily on fossil fuel prices, which tend to fluctuate.

Diversity and security of energy supply

Oil and gas have a fairly limited geographical availability, with Middle Eastern countries and the Russian Federation controlling over 70% of world crude oil reserves and about two-thirds of natural gas reserves. Quite aside from the political instability that has sometimes characterised the supplier regions, the long supply routes to major markets are also vulnerable to disruption by political action.

Conversely, OECD countries produce almost 55% of the world's uranium, and have 40% of the known reserves, as compared with about 7% of oil, 12% of gas and 40% of coal reserves. OECD countries are moreover self-sufficient in the essential services that turn natural uranium into finished nuclear fuels (see Chapter 3).

Unlike fossil fuels, nuclear fuel and fuel feedstock are compact and easy to stockpile; large inventories can be kept at comparatively low cost. About 25 tonnes of fuel assemblies will provide a year's fuel for a 1 GWe current generation pressurised water reactor. A coal-fired plant of similar output would require 3 million tonnes of fuel, i.e. more than one hundred thousand times as much.

As a nation's dependency on foreign sources for its energy increases, so do the costs and economic consequences of any disruption. Any energy source that reduces dependence on external fuel sources can be said to enhance the security of energy supplies and ultimately the security of the nation. Security has always been one of the main aims of energy policy in all OECD countries.

Balance of payments

Nuclear energy can be seen to have two potential positive influences on the balance of trade, assuming its costs are fairly competitive. First, importing relatively small amounts of low-cost uranium would be more attractive than importing relatively large amounts of high-cost coal, oil or gas. Second, the creation or extension of the high-technology infrastructure needed to support nuclear energy can assist technology export.

Price stability

Fuel costs are a major component in the price of fossil fuel electricity. Hence the tendency towards fluctuations in fossil fuel prices (see Figure 9.3) translates itself into variations in the price of electricity, especially in a competitive market. The low share of fuel costs and high share of fixed costs in the case of nuclear electricity generation have, by contrast, a potentially stabilising effect on electricity costs and prices.

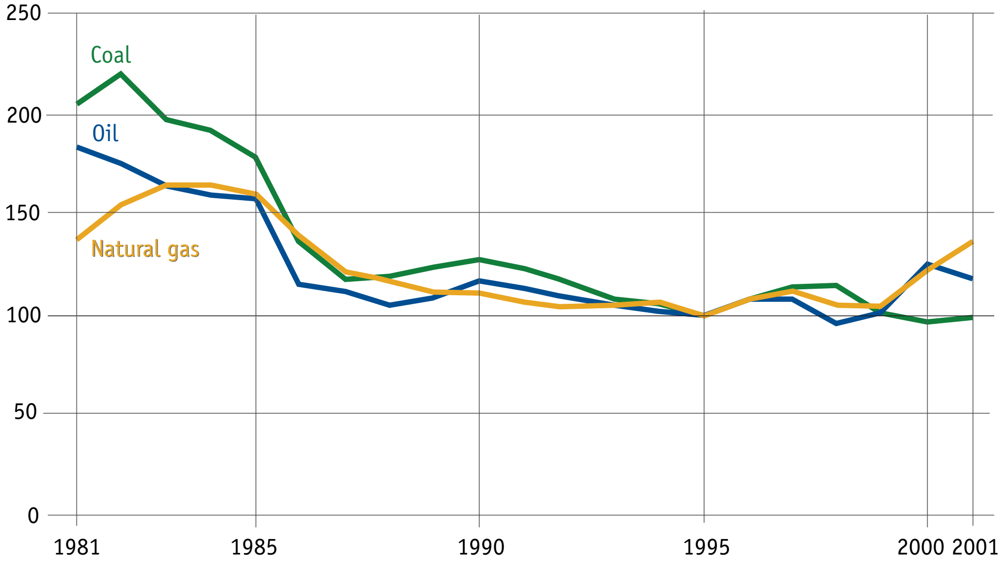
Generally, the availability and use of as wide a range as possible of alternative energy sources tends to reduce demand pressures on any one fuel source and so contributes potentially to macroeconomic stability overall.

Environmental aspects

The environmental sustainability of a particular material is usually discussed in terms of its availability, e.g. the adequacy of reserves, and its direct impacts on the environment.

Uranium resources are classified based on their economic attractiveness and on the confidence in their existence. Resources that are known to exist and are inexpensive to exploit using conventional mining techniques are classed as Known Conventional Resources. These resources are categorised into two sub-groups: Reasonably Assured Resources (RAR) and Estimated Additional Resources – category I (EAR-I). Resources believed to exist and to be exploitable using conventional mining techniques but not yet physically confirmed are classed as Undiscovered Conventional Resources. They include Estimated Additional Resources – category II (EAR-II) and Speculative Resources (SR).

Figure 9.3: Historical price fluctuation in fossil fuels



Note: The "real" price index is computed from prices in national currencies and divided by the country-specific producer price index for the industrial sector and by the consumer price index for the household sector. Here, the base year is 1995.

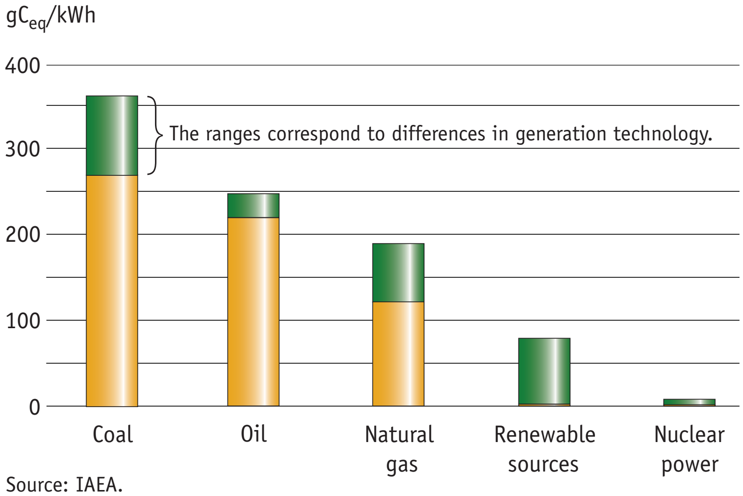
Source: IEA. *Energy Prices and Taxes* (Paris: IEA, Second quarter 2002).

Resource availability

Air pollution causes 2.7-3.0 million premature deaths a year, or 5-6% of global mortality. *World Health Organisation, 1997.*

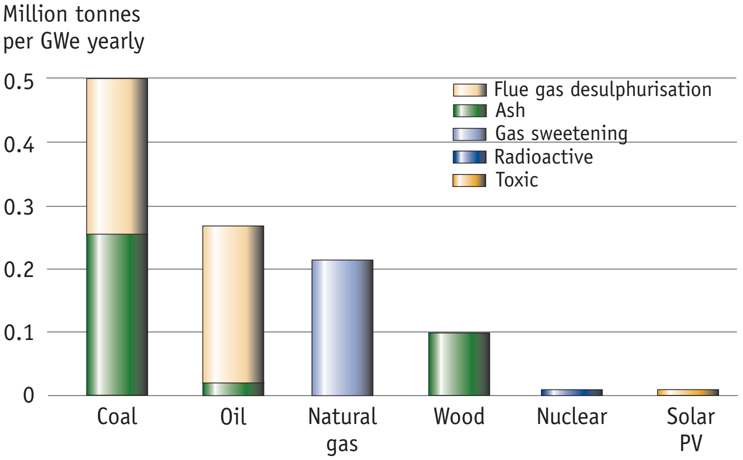
Uranium is widely dispersed in the earth's crust and in the oceans, being more abundant than silver. At the beginning of 2001, estimated conventional uranium resources (known and undiscovered) totalled above 16 million tonnes or nearly 250 years of supply at the prevailing rate of usage. There are, in addition, unconventional resources in which uranium exists at very low grades, or is recovered as a by-product. These amount to about a further 22 million tonnes that exist in phosphate deposits and up to 4 000 million tonnes of uranium contained in seawater. Research has hinted that it is possible to tap the vast seawater resources though, at present, only on a laboratory-scale. The cost of doing so is also estimated to be very high, approximately 5-10 times the current cost of conventionally mined uranium.

Figure 9.4: Greenhouse gas emissions from electricity generation by different sources



Source: IAEA.

Figure 9.5: Overall waste generation by fuel source



Source: IAEA.

In the long term however, the adequacy of natural uranium resources depends on the reactor technologies and fuel cycle strategies adopted. Reprocessing of spent fuel using current light water reactor technology could, in principle, reduce the demand for uranium by 10-15%. The introduction of fast reactors would further increase fuel efficiency; replacing all current thermal reactors with fast reactors and reprocessing fuel cycles would increase uranium resources by a factor of 50 (see Table 10.1). Other advanced techniques currently envisaged could employ thorium as a fuel feedstock rather than uranium, thereby further expanding nuclear fuel resources. India, in particular, with large thorium reserves, is working to implement a thorium fuel cycle. In essence, nuclear energy cannot be considered to be resource-limited.

Direct environmental impact

Nuclear power is one of the few energy sources that emit virtually no air-polluting or greenhouse gases. The entire nuclear fuel cycle including mining of ore and the construction of power plants has been estimated to emit between 2.5 and 6 grams of carbon equivalent per kWh of energy produced. This is roughly equal to the estimated releases from the use of renewable sources (wind, hydro and solar power) and about 20-75 times less than the emissions from natural gas power sources, the cleanest fossil fuel available (see Figure 9.4).

Nuclear power is thus one of the prime means available for limiting the emission of carbon into the environment. In OECD countries alone nuclear power plants avoid some 1 200 million tonnes of carbon dioxide (CO_2) emissions annually. Assuming that all nuclear power plants in the world were replaced by modern fossil-fuelled power plants, CO_2 emissions from the world energy sector would rise by some 8%.

Nuclear power avoids the emission of local air-polluting gases and particulates such as the sulphur and nitrogen oxides that have been linked to acid rain and respiratory diseases. The quantity of solid waste generated per unit of electricity is much lower for nuclear than for any fossil fuel source. It is essentially equivalent to that of renewable energy sources such as solar energy (see Figure 9.5).

However, for nuclear power to make a very large contribution to precluding undue global warming, a large expansion in nuclear generating capacity would be necessary. At present, nuclear power is applied only in the production of electricity, one sector of energy use. Under current estimates, even if installed nuclear power capacity were to increase by a factor of 10 by 2100, its proportion of primary energy use would rise from the current 7% to no more than 25%, thereby avoiding some 15% of the expected cumulative carbon emission during the period. However, if this expansion in nuclear capacity were to take place on the basis of current technology, there would be a considerable addition to the accumulated volume (and also the activity) of radioactive waste.

Nuclear energy is one of the options that could contribute to meeting the projected increases in the world's energy demand, essentially without adding to carbon emissions. But, to be effective and acceptable at this level, advanced reactor technologies and recycling fuel strategies would be required. In essence, as the century unfolds, the current fleet of thermal, light water reactors would need to be replaced by advanced technologies, such as fast-breeder reactors with fuel recycling. Such a change would require considerable investment, though not one likely to exceed the investment demands of other strategies for meeting increased energy demand while limiting global warming.

Waste longevity

High-level waste, though small in volume, remains radioactive for very long periods. Deep geological repositories have been investigated for several decades and the expert judgement is that there are no technical barriers to their construction to very high standards of integrity. Although there has been recent progress in Finland and the United States, no repository is yet operational. So the disposal of high-level waste remains, at present, a challenge to the sustainable development of nuclear energy.

Research and development on advanced fuel cycles and for the treatment of waste promise to reduce the volume of waste requiring isolation and the time this waste must remain isolated. Yet, the results of these investigations will not likely be available for several decades.

Social aspects

Technical infrastructure and employment

It is people who create and maintain any technology. In this respect nuclear energy has certain special characteristics, based as it is on major 20th century scientific and technological developments. Much of the high cost of nuclear facilities is embodied in science and technology, essential for their continued safety and future development. The nuclear industry also employs a high proportion of skilled, graduate staff relative to most other major energy and manufacturing industries. They are important, though vulnerable, social capital as well as a base for continuous improvement in performance within the industry (and in certain respects beyond it).

The sustainability of nuclear power depends upon the complex and expensive infrastructure that underlies this social capital, which, if it were lost, might be hard to replace either cheaply or quickly.

Spin-offs

Maintaining and improving the technical and intellectual infrastructure to support nuclear energy provides numerous spin-off benefits for a society. As with other very advanced technologies, nuclear energy has historically played a very important part in the development of new materials, techniques and skills, which have spun off into other sectors, e.g. medicine, manufacturing, public health and agriculture, with consequent economic benefit.

Social concerns

All energy technologies have a tendency to create social concern, even conflict. In the case of nuclear energy, concern has focused on questions of safety, proliferation and waste disposal. Coal has its own profound history of conflict and social division, as, on an international scale, has oil. The exploitation even of renewable energies has come under recent scrutiny and opposition arising from their visual intrusiveness and large-scale demands on land area. Large hydro projects have raised opposition on a global scale because of the social and environmental impacts of the massive inundations involved.

The risks from nuclear power plants

As with any other major industrial installation, and despite all precautions, nuclear power plants present risks to workers, to people living in the immediate vicinity, and, in the case of a very severe accident such as that at Chernobyl, to people living very far away. Usually, these risks are analysed in terms of radiological consequences as a result of (1) normal operation and (2) from accidents. Given the highly qualified personnel, sound operational practices, and strict regulatory oversight, nuclear energy from an industrial safety viewpoint, is relatively safe. For example, data from the United States for 2000 reveals an accident rate at nuclear power plants of 0.26 accidents per 200 000 worker-hours compared with a country-wide workplace average of 3.0.

Risks from normal operation

Radiological risks from normal operation arise from the day-to-day discharges both to air and to water of radioactive material. Such discharges are strictly governed in all OECD countries by authorisations from the relevant regulatory authorities. They are also the subject of international understandings, such as the OSPAR *Convention for the Protection of the Marine Environment of the North-East Atlantic*, of which the most recent Ministerial agreement, reached at Sintra, Portugal in 1998, called for the reduction of additional radioactive burdens from marine discharges, emissions and losses to be "close to zero" by 2020.

In principle, discharges of this kind can affect the human food chain (via shellfish for example) and so represent a hazard to the public. Estimates can be made of the chances of people being adversely impacted by low-level discharges stemming from living near nuclear plants or eating very large quantities of seafood. Where such estimates have been made they indicate a risk that is considerably less than one in 1 000 000 per annum to any of the people theoretically at risk.

Risks from accidents

The risks from accidents are much harder to estimate, partly because nuclear accidents of all kinds have been very rare, and partly because the consequences could vary over so wide a range.

Studies have been conducted to estimate the chances of the protective barriers built into modern power plants failing in the course of an accident, causing radioactive releases of various hypothetical sizes. The calculations typically show that the chances of any such accident at a modern reactor, one that has been upgraded in keeping with the lessons of Three Mile Island and Chernobyl, are less than 1 in 100 000 per annum. Designs for reactors planned for future deployment have more explicitly considered severe accidents in their design and calculations indicate the likelihood of a severe accident being even lower, on the order of 1 in 1 000 000 per annum. In considering these figures, however, it needs to be borne in mind that the effects of a major nuclear accident may have considerable impacts including the deaths of individuals (which may occur decades after the accident), the loss of use of land for living or farming, and the loss of large amounts of electricity generating capacity, all of which would have serious consequences for society.

In considering the potential risks of nuclear energy it is necessary to regard it in the context of meeting increasing societal energy demands. Looking at the potential risks from different energy sources shows that the potential environmental and public health burdens from nuclear energy are smaller than those associated with fossil fuels (see Figure 9.6).

Taking a wider view, one should also consider the more intangible risks such as placing undue reliance on fuels imported from distant countries that could cause significant economic disruption should those supplies be interrupted. Additionally, fossil energy sources, which are increasingly believed to contribute to global warming, could, in several centuries, have serious consequences such as parts of seaboard cities becoming uninhabitable.

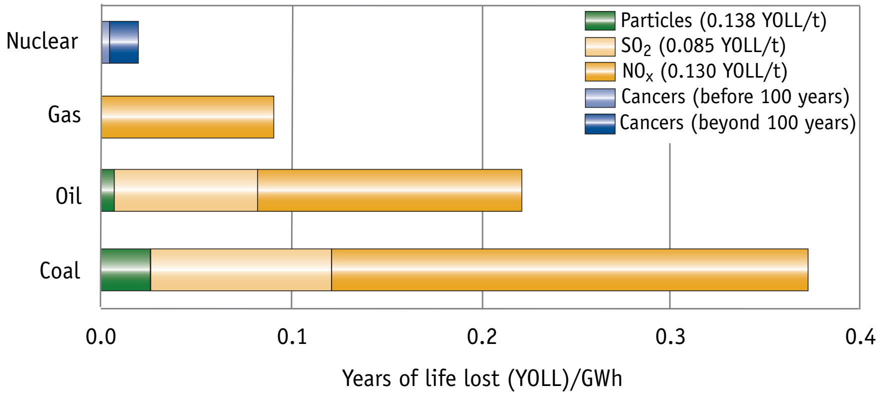
Nuclear installations of all kinds are among the numerous potential targets for terrorist activity. However, unlike many other industrial activities, nuclear power plants take active measures in response to this potential threat, though absolute security can never be guaranteed. It is very difficult to quantify or even describe risks of this kind, but nuclear power stations, because of their inherent robustness, built-in protection, security forces and generally remote locations, are comparatively unattractive and unrewarding targets for a terrorist attack.

Ultimately, only individuals can judge the extent to which particular risks concern them. Comparative risk figures can therefore have only a limited significance, but they are nonetheless a way of putting matters into proportion, and of reminding ourselves that the world is a risky place, and that all the available means for electricity production carry risks.

The social element in sustainable development can only be met by addressing public concerns and gaining public confidence. It will be important to enable the public to put the social, ethical and political issues raised by nuclear power into a perspective with the different, but not altogether dissimilar, issues raised by the alternative sources of electricity generation.

Generally, when viewed by applying the three dimensions of sustainable development, nuclear energy can be seen to have potential to meet a significant part of the world's future energy needs while meeting many of the objectives of sustainable development. The overall political trade-offs between the three dimensions of sustainability will differ from country to country, and will affect both the decisions taken and the means of addressing public concerns and securing public confidence.

Figure 9.6: Comparison of health risks for energy systems



Source: "Comparative Assessment of Emissions from Energy Systems", *IAEA Bulletin*, 41/1/1999.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- Projections of future world energy demand, see 1.4, 9.1 and 9.2.
- Projections of uranium resources and demand, see 9.3.
- Nuclear energy in a sustainable development context, see 9.4 and 9.5.
- The role of nuclear energy with respect to climate change, see 9.6 and 9.7.
- The broad impacts of nuclear energy, see 9.8.
- Spin-off technologies developed through nuclear activities, see 9.9.
- The education and supply of qualified personnel, see 9.10.

Chapter 10

The Future of Nuclear Energy

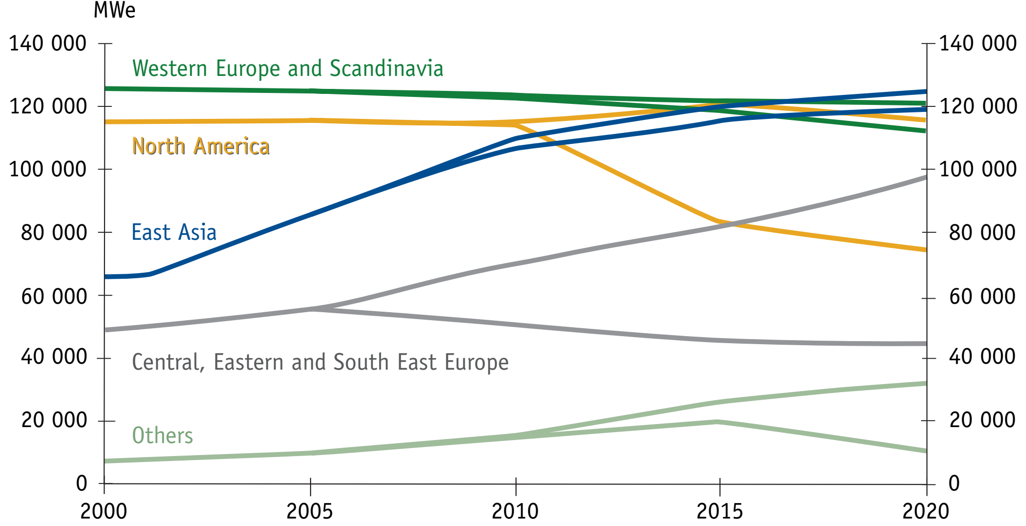
The future of nuclear energy depends on the interplay between four factors – growth in energy demand, cost-competitiveness with other fuel sources, environmental considerations, and questions of public attitude and perception.

Depending on the satisfactory resolution of these factors and on technical advances, many new and enlarged applications of nuclear energy can be envisaged, including hydrogen production, seawater desalination and expanded production of isotopes for medical purposes.

Much research is under way to develop these potential applications and to improve the performance of nuclear energy systems.

At the end of 2000, world nuclear generating capacity represented about 17% of the world's electricity. Most of this capacity had, however, already been installed by 1990 (see Figure 1.1). Since then, though new plants continue to come online, there have also been withdrawals due to the ageing of existing plants, and very little net capacity has been added. Capacity forecasts by national governments suggest a fairly stable picture up to and perhaps beyond 2020, with projections of installed nuclear capacity ranging between 334 and 466 GWe, compared with 362 GWe at present. Figure 10.1 shows, however, the considerable regional variations implicit in these projections. In Western Europe at least, it will only be a matter of time before a gradual

Figure 10.1: Projected installed nuclear generating capacity to 2020 (low and high projections)



Source: NEA. *Uranium 2001: Resources, Production and Demand* (Paris: OECD, 2002.

Where will future nuclear plants be built?

- As of January 2003, there were 33 reactors under construction in 10 countries: India (8), China (6), Republic of Korea (4), Ukraine (4), Japan (3), Islamic Republic of Iran (2), Russia (2), Slovak Republic (2), Argentina (1) and Romania (1).
- There are 26 reactors firmly committed or planned for construction in OECD countries, 24 of which are in Japan and the Republic of Korea.
- When its parliament voted on 24 May 2002, Finland became the first country in Western Europe in over ten years to authorise the construction of a new nuclear reactor.
- Though not yet formally committed, the United States government is working with utilities to plan for new nuclear power plants, with construction beginning before 2005.
- Conversely, Belgium and Germany have committed to phasing out nuclear power over the next several years.

reduction in installed capacity begins to take place, based on present trends and despite the increasing longevity of the existing stock. The Far East, by contrast, is experiencing strong growth that is projected to continue, with China, the Republic of Korea and Japan all building multiple plants. Eastern Europe – particularly Russia and Ukraine – are experiencing strong growth, though planned retirements of older plants in other countries will offset these gains. The outlook in North America is uncertain with a significant re-evaluation of nuclear energy under way, the results of which remain unclear.

For reasons discussed earlier in this book, the future course of nuclear energy depends on factors that are particularly hard to predict, including public attitudes. If the equation consisted only of economic factors with no change in current attitudes, nuclear energy's characteristic high construction and low generating costs could lead, in a deregulated and highly competitive market, to a situation where existing plants are run profitably to exhaustion and not replaced. However, increasing world energy demand will continue to require decisions on building new power plants and this limiting scenario could, then, be shifted positively or negatively, by other factors such as:

- environmental considerations, depending on the extent that nuclear energy is seen to be beneficial in meeting greenhouse gas reduction targets;
- concerns about security of fuel supplies;
- concerns about the proliferation of nuclear weapons;
- the cost-competitiveness of new nuclear power plants with other fuel sources, including "renewable" energy sources;
- public attitudes towards the safety of nuclear energy and proposed waste disposal plans;
- the extent that advanced technologies can alter the relative competitiveness of the various energy sources.

Alternative uses of nuclear energy

So far, nuclear energy has been applied almost exclusively to the production of electricity. There are other potential uses and the extent to which these other uses become important will also influence the future of nuclear energy.

Hydrogen production

Hydrogen is already an important industrial commodity with an annual world consumption of some 45 million tonnes. Its uses are primarily in the production of chemicals, fertiliser and in oil refining, where demand for it is expected to increase significantly as high quality oil stocks diminish and cleaner fuels are mandated.

Hydrogen also has a large potential as a "clean" fuel in its own right. A great deal of research is currently taking place on the possibility of hydrogen replacing carbon fuels used in motor vehicles – currently the fastest expanding component in world energy demand. If this were to prove successful, the demand for hydrogen would expand dramatically. However, its production currently involves the use of natural gas, itself a carbon-emitter. Before it can pass the "sustainability" test, and notwithstanding its inexhaustible availability, more economic methods for producing hydrogen directly from water without using carbon fuels are required.

Nuclear energy could become an important source of "sustainable" hydrogen either through producing the necessary high-temperature heat, or through electricity. The NEA report on *Nuclear Production of Hydrogen* (2001) concluded that:

> *Nuclear production of hydrogen holds the potential to significantly contribute to the global energy supply of the 21st century. Production of hydrogen through water-cracking and through nuclear-assisted conversion of fossil feedstock is technically feasible and could provide energy in a way that would diminish global greenhouse gas production.*

Several types of high-temperature reactor could provide the near-1 000 °C temperatures necessary for the direct production of hydrogen, such as high-temperature gas reactors or molten metal reactors. Research and development into the use of nuclear energy to produce hydrogen is being conducted in a number of countries and through several international agencies, including the NEA and the IAEA, which are tracking and supporting this potentially important future role for nuclear energy.

Seawater desalination

Fresh water of the requisite quality is essential to life. In many parts of the world, particularly in

Africa, Asia and the Middle East, there is increasing difficulty in meeting growing demands from agriculture, industry, urban development and growing population.

The purification of seawater requires considerable heat, and nuclear-powered desalination plants are already operating in Japan and the United States. These mainly provide pure water for onsite uses rather than large-scale consumption. They have nevertheless successfully demonstrated that, as the demand for desalination grows, nuclear energy is a viable alternative to fossil fuels as the heat source. Argentina, China, India, Morocco, Pakistan, the Republic of Korea, and the Russian Federation have shown interest in this possibility.

Process and district heating

One application of nuclear energy that has existed from the outset and has the potential to grow in future is to use reactor heat to produce hot water or steam for industrial or residential heating purposes – usually, but not necessarily, in conjunction with the generation of electricity. Significant experience in this use of nuclear energy has been gained in Bulgaria, Canada, China, Germany, Hungary, Japan, Kazakhstan, the Russian Federation, the Slovak Republic, Switzerland, Ukraine and the United States. About 1% of the heat generated in nuclear reactors worldwide is applied in this way, and the development of small or medium-sized reactors especially for heat production could stimulate further growth. This possibility is being pursued in China and the Russian Federation.

Isotope production

Both radioactive and stable isotopes are very widely used, particularly in medicine, industry, agriculture, food processing and research. In 2000, isotopes were produced by more than 70 research and power reactors in over 60 countries.

In many applications, isotopes have no substitute and in most, they are more effective and cheaper than alternatives. So far they have principally been produced as by-products of research activity, but a number of purpose-built isotope production reactors are now planned or under construction. A brief look at representative uses will illustrate their importance and diversity.

At the beginning of the 21st century over 1.2 billion people do not have access to safe drinking water. *Ministerial Declaration, International Conference on Fresh Water, Bonn, December 2001.*

Medical applications

Isotopes have been routinely used in medicine for over thirty years, and are now applied in over 30 million critical medical procedures annually worldwide. They are used extensively in the detection of tumours and a wide variety of other ailments (e.g. cardiological diseases) through diagnostic gamma-imaging cameras. The primary isotope for these purposes is reactor-produced technetium-99.

In therapy, the implantation in the body of sealed radioactive sources (brachytherapy) has been used to treat cancers of the cervix, uterus, breasts, lung, pancreas, prostate and oesophagus. The important isotopes for this purpose are reactor-produced iodine (^{125}I) and palladium (^{103}Pd).

A positron emission tomography (PET) imaging device used in medical applications.

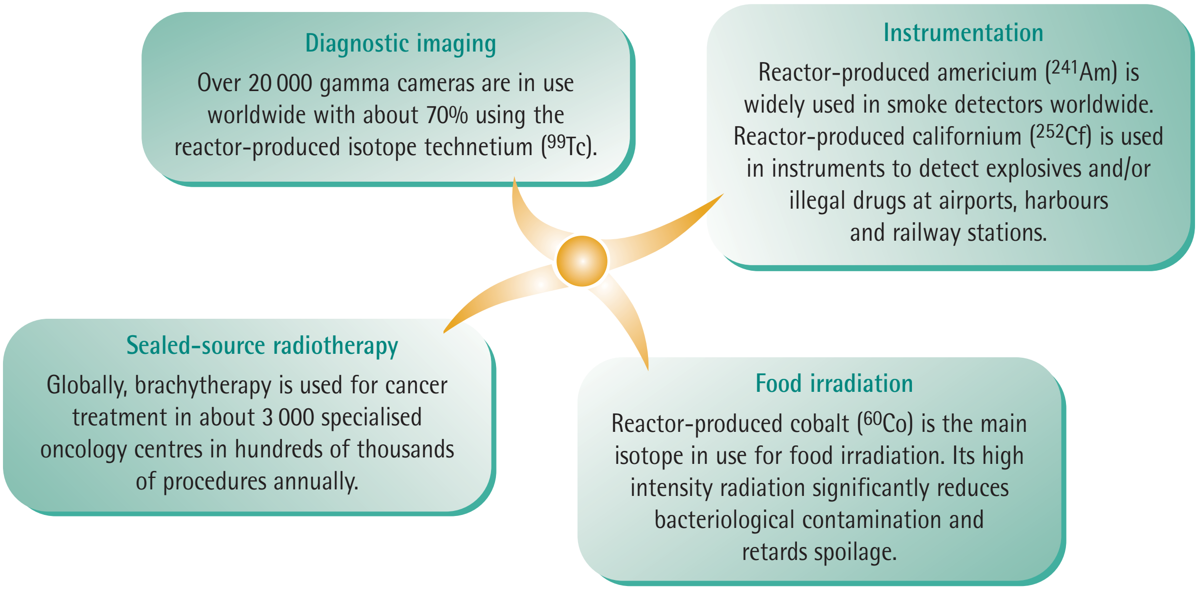


Figure 10.2: Various uses of reactor-produced isotopes

Diagnostic imaging

Over 20 000 gamma cameras are in use worldwide with about 70% using the reactor-produced isotope technetium (^{99}Tc).

Instrumentation

Reactor-produced americium (^{241}Am) is widely used in smoke detectors worldwide. Reactor-produced californium (^{252}Cf) is used in instruments to detect explosives and/or illegal drugs at airports, harbours and railway stations.

Sealed-source radiotherapy

Globally, brachytherapy is used for cancer treatment in about 3 000 specialised oncology centres in hundreds of thousands of procedures annually.

Food irradiation

Reactor-produced cobalt (^{60}Co) is the main isotope in use for food irradiation. Its high intensity radiation significantly reduces bacteriological contamination and retards spoilage.

Agriculture and industry

Industry is a large user of isotopes, principally in instrumentation and process equipment. The applications include analytical and security instrumentation, pollution measurement, physical measurement, food irradiation and non-destructive testing. Food irradiation has been successfully applied to spices, fruit, grains, meat, fish and poultry-meat. Among others, the World Health Organisation, the UN Food and Agriculture Organisation and the US Food and Drug Administration have endorsed it; the number of countries allowing it as a means to improve the safety and nutritional value of food is increasing.

Trends in isotope uses

Trends in isotope uses are not easily defined as they vary from sector to sector as well as from region to region, with some isotopes declining in importance while others increase. In the medical field, as a whole, isotopes are increasingly used in an ever-widening range of applications. Trends vary, however, for each specific application. For example, remotely controlled cobalt therapy is projected to progressively decrease while the use of isotopes in brachytherapy is projected to sharply increase. The development of new applications, such as palliative care, create additional demand for isotopes already in use as well as demand for new isotopes.

For industrial applications as a whole, the demand for isotopes is relatively stable. However, if food irradiation becomes widespread it would create a demand for large volumes of radioactive cobalt.

Given that many of these isotopes are capable of being produced in accelerators, it is difficult to predict how changes in isotope demand will be reflected as a need for new reactor-based production capability.

Research and development

Research and development (R&D), which has throughout its existence been central to all applications of nuclear energy, has been the cause of many important advances in human knowledge. Among many areas of R&D interest, three dominant themes are now apparent: advanced reactors and fuel cycles; advanced treatments for waste; and support for safe operation. Research is conducted by academics, governments (including regulatory authorities) and industries, either singly or in combination, and with a growing emphasis on international collaboration in nuclear R&D.

Advanced reactors and fuel cycles

Light water reactors (LWR) are now essentially mature technologies. Consequently, in the near term, new reactor designs under development represent an evolution of existing concepts, in order to improve safety, operational economy and flexibility. Several improved designs likely to be ready for commercial development by or before 2015 include:

- new boiling water reactor (BWR) designs, including the advanced boiling water reactor (ABWR), two of which have already been built in Japan, plus the BWR 90+ and the simplified water reactor (SWR) 1000;
- advanced pressurised water reactors, such as the AP600, already approved by regulatory authorities in the United States, with its upsized 1 000 MWe version now under regulatory review, plus the European pressurised water reactor (EPR) and the "international reactor, innovative and secure" (IRIS);
- gas-cooled designs, including the pebble bed modular reactor (PBMR) and the gas turbine, modular helium reactor.

For the long term, the focus is on more innovative nuclear energy technologies and fuel cycles. Concepts under investigation include liquid-metal reactors, high-temperature reactors, reactors that use thorium as fuel, and improved recycling technologies to better utilise the uranium and plutonium resources. These advanced technologies offer the promise to greatly improve the sustainability of nuclear energy. For example, fast breeder reactors can, in principle, improve the effectiveness of using uranium resources by about 50-fold (see table 10.1).

Two important international projects, described hereafter, are seeking to make advancements in nuclear energy systems and fuel cycles.

Table 10.1: Effect of technology advances on resource availability[1]

Reactor/fuel cycle	Years of electricity production	
	Conventional uranium & thorium resources only	Total uranium & thorium resources
Current fuel cycle (LWR, once-through)	326	8 350
Recycling fuel cycle (plutonium only, one recycle)	366	9 410
Light water and fast reactor mixed with recycling	488	12 500
Pure fast reactor fuel cycle with recycling	10 000	250 000
Advanced thorium/uranium fuel cycle with recycling	17 000	35 500

1. Assumes 1999 world electricity generation from *Key World Energy Statistics* (Paris: IEA, 2001).

Source: "Nuclear Fuel Resources: Enough to Last?", *NEA News*, No. 20.2 (2002).

Generation IV International Forum

This effort was started at the end of 2000 as a collaboration of interested governments, industry and the research community in an attempt to develop and demonstrate one or more advanced nuclear systems that could be commercially deployed by 2030 ("fourth generation" nuclear systems). The objective is to make advances over existing systems in the areas of economy; safety and reliability; sustainability; and proliferation resistance and physical protection. At the beginning of 2003, the members of the group were Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the United Kingdom and the United States.

In October 2002, six nuclear energy system concepts were selected to be the focus for collaborative R&D. The concepts include: a sodium-cooled fast reactor, a very-high-temperature reactor, a supercritical-water-cooled reactor, a lead-cooled fast reactor, a gas-cooled fast reactor and a molten salt reactor. All but one of these concepts involve recycling spent nuclear fuel.

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

This international collaboration, initiated and supported by the IAEA, was launched in 2001 with the stated objective of supporting the safe, sustainable, economic and proliferation-resistant use of nuclear technology to meet the global energy needs of the 21st century. At the beginning of 2002 the members of the initiative included the European Commission, Argentina, Canada, China, Germany, India, the Netherlands, the Russian Federation, Spain, Switzerland and Turkey.

Advanced treatment of waste

A fairly new approach that has the potential to change the nature of the wastes that will require geological disposal is partitioning and transmutation (P&T). This process involves the transmutation of long-lived radionuclides into shorter-lived ones through neutron capture or fission, thereby eliminating those parts of high-level waste that contribute most to its heat generation and radioactivity. Partitioning and

NEA Nuclear Safety R&D Projects (as of January 2003):

The **CABRI Water Loop Project** investigates the ability of high-burnup fuel to withstand sharp power peaks.

The **FIRE Project** aims to improve knowledge relating to fire events in nuclear environments.

The **Halden Reactor Project** conducts experiments related to improving fuels and operational safety.

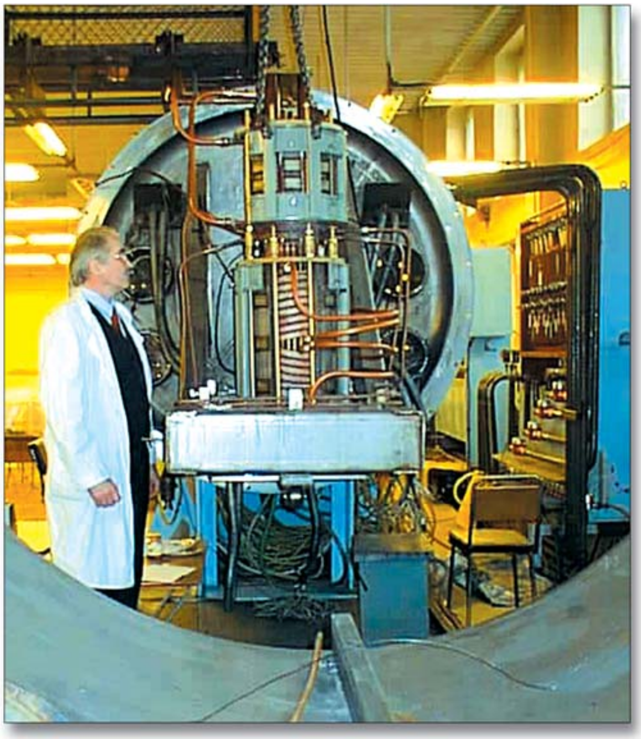
The **International Common Cause Failure Data Exchange** seeks to improve knowledge on important safety system components.

The **MASCA Project** investigates reactor vessel phenomena during a severe accident.

The **Melt Coolability and Concrete Interaction (MCCI) Project** addresses phenomena related to a hypothetical molten core.

The **OECD Pipe Failure Data Exchange (OPDE) Project** investigates the root causes of pipe failures.

The **SETH Project** involves experiments related to nuclear accident management.



View of the RASPLAV cylindrical wall facility during the preparation for the MASCA experimental programme.

transmutation therefore has the potential to reduce the time that waste needs to be kept isolated from several thousand to several hundreds of years – i.e. to periods that are within human experience, thereby reducing the uncertainties associated with predicting repository performance. However, sufficient conversion of the longer-lived isotopes to achieve these aims would require many stages of P&T and a fully developed reprocessing fuel cycle. Therefore, solutions along these lines seem a long way off.

The approaches to P&T that are being researched vary according to each country's fuel cycle practices and policies, but are similar enough to encourage collaboration. The main lines of the research are advanced separation technologies, to better remove the fission products and transuranic elements from spent fuel, and the use of accelerator-driven and reactor systems for transmutation.

Numerous countries including Belgium, China, France, Italy, Russia and the United States are investigating these research areas. Small-scale collaborative efforts currently involve France, Japan, the Republic of Korea, the United States and the European Commission.

Nuclear safety R&D

In addition to the R&D aimed at making advances in nuclear technologies, there have always been and continue to be both national and international programmes to support the safe operation of nuclear power plants. At the international level, the NEA manages a number of research projects, for example the Halden Reactor Project in Norway. This project has been in operation for over 40 years and is supported by approximately 100 organisations in 20 countries. Research is conducted on, among other things, fuels and materials, the improvement of plant performance and operational safety.

Other international R&D

The European Union, through the European Commission and its Joint Research Centre (JRC), sponsors and conducts numerous research projects in support of its member states' programmes. Research related to nuclear energy is conducted at four of the seven JRC centres. Thus, the Institute for Reference Materials and Measurements (IRMM) at Geel, Belgium, conducts measurements of neutron interactions with materials, including high resolution cross-section measurements. The Institute for Transuranium Elements (ITU) at Karlsruhe, Germany, conducts research related to alpha-immunotherapy, basic actinide research, safety of nuclear fuel, spent fuel characterisation, and partitioning and transmutation. The Institute for Energy (IE) at Petten, the Netherlands, conducts research related to nuclear safety, development of new nuclear energy systems and nuclear medicine. Finally, the Institute for the Protection and Security of the Citizen (IPSC) at Ispra, Italy, conducts research related to non-proliferation and nuclear safeguards.

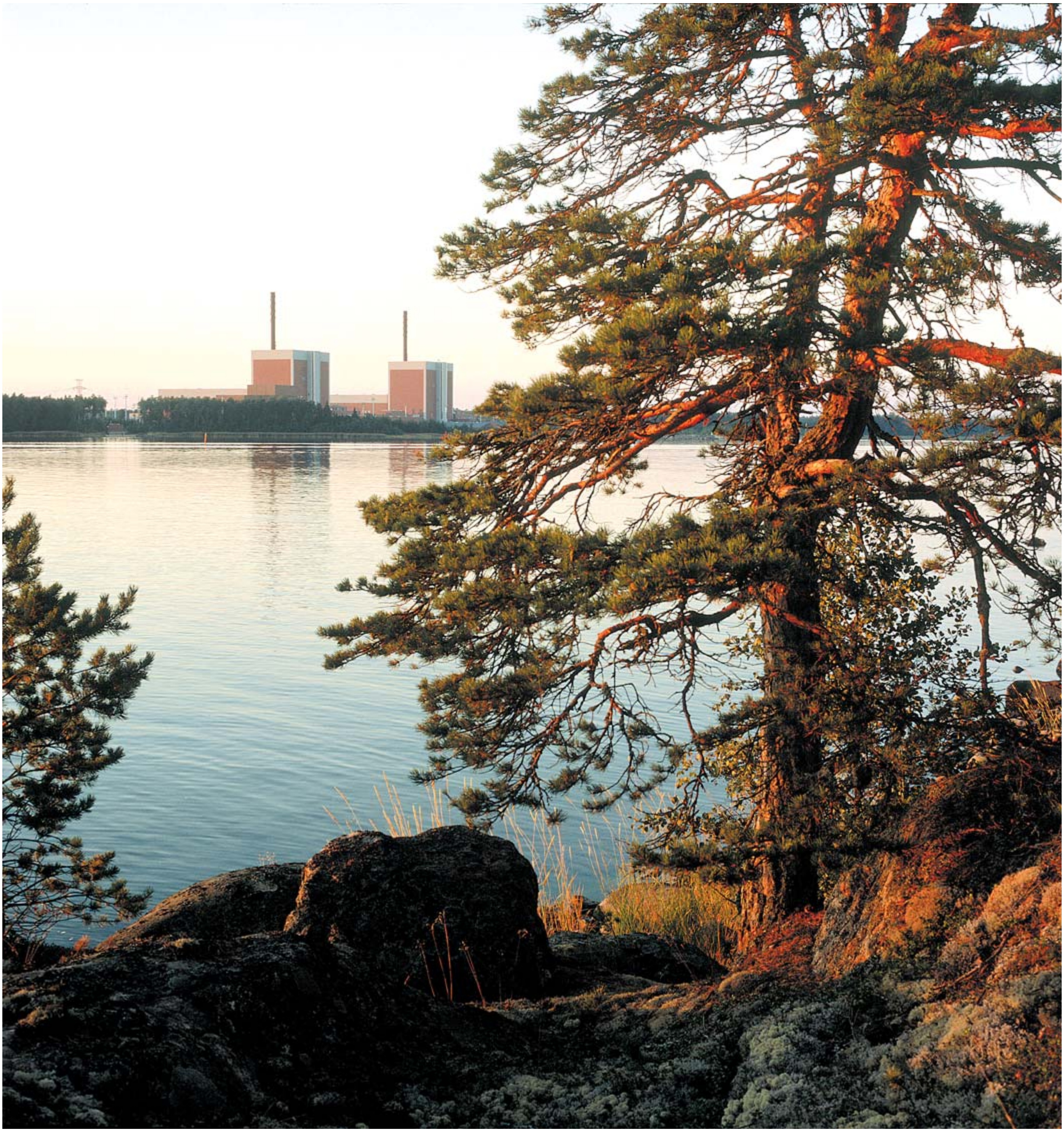
The IAEA also sponsors other nuclear R&D through its Co-ordinated Research Programme in nuclear energy, radioactive waste safety, waste technology and safeguards.

Partitioning is the separation of undesirable elements, i.e. minor actinides and long-lived fission products, from spent nuclear fuel. **Transmutation** is the changing of one element into another through neutron capture or fission. It can be used to transform these undesirable elements into short-lived or stable elements.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- Projections of future nuclear energy capacities and related uranium resources and demand, see 1.1 and 9.3.
- Hydrogen as an energy carrier and nuclear energy as a source of hydrogen, see 10.1 through 10.4.
- Alternative uses of nuclear energy including desalination and process heat, see 10.4.
- Production and uses of isotopes, see 10.5.
- Advanced reactor types, see 10.6 through 10.8.
- Several international nuclear energy research programmes including the Generation IV International Forum and INPRO as well as other interesting links, see 10.9 and 10.10.
- Advanced treatments of high-level waste, see 10.11.



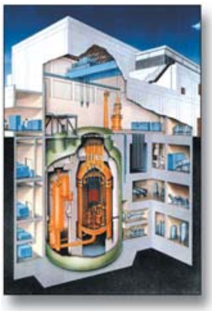
Conclusions

Nuclear energy is a technically complex source of energy that remains unique among energy sources as a result of a number of factors. In relation to nuclear energy in its current form, it has been shown that:

- Nuclear energy is a major source of energy in the world, producing about 17% of the world's electricity.
- The large majority of reactors use ordinary water as coolant and moderator, uranium as fuel and a once-through fuel cycle.
- The disposal of low-level waste and intermediate-level waste is a mature practice, but the disposal of high-level waste is not yet carried out; public opposition is the main constraint although progress towards implementing solutions is beginning to be made.
- Very high levels of safety are essential to nuclear energy deployment, though some degree of risk remains.
- An effective system of radiological protection has been developed based on three principles: justification, optimisation and limitation.
- Existing power plants are generally economically competitive, even in deregulated markets, but decisions to build new power plants may depend on public policy factors.
- A framework of national laws and international agreements governs virtually all aspects of the use of nuclear energy, indicating larger governmental involvement than for other energy sources.
- Nuclear energy has certain advantages over other energy sources: carbon-free and air-pollution-free generation of electricity as well as security of supply.
- Evolutionary and revolutionary advances in technology are being pursued to develop new applications of nuclear energy and to improve the performance of nuclear energy systems.

In light of these characteristics, nuclear energy is at something of a crossroad at the beginning of the second nuclear century as it undergoes a thorough review by governments, the public and industry. Decision makers are faced with the difficulty of how to meet the continued growth in world energy demand while minimising the environmental impacts of energy production. They must do so while accounting for public attitudes, the cost and competitiveness of the various energy sources and public policy objectives such as security of supply and non-proliferation. How they resolve the tension between these sometimes-conflicting factors will ultimately define the extent of nuclear energy's use worldwide. How soon promising advances in the state of the art can influence these decisions will also play a significant role.

If a case cannot be satisfactorily made that nuclear energy is economically competitive, safe and that there are acceptable solutions for its waste, then nuclear energy is likely to decline, at first slowly, in importance. Yet, if it can be demonstrated to the satisfaction of the public that nuclear energy does address these concerns, it is likely that there will be strong new growth in nuclear power.



Glossary

A

ALARA

Acronym for "as low as reasonably achievable". Making every reasonable effort to minimise exposure to ionising radiation as far below regulatory or legal dose limits with economic and social considerations taken into account.

Alpha particle

A positively charged particle emitted from the nucleus of an atom during radioactive decay. Alpha particles consist of two protons and two neutrons.

B

Becquerel

The SI unit of measure of radioactive decay equal to one disintegration of an atom per second. Because it is a very small unit, in practice, Gigabecquerel (GBq) or Terabecquerel (TBq) are the more common units.

Beta particle

A particle emitted from an atom during radioactive decay. Beta particles may be either electrons, negatively charged, or positrons, positively charged.

Boiling water reactor (BWR)

A very common type of light water reactor in use worldwide. Ordinary water, used as both coolant and moderator, is allowed to boil in the reactor core. The steam produced is then used to directly generate electricity.

Breeder reactor

A nuclear reactor designed to produce more fuel than it consumes. Typically these have fertile material placed in and around the reactor core in order to use neutrons produced during fission to transmute the fertile material into fissile material. For example, uranium-238 can be placed around a fast reactor and it will undergo transmutation to produce plutonium-239 which can then be recycled and used as fuel in the reactor.

C

CANDU reactor

CANDU is an acronym meaning Canadian deuterium uranium reactor. This type of reactor uses "heavy" water, i.e. deuterium oxide, as the coolant and moderator. The use of heavy water permits the use of natural uranium as the reactor fuel eliminating the need for enrichment of the uranium.

Closed fuel cycle

A fuel cycle that reprocesses spent fuel to recycle the unused fissile material. Once removed from the reactor the spent fuel is chemically processed to remove the uranium and plutonium which can then be used to make new reactor fuel. As practised today, only the recovered plutonium is recycled, to make mixed-oxide fuel (MOX). Because of the buildup of plutonium isotopes that are unable to fission in the thermal neutron spectrum of a light water reactor and the buildup of undesirable isotopes, especially curium, the plutonium can only be recycled two or three times before it must be managed as a waste similar to the once-through cycle. Using recycled fissile materials in a fast reactor eliminates this limitation.

Control rods

Control rods are made of materials which absorb neutrons, for example boron, silver, indium, cadmium and hafnium. They are introduced into the reactor to reduce the number of neutrons and thus stop the fission process when required, or during operation to regulate the level and spatial distribution of power in the reactor.

Conversion

The chemical process used to turn solid uranium oxide received from a uranium mill into volatile uranium hexafluoride, which is a gas at certain temperatures and pressures, and therefore suitable for the enrichment process.

Coolant

A coolant absorbs and removes the heat produced by nuclear fission and maintains the temperature of the fuel within acceptable limits. The absorbed heat can then be applied so as to drive electricity-generating turbines. If water is used as the coolant, the steam it produces when heated can be transferred directly to the turbines; alternatively, it, or any other coolant, can be passed through a heat-exchanger which will remove the heat and produce the necessary steam. Other possible coolants are gases like helium, or liquefied metals such as sodium or lead and bismuth. A coolant can also be a moderator; water is used in this dual way in most reactors.

Cosmic radiation

Radiation that originates in space and is generated through various processes, including the birth and death of stars. When cosmic radiation interacts with the nucleus of an atom it produces cosmogenic radionuclides with half-lives that range from thousands to millions of years. They can exist in the earth's atmosphere, on the solid surface of the earth and can also be produced in meteorites and other extraterrestrial materials, which then fall to earth. Examples include tritium (^3H), hydrogen with two extra neutrons, which forms part of all water on earth (12.3-year half-life) and carbon-14 (5730-year half-life), which exist in every living thing.

Criticality

The state of a nuclear reactor when enough neutrons are created by fission to make up for those lost by leakage or absorption such that the number of neutrons produced in fission remains constant.

Critical mass

The amount of fissionable material needed to maintain a fission chain reaction for a given set of conditions, e.g. shape of the fissionable material, amount and type of moderator or reflector.

D

Decommissioning

Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a nuclear installation. Decommissioning typically involves several stages: closeout, decontamination and dismantling, and demolition and site clearance.

Defence in depth

A design and operating philosophy used with regard to nuclear facilities that uses multiple layers of protection to prevent and mitigate the consequences of accidents. It includes the use of physical and administrative controls, physical barriers, redundant safety functions and emergency response measures.

Depleted uranium

Uranium having less than the natural occurring isotopic concentration of uranium-235 of about 0.711%. Depleted uranium is produced as a by-product of the enrichment process.

Design basis accidents

The range of conditions and events (e.g. rupture of piping, coolant pump failure) taken explicitly into account in the design of a nuclear facility such that the facility can withstand them without exceeding authorised safety limits. The ability to withstand design basis accidents presumes the functioning of engineered safety systems.

Deterministic effects

Deterministic effects are those effects that are sure to occur (e.g. measurable changes in blood) should a radiation exposure exceed the threshold for that effect. The magnitude of the effect is proportional to the exposure above the threshold.

Deterministic safety approach

The deterministic safety approach is a method of assessing the safety of a nuclear power plant using a defined set of initiating events, "design basis events". The design basis events are chosen to encompass a range of realistic possible initiating events that could challenge the safety of the plant. Examples include loss-of-coolant accidents, control rod ejection (for a PWR), control rod drop (for a BWR) and steam line break. Engineering analysis is used to predict the response of the plant and its safety systems to the design basis events and to verify that this response remains within prescribed regulatory limits.

Deuterium

A stable isotope of hydrogen having one proton and one neutron in its nucleus compared with the one proton in the nucleus of ordinary hydrogen.

Discount rate

The discount rate is an important element in economic analysis and the suitability of an economic decision can change depending on the value of the discount rate. In simple terms, if money can earn interest at a percentage rate per year (r) in real terms, then EUR 10 today will grow to $10(1+r)^t$ in t years time. Alternatively, an amount worth EUR 10 (t years in the future) can be discounted using the discount rate (d) such that it would be equivalent to EUR $10(1+d)^{-t}$ today.

Dry storage

Following an initial cooling period in a water-filled pool, spent fuel can be loaded into large, shielded casks in which natural air circulation maintains it at the required temperatures.

E

Electron volt

A unit of energy often used in the nuclear sciences. It represents a very small amount of energy that is equal to the amount of energy an electron would gain from the electric potential of one volt. Being so small it is often expressed in terms of mega-electron volts (MeV), that is a million (1×10^6 electron volts). An electron volt is equivalent to 1.602×10^{-19} joules.

Energy availability factor

The energy availability factor is a measure of operational performance of a nuclear reactor and is the percentage of the energy delivered to the electricity grid compared with the maximum energy generation that a reactor is capable of supplying.

Enriched uranium

Uranium in which the isotopic concentration of uranium-235 has been increased above the naturally occurring level of 0.711%.

Enrichment

The physical process of increasing the isotopic concentration of uranium-235 above the level found in natural uranium. Two processes are commercially used, gaseous diffusion and gas centrifugation.

Estimated additional resources – category I (EAR-I)

Uranium that is inferred to occur, based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposits' characteristics are considered to be inadequate to classify the resource as a "reasonably assured resource" (RAR). Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best-known parts of the deposit or in similar deposits.

Estimated additional resources – category II (EAR-II)

Uranium that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR-I.

External costs

External costs are costs that are imposed on society and the environment that are not accounted for in the cost to producers and consumers of energy and omitted when calculating the market price. In energy production these are typically waste disposal, environmental impact or population health effects.

F

Fast neutrons

Fast neutrons are defined as those with a high kinetic energy above about 0.1 eV but typically less than 1 000 000 eV (1 MeV). Fast neutrons can cause fission in fissile materials but the probabilities are less than that for thermal neutrons. However, the number of isotopes that can fission increases as the energy of the neutron increases.

Fertile materials

A fertile material in one that is capable of becoming fissile through the capture of a neutron(s), possibly followed by radioactive decay. Important examples are uranium-238, which can transform into fissile plutonium-239, and thorium-232, which can transform into fissile uranium-233.

Fissile materials

A fissile material is a material that is capable of fission after the capture of a thermal (slow) neutron. In practice, the most important fissile materials are uranium-233, uranium-235 and plutonium-239.

Fission

The process through which an atomic nucleus splits into two or more fragments accompanied by the release of neutrons and significant amounts of energy. It is possible for a heavy nucleus to spontaneously fission though it is usually due to the nucleus absorbing a neutron.

Fissionable materials

A fissionable material is a material that is capable of undergoing fission, normally differentiated from fissile in that it will fission if it captures a fast neutron. An example of a fissionable material is uranium-238.

Fission products

When a nucleus undergoes fission, it splits into two fragments, releases neutrons and a great deal of energy. The fragments are called fission products, which may be stable or unstable, i.e. radioactive.

Important fission product isotopes (in terms of their relative abundance and high radioactivity) are bromine, caesium, iodine, krypton, rubidium, strontium and xenon. They and their decay products form a significant component of nuclear waste.

Fuel

That part of the reactor that contains the fissionable material. Most reactors use uranium dioxide as their fuel. Most fuel for commercial reactors contains 2-5% uranium-235 (^{235}U) compared with the 0.711% found in nature; they are said to be enriched in ^{235}U. The remainder of the fuel, typically uranium-238 (^{238}U), can fission only when hit by fast neutrons; but when neutron capture occurs, it decays and gradually transforms into plutonium-239 (^{239}Pu). This fissile material is able to fission under the impact of thermal or fast neutrons, and its contribution to the energy output of the fuel gradually grows until it represents almost 30% of the power that is generated. Typically uranium dioxide powder is heated and pressed to produce dice-sized cylindrical pellets. These are loaded into hollow metal tubes (fuel rods) that are then bundled as fuel assemblies. Over 730 fuel assemblies, containing about 46 000 fuel rods would fuel a typical boiling water reactor. About 10% of reactors worldwide have been licensed to use mixed-oxide (MOX) fuel – a mixture of uranium dioxide and plutonium dioxide. The plutonium dioxide mainly results from the commercial recycling of spent fuel, though the Russian Federation and the United States are planning to use plutonium from surplus nuclear warheads. The production process for MOX is similar to that for uranium dioxide fuels. Other possible reactor fuels are thorium, which is a fertile material that produces fissile ^{233}U after neutron absorption and transmutation; uranium salts which can be used in liquid metal reactors; and other forms of uranium like uranium nitrides or uranium carbides.

Fuel cycle

The series of steps involved in creating, using and disposing of fuel for nuclear reactors. It can include mining and milling of uranium, conversion, enrichment, fabrication of fuel elements, use in a reactor, reprocessing and waste disposal. The precise steps defining a fuel cycle are dependent on a number of technological, economic and social factors. Early in the nuclear age, it was anticipated that fast breeder reactors would become the dominant design and a plutonium-based fuel cycle would exist. Thus the processes to produce and manage the nuclear fuel would be cyclical in the sense that the fuel would be recycled indefinitely. The term survives as the nomenclature for the processes used to produce and manage nuclear fuel even though the "once-through" fuel cycle does not recycle at all and the current "closed" fuel cycle does so only partially.

Fusion

Fusion is a nuclear reaction where light nuclei combine to form more massive nuclei with the release of energy. This process takes place continuously in the universe. In the core of the sun, at temperatures of 10-15 million degrees celsius, hydrogen is converted to helium, providing the energy that sustains life on earth.

G

Gamma rays

High-energy electromagnetic radiation, similar to X-rays, the difference being that they originate in the nucleus of an atom.

Gray

The SI unit of absorbed radiation dose equal to one joule per kilogram of absorbing medium.

H

Half-life

The time required for one-half of the atoms of a radioactive isotope to decay.

Heavy water

Water that contains significantly more deuterium atoms than normal water. Deuterium is an isotope of hydrogen that has one neutron and one proton compared with the one proton of ordinary hydrogen. Heavy water is used as a coolant and moderator in pressurised heavy water reactors (PHWRs) because its properties allow natural uranium to be used as fuel. Heavy water makes up less than 1% of water in nature and so must be separated and concentrated in dedicated plants for use in nuclear reactors.

Highly enriched uranium

Uranium enriched to at least 20% uranium-235.

High-level waste (HLW)

Radioactive waste is normally classified into a small number of categories to facilitate regulation of handling, storage and disposal based on the concentration of radioactive material it contains and the time for which it remains radioactive. The definitions of categories differ from country to country. However, in general, HLW contains long-lived radionuclides with high activity, which may also produce heat. It typically is concentrated as part of the process of reprocessing and solidified using vitrification to produce a glass-like substance suitable for interim storage and ultimately, disposal. Spent nuclear fuel that will not be reprocessed is included in this category. Geological disposal is foreseen for this type of waste.

I

Intermediate-level waste (ILW)

Radioactive waste is normally classified into a small number of categories to facilitate regulation of handling, storage and disposal based on the concentration of radioactive material it contains and the time for which it remains radioactive. The definitions of categories differ from country to country. However, in general, ILW needs specific shielding during handling and, depending on the specific content of long-lived radionuclides, it may need geological disposal or it may be suitable for surface or near-surface disposal.

Ion exchange

A chemical process that, in relation to nuclear energy, is often used in water purification or radioactive waste treatment. A waste solution containing ions (an atom or group of atoms with an electrical charge resulting from one or more electrons being added or removed) of waste is passed over an ion exchange medium where the waste ions are exchanged with acidic (H+) or basic (OH-) ions in the medium, thereby trapping the waste ions in the medium. Typically, the ion exchange medium is a granular resin. After a period of use the resin becomes saturated with waste ions and must be replaced. A saturated resin can either be recycled or disposed of. An ion exchange resin, in effect, concentrates the radioactive waste and thus the resins can become highly radioactive and be remotely handled.

Ionising radiation

When radiation, either particles or electromagnetic waves, has enough energy to remove the electrons of atoms with which it interacts from their orbits, causing the atoms to become charged, or ionised, it is called ionising radiation. The ions resulting from the interaction are capable of causing chemical changes damaging to human cells. Examples of ionising radiation include alpha particles, beta particles and gamma rays. If radiation, either particles or electromagnetic waves, has insufficient energy to ionise atoms, it is known as non-ionising radiation. Examples of non-ionising radiation include radio waves, light and microwaves.

Isotope

Different isotopes of an element have the same number of protons but different numbers of neutrons. For example, uranium-235 (^{235}U) and uranium-238 (^{238}U) are both isotopes of uranium with ^{235}U having 143 neutrons and ^{238}U, 146.

J

Justification

In the context of the nuclear industry, no public or worker exposure is allowed unless it is the result of an activity that has been "justified". Broadly, this means that risk incurred from the radiation exposure resulting from the activity is outweighed by the social benefit that the performance of the activity brings. The decision as to whether a particular activity is justified or not is principally a subjective value judgement, which uses as input scientific information regarding the absolute and relative values of the radiological risks involved. The decision regarding the justification of an activity will most likely be case-specific, and will be made by different levels of public official or public process, depending upon the situation and the national context.

K

Known conventional resources

The most readily accessible uranium resources; resources that are known to exist and are inexpensive to exploit using conventional mining techniques are classed as known conventional resources. These resources are categorised into two sub-groups: reasonably assured resources (RAR) and estimated additional resources – category I (EAR-I). Known conventional resources are reported in terms of the amount of uranium recoverable taking into account mining and milling process losses and are typically reported in cost categories of resources recoverable at less than USD 40/kilogram of uranium (kgU), USD 40-80/kgU and USD 80-130/kgU.

L

Light water reactor

A nuclear reactor type that is cooled and/or moderated by ordinary water, as opposed to heavy water.

Limitation

In the context of the nuclear industry, limitation is the process of assuring that planned, justified activities do not result in any individuals exceeding a pre-established regulatory level of exposure. The numerical level selected for the regulatory limit is a subjective value judgement that takes science and social judgement into account. The limit is fixed at a level above which regulatory authorities deem it to be socially justified to spend resources to reduce exposures.

Linear no-threshold hypothesis

There has been much scientific study of radiation exposures and their associated risks. However, at low exposure levels, biological science and the statistics of exposed populations have yet to conclusively identify whether there is or is not a risk. In the absence of scientific certainty as to the shape of the curve that relates the level of individual exposure to the probability of occurrence of a particular stochastic effect, it has been assumed that a linear curve, passing through zero, will not result in risks being underestimated. For this reason, it is standard practice to assume that any exposure, no matter how small, carries some risk, and to optimise radiological protection approaches accordingly.

Low enriched uranium

Uranium in which the isotopic concentration of uranium-235 has been increased above naturally occurring levels while remaining less than 20%. Typically, nuclear power reactors use low enriched uranium with 3-5% uranium-235.

Low-level waste (LLW)

Radioactive waste is normally classified into a small number of categories to facilitate regulation of handling, storage and disposal based on the concentration of radioactive material it contains and the time for which it remains radioactive. The definitions of categories differ from country to country. However, in general, LLW is a type of waste that does not need significant shielding for handling and, because of the absence of long-lived radionuclides, is suitable for surface or near-surface disposal. About 90% of the radioactive waste volume produced in the world each year is LLW.

M

Megawatt (MW)

The international unit of power that is equal to 1x10^6 watts. A megawatt electric (MW_e) refers to the electrical output from a generator. A megawatt thermal (MW_{th}) refers to the heat output from a nuclear reactor. The difference is a measure of the efficiency of the power generation process. Typically, the heat output of a nuclear reactor is three times its electrical output, thus a reactor with a thermal output of 2 700 MW may produce about 900 MW of electricity.

Milling

The process through which mined uranium ore is chemically treated to extract and purify the uranium. It also reduces the volume of material to be transported and handled in fuel manufacture. Reflecting its colour and consistency, the solid product (U_3O_8) of milling is known as yellowcake.

Mill tailings

The remnant of a metal-bearing ore consisting of finely ground rock and process liquid after some or all of the metal, such as uranium, has been extracted.

Mixed-oxide fuel (MOX)

MOX is the abbreviation for mixed-oxide fuel, a fuel for nuclear power plants that consists of a mixture of depleted uranium oxide and plutonium oxide.

Moderator

A moderator slows neutrons down to the thermal energy range so as to increase their efficiency in causing fission. The moderator must be a light material that will allow the neutrons to slow down efficiently without there being a high probability of them being absorbed. Usually, ordinary water is used; an alternative in use is graphite, a form of carbon.

N

Natural uranium

Uranium that has the same isotopic composition as found in nature, 99.2745% uranium-238 (^{238}U), 0.711% ^{235}U, and 0.0055% ^{234}U.

Neutron

An elementary particle with no electric charge and a mass slightly greater than a proton found in the nucleus of all atoms except hydrogen-1.

Nuclear reactor

A device that uses the nuclear fission process to produce energy. Though there are many types of reactors, certain features are inherent to all, including fuel, coolant, moderator (unless the reactor uses fast neutrons) and control rods. Other common features include a reflector to conserve escaping neutrons, shielding to protect personnel from radiation exposure, instrumentation to measure and control the reactor, and devices to protect the reactor.

Nuclear Suppliers Group (NSG)

The Nuclear Suppliers Group is a group of nuclear supplier countries, 39 as of October 2002, which work together to prevent the proliferation of nuclear weapons. These countries pursue the aims of the NSG through adherence to consensus guidelines concerning nuclear and nuclear-related exports and through the exchange of information.

Nuclear Suppliers Guidelines

The Nuclear Suppliers Guidelines are a set of principles and lists of materials, equipment and products that could be used for designing, manufacturing and testing nuclear weapons that have been developed by the Nuclear Suppliers Group. Two sets of guidelines have been developed: the Guidelines for the Export of Nuclear Material, Equipment and Technology and the Guidelines for Transfers of Nuclear-related Dual-use Equipment, Material and Related Technology.

Principles governing the use of the guidelines are:

- Suppliers should authorise transfers of identified items or related technology only upon formal governmental assurances from recipients explicitly excluding uses that would result in any nuclear explosive device.
- Suppliers should authorise transfers of identified items or related technology only when they are satisfied that the transfers would not contribute to the proliferation of nuclear weapons or other nuclear explosive devices.
- Suppliers should not be satisfied with an assurance from recipients if they have information or evidence, which leads them to believe that there is a risk that a transfer will contribute to nuclear weapons proliferation.

O

Once-through fuel cycle

A fuel cycle that does not recycle the spent fuel. Once removed from the reactor the spent fuel is conditioned and stored until a disposal repository becomes available.

Optimisation

In the context of radiation protection, optimisation is the process of assuring that the exposures of the public and/or workers resulting from the operation of a justified activity are as low as reasonably achievable, social and economic factors being taken into account. Both qualitative (e.g. stakeholder consensus discussions, common sense good work practice, best industrial practice) and quantitative (e.g. differential cost-benefit analysis, multi-attribute analysis) approaches are used to arrive at optimised solutions.

P

Partitioning and transmutation (P&T)

Partitioning is the separation of undesirable long-lived radioactive elements such as minor actinides (e.g. americium-243) and fission products from spent fuel. Transmutation is the transformation of these undesirable elements into short-lived or stable elements using nuclear reactions. Together these processes would, at least partly, eliminate those parts of high-level waste that contribute most to its heat generation and long-lived radioactivity. P&T therefore has the potential to reduce the time that waste needs to be kept isolated from several thousand to several hundreds of years.

Plasma

A state of matter (others are solid, liquid and gas) where all the electrons have been stripped from atoms leaving only the nuclei.

Pressurised water reactor (PWR)

A nuclear reactor maintained under a high pressure to keep its coolant water from boiling at the high operating temperature. The heat generated by the reactor is transferred from the core to a large heat exchanger that heats water in a secondary circuit to produce the steam needed to generate electricity.

Probabilistic safety assessment (PSA)

A PSA is a type of safety analysis that uses probabilistic risk assessment techniques during both the design and operation of a nuclear power plant to analyse the overall risk. Considering an entire set of potential events with their respective probabilities and consequences, the overall risk of a nuclear incident or accident can be assessed. For a power plant this risk is given in terms of a core melt frequency or the frequency of a large radioactive release. For existing power plants a value below about 1×10^{-4} per year for a core damage probability is generally accepted, while new designs should be even less than 1 x 10^{-5} per year. The current practice is that the computed results are generally viewed as targets rather than absolute values that would serve for regulatory acceptance or refusal.

Proton

An elementary nuclear particle with a positive electric charge located in the nucleus of an atom.

R

Radiation

Energy travelling in the form of high-speed particles or electromagnetic waves. We encounter electromagnetic waves everywhere. They make up our visible light, radio and television waves, ultra violet (UV), and microwaves. These examples of electromagnetic waves do not cause ionisation of atoms because they do not carry enough energy to separate molecules or to remove electrons from atoms. "Ionising radiation" is radiation with enough energy so that it can, during an interaction with an atom, remove tightly bound electrons from their orbits, causing the atom to become charged or ionised. Examples are gamma rays and neutrons.

Radioactivity

The spontaneous change of an unstable atom, often resulting in the emission of radiation. This process is referred to as a transformation, a decay, or a disintegration of an atom. Radioactive atoms are often called radioactive isotopes or radionuclides.

Reasonably assured resources (RAR)

Uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics.

Reprocessing

The process of treating used reactor fuel to recover the uranium and plutonium and to separate them from the fission products and other elements. In this way a larger percentage of the potential energy value of the uranium can be utilised and the volume of waste can be reduced.

S

Safeguards

The methods used to verify that the "peaceful use" commitments of non-proliferation agreements are honoured. Safeguards involve a country defining (i.e. declaring) what its inventory of weapons-usable nuclear materials is and where it is located. Safeguards consist of the verification of a nuclear installation's control of and accounting for weapons-usable nuclear materials within all the nuclear facilities that a signatory State has formally declared as subject to safeguards. Verification is performed using IAEA-installed monitoring instruments, some of which are sealed to prevent tampering. Physical inspection of nuclear installations on a random, yet pre-announced, basis is conducted at least annually to verify the operator's accounts and to ensure that all installed instruments are performing satisfactorily and that security seals have not been tampered with. Since 1997, IAEA inspections can also be carried out on a surprise or challenge basis once a State has ratified an additional safeguards protocol. The intended result of all inspections is that by verifying the inventories of nuclear material declared by a signatory government, the IAEA can announce that all nuclear material is being used for peaceful purposes.

Scram

A term used to describe the sudden shutting down of a nuclear reactor. It was originally an acronym meaning "safety control rod axe man" used with the first operating reactor in the United States, the Chicago pile.

Sievert (Sv)

The international unit indicating the biological effects caused by an exposure to radiation. The biological effects of radiation exposure vary depending on the type of radiation involved. For example, 1 joule of beta or gamma radiation per kilogram of tissue has 1 Sv of biological effect; 1 joule/kg of alpha radiation has 20 Sv effect; and 1 joule/kg of neutron radiation will cause 10 Sv of biological effect.

Speculative resources (SR)

Uranium that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable using existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative.

Spent nuclear fuel (SNF)

Fuel that has been irradiated in and then permanently removed from a nuclear reactor.

Stochastic effects

Stochastic effects are those effects (e.g. cancer or leukaemia) whose probability of occurring is proportional to the radiation exposure received.

SWU

An acronym for separative work unit that is the standard measure of enrichment services. This is a complex unit relating to the enrichment process that is a measure of the effort or energy required separating isotopes. The unit is a function of the amount of uranium fed into the process, the degree to which it is enriched, and the amount of uranium-235 in the waste stream. Typically, about 100 000-120 000 SWU is required to provide the enriched uranium needed to fuel a 1 000 MWe light water reactor for one year.

T

Terrestrial radiation

Radiation that comes from the earth itself and is produced by the decay of primordial and cosmogenic radionuclides. Most terrestrial radiation ultimately comes from uranium and thorium, common elements found in the earth's crust, as they decay gradually over millions of years eventually becoming lead, which is stable, does not decay and thus emits no radiation. The result is that the earth's crust is naturally full of not only uranium and thorium but also their radioactive decay products, such that the earth itself emits radiation. Additionally, the air we breathe also emits radiation naturally since one of the members of the uranium decay chain is radon. Radon is a gas, and if it is "born" near the surface of the earth, it enters into the atmosphere.

Technetium-99

A radioactive isotope of technetium, of which a particular form known as technetium-99m (^{99m}Tc) is extensively used in nuclear medicine for cancer diagnosis. Technetium-99m is normally formed from the radioactive decay of molybdenum-99 (^{99}Mo) which is produced by irradiating highly enriched uranium foil in a reactor. One of the fission products formed from the fission of the uranium in the foil is ^{99}Mo, which is then chemically separated for use as a generator of ^{99m}Tc.

Thermal neutrons

Thermal neutrons are those with a low kinetic energy, less than 0.1 electron volt (eV). Thermal neutrons have the greatest probability of causing fission in uranium-235 and plutonium-239.

Torus

A donut-shaped geometrical shape created by rotating a circle about a line. Fusion reactor research has focused on two types of containment of the plasma (fuel): magnetic and inertial. Magnetic containment can be spherical or torus-shaped. In a torus-type fusion reactor, torus-shaped magnetic fields are used to contain the plasma (fuel).

Transmutation

When a nucleus absorbs a neutron and changes the nucleus from one element into another. This process occurs in fission reactors and is the process by which some long-lived elements of radioactive waste are created. It is also a process being investigated as a means to transform long-lived elements of high-level radioactive waste into shorter-lived elements.

Tritium

A radioactive isotope of hydrogen having two neutrons and one proton. Tritium is being investigated for use as a fuel for fusion reactions. Because tritium is radioactive and can readily form water it has particular radiation protection concerns.

U

Undiscovered conventional resources

Uranium resources believed to exist and to be exploitable using conventional mining techniques but not yet physically confirmed are classed as undiscovered conventional resources. They include estimated additional resources – category II (EAR-II) and speculative resources (SR).

V

Vitrification

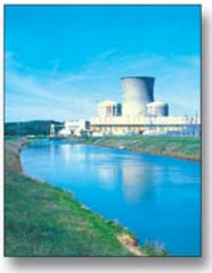
The process of producing glass. It is a technology commonly used to immobilise the high-level waste produced from the reprocessing of spent nuclear fuel. Typically this glass is of high durability, able to withstand the intense radiation and high heat associated with high-level waste and stable so as to be able to contain the radioactive isotopes over long periods of time.

X

X-ray

X-rays are electromagnetic waves emitted by energy changes in an atom's electrons. They are a form of high-energy electromagnetic radiation that interacts lightly with matter. Thick layers of lead or other dense materials stop them best.

For Further Information



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Chapter 10: The Future of Nuclear Energy

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NEA Issue Brief available online at www.nea.fr/html/pub/webpubs.

10.7 NEA, *Advanced Water Reactor Technology*. Paris: OECD, 1989.
NEA Issue Brief available online at www.nea.fr/html/pub/webpubs.

10.8 IEA, *Innovative Nuclear Reactor Development: Opportunities for International Co-operation*. Paris: OECD/IEA, 2002.

10.9 For information concerning US government nuclear energy initiatives including links to Generation IV and the Isotopes for Medicine and Science Program, see www.nuclear.gov.

10.10 The IAEA Nuclear Power Technology Development Section provides information on various uses of nuclear reactors including information and links to the INPRO project and desalination.
See www.iaea.org/programmes/ne/nenp/nptds/NPTDSHome.htm.

10.11 NEA, *Actinide and Fission Product Partitioning and Transmutation*, Sixth International Information Exchange Meeting, Madrid, Spain, 11-13 December 2000. Paris: OECD, 2001.
NEA Issue Brief available online at www.nea.fr/html/pub/webpubs.

Internet Resources

In addition to the resources cited above, below is a list of websites that have or host information related to nuclear energy:

OECD Nuclear Energy Agency	www.nea.fr
International Atomic Energy Agency (IAEA)	www.iaea.org/worldatom
International Commission on Radiological Protection	www.icrp.org
Euratom Supply Agency	http://europa.eu.int/comm.euratom/index_en.html
International Nuclear Law Association	www.aidn-inla.be
Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organisation	www.ctbto.org
United Nations First Committee (Disarmament and International Security)	http://disarmament.un.org
United Nations Scientific Committee on the Effects of Atomic Radiation	www.unscear.org
World Association of Nuclear Operators	www.wano.org.uk
IAEA Glossary of Nuclear Safety Terms	www.iaea.or.at/ns/CoordiNet/documents/safetyglossary.pdf

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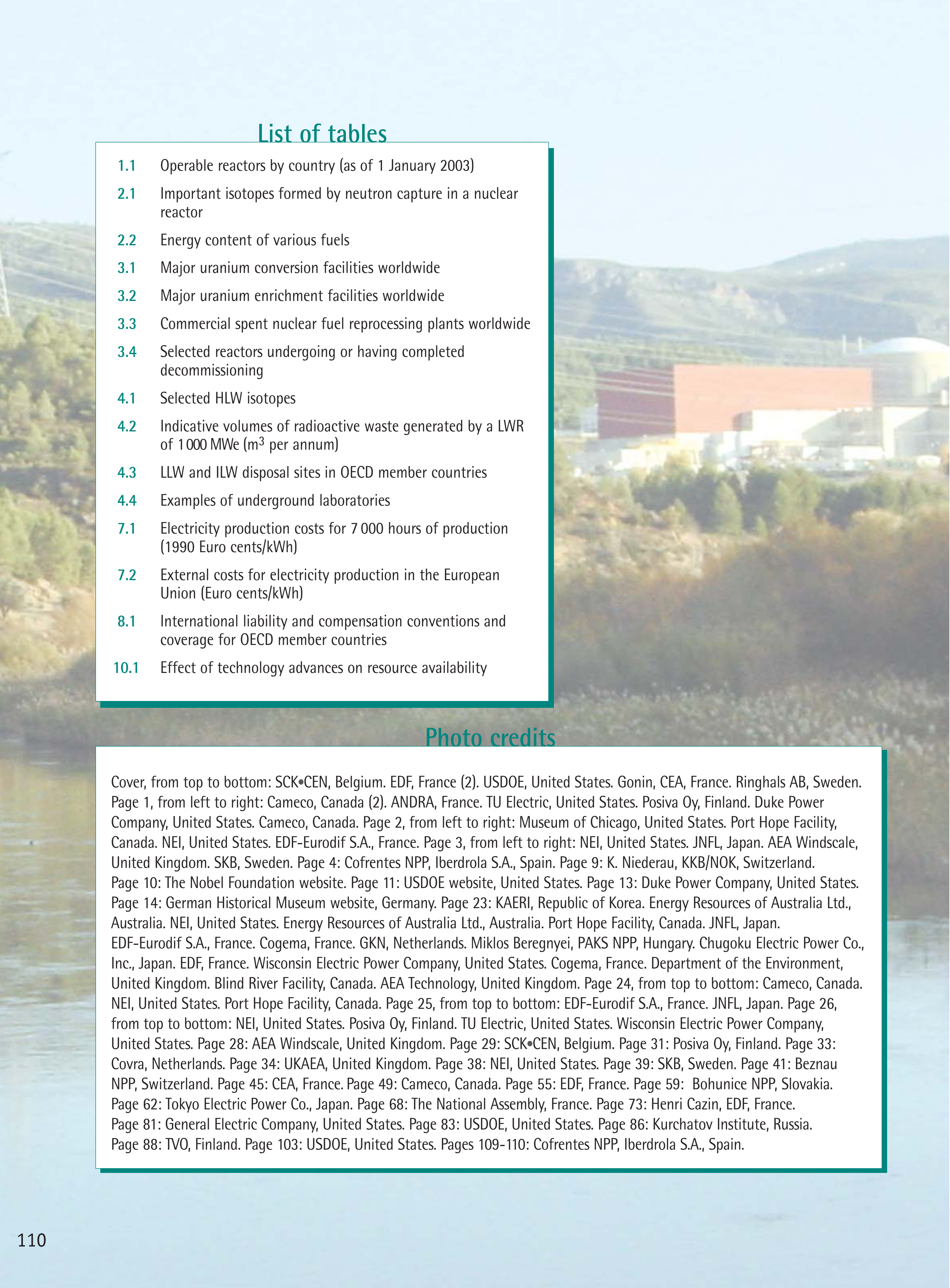

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Acknowledgements

The NEA Secretariat wishes to express its gratitude to John Rimington for his valuable contribution to this text as consulting editor.

The NEA drafting team included: Claes Nordborg (Ch. 2), Hans Riotte (Ch. 4), Miroslav Hrehor (Ch. 5), Ted Lazo (Ch. 6), Stefan Mundigl (Ch. 6 Accident response), Peter Wilmer (Ch. 7), Julia Schwartz (Ch. 8 International Law), Carol Kessler (Ch. 8 Non-proliferation), Jacques de la Ferté (Chs. 4 and 9 Social aspects), Robert Price as managing editor and contributing author (Chs. 1, 3, 9 and 10) and Cynthia Picot as editor.

Special thanks are extended to Annette Meunier for her dedication in preparing the design and layout of this publication.

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Publié en français sous le titre :
L'énergie nucléaire aujourd'hui

OECD PUBLICATIONS, 2 rue André-Pascal, 75775 Paris Cedex 16
OECD No. 53079 2003
ISBN 92-64-10328-7

OECD PUBLICATION, 2, rue André-Pascal, 75775 PARIS CEDEX 16
PRINTED IN FRANCE
(32 2003 04 3 P) – No. 52983 2003