Nuclear Development

Nuclear Energy Today

Second Edition

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 30 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as

– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the 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. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

Cover photo: Olkiluoto 3 nuclear power plant, Finland (TVO).

Foreword

During 2011, a number of events occurred which will have an impact on the development of nuclear energy in the years to come. The TEPCO Fukushima Daiichi nuclear power plant accident in Japan in March caused a widespread review of nuclear policies. The forecasts from the International Energy Agency's *World Energy Outlook* in November emphasised the growing energy needs of many countries, and the United Nations Climate Change Conference in Durban in December indicated that not enough is being done to reduce greenhouse gas emissions. Adding to this complexity were the continued impacts of one of the worst global economic crises ever. It is in this context that this edition of *Nuclear Energy Today* has been prepared, and I would like to underline the reasons why the OECD Nuclear Energy Agency believes this to be an important and timely publication.

On 11 March 2011, a major earthquake and ensuing tsunami hit the east coast of Japan and resulted in approximately 19 000 people dead or missing as well as the destruction of thousands of buildings, bridges, roads and industrial infrastructure. Eleven nuclear reactors in the region affected by the earthquake shut down automatically as designed. Unfortunately, at the Fukushima Daiichi nuclear power plant, a tsunami estimated to have exceeded a height of 14 m, overran the plant's flood protection dikes and flooded several emergency power supply units, thus preventing the reactors' decay heat removal systems from operating. This led to core damage in three reactors and to the release of radioactive matter into the environment. Although no fatalities due to the nuclear accident have been reported, tens of thousands of local citizens had to be evacuated and a large area around the site was contaminated. As a result, world public concern over the safety of nuclear energy intensified. Since the accident, the NEA and its member governments have been making numerous efforts to support and to further reinforce the safety of nuclear energy. Multiple verification activities and "stress tests" have been implemented by independent safety authorities in all NEA member countries using nuclear power, and safety upgrades have already begun to be implemented where judged necessary. As highlighted in *Nuclear Energy Today,* key lessons need to be identified, and the sharing of experience and the development of best practices at the international level will help ensure the highest levels of nuclear safety into the future.

In addition to the consequences that the Fukushima Daiichi accident had on public concern over nuclear safety, and more generally public acceptance of nuclear power, it also had an impact on nuclear energy policies. A few countries announced their intention to forego nuclear energy, but most countries that had plans to develop their nuclear programme confirmed their pursuit, albeit at a slower pace. The impact of these changes is discussed in terms of the most recent projections of energy supply and demand for the next decades, which continue to show significant increases in demand, especially in the developing world. This demand for energy will mainly be met by fossil fuels, and the associated emissions, in particular of carbon dioxide, show no signs of relenting despite warnings by international environmental organisations. In its 2011 edition of the *World Energy Outlook,* the International Energy Agency also warns that it will soon be too late to avoid global warming in excess of 2°C unless decisions to reduce emissions are taken rapidly. Indeed, by 2017 the energy-related infrastructure in place at that time would make it impossible to limit global CO_2 emissions below the level consistent with the 2°C trajectory. It describes three main scenarios up to 2035 which differ in the way they address the need to reduce emissions. The role of nuclear energy as an economically competitive, low-carbon technology is fully recognised in all of them, but the extent of its role depends on policy decisions and trends. Continuous developments in technology and the fuel cycle, as well as implementation of waste management policies and legal frameworks, are necessary for the use of nuclear energy.

This edition of *Nuclear Energy Today* gives an overview of recent developments in these areas, as well as recalling the basic principles of nuclear energy.

The global economic crisis that is affecting OECD countries, and Europe in particular, represents an additional threat to the necessary investments in the energy sector, and to the further development of capital-intensive technologies such as nuclear and renewable technologies. More than ever, policy-makers need informed arguments regarding the competitiveness of each technology, and financing models need to be developed to support investment in the power sector. Chapter 8 addresses these issues specifically and reports on recent developments and analyses carried out by the Agency and its member countries.

Let me finish by recalling that the NEA mission as established in its 2011-2016 Strategic Plan is: *"To assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes. To provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development."* This second edition of *Nuclear Energy Today* contributes to that mission, and in the context of the present challenges, it provides an up-to-date and timely overview of the full range of issues associated with the use of nuclear energy. It is aimed at assisting decision-makers in establishing energy policies that address the combined objectives of security of supply, diversification, competitiveness and protection of public health and the environment.

– **Luis E. Echávarri,** *NEA Director-General*

Table of contents

Chapter 1

Overview of *Nuclear Energy Today*

The use of nuclear energy for electricity generation began in the late 1950s and grew strongly until 1990. Although its growth since then has been much slower, it is today a major source of energy, supplying about 14% of the world's electricity, and 21% of the electricity in OECD countries. Rising concerns in recent years about carbon dioxide emissions from fossil-fuel burning and about security of energy supplies have led to renewed interest in expanding its use, either through power upgrades and life-extension of existing plants or through new build. The accident that occurred at the Fukushima Daiichi plant in Japan in March 2011 has however clouded the prospects for the "nuclear renaissance" which many had anticipated. Some countries have subsequently reconsidered their nuclear energy policy, opting for a nuclear phase-out or choosing not to introduce nuclear power in their energy mix. However, while some others are still reassessing their nuclear energy policy, a large number have reaffirmed their intention to build nuclear power plants. In the long term, the fundamental reasons for having nuclear energy in terms of reduction of greenhouse gas emissions, competitiveness of electricity production and security of supply still apply, and overall capacity is still expected to grow in the coming years to match rising electricity demands while moving to low-carbon energy sources.

The production of electricity using nuclear energy was first demonstrated in the early 1950s, and the first large-scale nuclear power plants entered operation before 1960. The first countries to employ this new energy source for power generation were the ex-USSR (1954), the United Kingdom (1956), the United States (1957) and France (1963). Several others followed in the early 1960s, including Belgium, Canada, Germany, Italy, Japan and Sweden.

First nuclear power plants in the world

◀ Obninsk APS-1, Russia 1954.

Shippingport, United States, 1956. ▶

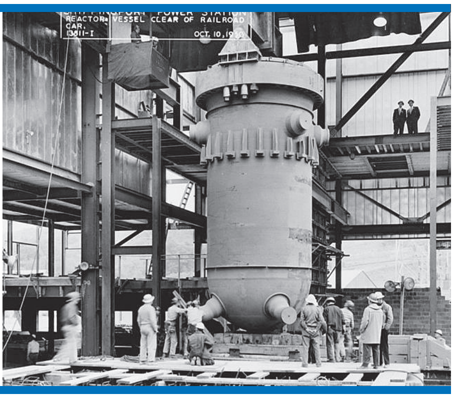


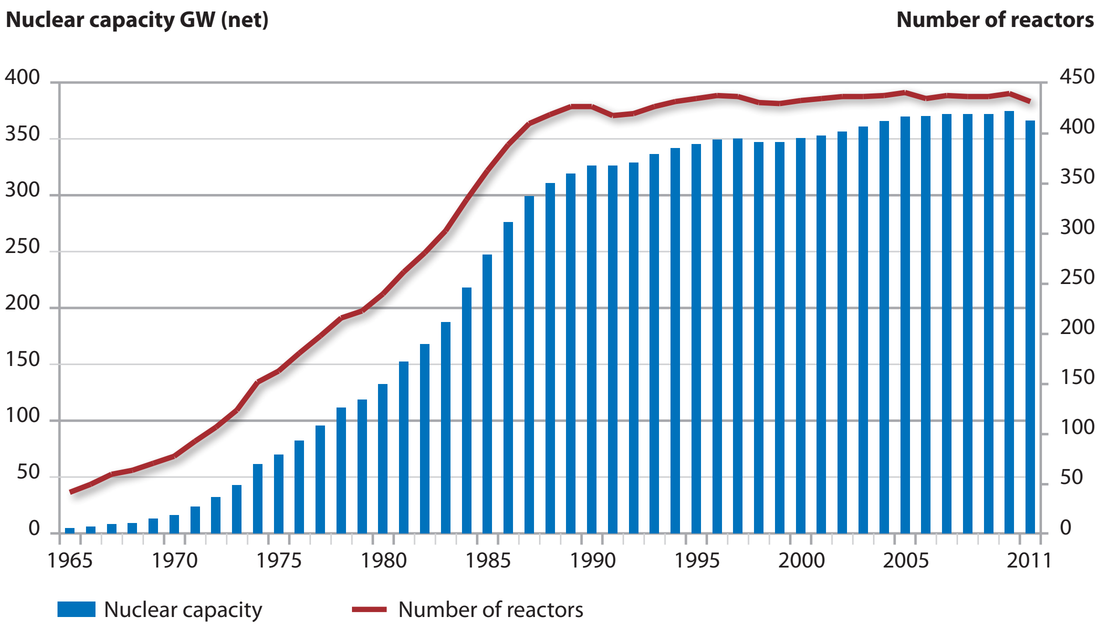
Table 1.1: **Nuclear generating capacity in operation and under construction (end 2011)**

	In operation		Under construction	
	No. of reactors	Capacity (MW)	No. of reactors	Capacity (MW)
Argentina	2	935	1	692
Armenia	1	375	—	—
Belgium	7	5 927	—	—
Brazil	2	1 884	1	1 245
Bulgaria	2	1 906	—	—
Canada	18	12 604	—	—
China	16	11 816	26	26 620
Chinese Taipei	6	5 018	2	2 600
Czech Republic	6	3 766	—	—
Finland	4	2 736	1	1 600
France	58	63 130	1	1 600
Germany	9	12 068	—	—
Hungary	4	1 889	—	—
India	20	4 391	7	4 824
Iran	1	915	0	0
Japan	50	44 215	2	2 650
Mexico	2	1 300	—	—
Netherlands	1	482	—	—
Pakistan	3	725	2	630
Republic of Korea	21	18 751	5	5 560
Romania	2	1 300	—	—
Russian Federation	33	23 643	10	8 188
Slovak Republic	4	1 816	2	782
Slovenia	1	688	—	—
South Africa	2	1 830	—	—
Spain	8	7 567	—	—
Sweden	10	9 326	—	—
Switzerland	5	3 263	—	—
Ukraine	15	13 107	2	1 900
United Kingdom	18	9 953	—	—
United States	104	101 465	1	1 165
Total	**435**	**368 791**	**63**	**60 056**

Source: IAEA Power Reactor Information System (PRIS).

The oil crises of the 1970s led to a surge in nuclear power plant orders and construction. However, an economic downturn and declining fossil fuel prices curtailed the growth in nuclear plant orders by the end of the 1970s. In addition, the accidents at Three Mile Island in the United States (1979) and Chernobyl in Ukraine (1986) raised serious questions in the public mind about nuclear safety. The overall effect was a significant slowing of nuclear energy's growth after the late 1980s (see Figure 1.1). Only a few countries (notably China, Japan and the Republic of Korea) continued with reactor construction during the 1990s and early 2000s. More recently the pace of construction of new plants increased with the launch of projects in Europe, India, Japan, the Middle East, the Republic of Korea, the Russian Federation, and especially China but it is too early to say how this upturn will be affected by the Fukushima Daiichi accident.

Figure 1.1: Worldwide nuclear generating capacity and number of operating reactors (1965-2011)



Source: IAEA Power Reactor Information System (PRIS).

At the end of 2011, 435 power reactors were in operation in 30 countries with a combined capacity of about 369 gigawatts (GW) of electricity,[1] providing over 2 500 TWh (or 2.5 trillion kWh) annually (see Table 1.1 and Figure 1.2). Nuclear energy supplies about 6% of the world's total primary energy and about 14% of all electricity (see Figures 1.3 and 1.4). Over 80% of all nuclear generation occurs in OECD countries, in which it provides about 21% of the overall electricity supply and represents the largest low-carbon energy source.

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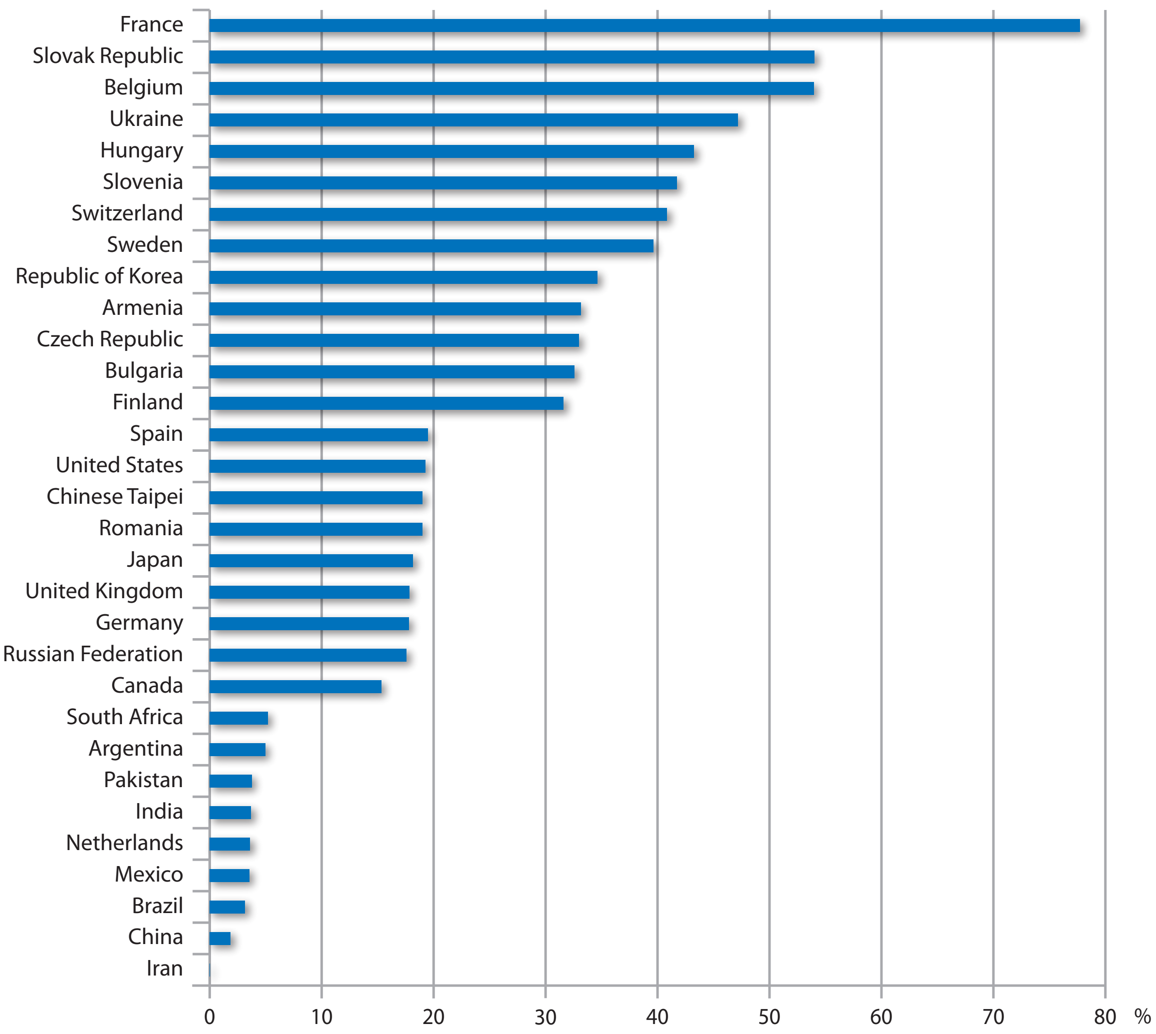
[1] The number of reactors in operation fell from 441 at the end of 2010 to 435 at the end of 2011, essentially as a result of the Fukushima Daiichi accident and the German decision to shut down 8 reactors.

Figure 1.2: Share of nuclear power in total electricity (2011)

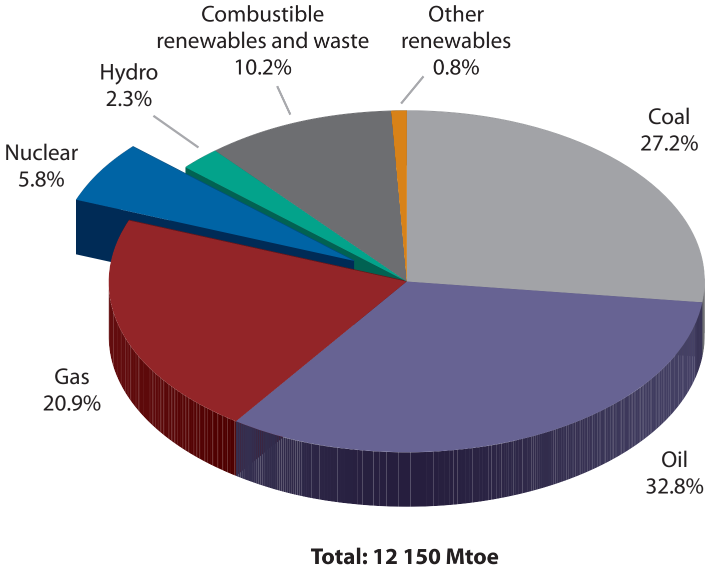


Source: IAEA Power Reactor Information System (PRIS).

Since 1990, there has been a significant improvement in nuclear plant performance as measured by the energy availability factor (the percentage of the time that plants are available to produce electricity) (see Figure 1.5). Over the same period, nuclear plants in several countries have had their licensed power output increased as a result of technical upgrades. These factors have led to increased production of nuclear electricity, even though the number of operating reactors has increased only slightly.

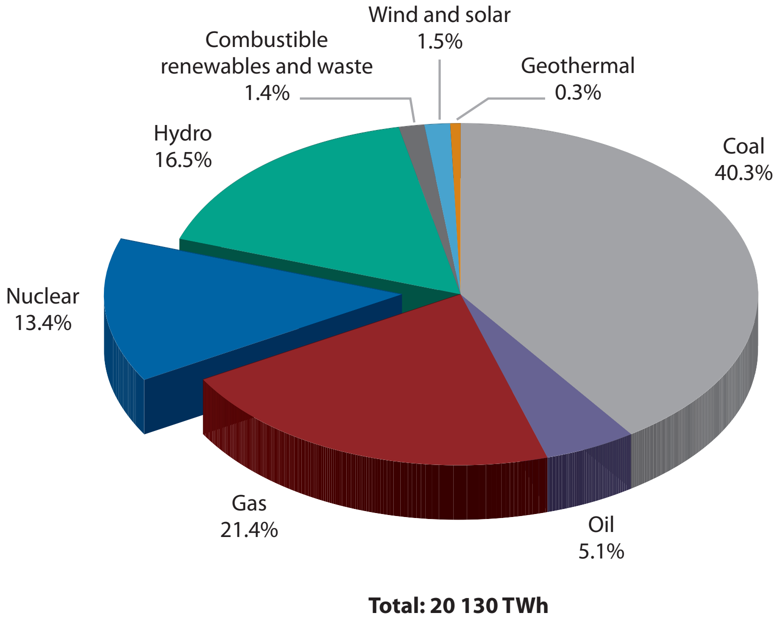
Figures 1.3 and 1.4 also show the high degree of reliance on fossil fuels to supply primary energy and electricity. The carbon dioxide (CO_2) produced as a result of electricity generation from fossil fuels is one of the main contributors to the build-up of greenhouse gases in the atmosphere that could lead to detrimental changes in the global climate. This has led many OECD countries to aim to largely "decarbonise" their electricity supply within the next few decades, as part of their overall strategy to drastically cut CO_2 emissions. Some non-OECD countries are also aiming to at least curb the growth in their emissions.

Figure 1.3: **World primary energy demand (2009)**



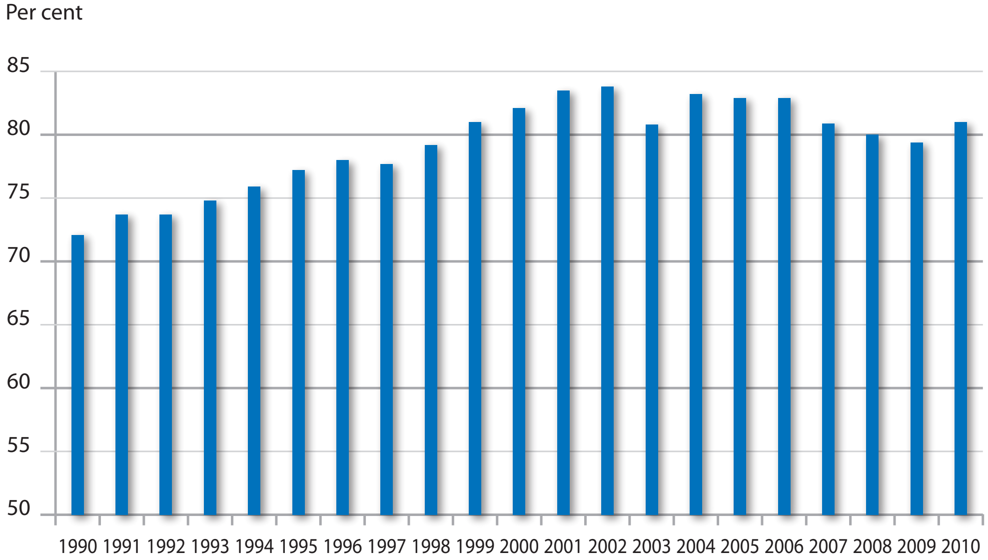
Source: IEA, *Key World Energy Statistics,* 2011.

Figure 1.4: **World electricity generation (2009)**



Source: IEA, *Electricity Information,* 2011.

Figure 1.5: **Worldwide nuclear power plant energy availability factor (1990-2010)**



Source: IAEA Power Reactor Information System (PRIS).

Nuclear energy and hydropower are the only two major established base-load low-carbon energy sources. Efforts to reduce CO_2 emissions are thus a major factor in the renewed interest in nuclear energy that has become apparent in recent years. Concern over security of energy supplies, arising from the concentration of oil and natural gas resources among relatively few suppliers, is also a consideration in some countries' energy policies that can be partly addressed through nuclear energy.

Worldwide, 63 reactors were under construction in 14 countries at the end of 2011; these should add over 60 GW to capacity in the next few years (of those 63 reactors, 7 were started before 1988 and had their construction halted or delayed for several reasons. Construction has now resumed for all but 1 – so overall 62 reactors can be considered as being actively constructed). This represents a significant upturn in construction activity compared to five years earlier, when only 26 units were under construction with a capacity of about 20 GW. In 2010 alone, 16 new construction starts were announced. In 2011, however, only 4 new construction projects were launched.

The trend that was observed until 2010 is likely to slow down in the coming years to allow lessons learnt from the Fukushima Daiichi accident to be fully assessed in terms of reactor design, siting and licensing, but nuclear capacity is then expected to grow more strongly from around 2015. Much of the present construction activity is in China, with 26 units now under construction. The Republic of Korea and the Russian Federation also each have several units under construction.

In the next few years, several other established nuclear countries are expected to start building additional capacity. The Republic of Korea and the Russian Federation will continue their nuclear expansion, and India is planning to step up the pace of its nuclear programme. New construction is underway at 2 sites in the United States after a 30-year hiatus, and the United Kingdom is planning for 4 new units initially with more possibly to follow. Finland and France, with one unit each under construction, are both planning at least a further unit. The Czech Republic has announced ambitious plans to increase its nuclear capacity, in part to fill the electricity-generation gap resulting from Germany's nuclear phase-out plans. Lithuania has launched a project to construct a new reactor to be in operation in 2020 to partially replace the two Russian design units at Ignalina which were shut down at the end of 2004 and 2009 respectively.

Of countries with no existing nuclear capacity, Turkey and the United Arab Emirates have already placed orders for nuclear units to be built in the next few years. Poland is preparing to develop nuclear capacity in the next decade. Many other countries (e.g. Indonesia, Jordan, Saudi Arabia, Thailand and Vietnam) are considering launching nuclear programmes but most are at an earlier stage in the process of policy debate, planning, preparation and infrastructure development.

Despite its status as a mature energy source and the advantages it provides in terms of low-carbon emissions, competitiveness of electricity generation and security of supply, nuclear energy continues to be the object of strong public and political concerns in many countries. Many factors contribute to this, including concerns about safety (especially in the wake of the Fukushima Daiichi accident), but also its technical complexity, the need for long-term management and disposal of nuclear waste, the complicated regulatory and legal requirements, and the large-scale investments required to build nuclear power plants. Understanding these issues is important for understanding the potential of nuclear energy today.

References

IAEA (2011), *Nuclear Power Reactors in the World*, Reference Data Series No. 2, International Atomic Energy Agency (IAEA), Vienna, Austria. Available at www.iaea.org/NuclearPower/Engineering/Publications/.

IAEA, Power Reactor Information System (PRIS). Online database available at www.iaea.org/programmes/a2.

IEA (2010), *Key World Energy Statistics 2010,* International Energy Agency, Paris, France.

NEA (2008), *Nuclear Energy Outlook 2008,* Nuclear Energy Agency, OECD, Paris, France.

NEA (2011), *Nuclear Energy Data 2011,* Nuclear Energy Agency, OECD, Paris, France.

Chapter 2

Basic Principles of Nuclear Energy

Nuclear fission is a process by which certain heavy atomic nuclei split into two, most often after collision with a neutron. The process produces heat and also releases neutrons; these neutrons can go on to cause further fissions, allowing a chain reaction to be sustained. Fission is the basic reaction that underlies our use of nuclear energy.

Nuclear reactors create and control fission reactions to produce heat for electricity generation or other purposes. There are several types of reactors in commercial operation, the most common of which are the pressurised water reactor (PWR) and the boiling water reactor (BWR). They are principally fuelled with uranium, extracted from the mining of mineral deposits.

Nuclear fusion is another type of nuclear reaction in which the nuclei of light elements are fused together under extreme temperatures and pressures, also producing heat and neutrons. This is essentially the same process that fuels the Sun and other stars. Research and development aimed at achieving controlled fusion has been pursued for many years, but any commercial fusion energy system is at least several decades away.

Introduction to nuclear physics and nuclear fission

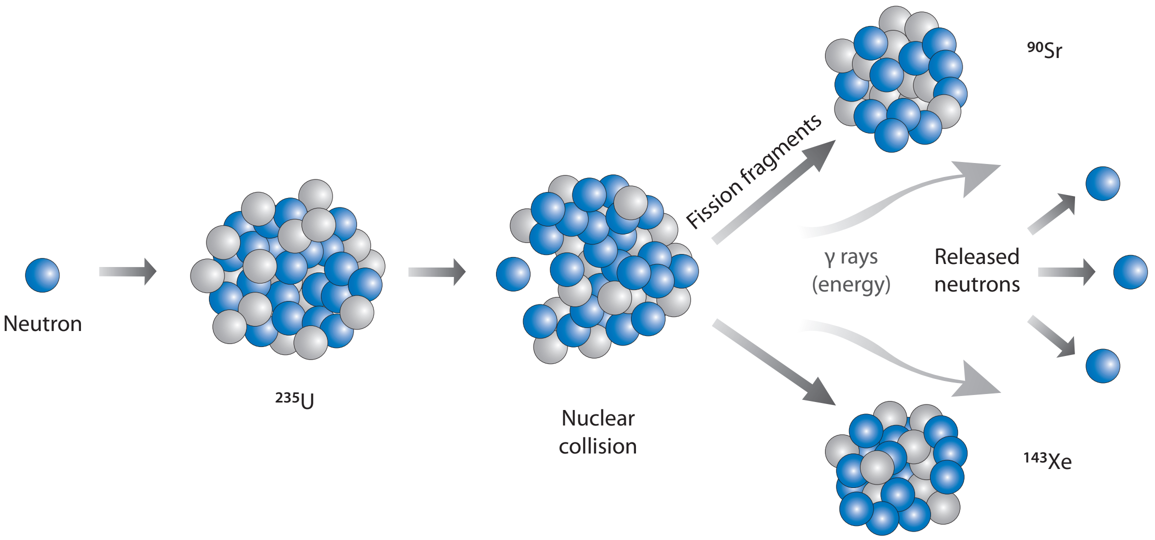
All atomic nuclei are made up of a combination of the sub-atomic particles protons and neutrons (except that of hydrogen, which comprises a single proton). Protons have a positive electrical charge, and their number in a nucleus is characteristic of each element. For example, the nucleus of a carbon atom always has six protons, that of oxygen eight. Neutrons have no electrical charge and their number in a nucleus can vary, meaning that more than one variety (or isotope) of nucleus can exist for a single element.

For example, carbon nuclei can have six, seven or eight neutrons (together with the six protons). These isotopes are known as carbon-12 (^{12}C), carbon-13 (^{13}C) and carbon-14 (^{14}C) (the number indicating the total number of protons and neutrons combined). The heaviest element found in nature, uranium, is more than 99% comprised of the isotope uranium-238 (^{238}U), which contains 92 protons and 146 neutrons.

Some isotopes are stable while others undergo radioactive decay, emitting a nuclear particle and/or electromagnetic radiation (see Chapter 5). Each radioactive isotope has a characteristic half-life which is the time it takes for half its nuclei to decay. Half-lives can range from fractions of a second to many millions of years. Only stable and very long-lived isotopes are found in nature, but many other (mainly short-lived) isotopes can be produced artificially as a result of nuclear reactions in a reactor or accelerator. Several artificial elements (heavier than uranium) can also be produced, including plutonium.

Certain isotopes of naturally occurring and artificial heavy elements, for example uranium and plutonium, can undergo a nuclear reaction known as fission. When such a nucleus is impacted by a neutron it can split into two fragments (known as fission products), releasing at the same time two or three free neutrons and some energy (see Figure 2.1). This is the basic reaction underlying the use of nuclear energy. Current nuclear reactors are based on the fission of uranium-235 (^{235}U), an isotope that comprises 0.71% of uranium found in nature.

Figure 2.1: A typical fission reaction



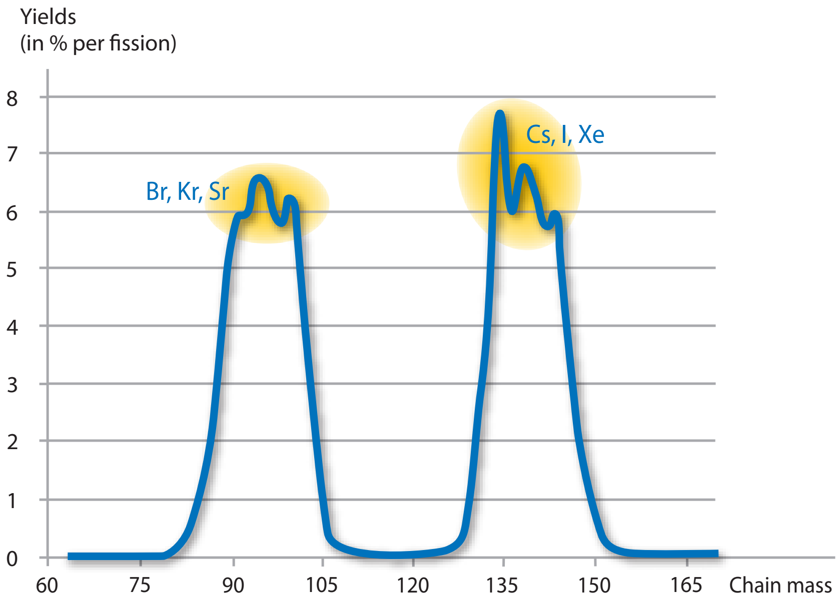
The fission products are unstable (i.e. radioactive) isotopes of lighter elements; many different combinations of these can be produced from the fission of any particular nucleus. Figure 2.2 shows the probabilities of isotopes of a given mass being formed by fission of ^{235}U. In terms of abundance and radioactivity, the most important fission products in this case are radioactive forms of bromine, caesium, iodine, krypton, molybdenum, strontium and xenon. These isotopes and their decay products form a significant part of high-level nuclear waste (see Chapter 6).

The total mass of the products of the reaction (fission products and neutrons) is minutely less than the original mass of the nucleus and impacting neutron, the difference having been converted into energy according to Einstein's famous formula $E = mc^2$. Most of this energy is carried by the fission products in the form of kinetic energy (energy due to their motion). As the fission products collide with nearby atoms they quickly lose most of their kinetic energy, which is converted into heat. In a nuclear power plant this heat is used to generate electricity.

When one of the free neutrons released as a result of fission impacts another suitable nucleus, it can cause a further fission, releasing more neutrons and energy. Alternatively, free neutrons may bounce off a nucleus (scattering), escape from the reactor without interaction (leakage), or be absorbed into a nucleus without causing fission (capture). The fuel and other materials in a nuclear reactor are arranged to produce a self-sustaining chain reaction, where on average just one of the neutrons released by each fission goes on to cause a further fission. At that point the reactor is said 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 low kinetic energy are known as thermal neutrons; these are the most efficient in causing fission in uranium and plutonium. Fast neutrons have many millions of times more kinetic energy than thermal neutrons. All free neutrons produced by a fission reaction are initially fast neutrons. In current nuclear power plants, a material known as a moderator (often ordinary water) is used to slow the fast neutrons released during fission to the thermal energies needed for fission.

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



However, although fast neutrons are less efficient than thermal neutrons in producing fission in certain isotopes, they can be effective in fissioning a wider range of isotopes. A "fast reactor" is one that contains no moderator and is based on fission caused by fast neutrons. Several countries have built and operated prototype and demonstration fast reactors.

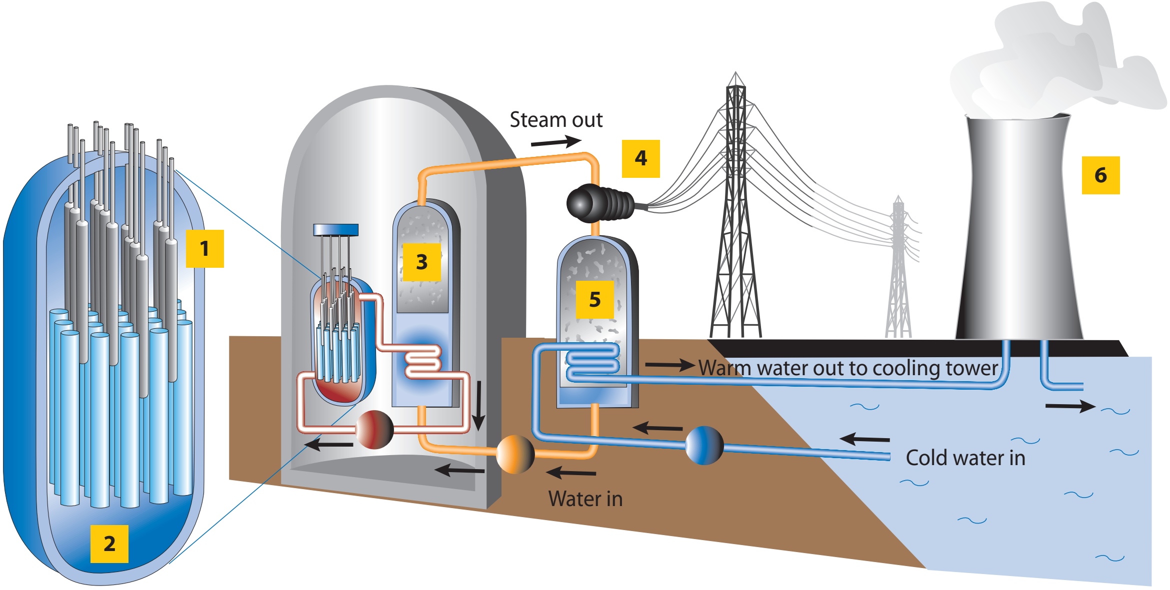
When the nucleus of an atom captures a neutron and does not fission, it may become less stable and change into another element as a result of radioactive decay. In a nuclear reactor, this results in the creation of isotopes of long-lived artificial elements, including neptunium-237 (^{237}Np) (half-life 2.1 million years), plutonium-239 (^{239}Pu) (24 000 years) and americium-243 (^{243}Am) (7 400 years). All these isotopes are radioactive, and some – particularly plutonium – can be used as nuclear fuel. Because of their long half-lives and toxicity they are another important component of high-level nuclear waste, and are the reason why such waste must be isolated for very long periods (see Chapter 6).

Nuclear fission is an extremely potent source of energy with a very high energy density, i.e. energy produced per unit mass of fuel. Compared to chemical reactions such as combustion of fossil fuels, fission requires a much smaller volume of fuel material to produce an equivalent amount of energy. The energy released from 1 kilogram of natural uranium used to fuel a typical light water reactor (LWR) is equivalent to that released by burning about 45 000 kg of wood, 22 000 kg of coal, 15 000 kg of oil or 14 000 kg of liquefied natural gas.

Main components of nuclear reactors

A nuclear power plant comprises a number of systems and components, including the reactor itself and the so-called conventional island or turbine hall, that together are designed to harness and control the energy of nuclear fission, and to turn it into electricity (see Figure 2.3). Though there are many types of nuclear reactors, they have several components in common: fuel, moderator, coolant and control rods.

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



Source: *New Scientist.*

1 – Reactor : fuel (light blue) heats up pressurised water. Control rods (grey) absorb neutrons to control or halt the fission process.
2 – Coolant and moderator: fuel and control rods are surrounded by water (primary circuit) that serves as coolant and moderator.
3 – Steam generator: water heated by the nuclear reactor transfers heat through thousands of tubes to a secondary circuit of water to create high-pressure steam.
4 – Turbo-generator set: steam drives the turbine, which spins the generator to produce electricity.
5 – Condenser: removes heat to convert steam back to water, which is pumped back to the steam generator.
6 – Cooling tower: removes heat from the cooling water that circulated through the condenser, before returning it to the source at near-ambient temperature.

Nuclear fuel

Uranium is the only fissile material found in nature; hence, almost all reactors use uranium fuel. As noted above, ^{238}U makes up more than 99% of natural uranium, with most of the remainder (0.71%) being ^{235}U. The latter easily fissions after absorbing either a thermal or a fast neutron. Most uranium for use in nuclear fuel is "enriched" so as to contain a higher concentration of ^{235}U than found in nature, typically in the range of 2-5%.

^{238}U fissions relatively rarely, only after absorbing a fast neutron of a particular energy. More commonly neutron capture occurs, eventually transforming ^{238}U into ^{239}Pu. This isotope of plutonium is able to fission with thermal or fast neutrons. Hence, as nuclear fuel is irradiated in a reactor the fission of ^{239}Pu contributes a growing proportion of the energy output (eventually up to 30%). Some reactors also use fuel in which plutonium extracted from spent fuel is blended with depleted uranium. This fuel is called mixed-oxide fuel (MOX); in this case the fission of ^{239}Pu is the main source of energy production.

Fabricated fuel for use in the great majority of power reactors comprises uranium dioxide (UO_2) in the form of ceramic pellets, encased in metallic tubes to form fuel rods. These are arranged in a square lattice within a fuel assembly; the number of rods in each assembly depends on the reactor type and design. The core of a large power reactor contains several hundred fuel assemblies (see Chapter 3 for more details about nuclear fuel and the fuel cycle).

Moderator

A moderator is necessary in most reactors to slow down the fast neutrons created during fission to the thermal energy range so as to increase their efficiency in causing further fissions. The moderator must be a light material that will allow the neutrons to slow down through collisions without being captured. In most reactors, ordinary (or "light") water is used. Other moderators used in some less common reactor types are graphite and heavy water (water formed with the heavier deuterium isotope of hydrogen). Fast reactors, based on fission of plutonium fuel by fast neutrons, do not have a moderator.

Coolant

The coolant circulates through the reactor core to absorb and remove the heat produced by nuclear fission, thus maintaining the temperature of the fuel within normal limits. It transfers this heat to the turbine-generator system to produce electricity. If water is used as the coolant, steam can be produced directly by the reactor and fed to the turbines, this is the concept of a boiling water reactor. Alternatively, heated water from the reactor can be passed through heat-exchangers (steam generators) which produce steam for the turbines as in a pressurised water reactor. Other coolants in use in some reactor types are heavy water and gases such as carbon dioxide or helium. Designs for some advanced reactors use molten metals such as sodium, lead or alloys of lead as the coolant.

In the great majority of reactors in use today, ordinary water is used as both coolant and moderator. Heavy water moderated reactors usually also use heavy water as the coolant (although a few have a separate light water cooling circuit). In most existing gas-cooled reactors, graphite in the core acts as the moderator.

Control rods

Control rods are made of materials that absorb neutrons, for example, boron, silver, indium, cadmium and hafnium. In normal operation, their position in the reactor core is adjusted to regulate the number of neutrons available for fission and thus to control the level and spatial distribution of power in the reactor. In an emergency, the control rods can be rapidly inserted by operators or by automatic systems to shut down the reactor.

Other components

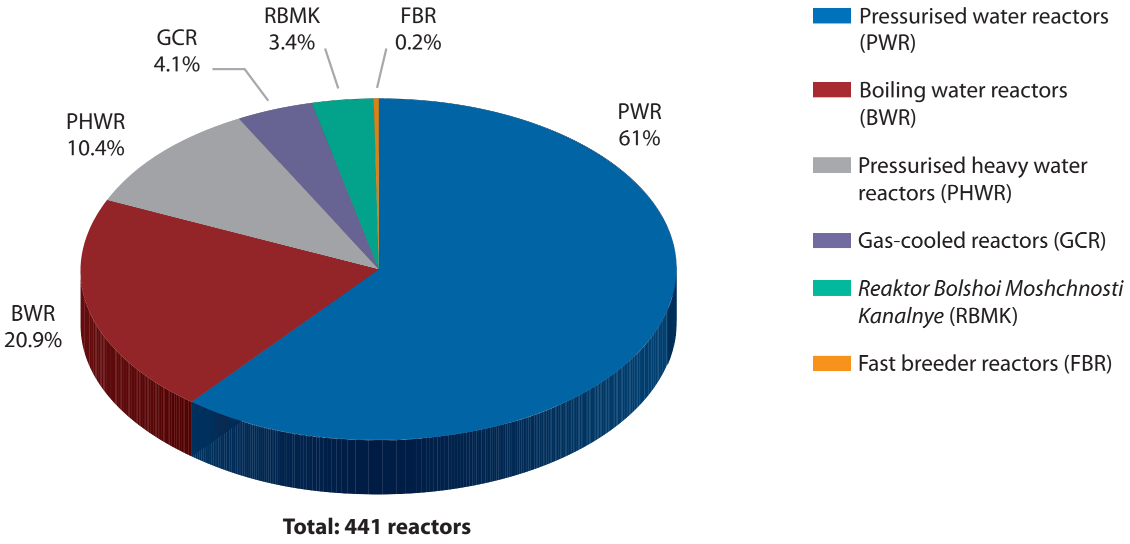
The nuclear fuel and the mechanical structures that hold it in place, form the reactor core. Typically, a neutron reflector surrounds the core to return some of the escaped or "leaked" neutrons. In most reactors, the core and reflector are housed in a thick steel container called the reactor pressure vessel. Radiation shielding protects operators and equipment against the radiation produced by the fission process (see Chapter 5). Numerous instruments are inserted into the core and the supporting systems to permit the monitoring and control of the reactor. The entire reactor structure and other major components such as steam generators are usually within a large reinforced concrete and steel containment building, designed both to protect the reactor from external shocks and to prevent the release of radioactive materials in the event of a severe accident. Finally, power conversion equipment (turbogenerator, heat exchangers and cooling pumps) which convert the steam into electricity are housed in a separate building called the turbine hall or conventional island. This equipment is specifically designed for nuclear power plants to take into account the steam characteristics, the power output of the reactors as well as grid constraints.

Reactor technologies and types

Reactors are usually categorised according to the type of coolant and/or moderator used. Over 80% of commercial reactors in operation at the end of 2010 were cooled and moderated with ordinary water; these are known as LWRs. Of these, two major types exist – PWRs and BWRs. The majority of the remaining reactors are cooled either by heavy water or gas. Some water-cooled graphite-moderated reactors (RBMK) remain in operation in the Russian Federation. Figure 2.4 shows how the main types of commercial reactors are distributed worldwide.

Each of the main types of commercial reactors is briefly described below. It should be noted that within each basic type there are often several different designs built by different constructors at different times, in accordance with national and customer requirements and the state of technological development at the time.

Figure 2.4: Reactor types in use worldwide (end 2010)



Pressurised water reactors

At the end of 2010, there were 269 PWRs worldwide, or over 60% of all reactors in operation. This includes the Russian Federation designed PWRs, often referred to as VVERs.

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 as a liquid. It is contained within the pressure boundary formed by the reactor pressure vessel and piping in the primary coolant system, and is circulated through the core using powerful pumps. Heat is transferred within steam generators to a separate, secondary coolant circuit, where water is boiled to create steam. This steam drives the electricity-producing turbine generators (see Figure 2.5).

Boiling water reactors

There were 92 BWRs in operation worldwide at the end of 2010. As in PWRs, 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 it to boil as it absorbs 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 steam generators simplifies the design, the absence of a secondary circuit can result in some radioactive contamination of the turbine.

Figure 2.5: A pressurised water reactor (PWR)

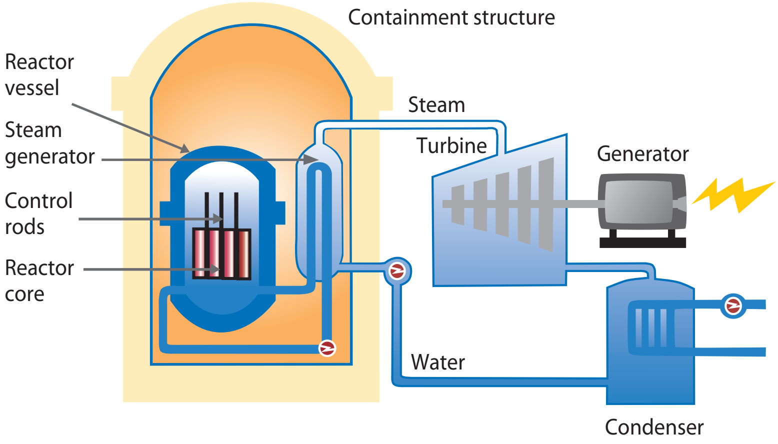
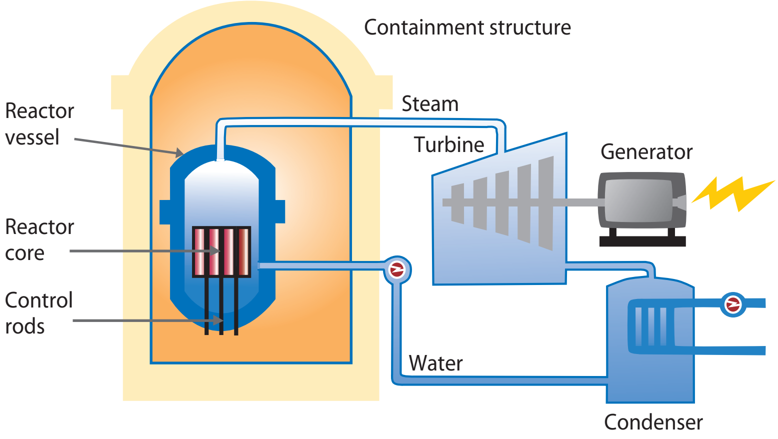


Figure 2.6: A boiling water reactor (BWR)



Source: Nuclear Energy Institute website.

Pressurised heavy water reactors

Pressurised heavy water reactors (PHWRs) are the third most common type of reactor, with 46 plants operating worldwide at the end of 2010. Most of these are the Canadian type known as CANDU reactors (short for Canadian deuterium uranium). They use heavy water as both coolant and moderator. Up to 99% of the molecules in heavy water (D_2O) contain the heavier deuterium isotope of hydrogen (which has one proton and one neutron, compared to just one proton in ordinary hydrogen).

Heavy water is a more effective moderator than light water, allowing natural uranium to be used as the fuel, thereby eliminating the need for uranium enrichment. On the other hand, the production of almost-pure heavy water requires facilities to separate D_2O from ordinary water, of which it comprises much less than 1%.

As in a PWR, the coolant is passed through a steam generator so as to boil ordinary water in a secondary circuit. However, the design differs markedly in that CANDUs do not have a reactor pressure vessel, but a series of horizontal pressure tubes. An advantage of this design is that refuelling can take place during operation, one tube at a time, whereas LWRs must shut down to refuel.

Gas-cooled reactors

At the end of 2010, only 18 gas-cooled reactors (GCRs) were in commercial operation, all in the United Kingdom. GCRs were among the first reactors to enter commercial use, but have since been eclipsed by other reactor types. Over 50 were once in operation, mainly in the United Kingdom but also in a few other countries. They use carbon dioxide as the coolant and graphite as the moderator. Early models used natural uranium fuel, with later UK designs using enriched uranium. As with CANDU reactors, GCRs are designed to be refuelled online.

A few prototype high-temperature gas-cooled reactors (HTRs) were in operation in the past. These used helium gas as coolant with fuel in the form of pellets incorporating the graphite moderator. Development of such reactors is still continuing, either for electricity production or for process-heat applications [e.g. Next Generation Nuclear Plant (NGNP) project in the United States or the Nuclear Hydrogen Development and Demonstration (NHDD) project in the Republic of Korea]. China is currently building two coupled HTR reactors in Shidaowan, based on the Pebble Bed core concept, to be connected to a 210-MW steam turbine.

Graphite moderated light water-cooled reactors (known under their Russian Federation abbreviation RBMKs)

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 the turbine generators. The accident at Chernobyl in Ukraine in 1986 occurred at a reactor of this type. The design lacked some of the safety characteristics and features of other reactor types, and was only built in the ex-USSR. Eleven large RBMKs remained in operation at the end of 2010, all of which were in the Russian Federation. These plants were all extensively upgraded following the accident, with improved shutdown systems, modifications to core behaviour and changes to the design of control rods.

Fast reactors

The reactor types described above are thermal reactors, i.e. most of the fissions are due to thermal neutrons. Fast reactors are designed to make use of fast neutrons with much higher kinetic energies. They create more neutrons per fission than thermal reactors, and can also make more efficient use of them. The excess neutrons created can be used to convert certain isotopes, e.g. uranium-238 (^{238}U) and thorium-232 (^{232}Th) (known as "fertile" isotopes), into fissile materials through neutron capture. This process is known as "breeding", and fast reactors that include this process are often referred to as fast breeder reactors (FBRs).

This newly created fissile material can, after processing, be used to produce additional fuel. It is possible to design a FBR capable of producing more fuel than it consumes. By creating fuel from non-fissile isotopes and improving the efficiency of uranium utilisation through recycling, FBRs could potentially increase the energy extracted from a given quantity of natural uranium by between 30 and 60 times or more compared to using the uranium once only in a thermal reactor. They are thus a key element in the sustainability of nuclear energy in the long term. Prototype and demonstration FBRs have been built and operated in a number of countries, though at the end of 2010 only two were operable, in Japan and the Russian Federation. Two further large FBRs are currently under construction, the 500-MW prototype fast breeder reactor (PFBR) in Kalpakam, India and the 880-MW BN800 in Beloyarsk, Russian Federation, which are to be connected to the grid between 2013 and 2014. China has signed an agreement with the Russian Federation to build two BN800 reactors at Sanming, while pursuing its own FBR technology development programme.

Reactor lifetimes

Many of today's nuclear power plants (belonging to what is often termed "Generation II") were built in the 1970s and 1980s and will reach the end of their originally planned operating lifetimes of 40 years from 2015 onwards. However, most components and systems can be replaced as they wear out or become obsolete, meaning that there are just a few major components (in most cases, the reactor pressure vessel, some of its internal components, and the containment) that limit operating lifetimes. Operating experience and studies of the properties of materials used in these components have revealed no technological barriers preventing long-term operation (LTO) of many reactors, particularly PWRs and BWRs.

With careful monitoring of plant performance, analysis of operating experience, modernisation programmes and refurbishments, many plants have good prospects for life extensions beyond 40 years. As of July 2011, the nuclear safety authorities in the United States had granted licence renewals to more than 70 reactors allowing them to operate for 60 years, with more than 14 further applications under review. Other countries with similar reactors are also planning to extend their operating lifetimes. In many countries, decisions on extending plant lifetimes are made through the periodic renewal of operating licences, which involves comprehensive safety analyses.

Generation III/III+, Generation IV and other reactor concepts

Most light water reactors being constructed in the world today belong to what is called Generation III/III+, and are derived from the PWRs and BWRs that were constructed in the 1980s and still in operation today. Evolutionary improvements in the design of the fuel, the thermal efficiency and the safety systems were incorporated in the design of the Generation III reactors in the 1990s. More recent improvements leading to even higher levels of safety and efficiency characterise the so-called Generation III+ reactors (ABWR, ACR1000, AP1000, APWR, EPR and ESBWR). Generation III/III+ reactors, and their subsequent evolutions, are expected to represent the bulk of nuclear generation in the 21st century.

Generation IV reactors are being designed as reactors that incorporate revolutionary design features, offering higher levels of safety, economics, non-proliferation and sustainability than the current generation. An international co-operation framework, the Generation IV International Forum or GIF, has been set up with ten active members (Canada, China, Euratom, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland and the United States) to carry out the development of six systems that have been identified as most promising: the gas-cooled fast reactor (GFR), the very-high-temperature reactor (VHTR), the supercritical-water-cooled reactor (SCWR), the sodium-cooled fast reactor (SFR), the lead-cooled fast reactor (LFR) and the molten salt reactor (MSR). Industrial deployment of such reactors, in parallel to LWR technology reactors, is not expected before 2040.

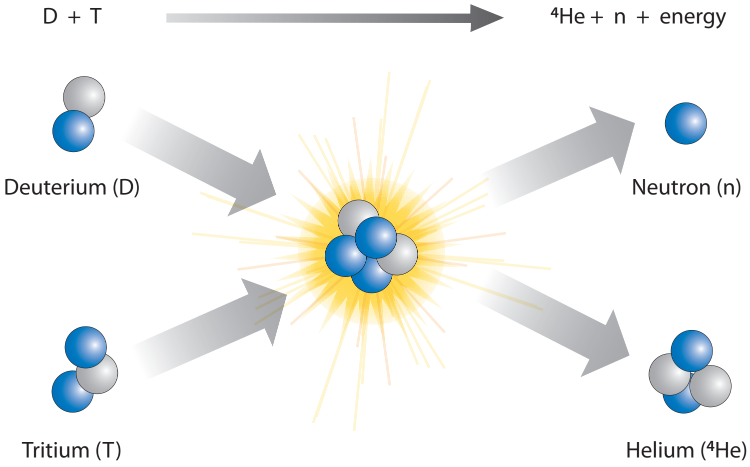
Finally, new reactor concepts have recently emerged, which could be deployed in the next decades, and which do not fall into the above categories. Among those concepts are the small modular reactors (SMR) characterised by their small size (in terms of electrical power output, typically less than 300 MW – significantly less than today's large Generation III+ reactors which offer between 1 200 MW and 1 700 MW), a high level of modularity in design and construction, as well as the ability to be scalable (i.e. to allow for incremental capacity increase by adding modules to generate as much power as a larger reactor). Proponents of such reactors claim that this would offer utilities lower investment costs, faster and more economical construction and assembly – all compensating for the "economy of scale" which benefits today's very large reactors.

Nuclear fusion: a potential energy source

Whereas nuclear fission involves the splitting of a heavy atomic nucleus, nuclear fusion is the process of combining two light nuclei to form a more massive nucleus. This process takes place continuously in stars throughout 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 from fusion has been researched for decades. The most widely studied fusion reaction [the deuterium-tritium (D-T) 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) two neutrons and one proton, combine to form helium and a neutron, releasing energy in the process. Deuterium can be extracted from ordinary water. Tritium could be produced by the fusion reactor itself, through neutron irradiation of an isotope of lithium Li^6, the main producers of which are Bolivia and Chile.

Figure 2.7: **Typical fusion reaction**



Source: Joint European Torus.

At the extremely high temperatures required for fusion reactions to take place, the fuel is in the form of a plasma, a state of matter where all the electrons have been stripped from atoms, leaving only nuclei. The understanding and control of plasmas is a major challenge in the development of fusion power. The principal problem in designing a fusion reactor is the containment of the plasma fuel, which needs to be kept at very high temperatures to initiate and maintain the reaction. One of the most promising means for achieving this is a toroidal (torus or doughnut-shaped) magnetic confinement system. The other is inertial confinement.

If they become practicable, fusion reactors could offer several advantages, including:

- an essentially unlimited fuel supply (deuterium and tritium);
- production of only small amounts of mostly short-lived radioactive waste (mainly tritium and the structural components of the reactor itself);
- no possibility of an accident with any significant off-site impacts, as the fuel load would be just a few grams at any time and collapse of the plasma would instantly stop the fusion reaction, with no residual heat production;
- no requirement for materials and technologies of concern for the proliferation of nuclear weapons.

Existing magnetic confinement fusion test facilities include the European Union's Joint European Torus (JET) in the United Kingdom, the Princeton Plasma Physics Laboratory in the United States, and the JT-60U Tokamak of the Japanese Atomic Energy Agency. The next step in the development of fusion will be the international thermonuclear experimental reactor (ITER), now under construction in France. Jointly funded by China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States, ITER is expected to have a 20-year operating life. It will aim to demonstrate the feasibility of fusion energy. A further project will then be required to fully demonstrate a practical fusion energy system; the earliest date for this is likely to be around 2040. Hence, commercial use of fusion energy is at least several decades away.

In parallel, projects investigating laser-driven fusion or fusion by inertial confinement are being performed in the National Ignition Facility in the United States in the frame of the LIFE project, and in Europe in the frame of the HiPER project. Demonstration of power generation is not foreseen before at least two decades, and commercial deployment is even further away.

References

GIF website, provides information on the development of the six Generation IV reactor concepts selected as most promising, www.gen-4.org/.

ITER website, provides information on the basics of nuclear fusion and about ITER, www.iter.org.

LIFE and HiPER websites, provide information on fusion by inertial confinement and research performed at the National Ignition Facility, https://life.llnl.gov/ and in Europe www.hiper-laser.org/.

Murray, R.L. (2009), *Nuclear Energy: An Introduction to the Concepts, Systems, and Applications of Nuclear Processes,* Sixth Edition, Butterworth-Heinemann, Woburn, MA, United States.

NEA (2008), *Nuclear Energy Outlook 2008,* Chapter 13 and Appendix 5, Nuclear Energy Agency, OECD, Paris, France.

NEA (2011), “Current Status, Technical Feasibility and Economics of Small Nuclear Reactors”, Nuclear Energy Agency, OECD, Paris, France.

WNA website, provides a range of basic information about how nuclear power works, www.world-nuclear.org.

Chapter 3

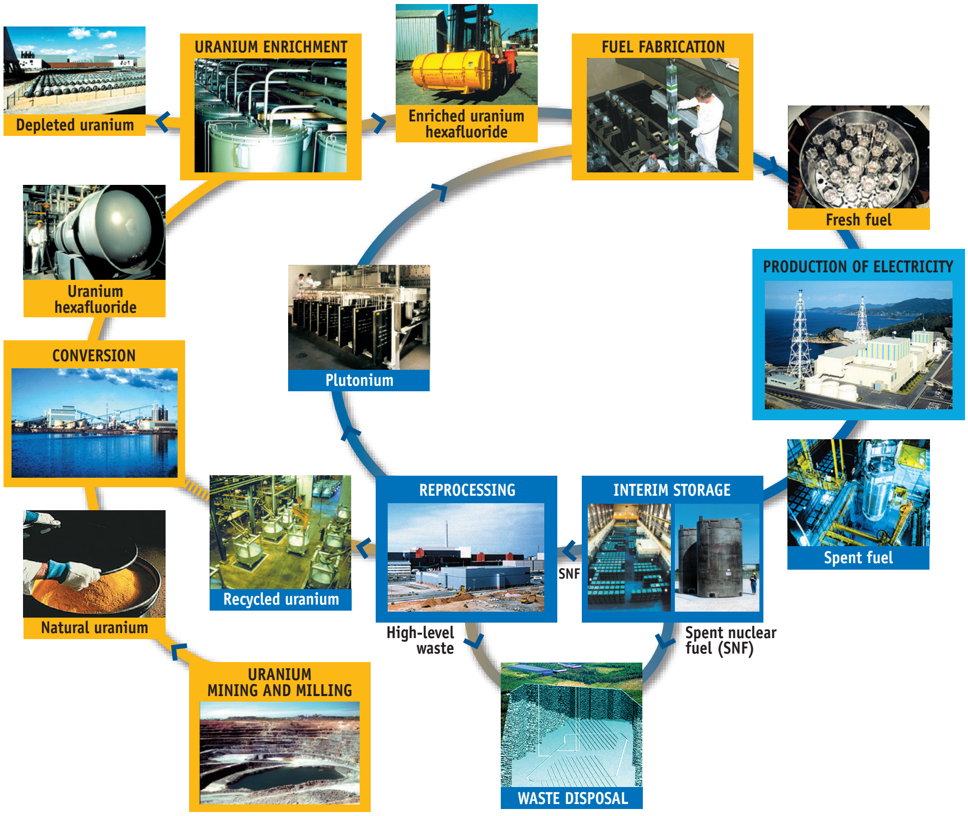
The Nuclear Fuel Cycle

The nuclear fuel cycle is the chain of processes whereby nuclear fuel is prepared and managed before and after its use in a reactor. The steps to prepare new fuel, up to its insertion in the reactor, are known as the "front end" of the fuel cycle, while the management and processing of spent fuel after it is unloaded from the reactor is known as the "back end" of the fuel cycle.

Two basic types of fuel cycle exist – once-through and closed – the difference being the way the spent nuclear fuel (SNF) 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 placed in storage facilities pending its disposal in an underground repository. In a closed fuel cycle, spent fuel is recycled, allowing the unused fissile material to be recovered and reused in new fuel.

Decommissioning is the term used to describe all the procedures that are undertaken following the final closure of a reactor or fuel cycle facility to maintain the facility in a safe condition while removing and managing all radioactive materials, dismantling the facility and eventually making the site available for other purposes.

Figure 3.1: **The nuclear fuel cycle**



The front end: preparing fuel for the reactor

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. About 55% of uranium production in 2009 involved the extraction of ore using conventional open pit or underground mining methods. Over 35% was accounted for by *in situ* leaching (ISL), a method whereby a solvent solution is injected underground, dissolves the uranium into the solution and is then recovered from extraction wells (this technique is not suited to all geological conditions). The majority of the remainder was produced as a by-product, mainly from the mining of copper or gold.

The proportion of uranium produced from conventional mines has declined over recent years while the use of ISL has increased. This reflects the lower costs, shorter lead times and lower environmental impacts of ISL. In general, ISL facilities can be brought into operation relatively quickly, and can economically exploit smaller and lower grade deposits. However, care must be taken to avoid contaminating groundwater. In that respect, international best practices have been established over the last decade which mining companies and producer nations have been adopting to maintain the high levels of environmental management of uranium production.

Milling is the process through which mined uranium ore is physically and 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 product of milling is a powder of uranium oxide (U_3O_8) known as "yellowcake", though it can also be grey in colour.

In 2010, there were 18 uranium producing countries, of which 8 (Australia, Canada, Kazakhstan, Namibia, Niger, the Russian Federation, the United States and Uzbekistan) produce over 90% of the world's output (see Table 3.1). Kazakhstan became the world leader in production in 2009 and continues to increase production today. Australia and Canada remain important producers. These three countries accounted for over 60% of world output in 2010.

Table 3.1: Uranium production by country (2010)

	Uranium production (tonnes)
Australia	5 918
Brazil	148
Canada	9 775
China	1 350
Czech Republic	254
India	400
Kazakhstan	17 803
Malawi	681
Namibia	4 503
Niger	4 197
Russia	3 562
South Africa	582
Ukraine	837
United States	1 630
Uzbekistan	2 874
Others	156
Total	**54 670**

Mining and milling of uranium ore produces waste of different types, all of which require appropriate management. The principle waste from open pit and underground mining is waste rock. This rock may also include ore with sub-economic levels of uranium or high levels of contaminants. Milling produces waste in the form of mill tailings, which are a mixture of finely ground rock, process liquids, fission products and other contaminants. ISL produces no waste rock or mill tailings, but it must be appropriately managed to protect groundwater.

The quantity of ore required to produce a tonne of product using open pit or underground mining depends primarily on the average grade of the ore and can range from 10 to 1 000 tonnes or more (i.e. average grades of 10% to 0.1%). Thus, the volume of tailings that results from milling this ore can be large when mining low grade ore. Because of their volume and the presence of radiological and chemical contaminants, tailings have to be contained and treated in designated areas close to the milling site.

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

Uranium hexafluoride 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 and the Russian Federation (see Table 3.2). Uranium hexafluoride is a 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 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.

Table 3.2: **Major uranium hexafluoride conversion plants**

	Site	Nominal capacity (tonnes U/yr)
Canada	Port Hope, Ontario	12 500
China	Lanzhou	3 000
France	Pierrelatte	14 000
Russian Federation	Irkutsk and Seversk	25 000
United Kingdom	Springfields	6 000
United States	Metropolis, Illinois	15 000

Source: WNA, 2011.

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 (0.71%), with the second correspondingly depleted. Uranium enriched to less than 20% ^{235}U is known as low-enriched uranium (LEU), while that enriched to higher levels is known as highly-enriched uranium (HEU). However, commercial reactors use uranium enriched to less than 5% ^{235}U. In contrast, weapons-grade HEU is enriched to more than 90% ^{235}U.

Two methods of enrichment are presently in commercial use, gaseous diffusion and centrifugation, both based on UF_6 (see Table 3.3). Gaseous diffusion is the older technology, and the two remaining plants in France and the United States will be replaced by new centrifuge plants over the next few years. Diffusion plants need to be very large and have high electricity requirements, making them less flexible and more costly than centrifuge plants. Centrifuge technology has been progressively developed to the point where the latest designs consume 50 times less energy than diffusion plants. This greater efficiency allows a higher proportion of the ^{235}U in natural uranium to be economically extracted. Altogether, eight countries have commercial centrifuge enrichment plants in operation or under construction, and centrifugation is expected to remain the dominant technology for the foreseeable future.

Table 3.3: Major uranium enrichment plants in operation and under construction, capacities in thousand separative work units (SWU)/year

Country	Supplier	Site	**Nameplate capacity 2010** (tSWU/yr)	**Effective supply 2010** (tSWU/yr)	**Planned capacity 2015** (tSWU/yr)
Operational centrifuge plants					
China	CNNC	Hanzhun and Lanzhou	1 300	1 300	3 000
Germany, Netherlands, United Kingdom	URENCO	Gronau (D), Almelo (NL), Capenhurst (UK)	12 800	12 800	12 300
Japan	JNFL	Rokkasho	Refurbishment	0	150
Russian Federation	ROSATOM/TVEL	Angarsk, Novouralsk, Zelenogorsk and Seversk	28 600	24 350	30 000
United States	URENCO	Eunice, New Mexico	Test operation	–	5 700
Gaseous diffusion plants, expected to close before 2015					
France	AREVA	Georges Besse	10 800	8 500	Closed
United States	USEC	Paducah, Kentucky	11 300	6 000	Undecided
New centrifuge plants, expected to be in operation by 2015					
France	AREVA	Georges Besse II	Inaugurated Dec. 2010	–	7 000
United States	USEC	Piketon, Ohio	Under construction	–	1 000
United States	AREVA	Eagle Rock, Idaho	Planned*	–	–

* Construction suspended in December 2011, AREVA press release.

Source: WNA, 2011.

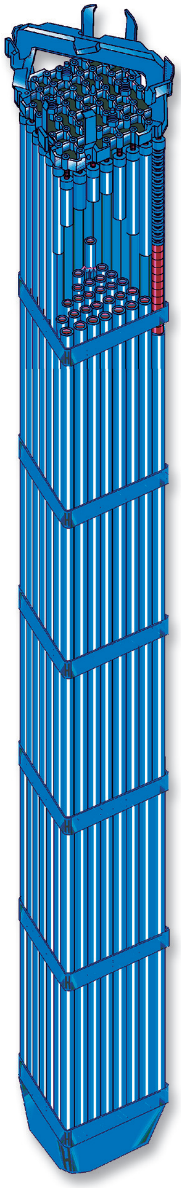
Technology for uranium enrichment using lasers is still under development. It has not yet been fully demonstrated at large scale. If successfully deployed for commercial use, laser enrichment technology could offer even lower operating costs and further increase the proportion of ^{235}U extracted. However, concerns over proliferation risks associated with this technology, due to its smaller footprint and detectability, will need to be fully addressed.

The enrichment process also produces depleted uranium, of which there existed, at the end of 2010, an estimated stock of over 1.5 million tonnes. The depleted uranium from the gaseous diffusion process often contains recoverable ^{235}U, normally around 0.3% ^{235}U (compared with the initial 0.71%). Hence, with sufficiently high uranium prices and excess enrichment capacity, it can be economic to process such material in more efficient centrifuge plants to extract additional LEU for use as nuclear fuel, leaving “new” depleted uranium containing 0.2% ^{235}U or less.

Different countries have adopted different strategies for managing this material. Typically, the depleted uranium is stored in UF_6 form in large cylinders (for example, in the United States and the Russian Federation). In this form, it can represent a potential chemical hazard if the cylinders were to leak. France has begun converting its stock of depleted UF_6 into a stable oxide for long-term storage and possible eventual re-use as a fuel in fast breeder reactors.

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

Figure 3.2:
Typical BWR fuel assembly
(about 4 m tall and about 15 cm on each side; weighs about 300 kg)



Fuel fabrication

Most reactors use uranium dioxide (UO_2) as their fuel. Its production involves the transformation of UF_6 into UO_2 powder, which is then pressed and heated at high temperatures (up to 1 400 °C) to produce small cylindrical pellets. These are loaded into hollow metal tubes (fuel rods), each usually about 4 metres long and containing a few hundred pellets. Once sealed, the rods are placed in a fuel assembly, usually in a square lattice arrangement. They are held together by top and bottom nozzles and spacer grids (see Figure 3.2). The metal used for the rods and other fuel components is highly corrosion-resistant, typically stainless steel or zirconium alloy. As well as fuel rods, some positions in the lattice are used for control rods.

For PWRs, fuel assemblies usually have between 14 and 17 rods on each side, depending on the reactor model. A typical large PWR will contain around 200 or more assemblies, meaning that the core will contain over 50 000 fuel rods and around 20 million fuel pellets. BWR fuel assemblies are generally smaller, usually having between 7 and 9 rods per side, with a correspondingly larger number of assemblies (typically around 700) in the core.

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

Although there are a large number of fuel fabricators worldwide, commercial competition between them is limited, largely due to the highly specific requirements for each reactor reload, different national regulatory systems and the wide variety of reactor designs. Furthermore, the fuel management strategies pursued by different reactor operators vary according to local conditions and market circumstances.

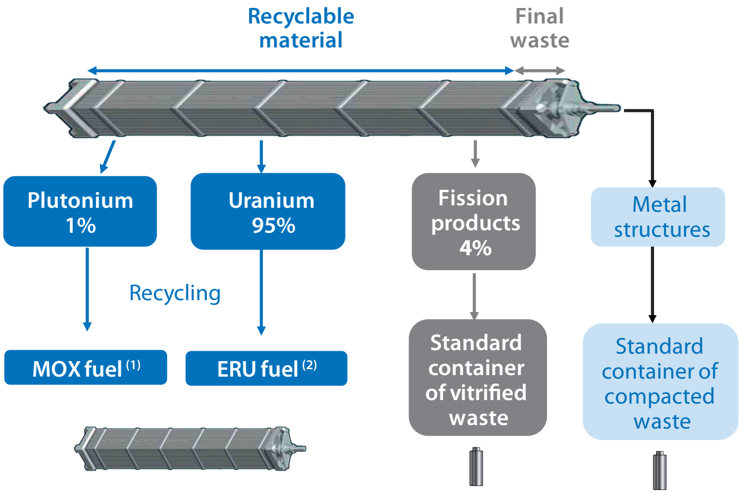
The back end: options for managing spent fuel

The back end of the fuel cycle starts when the irradiated or "spent" fuel is unloaded from the reactor. It is invariably 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 temperature of the fuel is much lower. It is then ready for long-term storage or for reprocessing if a closed or partially closed fuel cycle with recycling is being pursued.

Long-term storage of spent fuel may be under wet or dry conditions. If wet storage is chosen the spent fuel can be transferred to another pool similar to that in which it has rested during the initial period of cooling. Alternatively, and increasingly, the fuel can be loaded into large, 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 at least 50 years before packaging or repackaging becomes necessary or before disposal in an underground repository (see Chapter 6).

Reprocessing or recycling is the operation by which the unused fissile material (uranium and plutonium) in spent fuel can be recovered with the intention of re-using it in new nuclear fuel (see Figure 3.3). It also reduces the volume, heat production and long-term radiotoxicity of the remaining waste that requires disposal. This approach to spent fuel management has been chosen for some or all of their spent fuel by several European countries (including Belgium, France, Germany, Switzerland and the United Kingdom), China, India, Japan and the Russian Federation.

Figure 3.3: **Composition and reprocessing of spent fuel**



(1) MOX : mixed oxide.
(2) Enriched recycled uranium.
Source: AREVA.

Reprocessing using current reactors and fuel cycles 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 mixed-oxide fuel (MOX). The separation of uranium and plutonium is achieved using a chemical process called PUREX (plutonium uranium reduction-extraction). The remaining fission products and minor actinides are high-level waste (see Chapter 6). Another remnant is the non-dissolvable metallic structures of the fuel assemblies. Current reprocessing plants are large, complex facilities that have been built in only a few countries (see Table 3.4).

Spent MOX fuel can itself be reprocessed and the plutonium it contains recycled again. However, with current reprocessing and reactor technologies the number of plutonium recycles is in practice limited to two or three. This is due to the build-up of non-fissile plutonium isotopes, which make it harder to sustain a chain reaction. In addition, isotopes of other heavy elements created during irradiation make the fuel material more difficult to process. This limitation on the number of recycles, however, would not apply if the recycled material were to be used in fast reactors.

Table 3.4: **Major LWR spent fuel reprocessing plants**

	Site	Nominal capacity (tonnes U/yr)
France	La Hague	1 700
Japan	Rokkasho*	800
Russian Federation	Ozersk	400
United Kingdom	Sellafield	900

* In commissioning, start up expected in 2012.

Source: WNA.

The uranium recovered during reprocessing can also be recycled into fuel. Although this is being carried out on a limited scale by some reactor operators, most recycled uranium is presently stored for future use. This is because the recovered uranium is more radioactive than natural uranium and hence it requires dedicated enrichment and fuel fabrication facilities to avoid contaminating fresh uranium, which adds to the costs of such recycling.

Decommissioning of nuclear facilities

When any nuclear plant closes permanently, whether it is a reactor, an 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 includes removal of all radioactive materials, decontamination and dismantling, and finally demolition and site clearance. If the site is no longer used as a nuclear site, it will be prepared for eventual release for other purposes. This process, known as decommissioning, usually consists of several stages that may take place over many years.

As of 2010, some 125 prototype and commercial reactors had been shut down and were in various stages of decommissioning. The remainder of this section mainly describes the processes involved in the decommissioning of power reactors.

Close-out

In this initial stage of decommissioning, all remaining spent fuel is removed from the reactor and stored in the usual way, the coolant and other liquid systems are drained, the operating systems are disconnected, and external apertures in the plant are sealed. The atmosphere in the containment building is controlled and access is limited, with surveillance systems installed. Usually, close-out takes place very soon after permanent shutdown.

Decontamination and dismantling

In this next phase, 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 permanent 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 can be removed and the site de-licensed 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 considerable 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 periods 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.

Several closed nuclear power plants have reached advanced stages of decommissioning in the United States and Europe, including unrestricted site release in some cases. Decommissioning practices are maturing and sufficient experience has been gained so that the processes involved 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 6). The European Commission estimates that decommissioning of a typical nuclear power plant can produce up to 10 000 m^3 of radioactive waste. However, 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 inventory of radioactivity at 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 either be cut into more manageable pieces or, more commonly, can be removed and transported intact to a low-level waste repository.

One decommissioning issue currently under discussion is the lack of 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.

References

IAEA website, provides details and statistics for nuclear fuel facilities worldwide, www-nfcis.iaea.org (registration required).

NEA (2008), *Nuclear Energy Outlook 2008,* Chapters 5 and 14, Nuclear Energy Agency, OECD, Paris, France.

NEA (2009), *Decommissioning of Nuclear Facilities: It Can and Has Been Done,* Nuclear Energy Agency, OECD, Paris, France. Available at www.oecd-nea.org/rwm/wpdd.html.

NEA (2011), *Trends towards Sustainability in the Nuclear Fuel Cycle*, Nuclear Energy Agency, OECD, Paris, France.

NEA (2012), *Uranium 2010: Resources, Production and Demand*, published biennially by the OECD/NEA and the IAEA, Nuclear Energy Agency, OECD, Paris, France.

WNA (2011), *The Global Nuclear Fuel Market, Supply and Demand 2011-2030*, World Nuclear Association, London, United Kingdom.

WNA website, provides information on the nuclear fuel cycle and uranium production, www.world-nuclear.org.

Chapter 4

Nuclear Safety

The safety of a nuclear facility depends on the engineered protection built into it, on the organisation, training, procedures and attitudes of the operator, and on the verification and inspection activities carried out by an independent regulatory body with the powers to suspend the operation of the facility if necessary.

Radioactivity generated during nuclear power production has the potential to harm people and the environment if released accidentally. Thus, very high levels of safety are considered essential to the use of nuclear energy. The primary purpose of all nuclear safety measures is thus to ensure that radioactivity remains contained or, if released, then only in controlled amounts that ensure no significant harm is done. There nevertheless remains some degree of risk, which must be effectively managed by the operator with oversight by a strong regulatory body.

In general terms, the safety of a nuclear installation can be understood as the ability of its systems and personnel to first prevent accidents from occurring, and second to mitigate the consequences if an accident should occur. The overarching goal is that the radiological impact on people and the environment from nuclear installations remains as small as possible for both normal operation and potential accidents. To achieve this, technical and organisational measures are put in place at all stages of a nuclear facility's lifetime starting with its siting and design, through manufacturing, construction and commissioning, during operation, and finally during its decommissioning. At every step, adherence to certain principles and practices which define what is known as safety culture is essential to ensure the safe operation of nuclear facilities (see Figure 4.1).

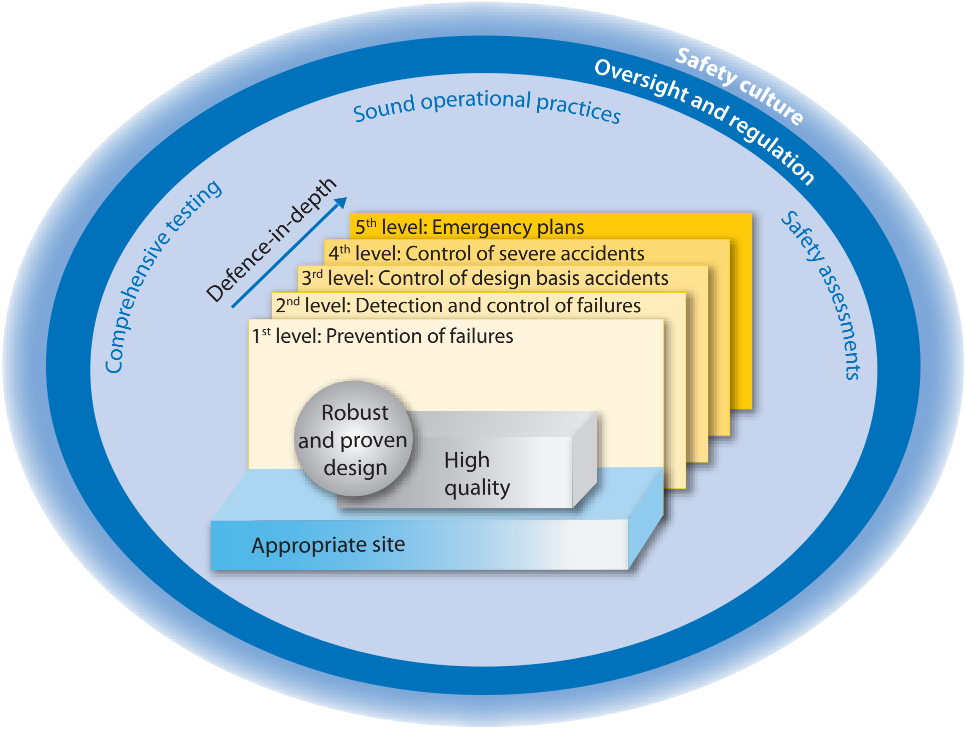
This chapter discusses safety considerations pertaining primarily to nuclear power plants, but the same principles apply to other nuclear installations. The chapter first describes the technical aspects of nuclear safety (siting, design using the defence-in-depth principle, engineering, manufacturing and testing), then the methods to assess the safety of the plant. Safety principles and practices are then described, highlighting the importance of organisational and human factors in ensuring the highest levels of safety. Finally, the chapter ends by identifying lessons learnt from three severe accidents, Three Mile Island (1979), Chernobyl (1986) and Fukushima Daiichi (2011). These lessons have led to increased safety requirements for the current and future nuclear reactor technologies.

Technical aspects of nuclear safety

Siting

The selection of a site for a nuclear facility is governed by national legislation and requires regulatory approval. The safety factors taken into account include a potential site's hydrological, geological, meteorological, seismic and demographic characteristics. In assessing a site, the aims are to minimise the human and environmental exposure to any release of radioactivity and to ensure that safety-related structures and systems are able to withstand any reasonably predictable natural event, e.g. an earthquake or a major flood. As the accident at Fukushima Daiichi showed, site assessments also need to take into account combinations of such events. For all these reasons nuclear power plants are, to the extent possible, generally sited away from large population centres.

Figure 4.1: Elements of nuclear safety



Defence-in-depth

A basic design philosophy of nuclear facilities is defence-in-depth, which provides multiple independent levels of protection against the release of radioactive substances (see Figure 4.1). The first level of defence when designing a nuclear facility is the prevention of failures. Thus nuclear designs strive to ensure reliable, stable and easily manageable operation. The use of high-quality technology with considerable safety margins in the strength and capacity of safety-critical components are vital elements in achieving this goal.

The second level of defence-in-depth, the detection and control of failures, involves the rapid detection of any deviation from normal operation and, where possible, its automatic correction by process control and protection systems, without interfering with normal operation. In case such systems fail, engineered safety systems (discussed below) automatically place the reactor into a safe condition and 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 design basis accidents is the third level of defence.

The design characteristics summarised above represent the first, second and third levels of defence-in-depth against a nuclear accident. The fourth level is to control any severe accident with the aim of limiting its consequences and preventing an external release of radioactivity (if necessary, at the expense of the future operability of the plant). The final level is the mitigation of the radiological consequences if a serious release does occur through implementing an off-site emergency plan.

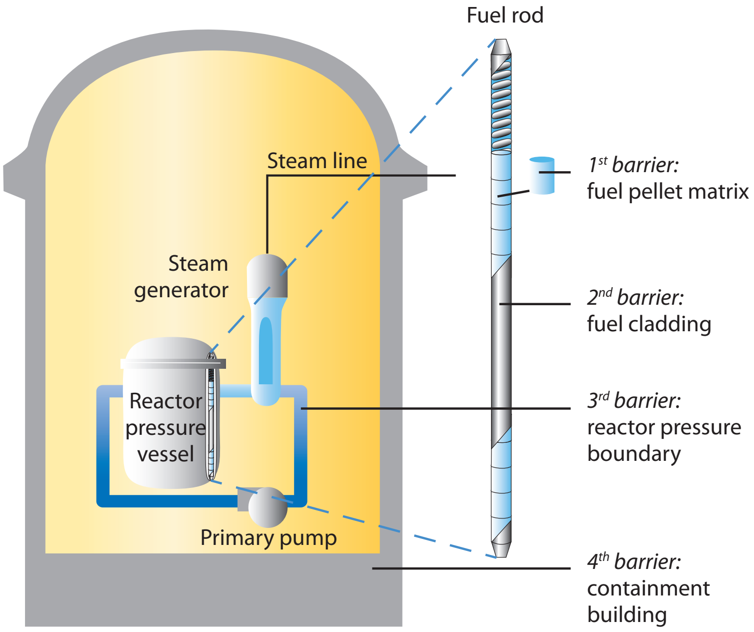
Engineered safety systems

In a nuclear power plant, systems are put in place to ensure that:

- radioactive material is contained at all times;
- the fission process, responsible for about 93% of the heat generated in the reactor core, can be shut down at all times almost instantaneously to terminate the generation of all but residual, or decay, heat;
- decay heat, which is generated by the decay of fission products and represents about 7% of the heat produced in the core during operation, is removed after shutdown in order to protect the integrity of the barriers against a radioactive release.

Multiple physical barriers are provided to prevent the release of radioactivity. The primary physical barriers are the fuel matrix and its hermetic container – the fuel cladding; next is the reactor pressure boundary within which the coolant circulates during normal operation, particularly the reactor pressure vessel that contains the reactor core itself; the final physical 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 reactor pressure boundary from external hazards such as projectile impact, fires or explosions (see Figure 4.2).

Figure 4.2: Typical barriers confining radioactive materials



Although not a physical barrier to the release of radioactive material, the final element of defence-in-depth is the zone around the plant. This zone provides separation between the public and a potential radioactive release. The detailed requirements for this zone vary from country to country, but they include siting nuclear facilities away from large population centres, avoiding new developments near to existing sites, and limiting access to areas close to nuclear plants. Emergency plans for dealing with a nuclear incident will include protective measures such as evacuation of the local population in the event of a significant release of radioactivity.

The engineered safety systems include the equipment and components necessary to monitor the nuclear facility's operation and to ensure three safety functions:

- shut down the reactor;
- provide cooling to the fuel;
- and in the event of an accident, ensure that radioactive material is securely maintained inside the containment of the reactor.

An important first step is to stop the fission process through reactivity control when necessary to mitigate the consequences of an event. The fission process can be shut down by means of neutron-absorbing rods (see Chapter 2). These rods can be rapidly inserted to almost instantly stop the fission reaction in what is known as a scram or reactor trip. In addition, a secondary means of emergency shutdown is provided, e.g. by the injection of neutron-absorbing liquids, to ensure long-term reactor shutdown. The Chernobyl accident, described below, occurred as a consequence of inadequate reactivity control.

Heat is normally removed from a reactor by pumped circulation of coolant through the core. Should the cooling system fail, separate engineered backup systems (emergency core cooling systems) ensure that decay heat is removed. When the plant is shut down, electricity for the cooling and other essential systems is supplied from the plant's connection to the electrical grid. If this is not available, on-site emergency backup generators can be used. Failure to remove decay heat can lead to the degradation of the reactor core, as was the case in the TMI-2 and Fukushima Daiichi accidents discussed below.

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 safety function.

Moreover, the safety systems are designed by applying the principles of reliability; redundancy, i.e. providing additional backups or greater strength than is needed based on already pessimistic assumptions; diversity, i.e. the avoidance of 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 the assumptions about risks of failure, the practice of basing design safety on a "what if?" approach, and the careful analysis of previous component and materials performance. The notion of "conservatism" requires however that risks – which are a function of severity and probability of hazards – are correctly assessed. Although the detailed analysis of the accident in the Fukushima Daiichi plant will probably take a few years to be completed, current assessments of the accident indicate that the risk of flooding from a tsunami was underestimated. The tsunami run-up wave which hit the plant is estimated to have been at least 14 metres high – whereas the plant was designed for a 5.7 metres maximum water elevation.

Manufacturing and construction

High-quality equipment is a prerequisite for reliable operation. Thus quality assurance is a vital component of nuclear safety. Special codes and standards have been developed for the equipment and components used in any nuclear facility. These include rigorous testing and inspections to confirm that quality standards are met, and their criteria ensure that only well-proven and established technologies are employed. The operator has the primary responsibility for assuring that the quality assurance and control programmes are effectively implemented for their nuclear facilities. In addition, national regulatory authorities oversee the implementation of these quality assurance and control programmes.

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 the pre-defined success criteria are met.

Extensive testing is also conducted after major maintenance operations and when components are either replaced or upgraded.

Safety assessments

Before allowing a nuclear installation to be constructed, commissioned and operated, its safety must be assessed through a systematic and rigorous analysis of the installation's design against a defined set of conditions. These conditions include factors such as potential failures, natural and man-made hazards, and their interactions with safety barriers. This assessment typically relies upon a deterministic safety approach where 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 the potential failures or hazards, it factors in the single worst failure of a safety component or subsystem, and it assumes that all other designed safety systems will be available to perform their designed safety function.

This process is used by the designer before the design is finalised to confirm the plant's ability to operate successfully within prescribed operating and regulatory limits given the characteristics of the proposed site. These assessments are documented in "safety analysis reports" or "safety cases". The final versions of these are critically reviewed by regulatory authorities prior to licensing; afterwards they constitute the baseline point of reference for understanding how to safely operate the facility.

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. Self-assessment and independent safety peer reviews are essential elements in operational safety. Self-assessments are conducted by the organisation operating the installation or by independent peers; they may cover specific safety issues or the whole installation. International peer reviews of different types are conducted by the IAEA under the request of member states. The World Association of Nuclear Operators (WANO) also conducts in-depth periodic reviews of the operating plants. Global reviews are also conducted by signatories of the Convention on Nuclear Safety (see Chapter 7). This convention is an incentive instrument requiring that contracting parties submit reports on the implementation of obligations defined in the convention, which are reviewed by other contracting parties in a formal process every three years at most.

Since the 1980s, the deterministic approach to safety assessment has been supplemented by using probabilistic safety assessment (PSA) methodologies. Following the PSA approach, information on the probability of equipment failures and human errors are estimated, in part, based on equipment performance data and operational experience. Using this information, insights useful in enhancing the safe operation and maintenance of the nuclear installation can be developed. Further, insights can be gained on which sequence of events, or combinations of events, could potentially lead to core damage (Level 1 PSA), and thus to a severe accident. An improved understanding of the frequency of these severe accidents can be developed for the specific design of the nuclear installation. A standard practice used when implementing a PSA methodology is to perform at least a Level 2 PSA that identifies the ways in which radioactive releases from the plant can occur and estimates the magnitude and frequency of these releases. This analysis provides additional insights into the relative importance of the accident prevention and mitigation measures such as the reactor containment. Level 3 PSAs are used to estimate public health and other societal risks such as contamination of land or food. The results of these studies are used for a variety of purposes, such as assessing the impact of new design features on the safety of the nuclear installation, prioritising plant safety improvements, training operators and setting inspection priorities.

The probabilistic methodology has supplemented rather than replaced the deterministic safety approach, noting that high-quality Level 1 PSA and limited scope Level 2 PSA studies could be an effective complement to the deterministic approach. This recognition was termed risk-informed regulation by the US NRC and is now used in other countries. To remain a useful decision-making tool in the area of nuclear safety, the PSA must remain a living document (a living PSA). This requires that the PSA of the nuclear plant and its supporting documentation be continuously updated to take into account changes in design and operational features, plant data or scope and improvements in the methodology.

Organisational and human factors, safety culture

Safety principles

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

- Laying the prime responsibility for safety on the operator, with management principles that give the necessary priority to safety.
- Establishing an environment where issues are encouraged to be raised and addressed without fear of reprisal.
- Establishing a strong operating organisation, ensuring among other things an adequate number and deployment of qualified and experienced personnel.
- Defining conservative operating limits and conditions that establish safe boundaries for operation.
- Using approved procedures for all operations, including tests, maintenance and non standard operations, which include self-checking and independent verification processes.
- Implementing extensive quality-assurance programmes for all operations, inspections, testing and maintenance.
- Conducting training programmes for all activities having an impact on nuclear safety.
- Providing all necessary engineering and technical support throughout the lifetime of the installation.
- Timely reporting of all incidents to the appropriate regulatory body.
- Establishing 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.
- Preparing emergency procedures and plans, and regularly rehearsing them, so as to harmonise the responses of the various organisations that would be involved in mitigating the consequences of any accident.
- Giving careful consideration to human factors engineering principles in the design and layout of the control room, alarm and indicating systems.

These safety principles were formalised and approved by the member countries of the IAEA in 2006.

In spite of 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 attitude and state of mind of all the individuals whose actions can impact safety, is a key nuclear safety principle. The management system is also an essential component, by ensuring that safety culture is promoted, continuous surveillance and periodic safety analyses are conducted and lessons learnt from operating experience are applied. A strong safety culture encourages the individual to identify errors without fear of reprisal or recrimination. 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. It must be transmitted continuously from the top, and permeate the whole industry, but most essentially in the operating and regulatory organisations.

Responsibility for safety and regulation

Each country is responsible for the safety of the nuclear power plants within its borders. Governments are responsible for enacting legislation and for establishing an independent regulatory authority. A regulatory authority should have legal authority, technical competence and financial resources to carry out its missions, namely: (1) to develop and enact a set of appropriate, comprehensive and sound safety requirements and guides; (2) to verify compliance with such regulations; and (3) to enforce the established regulations by imposing the appropriate corrective measures. Regulatory authorities adhere to principles of *good regulation,* which include independence, technical competency, transparency, efficiency, clarity and reliability. There is also an inherent responsibility for the broader international nuclear regulatory community to encourage all countries with nuclear power plants to establish and maintain a robust, independent and technical competent regulatory authority.

Notwithstanding the responsibilities of the regulator, the prime responsibility for safety is assigned to the licence holder or operator. This responsibility is retained throughout the life of the facility and cannot be delegated. The licensee fulfils its responsibility in accordance with the requirements established by the law and the specific license. Other actors such as designers, plant vendors, manufacturers, constructors and carriers are responsible for their professional activities regarding safety, normally defined in the corresponding contracts. However, regulatory review and control are essential in all countries that operate nuclear power plants and as such there needs to be an independent nuclear regulatory organisation responsible for licensing nuclear installations and for enforcing the relevant regulations.

These regulatory organisations:

- develop and implement appropriate regulatory requirements and safety standards;
- assess plant designs against these safety requirements and issue licences for siting, construction and operation;
- inspect, monitor and review the safety performance of licensees;
- verify compliance with regulatory requirements;
- and ensure that actions are taken to address departures from regulatory requirements or other safety concerns that can have an impact on public health and the environment.

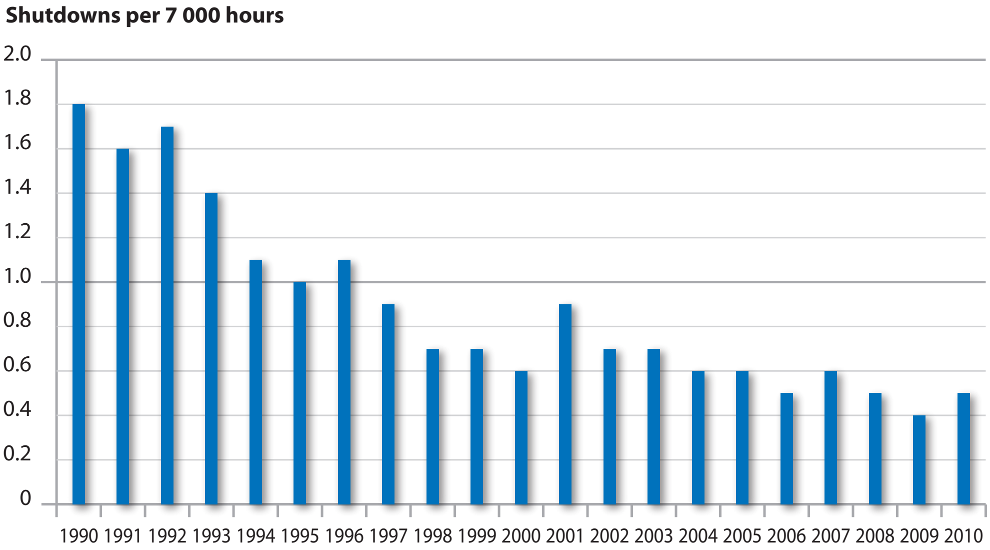
International co-operation through organisations such as the NEA and the IAEA also makes a vital contribution to the development of relevant safety and regulatory concepts and the spreading of good practice. For example, the Convention on Nuclear Safety, to which all countries operating nuclear power plants are signatory, defines a set of internationally accepted principles and a set of obligations relating to the basic elements of nuclear safety. An important principle reflected in the 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 processes are protected from undue external pressure.

Learning from operating experience

A great deal of information and many lessons have been gathered from nearly 15 000 reactor-years of operating experience worldwide. These lessons are routinely shared through operational experience feedback mechanisms such as: databases, reports by international organisations, journals and conferences. The IAEA/NEA International Reporting System for Operating Experience (IRS) is the most relevant public database on operating experience. The WANO comprehensive system, only open to its members, is also a major source of information. Regulatory authorities require that operators report on a large variety of safety significant events, such as departures from requirements, unauthorised acts, human errors, equipment failures, near misses, accident precursors, incidents and accidents.

This has resulted in a steady improvement over many years in the operational safety performance of nuclear plants. For example, the number of unplanned automatic scrams (reactor shutdowns) has decreased markedly since the early 1990s, indicating a widespread improvement in plant operation (see Figure 4.3).

Figure 4.3: Worldwide unplanned automatic shutdown rate (1990-2010)



Source: WANO Performance Indicators.

The overall good safety record of commercial nuclear power plants is however marred by three severe accidents: at Three Mile Island (TMI) in the United States in 1979, at Chernobyl in Ukraine in 1986 and more recently, at the Fukushima Daiichi plant in Japan in 2011. The latter two accidents involved significant releases of radioactivity into the environment.

To quantify the severity of nuclear and radiological incidents and accidents, and to communicate the information to the public in consistent terms, the International Nuclear Event Scale (INES) was designed by a group of experts from the IAEA and NEA in 1989. An updated manual to clarify the use of INES was published in 2009. Events are classified on the scale at seven levels (see Figure 4.4): Levels 4-7 are termed “accidents” and Levels 1-3 “incidents”. According to this scale, TMI-2 was rated 5, and both Chernobyl and Fukushima Daiichi were rated 7.

The TMI-2 accident

TMI-2 was a 900 MWe PWR, located near Harrisburg, Pennsylvania in the United States. The accident, which occurred on 28 March 1979, was initiated by an automatic reactor shutdown that demanded the operation of the steam-driven auxiliary feed water system. This system was unable to operate because a maintenance error left the steam inlet valve closed. As a consequence, the primary water pressure increased to the point that the pilot-operated relief valve (PORV) automatically opened. This PORV remained stuck open draining coolant away from the core. Inadequate instrumentation and training led the operators to stop the high pressure emergency cooling system that had started automatically and hampered the operators’ efforts to respond to the accident, resulting in serious damage to the reactor core. It took the operators more than two hours to realise

Figure 4.4: The International Nuclear Event Scale (INES)

* Three Mile Island, United States, 1979.
** Chernobyl, Ukraine, 1986 – Fukushima, Japan, 2011.

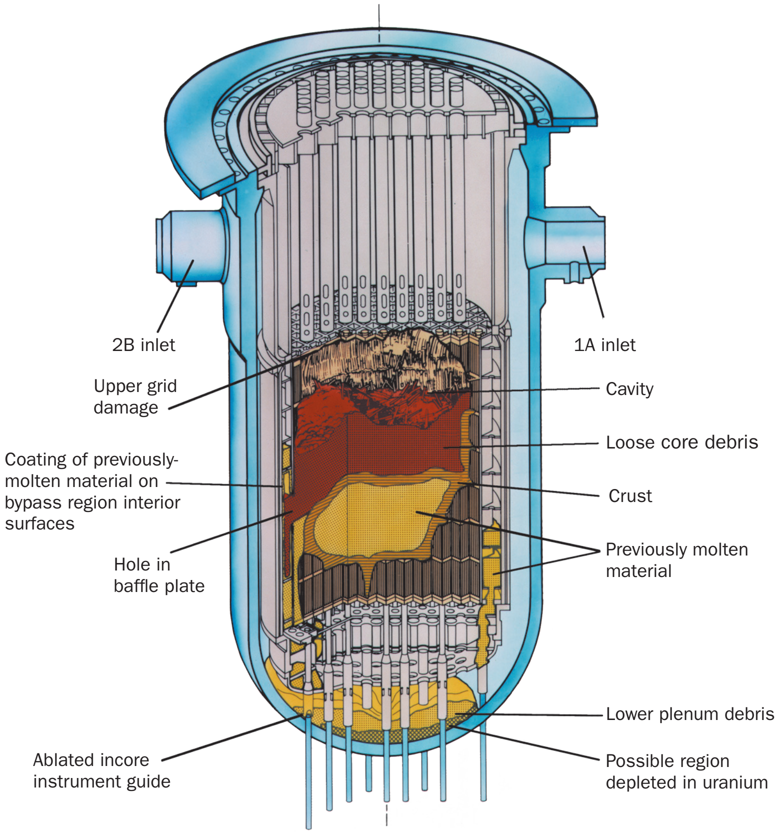
that the PORV had not closed. When the PORV was closed, the loss of coolant stopped, but the damage to the core was already in progress. As a result, the operators were unable to achieve the fundamental safety function of removing decay heat.

During the time that the PORV was open, water and volatile fission products, mainly noble gases, iodine and caesium isotopes were transported to the containment building, together with hydrogen generated from the metal-water reaction (zirconium in the cladding reacting with the steam) at high temperature. Over the whole accident sequence, about 460 kg of hydrogen were generated and then subsequently released into the containment. Hours into the accident, a slow deflagration occurred in which an estimated 320 kg of hydrogen were burnt, raising the pressure and temperature but fortunately never exceeding the design values of the containment. The ventilation system of that building allowed the release to the atmosphere of some 5% of the noble gases and minute amounts of the ^{131}I. Such small releases did not represent any radiological harm to the population. As such, the safety function of keeping radioactivity contained was essentially achieved. Figure 4.5 illustrates the extensive degradation of the reactor core at the end of the accident.

Large amounts of contaminated water and gases remained in the containment, that included the noble gases, 20% of iodine, 40% of caesium and about 1% of barium and strontium in the core inventory. To allow operators to enter into the containment, the noble gases were vented under favourable meteorological conditions and the contaminated water was cleaned to separate the radioactive isotopes. As the accident caused severe damage to the reactor core and the release of radioactivity inside the installation was high, the accident was rated 5 on INES.

Soon after the accident many analytical efforts were initiated by national and international organisations. The US President established the Kemeny Commission and the Nuclear Regulatory Commission (NRC) created its own investigations group. From these analyses it was clear that had the operating experience feedback from a similar event that occurred a month before at Davis-Besse, a sister plant, been considered, the operator of TMI-2 may have been better able to prevent this accident from occurring. Apart from these findings, the TMI-2 accident proved that a core meltdown was possible, that the phenomena associated with severe accidents were mostly unknown and that human factors engineering (including man-machine interface) was poorly developed.

Figure 4.5: End state configuration of the TMI-2 reactor core



Source: NRC.

To improve the situation, the American nuclear industry created the Institute of Nuclear Power Operations (INPO) as a private independent industry-led oversight organisation that is funded by the reactor operators and patterned after the US nuclear navy practices, which included systematic safety self-assessments, operator training and corrective action programmes. Although this was an American programme, Western countries were invited to participate.

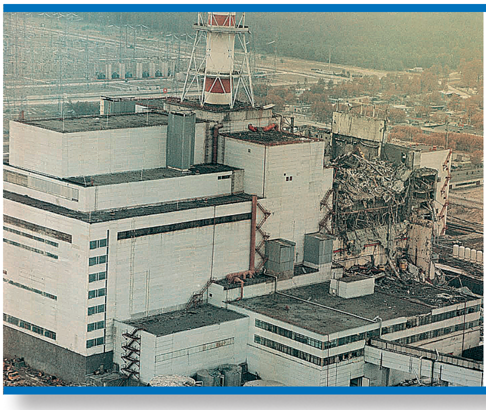
Prior to the TMI-2 accident, the focus of reactor safety was on the capability of safety systems to prevent or mitigate design basis accidents. Following the accident, improvements were made to the understanding of the physical and chemical phenomena associated with a severe accident leading to core melt. The accident identified the need for substantial research efforts to better understand fission product releases, cooling a degraded reactor core, core melts (called corium) interactions with the reactor pressure vessel and the containment concrete cavity, containment integrity and hydrogen behaviour in containments. Gaining knowledge through research was considered essential and important research programmes on severe accidents were initiated at national and international levels. As a result of this major research effort, improvements in the design of reactors were made, taking into account the risk of severe accidents. Today's Generation III reactors for instance include systems such as core catchers and hydrogen recombiners. In many countries, regulators also requested existing reactors to develop and implement severe accident mitigation measures.

The Chernobyl accident

The accident, which occurred on 26 April 1986 at unit 4 of the Chernobyl nuclear power plant in Ukraine near the border with Belarus, was a major disaster and rated at 7 on INES, meaning that a "major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures" had occurred. The accident, caused by a power surge during a particular test phase carried out by operators in violation of safety regulations (important control systems had been switched off), led to an extremely rapid heat up of, and significant damage to, the nuclear fuel that combined with a steam explosion and the lack of a containment building resulted in large amounts of solid and gaseous radioactive materials being widely distributed over Europe.

The Chernobyl nuclear power plant included four 1 000 MWe RBMK reactors in operation and two additional ones under construction. The RBMK uses graphite as neutron moderator, and low enrichment fuel is inserted in pressure channels cooled by boiling water. This type of reactor was only ever built in the ex-USSR, and is now only in operation in the Russian Federation.

In the RBMK design the reactivity coefficients related to the neutronics and thermal characteristics of the reactor core are such that the RBMK core design in use at that time became intrinsically unstable at powers below 20% of nominal. Moreover, to ensure reactor stability in the RBMK, it was necessary to insert a certain number of control rods into the core. These basic facts were well known to the designers and the operators. Nevertheless, during a planned test (experiment) aimed at proving that after a reactor shutdown the turbine inertia would be sufficient for the generator to provide electrical power to operate the equipment necessary to cool the reactor until the emergency diesel generators could come up to speed and provide the required electrical power, the operators did not adhere to these conditions. Specifically, when at very low power and with the reactor protection system disconnected, the unstable reactor was perturbed by the test, a sudden increase in power occurred, up to 100 times the nominal value, and the accident was initiated. The nature of the accident was not a loss of cooling, as in TMI-2 or Fukushima Daiichi, but a reactivity transient.



Chernobyl unit 4
after the accident.

Source: De Cort *et al.*, 1998.

The power surge led to an extremely rapid heat up of the nuclear fuel, which subsequently disintegrated. The sudden contact of the fuel fragments with the cooling water in the channels produced a steam explosion that severely ruptured the core pressure containment. Large amounts of hydrogen were also produced and released to the reactor building. The reactor building was then destroyed by a hydrogen explosion. The explosive events ejected hot pieces of graphite from the reactor that fell on the roofs of nearby buildings starting several fires. The explosions and the lack of a containment building resulted in large amounts of solid and gaseous radioactive materials being released to high altitude in the atmosphere. During the following ten days, an intense graphite fire burnt within the remains of the reactor cavity, further releasing large amounts of radioactive material into the atmosphere. These releases ended when the fire was extinguished after relentless efforts by helicopter crews to dump mixtures of sand, clay, lead and neutron-absorbing boron over the fire. A concrete sarcophagus to confine the partially destroyed reactor and its contents (see picture above) was then erected over the following six months. This sarcophagus is now being covered by a structure called the "new safe confinement", which is expected to be commissioned in 2015 and will eventually facilitate the safe dismantling of the sarcophagus and the reactor remains.

One of the many lessons learnt from the Chernobyl accident was the importance of safety culture in design and operation of nuclear power plants. The analysis of the accident underscored the deficiencies in the original RBMK reactor design, as well as deficiencies in the management and training of the operators. It showed that a weak safety culture stemming from weak management could lead to operational behaviour breaching every element of the defence-in-depth principle. To prevent such deficiencies in other countries, the electrical utilities decided to create WANO patterned after INPO. As far as RBMK reactors are concerned, design changes and safety improvements were implemented in the remaining reactors in operation in the Russian Federation, Ukraine and Lithuania. The last of the RBMK reactors in the latter two countries were shut down in 2000 and 2009 respectively, but 11 are still in operation in the Russian Federation.

The Chernobyl accident released substantial amounts of radioactivity to the atmosphere, some 60 radionuclides were emitted from the stricken reactor, but only a few – ^{131}I, ^{137}Cs, ^{134}Cs, strontium-89 (^{89}Sr), ^{90}Sr and plutonium-239 (^{239}Pu) – were deemed to be serious health hazards. The inventory of radioactive products before the accident and the corresponding releases were studied by NEA ten years after the accident. From that information and from the INES User's Manual, the ^{131}I release equivalent was deduced for the Chernobyl accident. The results, limited to ^{131}I and ^{137}Cs are given in Table 4.1. The total release from the Chernobyl accident measured in ^{131}I equivalent release activity, neglecting non-volatile elements and plutonium isotopes, amounted to 5 160 PBq (5 160 000 TBq).[1] This release is more than 150 times higher than the INES Level 7 criterion – an event resulting in an environmental release corresponding to a quantity of radioactivity radiologically equivalent to a release to the atmosphere of more than several tens of thousands of terabecquerels of ^{131}I (taken here to mean more than about 30 000 TBq).

Table 4.1: ^{131}I and ^{137}Cs releases and INES equivalent release in the Chernobyl accident

Nuclide	Half-life	Core inventory (x10^{15} Bq)	Release fraction (%)	Activity released (x10^{15} Bq)	Equivalence factor	Equivalent release (x10^{15} Bq)
^{131}I	8.05 days	3 200	55	1 760	1	1 760
^{137}Cs	30 years	280	30	85	40	3 400
						5 160

Source: NEA (1996).

The Fukushima Daiichi accident

The Fukushima accident, which occurred on 11 March 2011, resulted from the massive Tohoku earthquake (magnitude 9 on the Richter's scale, the largest ever recorded in Japan) and the ensuing tsunami that hit the Fukushima Daiichi nuclear power plant. All the units that were operating at the time, units 1 to 3, shut down safely following the earthquake. Unit 4 was in periodic inspection outage, with its fuel relocated to the spent fuel pool. Units 5 and 6 were also in a periodic inspection outage, with the fuel still in the reactor cores, and the reactors were in a cold shutdown condition. The earthquake caused the off-site power supplies to be lost. However, the on-site emergency diesel generators (EDGs) started and provided electrical power to emergency systems used to remove the heat generated in the fuel by the decay of the radioactive fission products.

About one hour after the earthquake, a tsunami estimated at more than 14 metres struck the site (see picture below). This caused wide-scale flooding of the site with the subsequent failure of the EDGs (with the exception of one air-cooled EDG at unit 6) and the pumps that provided cooling water from the ultimate heat sink (the Pacific Ocean). All of the safety systems that relied on electrical power to meet their function to protect the fuel in the cores at units 1, 2 and 3 failed.

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[1] A terabecquerel, symbol TBq, is equivalent to 10^{12} becquerel and a petabecquerel, symbol PBq, is equivalent to 10^{15} becquerel, symbol Bq. The Bq is the activity of a nuclide decaying at a rate of one disintegration per second, it is measured in inverse seconds.

The systems that did not rely on electrical power were available for a short time following the accident; however, they also eventually failed. The operating EDG at unit 6 was used to power the systems necessary to bring units 5 and 6 back to a safe shutdown condition.

When cooling was lost to the cores at units 1, 2 and 3, significant fuel damage occurred. Core melting was estimated to have begun at unit 1 several hours after the tsunami struck the site and cooling was lost, at unit 3 on 13 March and at unit 2 on 14 March. To protect the primary containments, venting of the unit 1, 2 and 3 containments was implemented through ventilation piping that discharged to the site stacks on 12, 15 and 13 March 2011, respectively. Included in the gases being vented from the primary containments was hydrogen generated from the reaction of the cladding (zirconium) with the steam at high temperatures when cooling was lost. Some of the hydrogen gas collected in the upper portion of the reactor buildings (secondary containment) where the spent fuel pools are located at units 1 and 3, and within the reactor building near the suppression chamber in unit 2. This hydrogen exploded causing significant damage to the reactor buildings at units 1 and 3 and may have caused damage to the suppression pool at unit 2. In addition, hydrogen build-up in unit 4 through a common ventilation system caused an explosion at unit 4 in the upper portion of the reactor building. As a result of the significant fuel damage, large amounts of radioactive material were released into the environment.

Tsunami wave overrunning the sea walls and flooding the Fukushima Daiichi nuclear power plant on 11 March 2011 (photo taken from unit 5).

Source: TEPCO.

According to the September 2011 report from the Japanese government to the IAEA, the majority of radioactive releases from the plant seem to have taken place before 19 April 2011. Releases of two of the most radiologically significant isotopes, ^{137}Cs and ^{131}I, were estimated at the time at 20 PBq and 200 PBq, respectively. This would have corresponded to a total release of these isotopes of the order of 12% of the amount released by the Chernobyl accident (85 PBq and 1 760 PBq respectively). New data released by the Fukushima Daiichi operator TEPCO in May 2012 indicate a release of approximately 10 PBq ^{137}Cs (12% of the corresponding Chernobyl releases) and 500 PBq ^{131}I (28% of the corresponding Chernobyl releases) into the atmosphere between 12 and 31 March 2011. Subsequent releases, in April and later in 2011, are estimated at less than 1% of those which occurred in March. Based on the large releases of radioactive material to the environment, about 30 times the INES Level 7 criterion, the accident at Fukushima Daiichi has been rated 7 on that scale (see Table 4.2).

Table 4.2: **^{131}I and ^{137}Cs releases (estimations from TEPCO, May 2012) and INES equivalent release in the Fukushima Daiichi accident**

Nuclide	Half-life	Activity released (x10^{15} Bq)	Equivalence factor	Equivalent release (x10^{15} Bq)	Ratio to Chernobyl releases
^{131}I	8.05 days	500	1	500	28%
^{137}Cs	30 years	10	40	400	12%
				900	**17%**

Several years will be necessary to collect the data from the three damaged reactors at Fukushima Daiichi and fully analyse the accident and its consequences. Nuclear regulators across the world, as well as international organisations, mainly the IAEA and the NEA, are working to draw lessons from the accident. The NEA hosted a Ministerial G8 extended seminar in early June 2011, and then a forum gathering the nuclear regulatory authorities of the G8, OECD NEA member countries and associated countries. Later that month, in the IAEA Ministerial Conference on Nuclear Safety, the Japanese government representatives presented some 28 lessons learnt, many of those of an organisational nature that are somewhat country specific. Recommendations on regulatory independence and emergency preparedness and response are of particular interest. The Japanese Parliament (Diet) Independent Investigation Commission on the Fukushima Daiichi Accident, which published its final report in July 2012, believed the accident could have been prevented or at least its consequences mitigated by more appropriate response. It identified organisational deficiencies, bureaucracy, unclear definitions of responsibility between the operator, the regulator and the government and more generally a cultural mindset that prevented lessons learnt from the TMI and Chernobyl accidents to be fully implemented. These findings stress again the importance of promoting safety culture at all levels in every country.

In the rest of the world, improvements in the safety of nuclear power plants are also being sought. The US NRC created a task force to review the Fukushima accident. It produced 12 recommendations to enhance safety in the operating plants in the United States. Within the European Union it was decided that member states should re-evaluate the safety of the currently operating plants by implementing a set of stress tests previously adopted by the European Nuclear Safety Regulators' Group (ENSREG). The process considers extreme natural and manmade events and combinations of those; consequential loss of safety systems, mainly long-term loss of electrical supplies and the ultimate heat sink; and severe accident managements systems: loss of core and fuel pool cooling and containment integrity. Such lessons learnt will be applicable to the current operating fleet, to new designs as well as to fuel cycle facilities. Other countries have performed similar safety assessments. At international level, the IAEA Action Plan on Nuclear Safety, endorsed unanimously at the September 2011 General Conference provides an overall framework to draw lessons from the Fukushima Daiichi accident and develop enhancements to the safe operation of nuclear facilities.

Emergency preparedness and response

It is the responsibility of governments to ensure that an efficient emergency plan is formally established for every nuclear power plant. It is recommended that nuclear emergency preparedness and response be part of the national infrastructure for responding to other type of emergencies. The three accidents described above also provided lessons learnt in the area of off-site protective measures:

- Although in TMI-2 radioactive releases were insignificant, an evacuation, limited to preschool children and pregnant mothers, was ordered by the Governor of the State of Pennsylvania. It became clear that the national infrastructure for general emergencies was not fully prepared for nuclear events.
- Shortly after the Chernobyl accident, but not immediately, the authorities evacuated about 116 000 people from areas close to the plant and later on about 220 000 people from Belarus, the Russian Federation and Ukraine. The evacuation and relocation of people did not prevent the approximately 4 000 cases of thyroid cancer that have been reported up to the year 2000 in children and adolescents exposed at the time of the accident.
- In the case of the Fukushima Daiichi accident, a timely evacuation and relocation of close to 100 000 persons prevented high radiation exposures and it will be very difficult to identify induced radiation fatalities and radiation diseases among members of the affected public.
- The only accident at a nuclear power plant where casualties can be directly attributed to radioactive releases is the Chernobyl accident. No casualties can be attributed to the release of radioactive material at TMI-2 or to date at Fukushima Daiichi.

In summary, these accidents have underlined the importance of technology, knowledge management, human and organisational factors, responsibility, accountability and regulation in ensuring the safe operation of nuclear power:

- The TMI-2 accident emphasised the need for greater attention to human factors, including improved operator qualification and training and better emergency procedures. It also emphasised the need to improve knowledge in the area of severe accidents.
- The Chernobyl accident as well as highlighting weaknesses in the RBMK reactor design led to increased recognition of the importance of safety culture. It showed that a weak safety culture, not only among operators but also stemming from weak management, could lead to operational behaviour breaching every element of defence-in-depth.
- The Fukushima Daiichi accident demonstrated that a clear understanding of external events is an important element of a robust defence-in-depth approach for assuring public health and safety and protection of the environment. It also emphasised the importance of promoting safety culture and strong independent regulation of nuclear power.

Safety of advanced reactors

Safety upgrades may be requested for some of the Generation II plants in operation in the world following the post-Fukushima "stress tests" and the recommendations that will be issued by the relevant nuclear regulatory authorities. For the Generation III/III+ reactors that are currently under construction, safety upgrades are expected to address lessons learnt from the Fukushima Daiichi accident, but the safety upgrades may be more limited as these reactors have incorporated design features that apply passive safety features and consideration of severe accident mitigation.

Over the next few decades new reactors will be introduced to meet the challenge of reducing generating costs while maintaining or improving safety levels. These designs are characterised by:

- explicit consideration of severe accidents as part of an extended design condition;
- effective elimination of some severe accident sequences by inherent safety features using passive systems;
- significant reduction or elimination of radioactive releases even in the unlikely case of severe accidents;
- improved operability and maintainability by extensive use of digital technology;
- reduction in system complexity and the potential for human error.

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

References

IAEA (1999), *Basic Safety Principles for Nuclear Power Plants*, a report by the International Nuclear Safety Advisory Group (INSAG-12), IAEA, Vienna, Austria. Available (along with other INSAG reports) at www-ns.iaea.org/committees/insag.asp.

IAEA (2006), *Fundamental Safety Principles,* IAEA Safety Standards, Safety Fundamentals, N° SF-1, IAEA, Vienna, Austria.

IAEA (2009), *INES, The International Nuclear and Radiological Event Scale, User's Manual, 2008 Edition,* IAEA, Vienna, Austria.

IAEA (2011), "International Fact Finding Expert Mission of the Fukushima Daiichi NPP Accident following the Great East Japan Earthquake and Tsunami", June, Vienna, Austria.

IAEA (2011), "Report of Japanese Government to IAEA Ministerial Conference on Nuclear Safety – Accident at TEPCO's Fukushima Nuclear Power Stations", June 2011, Additional report September 2011, IAEA, Vienna, Austria.

IAEA website, International Nuclear and Radiological Event Scale (INES). Details available online at www-ns.iaea.org/tech-areas/emergency/ines.asp.

IAEA (2011), *A Framework for an Integrated Risk Informed Decision Making Process,* INSAG-25, International Nuclear Safety Group, IAEA, Vienna, Austria.

IAEA (2011), IAEA Action Plan for Nuclear Safety, endorsed unanimously by the IAEA General Conference of 22 September 2011, available at: http://www.iaea.org/newscenter/focus/actionplan/reports/actionplanns130911.pdf.

NEA (1996), *Chernobyl-Ten Years On: Radiological and Health Impact, An Assessment by the NEA Committee on Radiation Protection and Public Health*, November 1995, Nuclear Energy Agency, OECD, Paris, France.

NEA (2002), *Chernobyl: Assessment of Radiological and Health Impacts – 2002 Update of Chernobyl: Ten Years On*, Nuclear Energy Agency, OECD, Paris, France. Available at www.oecd-nea.org/rp/chernobyl/.

NEA (2008), *The Regulatory Goal of Assuring Nuclear Safety*, Nuclear Energy Agency, OECD, Paris, France. Available (along with other NEA safety publications) at www.oecd-nea.org/html/pub/ret.cgi?div=NSD.

NEA (2008), *Nuclear Energy Outlook 2008*, Chapter 7, Nuclear Energy Agency, OECD, Paris, France.

NRC (2012), *A Proposed Risk Management Regulatory Framework,* NUREG-2150, US Nuclear Regulatory Commission, Washington D.C.

ENSREG (2012), *Peer Review Report: Stress Tests Performed on European Nuclear Power Plants,* European Nuclear Safety Regulators Group, Brussels, Belgium.

Chapter 5

Radiation and Radiological Protection

The world is awash with natural radiation, and the living creatures on it are constantly exposed to this background radiation. Since man's discovery of their existence in the late 1800s, many beneficial 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. Ever since, the use of radiation has been a matter of balancing benefits and risks.

As a result, radiation 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: justification, optimisation and limitation.

Scientific and medical background

Types of radiation

Radiation is energy in the form of sub-atomic particles or electromagnetic waves. Radioactivity is a 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 radioactive "decay".

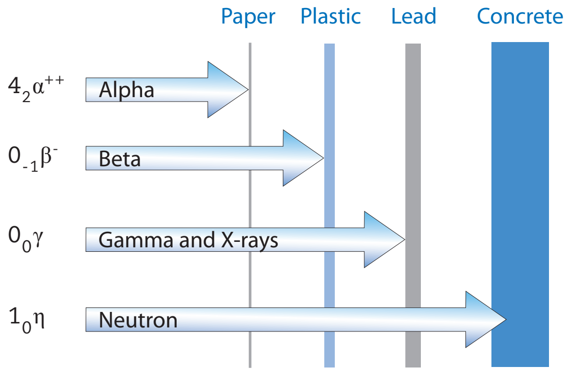
When radiation, either particles or electromagnetic waves, has enough energy to remove the electrons of atoms with which it interacts, it causes the atoms to become charged, or "ionised". This is called ionising radiation. The ions resulting from the interaction are capable of causing chemical changes that are damaging to living cells. If radiation 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 5.1).

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 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 may 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 or lens of the eye if the exposure is large enough.

Figure 5.1: Penetrating distances for different radiation types



Source: University of Michigan Student Chapter of the Health Physics Society, United States.

Neutrons are contained in the nucleus of an atom, from which they may be expelled during fission (see Chapter 2). They are electrically neutral particles with approximately the same mass as a proton. Being neutral, they interact only weakly with matter and are thus very penetrating. 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 former being emitted from the nucleus of an atom, the latter 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.

Sources of radiation

There are two primary categories of radiation sources to which people and the environment are exposed: natural sources and artificial sources.

Natural radiation, which may be either ionising or non-ionising, can be characterised either as "cosmic" or "terrestrial". Cosmic radiation comes from space and is generated through various processes, including the birth and death of stars. The biggest emitter of cosmic radiation, so far as the Earth is concerned, is the Sun. Terrestrial radiation comes from the Earth itself, and is produced by the decay of radionuclides embedded in the Earth's crust. Two common elements, uranium and thorium (and their decay products), 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 created near the Earth's surface. Hence, radiation is not only emitted directly from its sources in the Earth, but forms part of the atmosphere. The amounts and types of radioactive materials, and hence human exposure, vary considerably between different locations on the Earth's surface.

Even food is naturally radioactive, since plants and animals absorb radioactive materials from the environment. As a result, human bodies and particularly bones contain small amounts of radioactive isotopes such as carbon-14 (^{14}C), potassium-40 (^{40}K) and radium-226 (^{226}Ra). Tritium, a naturally occurring radioactive isotope of hydrogen found in water, is also found in small amounts in human bodies.

The development of nuclear energy and nuclear science has created various new sources of radiation, referred to as artificial radiation. Nuclear weapons tests conducted above ground in the 1940s and 1950s 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 hemisphere was, and continues to be, exposed to radiation from this material.

The development of civil nuclear power since the 1950s has also led to releases of radioactivity into the environment 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. These releases have been greatly reduced over the years and are now very small, but radioactivity from earlier releases remains.

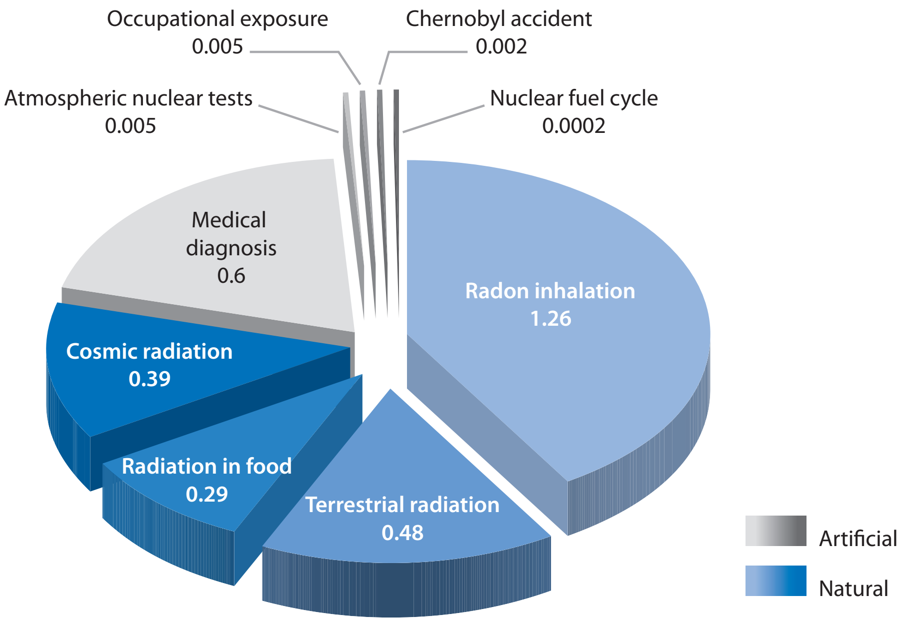
Radiation has been extensively used in medicine since its discovery. The use of X-rays and other medical imaging techniques such as computerised tomography (CT) and positron emission tomography (PET) involve significant exposure to ionising radiation. The risks of this are considered to be outweighed by the benefits to the patient. However, the use of such techniques has grown rapidly in recent years with a consequent rise in radiation exposures of medical staff and patients.

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 (although the latter are shielded from it to the extent possible).

Levels of radiation exposure

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has gathered information since 1955 on the typical levels and most important sources of human radiation exposure, and produces a report every few years summarising the average exposures from all sources. Figure 5.2 summarises the results from the 2008 report.

Figure 5.2: Annual average radiation doses from different sources (millisieverts)



Source: UNSCEAR, *Sources and Effects of Ionizing Radiation,* Vol. 1, United Nations, 2008.

These figures are worldwide averages. The exposure of any individual to these various natural and artificial sources of radiation will depend on location, diet, occupation, use of medical services, etc. Exposures may be either voluntary or involuntary.

Measuring radiation exposure

The principal result of exposure to radiation of any material – such as human tissue – is the deposition of energy. So the unit used to measure radiation exposure is based on the amount of energy absorbed. Radiation exposure (also referred to as "dose") is measured in grays (Gy). One gray is defined as the deposition of one joule of energy in one kilogram of material.

Some types of ionising radiation are more damaging than others. To take this into account, different types of radiation are given different weighting factors that are used to relate the energy they deposit to the biological significance of the damage they cause; the higher the factor, the greater the 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 only a part, and if so, which part. Different tissues (e.g. lungs, liver and bones) have different sensitivities to radiation damage. Exposure to uranium dust (which emits alpha particles) on the skin is generally not hazardous, but if the same dust is inhaled and comes into contact with sensitive lung tissue it can be very damaging. To allow for this, researchers have also developed tissue weighting factors.

The unit used to measure the biological risks caused by exposure to ionising radiation is the sievert (Sv). It is equal to the amount of energy deposited (in grays) multiplied by the relevant radiation weighting factor and by the tissue weighting factor, to yield the effective dose.

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 is – unlike, for example, cancer-causing chemicals – 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 radiation exposure has on humans and other living organisms.

The energy from ionising radiation is transferred to the atoms of the substance through which it passes. Water is the most abundant molecule in living organisms; when water molecules are ionised within a living cell, they can damage the cell's DNA. There can be three principal results when a living cell is damaged by radiation:

- 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 concerns 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 soon after an exposure to radiation takes place – these are 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 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. For example, a dose of 4 000 mSv would result in the death of about 50% of those exposed in the absence of medical treatment.

Stochastic effects are not certain to occur, but their chance of occurrence increases with increasing exposure. The most important type of stochastic effects is cancer, including leukaemia. Should reproductive cells be exposed, genetic modifications can theoretically occur, though none have ever been observed in any studied human population.

Risks at high doses

A fair amount is known about the effects of large radiation doses received instantaneously. Since the atomic bombing of the Japanese cities of Hiroshima and Nagasaki in 1945, 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. By making a comparison with similar Japanese populations that were not exposed to the bombing, it has been concluded that about 500 of the cancer deaths among the atomic bomb survivors can be attributed to radiation received in the bomb blasts.

Using the information gathered from high-dose events, including the Japan bombings, it has been possible to develop a dose-response curve that correlates the predicted number of cancer deaths to calculated individual exposures. This curve has been used to predict the additional risk of cancer death associated with any given level of exposure.

Risks at low doses

The statistics so far considered are based on relatively high doses; the increased cancer risk due to high radiation exposures is well understood. What is not known is whether an increased risk can result from low doses of radiation, such as we all naturally receive from background radiation, or that certain workers may receive as part of their job.

The data from the high-dose groups show a definite link between the level 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. However, very large populations of both exposed and unexposed individuals would have to be studied over a long period to demonstrate the existence of an effect at lower doses. The fortunate fact that no such large population of exposed individuals exists makes it difficult to statistically assess these risks.

Because it is known that radiation can cause cancer at the higher doses, and because understanding of the relevant biological mechanisms is incomplete, it has always been deemed prudent to assume that every dose received, no matter how small, carries a certain risk proportionate to the dose. In other words, it is assumed that there is no threshold below which radiation exposure can be considered to have no effect.

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 (LNT) hypothesis. This conservative hypothesis forms an important basis for the regulation and practice of radiological protection.

The radiological protection system

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

The radiological protection system applied worldwide has its origins in 1928 with the creation of the International Commission on Radiological Protection (ICRP). Since then it has developed through applying the knowledge gained by numerous studies of exposed populations and through studies of the effects of radiation on plants, insects and animals. This 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 ICRP Recommendations, has been implemented in virtually all national regulatory arrangements. The ICRP periodically updates its recommendations to respond to new developments and improved understanding of the effects of radiation. The current system of radiological protection in most countries is based on the latest ICRP Recommendations, published in 2007. 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.

Justification

The principle is that no practice should be allowed unless it is justified, in that the benefits outweigh the risks. In such a matter, decision criteria cannot rest on scientific considerations alone, but necessarily include social, economic and ethical factors. The principle is applied on a case-by-case basis, the important point being that the reasons for decisions to allow exposure must be made public, so that they are open to challenge.

For example, 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 benefits of using nuclear energy to produce electricity have been challenged in light of the risks involved. Public policy decisions have to take both benefits and risks into account.

Optimisation

The principle of optimising protection applies only for practices that have been judged to be justified. It requires that the number of individuals exposed and the magnitude of the exposures be kept as low as reasonably achievable (ALARA). It should be noted that the objective of optimisation 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 reduce exposures, 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 are also important considerations in the optimisation process.

Limitation

Over and above the principle that protection must be optimised to ensure that exposures are ALARA, individuals must not be exposed above stipulated dose limits. The exposure limit for members of the public is in most countries set at 1 mSv per year in accordance with ICRP Recommendations. For radiation workers the ICRP 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 year. In practice, the rigorous application of the ALARA principle, and of such measures as the limitation of gaseous and liquid discharges, has ensured that actual and average doses are normally far below dose limits.

Radiological protection in the nuclear industry

Uranium and its decay products naturally emit radiation. Nuclear fission emits radiation and creates radioactive waste. For all these reasons, 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, in particular radon gas. These alpha-emitting radionuclides can be hazardous to the lungs if inhaled, thus adequate mine ventilation and worker respiratory protection is required. These same alpha-emitting radionuclides are also the main source of potential hazard during other front-end fuel cycle processes.

In nuclear power plants, radiation exposure of workers generally comes from more penetrating gamma-emitting radionuclides such as cobalt-60 (^{60}Co). Such radiation is limited to piping and systems directly associated with cooling the reactor core. During normal operation these systems are shielded and workers are excluded from these areas. Hence the main exposures occur during maintenance. Worker protection is provided during maintenance by the use of shielding and by managing the work to minimise time spent in proximity to radiation-emitting sources.

Drainage of the facilities of the AREVA MOX fuel fabrication plant.
Dismantling of the glove boxes.
Cadarache, France.

© AREVA, Taillat Jean-Marie.

Exposure hazards during waste management operations, including spent fuel handling, are largely from gamma-emitting radionuclides. With LLW and ILW, cobalt-60 (^{60}Co) is a significant source of radiation. Fission products, e.g. caesium-137 (^{137}Cs) and strontium-90 (^{90}Sr), are the most significant sources of radiation from HLW and spent nuclear fuel. Radiation exposure associated with waste management is minimised through the use of specially designed facilities, equipment and procedures.

Occupational exposures in the nuclear industry worldwide have steadily decreased over the last 20 years. Much of this reduction has resulted from improvements in operational procedures and work management in the industry, as well as from technological advances and design improvements. The strengthening of safety culture and increased exchanges of experience between nuclear operators have also contributed significantly to this reduction. To a large extent, these changes have been driven by the application of the ALARA principle.

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 the environment. Filtering and purification of atmospheric and water effluents minimise these releases, and extensive environmental monitoring around all nuclear installations verifies that they are consistent with radiological protection regulations.

References

ICRP (2008), *Recommendations*, International Commission on Radiation Protection, Publication 103, Elsevier. A free summary is available at www.icrp.org.

NEA (2007), *Radiation Protection in Today's World: Towards Sustainability*, Nuclear Energy Agency, OECD, Paris, France. Available (along with other NEA radiological protection publications) at www.oecd-nea.org/html/pub/ret.cgi?div=RP.

NEA (2009), *The NEA Contribution to the Evolution of the International System of Radiological Protection,* Nuclear Energy Agency, OECD, Paris, France.

UNSCEAR (2008), *Sources and Effects of Ionizing Radiation,* United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report, United Nations, New York, United States. Available (along with other UNSCEAR reports) at www.unscear.org. See also Annex D to the 2008 report, "Health Effects due to Radiation from the Chernobyl Accident".

Chapter 6

Management of Radioactive Waste

Radioactive waste of various types results from any activity that makes use of nuclear materials, including medical and industrial uses. However, nuclear energy is the most important source of such wastes because of the larger volumes generated and its long-lived nature. Whatever their origin, radioactive wastes have to be managed safely and economically.

In general, radioactive waste is 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, while most HLW is safely stored in dedicated facilities. The permanent disposal of HLW in deep geological repositories is accepted to be practicable by the scientific and technical community, but has yet to be accepted by civil society in many countries.

Types of radioactive waste

Radioactive wastes are 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 these categories differ in detail from country to country; however, in general, they can be considered as low-level, intermediate-level and high-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 LLW.

ILW typically arises from industrial processes, e.g. equipment that has been used in conjunction with nuclear materials or 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 of spent nuclear fuel, the non-dissolved metal structures of the fuel are categorised as ILW.

HLW consists mainly of the highly radioactive and often long-lived remnants of the fission process, either contained within spent fuel or as a waste stream from reprocessing. It must be heavily shielded and generally requires cooling. Though spent fuel and reprocessing waste are in many respects managed similarly, they are different in form and content, not least because HLW from reprocessing is 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 require isolation for many thousands of years. On the other hand, some wastes containing only short-lived radioactive isotopes can simply be stored until their activity has decayed to negligible levels, at which point they are no longer classified as radioactive waste.

The half-life of a radioactive isotope is the time it takes for half of any given number of atomic nuclei to decay. This can vary from less than one second to many thousands of years, according to the isotope. Figure 6.1 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 6.1 shows some isotopes that are important in determining conditions for disposal of HLW. Those with short half-lives dominate the overall activity of the waste in the early years, but in the longer term the less active but longer-lived isotopes predominate.

Figure 6.1: Decay of a radioactive element with a half-life of five days

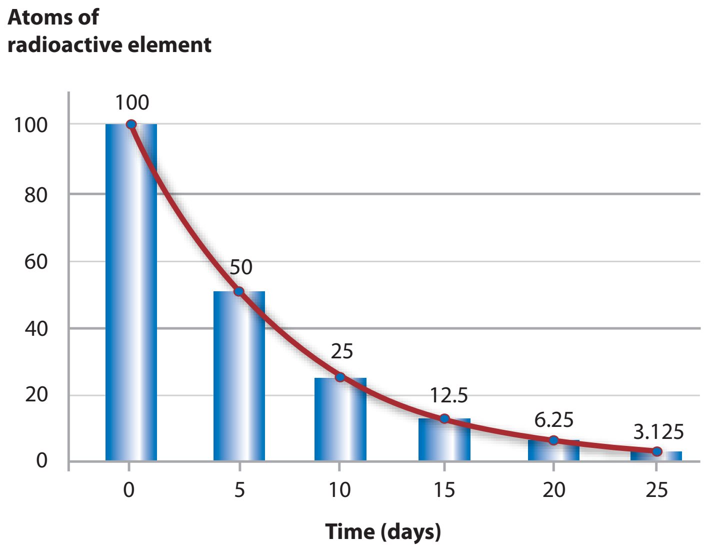


Table 6.1: Radioisotopes with very different half-lives that are significant at different stages of HLW management and disposal

Isotope	Approximate half-life
Strontium-90	29 years
Cesium-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 6.2 gives a general idea of the volumes of waste generated in producing nuclear energy. Over the years there has been a general trend towards a reduction in the volume of waste generated per unit of electricity produced through improved practices and technologies.

Table 6.2: Indicative volumes (m^3) of radioactive waste produced annually by a typical 1 000 MW nuclear plant, for once-through cycle and with reprocessing of spent fuel

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* (1998).

To put these quantities into perspective, it should be borne in mind that quantities of radioactive waste are also generated by factories and hospitals, 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.

Waste management principles and practice

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 Principles of Radioactive Waste Management of the International Atomic Energy Agency (IAEA) are an example of this. In summary, these specify 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.

On a practical level, the activities necessary for managing radioactive waste properly can be categorised into the following steps:

- 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 often be super-compacted into much smaller volumes. Since liquid wastes cannot be disposed of, they need to be transformed into solids. 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 such conditioning, ILW and LLW can be packaged for interim storage or disposal in steel drums or containers. For example, the metallic remnants of fuel assemblies left over from reprocessing are typically compacted, then cemented in steel drums for disposal.

HLW produced during reprocessing emerges as a liquid and needs to be transformed into a solid for long-term storage and disposal, normally by a process of vitrification (incorporating it into a special type of glass). Other waste forms using ceramics have also been tested. These waste forms share the characteristics of being extremely durable and able to immobilise the waste for very long periods. Spent nuclear fuel that has not been reprocessed is initially stored underwater in a storage pool, usually at the reactor site. After some years it can be placed in specialised containers for interim storage and/or disposal.

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, a period of interim storage is always necessary to allow the initially very high levels of radiation and heat generation to fall. It has been demonstrated that interim storage of such wastes can be continued safely for many decades.

Final 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. However, in some repository concepts retrieval of the waste would be possible, at least until a future decision is made to seal the repository. Possible reasons to retrieve the waste could include the availability of more advanced technologies for waste treatment or a decision to recycle spent fuel in future reactors.

Radioactive waste is disposed of in dedicated facilities, and is not mixed with non-radioactive waste. Short-lived ILW and LLW are disposed of routinely at numerous sites in many countries; 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.

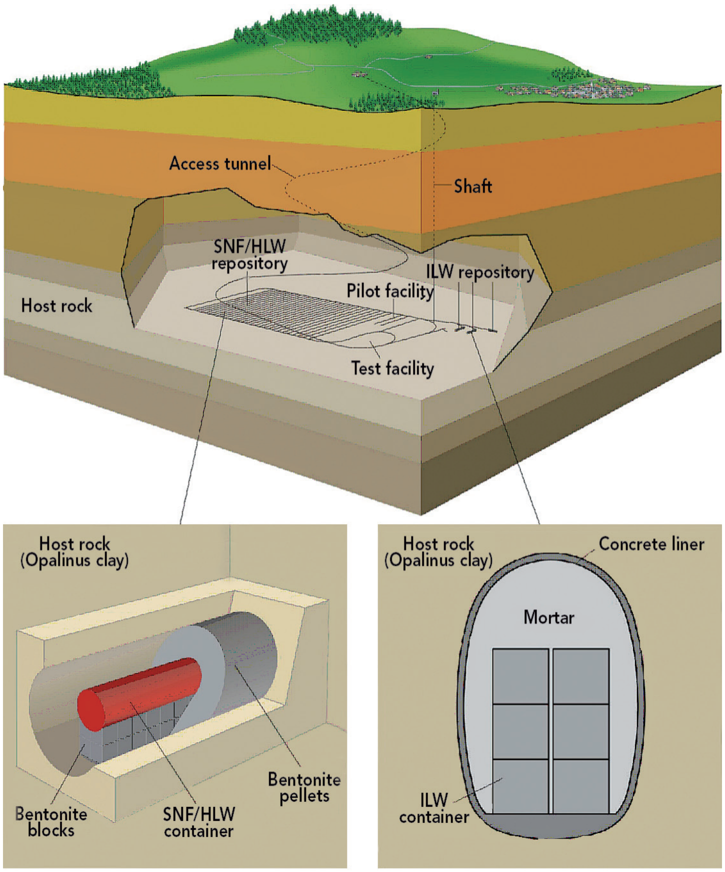
These precautions extend the life of the waste packaging and are intended to prevent the possibility of migration of radioactivity from the site. Nevertheless it is expected that for a period of about 100 to 300 years following closure of an ILW/LLW disposal site active or passive controls will be applied, 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.

Solutions for long-lived waste, either HLW or long-lived ILW, have proved more elusive. No repository for HLW (including spent fuel) has yet been opened, though a facility for disposal of non-heat generating HLW is in operation in the United States. Many countries using nuclear energy have set up programmes to develop disposal facilities for long-lived waste. These plans are discussed in more detail in the next section.

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 6.2). 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 to demonstrate sufficient understanding of geological processes and material properties to guarantee containment over the long timescales being considered.

Figure 6.2: **Multiple-barrier system concept for geological disposal**



Emplacement drift for SNF/HLW

Emplacement tunnel for ILW

Note: Based on the Swiss concept.

Source: Nagra.

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. In addition to their isolation deep underground, a key feature of potential host formations is low groundwater flow, this 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. The engineered barriers typically consist of:

- in the case of HLW, the glass matrix;
- in the case of spent fuel, 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.

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.

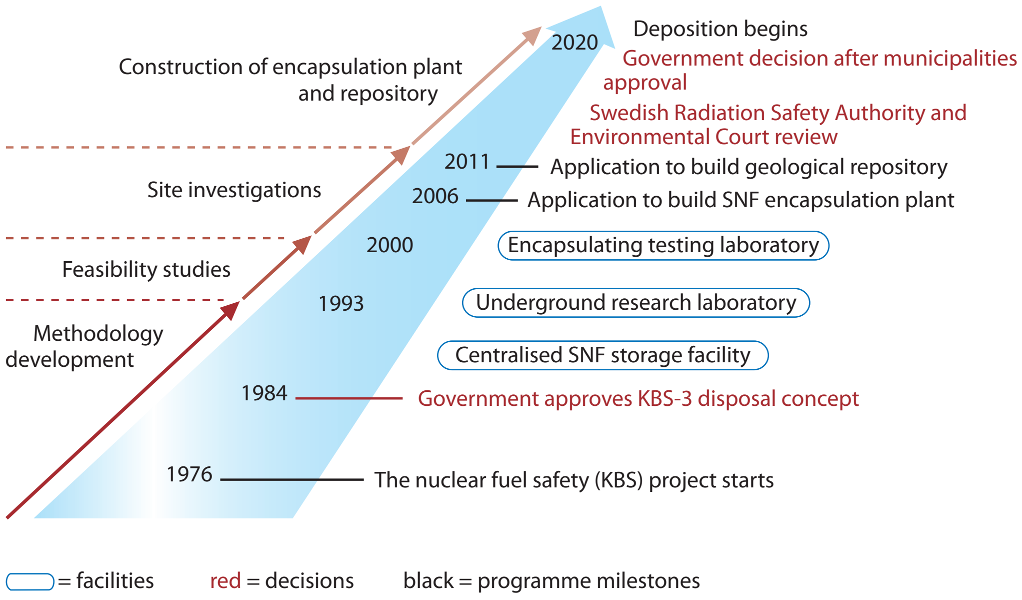
Technical confidence in the practicality of geological disposal stems from basic scientific knowledge of geology, hydrology, material sciences and geochemistry, reinforced by research underground. Laboratories, mostly established in used mines, have helped to obtain information on site-specific characteristics and to test the models used to assure performance. 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.

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. This is currently the only example of an operating deep geological repository for HLW. In several countries, including Canada, the United Kingdom and the United States, plans to develop geological repositories have suffered from public and political opposition leading to programmes being delayed.

However, some countries are proceeding successfully with their long-term plans to develop repositories, notably Sweden and Finland. In Sweden, following many years of site investigations and public consultations, a site for a spent fuel repository was selected in 2010 near to the Forsmark nuclear power plant. An application for a permit to begin construction was submitted in 2011, with operation planned for soon around 2020 (see Figure 6.3). Similarly, in Finland a site has been selected at Eurajoki, near the Olkiluoto nuclear power plant. A construction permit application will be submitted in 2012, with operation planned by 2020.

Figure 6.3: Time frame for the development and implementation of a deep geological disposal system in Sweden



Source: SKB, Sweden.

Transport of radioactive materials

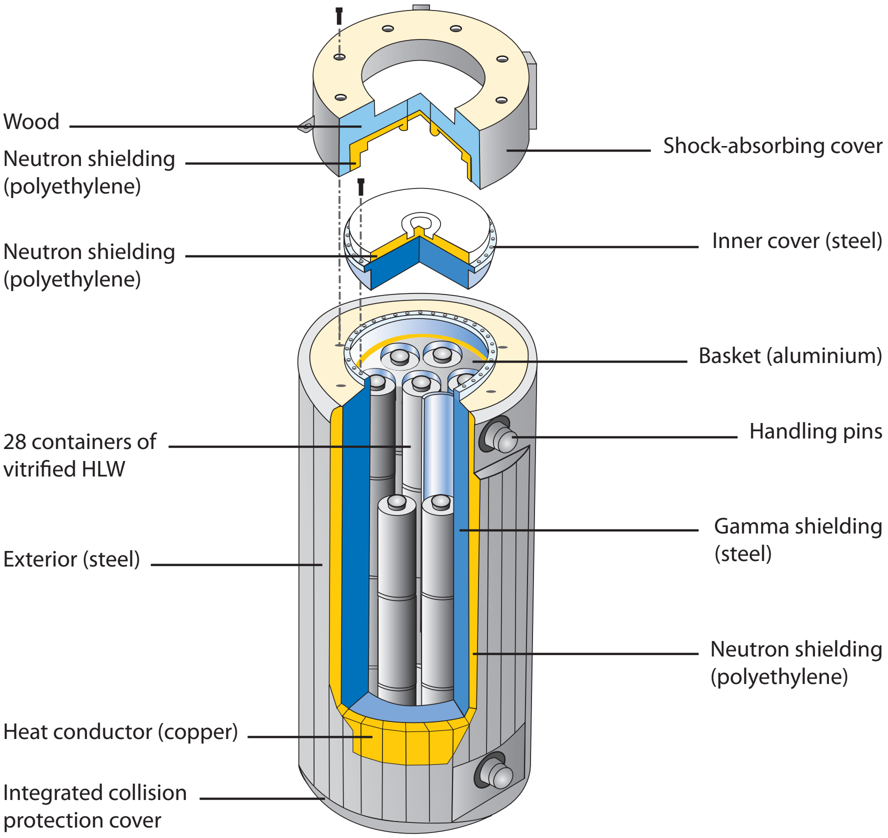
Because of the comparatively small volumes of radioactive waste and the need for long-term isolation, centralised storage and disposal is generally practised. This in turn necessitates transport to the chosen localities. Transport is also required for materials in the front end of the fuel cycle, although these are generally less hazardous than radioactive wastes, especially HLW and spent fuel.

Radioactive materials used in industrial and medical applications also require transport to and from the end user. These materials form the great majority of movements of radioactive materials, but they are mostly small-scale. Transport movements in the nuclear fuel cycle are relatively few in number but involve much larger quantities of material.

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 and the International Maritime Organisation incorporate these IAEA principles, making them 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. This principle works to prevent any radiological consequences even if the package were to be involved in a severe transport accident.

The requirements and controls are proportional to the hazard presented by the material. For example, some medical isotopes may be shipped in simple cardboard packages, provided the radioactive contents are strictly limited and the packages clearly labelled. Spent fuel or HLW, on the other hand, must be shipped in high integrity containers designed to shield people and assure containment under extreme accident conditions (see Figure 6.4).

Figure 6.4: A typical HLW transport cask



Source: AREVA, France.

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;
- 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.

Transport of radioactive materials has been carried out routinely since the 1960s without any incident leading to significant radiological impact on people or the environment. Several million shipments of all forms of radioactive materials and waste now take place worldwide each year, of which only about 5% relate to the nuclear fuel cycle. Since 1970 there have been over 25 000 shipments of spent fuel and HLW using trains, trucks and ships. None has 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 often been difficulty in achieving social and political confidence in radioactive waste disposal strategies.

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 burden on future generations that is ethically unsatisfactory. Others tend to regard risks of this low order, applying to future 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. This conflict of philosophies is hindering the adoption 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 final disposal of HLW and spent fuel 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 less preferable solution. The need to maintain security and environmental surveillance of the site increases costs. The inevitable long-term deterioration of the storage facilities and the waste packages they contain leaves to future generations the costs and risks of their periodic replacement. This option also leaves open the question of the disposal of the waste, should this eventually be decided upon. Nonetheless, it remains a viable option, either on a medium-term or a semi-permanent basis.

Retrieval of waste

Closely related to the concept of long-term storage, with many of the same issues of cost and risk, is making provision for retrieval of waste that has already been placed in a repository. As noted above, this is technically feasible, at least until a future decision is made to seal a repository once no further waste is to be deposited. But keeping open the possibility of retrieval could conflict with the aim of securing maximum isolation of waste in a repository. Moreover, it may require financial provision for further disposal once the retrieved material had been treated or recycled. However, a phased approach to disposal could be adopted, progressing gradually towards the final configuration of a repository while postponing steps that would be difficult to reverse.

International repositories

The quantities of waste requiring 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 significant, 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.

References

IAEA (2009), *Policies and Strategies for Radioactive Waste Management,* International Atomic Energy Agency, Vienna, Austria. Available (along with other IAEA radioactive waste management publications) at www.iaea.org/newscenter/focus/radwaste/.

NEA (2008), *Nuclear Energy Outlook 2008*, Chapter 8, Nuclear Energy Agency, OECD, Paris, France.

NEA (2008), *Moving Forward with Geological Disposal of Radioactive Waste,* a collective statement by the NEA Radioactive Waste Management Committee, Nuclear Energy Agency, OECD, Paris, France.

NEA (2010), *Radioactive Waste in Perspective,* Nuclear Energy Agency, OECD, Paris, France.

NEA (2010), *Partnering for Long-term Management of Radioactive Waste: Evolution and Current Practice in Thirteen Countries,* Nuclear Energy Agency, OECD, Paris, France. Available (along with other NEA radioactive waste management publications) at www.oecd-nea.org/html/pub/ret.cgi?div=RWM.

Chapter 7

Nuclear Law and Non-proliferation

The use of nuclear energy in each country is governed by a framework of national laws, frequently based on principles that have been internationally agreed and which are often reflected in international conventions or other instruments.

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 gives an outline on two particularly important aspects of nuclear energy use – its legal framework and the non-proliferation of nuclear weapons.

The legal framework of nuclear energy

Responsible regulation of the use of nuclear energy has always been indispensable to maintain public confidence. Achieving that confidence requires the existence of a comprehensive and effective legal framework to protect the health, safety and security of the public and the integrity of the natural environment.

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. Furthermore, because the impacts of the use of nuclear energy can extend beyond national borders, the framework must take into account its international implications.

That part of nuclear law devoted to the safety and security of peaceful nuclear activities continues to evolve at both the national and international levels. This evolution reflects 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 the environment.

National requirements

All countries using nuclear energy have established legal requirements for the conduct of civil nuclear activities, and a public authority empowered to enforce compliance with these requirements.

Nuclear energy-related legislation generally establishes a mandatory licensing system 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 licence conditions can result in the suspension or revocation of the licence, and/or other penalties.

With the rapid development of nuclear science and technology over the past decades, governments have had to ensure that legislative requirements kept pace with the introduction 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.

As a result, national legislative requirements now often cover a wide range of nuclear-related 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 types of nuclear installations from radiation therapy units to power plants, 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 an accident.

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 (ICRP) with regard to radiation dose rates (see Chapter 5), though some apply still stricter requirements. Similarly, they follow the International Atomic Energy Agency 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 internationally accepted principles and standards result from the co-operation between national governments and the advice of experts.

International legal framework

There are a variety of international conventions in the nuclear field, to which most countries with significant nuclear activities are parties. These deal 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 the safe management of radioactive waste and spent fuel.

Some of the most important conventions are:

- The Treaty on the Non-proliferation of Nuclear Weapons (NPT), which has been in force since 1970. It aims at preventing the spread of nuclear weapons and associated technology, at fostering the peaceful uses of nuclear energy and at furthering the goal of disarmament.
- The Convention on the Physical Protection of Nuclear Materials (in force since 1987), that imposes obligations in relation to the physical protection of nuclear materials within national territory and in the course of international transport.
- The Convention on Early Notification of a Nuclear Accident (in force since 1986), that establishes a notification system pursuant to which a State is required to report to the IAEA and the affected States a nuclear accident which has potentially transboundary consequences that could be of radiological safety significance for other States.
- 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.
- The Convention on Nuclear Safety (in force since 1996), that aims to maintain a high level of safety at land-based civil nuclear power plants by setting international benchmarks for nuclear safety practices and regulation (see Chapter 4 for more information on nuclear safety).
- The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (in force since 2001), that aims to achieve and maintain a high level of safety in the management of spent fuel and radioactive waste through the enhancement of national measures and international co-operation (see Chapters 3 and 6 for more information on radioactive waste management).

In addition to the international conventions, a considerable number of multilateral agreements have been entered into, often by neighbouring countries, as for example the 1998 agreement between the Government of the Czech Republic, the Government of the Russian Federation, the Government of the Slovak Republic and the Government of Ukraine on co-operation in the field of transport of nuclear materials between the Czech Republic and the Russian Federation through the territories of the Slovak Republic and Ukraine. There are also bilateral co-operation agreements 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.

There is also extensive assistance activity by supranational bodies such as the European Union and international organisations such as the IAEA and the 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.

The legal regime for liability and compensation

Most countries using nuclear energy have adopted special liability and compensation legislation to ensure that anyone who suffers damage as a result of a nuclear accident has recourse to adequate compensation. These special regimes are unique, as they deviate from the normal legal principles that determine liability for damages resulting from a hazardous activity.

Under these regimes, the operator of a nuclear installation 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. This means that the operator of a nuclear installation is the only legal entity liable for personal injuries or property 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. 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. In most cases, 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 government guarantee or through a form of government-backed insurance, in practice, private insurance is the most common form of financial security.

It is acknowledged that the operator's liability coverage may not be sufficient to cover the consequences of a catastrophic nuclear accident. Therefore, supplementing these financial security requirements, many countries have mechanisms or policies in place to provide additional financial assistance or compensation out of public funds. 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 in case of a nuclear accident with transnational effects. These regimes, established during the early years of nuclear energy development, were significantly modified subsequent to the 1986 Chernobyl accident in Ukraine. That event demonstrated the need to increase the amounts of liability, to broaden the types of damage to be compensated, and to permit a greater number of victims to benefit. The nuclear liability conventions are:

- The 1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy (the Paris Convention), as amended in 1964, 1984 and 2004 (2004 amending protocol is not yet in force);
- The 1963 Brussels Supplementary Convention (BSC) to the Paris Convention, as amended in 1964, 1982 and 2004 (2004 amending protocol is not yet in force), only open to parties to the Paris Convention;
- The 1963 Vienna Convention on Civil Liability for Nuclear Damage (the Vienna Convention) as amended in 1997;

- The 1988 Joint Protocol relating to the Application of the Vienna Convention and the Paris Convention (the Joint Protocol), only open to parties to either the Vienna Convention or the Paris Convention;
- The 1997 Convention on Supplementary Compensation for Nuclear Damage (CSC), which is not yet in force.

All these conventions contain the same basic principles:

- strict and exclusive liability of the operator for third party nuclear damage;
- limitation of the operator's liability in amount and in time;
- the operator's obligation to secure its liability financially;
- non-discrimination among victims on grounds of nationality, domicile or residence;
- unity of jurisdiction, meaning that a single court of the State in which the nuclear incident occurs will have jurisdiction to hear all claims for compensation resulting from that particular accident.

The amounts of liability imposed upon nuclear operators under these conventions depend on the international convention to which the country concerned is a party to. There are also very significant variations in the liability amounts set by national legislations. In addition, the CSC (upon its entry into force) and the BSC provide for a pooling of public funds from participating countries to enable a larger sum of compensation to be made available. Under these supplementary funding conventions, the contracting parties will be able to access up to EUR 1.5 billion under the BSC (upon entry into force of the 2004 amending protocol) and up to 600 million Special Drawing Rights (about USD 930 million) under the CSC.

Many countries that generate significant amounts of nuclear power have not ratified any of the nuclear liability conventions. These countries include Canada, China, India, Japan and the Republic of Korea. However, most of them have adopted the principles of the conventions in their national legislation.

Environmental concerns

As the scope of environmental law has expanded in recent years, an increasing number of environmental standards, both at the international and national levels, now touch upon areas that were previously subject only to nuclear-specific law. This overlap between nuclear and environmental law has resulted in a number of initiatives, such as the application to nuclear activities of the 1991 Espoo Convention on Environmental Impact Assessment in a Transboundary Context, and the 1998 Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters.

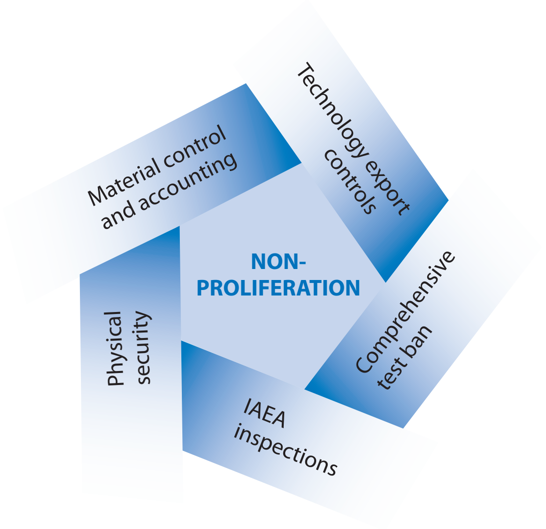
The non-proliferation regime

The enormous destructive potential of nuclear weapons has led the international community to take steps to prevent the proliferation of weapons-related nuclear materials and technologies. Because a good deal of knowledge relevant to the development of a nuclear weapon programme is intrinsically acquired during the course of developing and using nuclear energy for civilian purposes, preventing nuclear weapons proliferation while allowing peaceful nuclear development to proceed is a complex task. A number of international agreements and instruments seek to prevent the proliferation and use of nuclear materials and technologies for non-peaceful purposes, responding to widely held public concerns regarding the proliferation of nuclear weapons.

Developing a nuclear weapon programme is a complex undertaking requiring not just specialised fissile nuclear material, but also the necessary knowledge and technology to be able to design, build, handle, maintain and deliver such weapons. Relatedly, a country may consider testing an essential aspect of its nuclear weapon design and maintenance programme.

Beginning in 1946, the international community targeted each of these essential steps in the process of developing a nuclear weapon programme with the objectives of preventing access to the materials and critical technologies required to build a nuclear warhead, of preventing testing, and of controlling access to the technologies needed to deliver a nuclear weapon (Figure 7.1). These efforts culminated in a series of treaties, notably the 1968 Treaty on the Non-proliferation of Nuclear Weapons (NPT), which established the legal foundation for the international nuclear non-proliferation regime. The NPT entered into force in 1970 and was extended indefinitely in 1995.

Figure 7.1: **The elements of non-proliferation**



The NPT divides the signatories into two groups: countries that had manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1 January 1967 (defined in the treaty as "nuclear weapons States") and all other countries. In essence, the NPT requires that the "nuclear weapons States" (China, France, the Russian Federation, the United Kingdom and the United States) do not transfer nuclear weapons and do not assist any non-nuclear weapons State with the development of nuclear weapons. The NPT obligates all state parties to pursue nuclear and general disarmament. In essence, the non-nuclear weapons States agree to forego nuclear weapons while retaining the right to peaceful uses of nuclear technology. Almost all countries in the world are signatories to the NPT, with the significant exceptions of India, Israel and Pakistan. North Korea is a signatory, but announced its withdrawal from the treaty in 2003. The NPT state parties have never taken a collective position on the legality of North Korea's withdrawal from the NPT.

IAEA safeguards on nuclear materials

The IAEA's system of safeguards is the international community's primary means of detecting and deterring the diversion of nuclear material, through the use of inspections, monitoring equipment and other verification measures. 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 country 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 a voluntary safeguards agreement that permits the IAEA to verify some or all of its civil nuclear activities. The IAEA has a limited number of "item-specific" safeguards agreements in place with India, Israel and Pakistan to monitor certain nuclear activities in these countries that have not signed the NPT. In 1997, the IAEA adopted a “Model Additional Protocol” which includes measures to improve the capability to detect possibly undeclared nuclear activities.

The essence of IAEA safeguards is a country’s declaration about its nuclear material, facilities and activities, coupled with IAEA inspections or access to verify this information. Inspections are usually conducted on a random but pre-announced basis at least once a year. In the most sensitive facilities, physical inspections may be performed continuously. IAEA inspection activities include verification that the design of nuclear facilities is as declared, examination of operating records, measurement and sampling of the nuclear material itself, and use of surveillance equipment and sealing devices. The Model Additional Protocol requires that countries 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.

IAEA safeguards are complemented by other regional arrangements, such as the Euratom safeguards programme of the European Union, and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials. In addition, many countries have robust security measures in place to prevent theft or diversion of nuclear materials and technologies as well as to prevent sabotage.

Other controls on key materials and technologies

Certain key nuclear materials and technologies are subject to strict international export controls to ensure that they are not diverted to non-peaceful purposes. The Nuclear Suppliers Group (NSG), which includes all major countries with the capability to supply nuclear materials and technology, has a series of guidelines concerning the transfer to other countries of nuclear material, equipment, technology, components and facilities defined in an export “trigger list”. In addition to specifically nuclear items, the NSG guidelines relate to the transfer of certain “dual-use” items or technologies that can have nuclear weapons-related uses in addition to legitimate non-nuclear uses, such as high-speed computers.

Similarly, most parties to the NPT already co-operate to control technologies for missiles that could deliver nuclear weapons, through the Missile Technology Control Regime. Actions are also being taken to stop the smuggling of nuclear materials, with many governments sharing information on suspected illegal exports and imports of nuclear technology and materials.

Events in recent years have renewed concerns about the possible use of radioactive or nuclear materials for terrorist purposes. The possibility of using conventional explosives to disperse radioactive material, a so-called “dirty bomb”, reinforces the importance of national and international controls of such material. For example, the IAEA is working to establish an international framework to improve the security of radioactive sources.

Lately, the world’s leading nuclear power plant vendors have adopted the Nuclear Power Plant Exporters’ Principles of Conduct, an industry code of conduct resulting from an initiative to develop norms of corporate self-management in the exportation of nuclear power plants. In developing and adopting the Principles of Conduct, the participants have articulated and consolidated a set of principles that reaffirm and enhance national and international governance and oversight, and incorporate recommended best practices in the areas of safety, security, environmental protection and spent fuel management, non-proliferation, business ethics and internationally recognised systems for compensation in the unlikely event of nuclear-related damage.

Controls on the testing of nuclear weapons

Negotiations for an end to the testing of nuclear weapons culminated in the 1996 adoption of the Comprehensive Nuclear Test Ban Treaty (CTBT). This treaty prohibits all nuclear explosions, either for military or civilian purposes. Its signatories (numbering 182 countries at the end of 2011) 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. It will however only enter into force when all of the 44 states named in Annex 2 of the treaty as having nuclear power or research reactors at the time of the negotiations, have ratified it. As of February 2012, only 36 countries out of these 44 had ratified the treaty.

Effectiveness

To date, national and international controls on nuclear materials and key technologies have largely succeeded in preventing the proliferation of nuclear weapons. Nevertheless, the challenges posed by countries that have violated their international commitments or have refused to join the international non-proliferation regime demonstrate that continued efforts and vigilance are needed.

References

IAEA website, conventions and agreements under IAEA auspices are available at http://ola.iaea.org/OLA/treaties/multi.asp.

IAEA website, information about the IAEA's safeguards programme is available at www.iaea.org/OurWork/SV/Safeguards/.

NEA (2010), *International Nuclear Law: History, Evolution and Outlook*, *10th Anniversary of the International School of Nuclear Law,* Nuclear Energy Agency, OECD, Paris, France.

NEA/IAEA (2006), *International Nuclear Law in the Post-Chernobyl Period,* a joint report by the Nuclear Energy Agency and the International Atomic Energy Agency, OECD, Paris, France.

NEA website, Regulatory and Institutional Framework for Nuclear Activities, information on legislation and institutions governing the peaceful uses of nuclear energy in OECD member countries. Available at www.oecd-nea.org/law/legislation/.

NEA website, legal instruments concerned with nuclear liability are available at www.oecd-nea.org/law/legal-documents.html.

The Nuclear Suppliers Group Guidelines are available at www.nuclearsuppliersgroup.org.

Chapter 8

The Economics and Financing of Nuclear Energy

In comparison with most other electricity generating technologies, nuclear energy has low fuel costs and hence low marginal production costs, making its overall costs less sensitive to variations in fuel prices. This is offset by the long construction periods and high investment costs involved in building nuclear power plants, which make overall costs more sensitive to financing costs. But once in operation, nuclear plants usually have longer operational lifetimes than other types of power plant.

Operating nuclear power plants are generally very competitive with other forms of generation due to their low marginal costs. This makes them valuable assets for electricity utilities, particularly once the initial investment costs have been amortised. However, the risks associated with such large, long-term investments in a complex and often controversial technology can make purely commercial financing difficult to obtain. Hence, decisions to build new nuclear power plants require a supportive public policy framework and appropriate financing models.

Nuclear generating costs and investment risks

There are a number of special factors that characterise the economics of nuclear energy:

- high investment costs;
- long construction periods relative to other types of power plant;
- long operational lifetimes;
- low fuel costs;
- the need to provide for decommissioning and waste management costs incurred after cessation of power generation.

Figure 8.1 shows an illustration of the life-cycle revenues and costs for a nuclear power plant, with detailed planning, design and construction taking around 10 years, an operating lifetime of 40 years, and a decommissioning period that could also last for several decades (depending on the decommissioning strategy adopted).

Elements of nuclear generating costs

The costs of generating electricity can be broken down into three major categories: investment (capital) costs; operation and maintenance (O&M) costs; and fuel costs. The relative size of these costs varies between different countries and types of nuclear plant, with a typical breakdown shown in Figure 8.2, corresponding to a 5% discount rate. It is important to note that decommissioning and waste management are taken into account in the electricity generation costs.

Investment in the plant includes the costs of licensing, design, construction and commissioning. Over a plant's lifetime, it also includes the costs of possible major refurbishments and eventual decommissioning. However, the costs of construction are by far the most significant, particularly as they are incurred up front. These costs must be financed, usually through a combination of loans and the capital resources of the companies owning the plant, and thus financing costs (interest charges or a return on investment) are incurred.

Figure 8.1: Illustrative life-cycle cash flow for a nuclear power plant

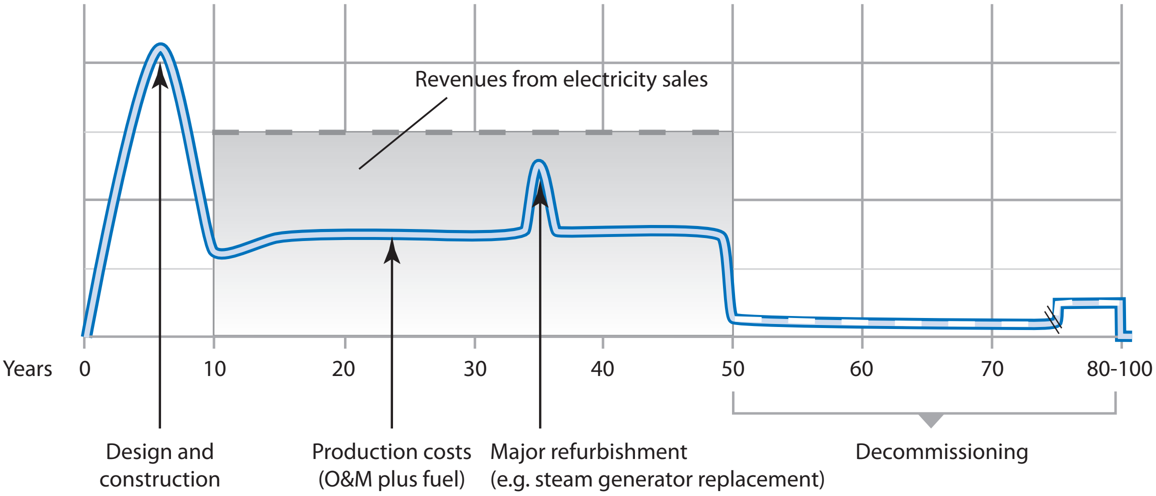
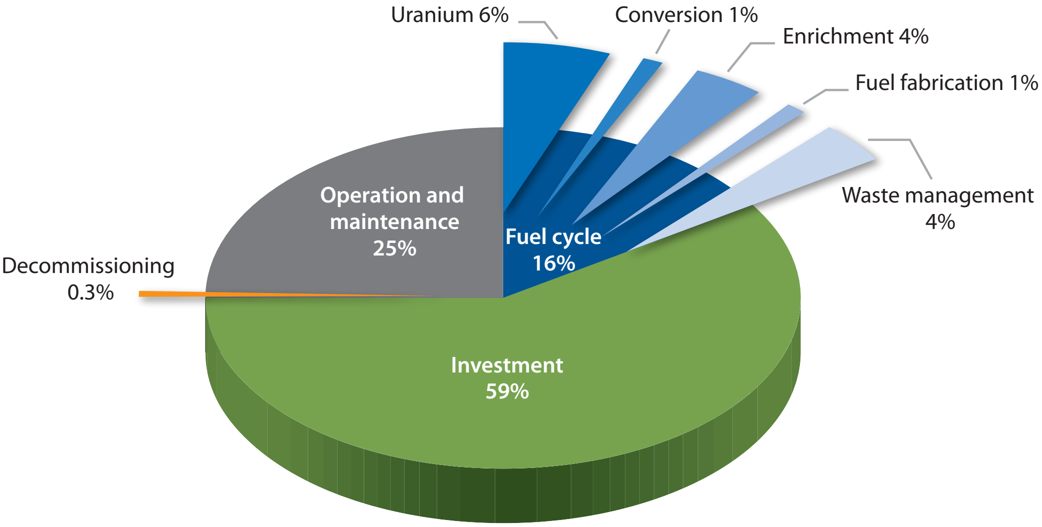


Figure 8.2: Typical nuclear electricity generation cost breakdown
(5% discount rate)



Source: IEA/NEA, *Projected Costs of Generating Electricity,* 2010.

The financing costs incurred during construction, i.e. before any revenues are generated by the plant, are added to the overall investment cost. This means that the total cost of building a nuclear plant is very sensitive to the financing costs. The total up-front investment costs are amortised over a significant proportion of the plant's operating lifetime, with the cost of debt servicing being part of the overall cost of electricity generation.

Financial provision must also be made during the operating lifetime for the estimated costs of decommissioning and of management and disposal of the associated radioactive wastes. These estimates are based on extensive studies and on current experience of decommissioning, with allowance for cost increases due to uncertainties and possible changes in regulatory requirements. There is generally a regulatory requirement to make such provision according to a formula (often either an amount for each unit of electricity generated or a proportion of the plant's investment costs), subject to periodic review.

The decommissioning costs represent a small component of the total life-cycle costs, not least because the long period between start of operation and decommissioning allows time for funds set aside to grow. The potential also exists for technological advances to reduce costs below those envisaged. However, there remains a risk of a shortfall should the plant close earlier than expected for any reason.

At some point in the plant's lifetime a major refurbishment (such as replacement of steam generators or other major systems or components) may become desirable or necessary to improve operating efficiency and/or extend operating lifetime. By the time such investment is required, the construction costs are likely to have been fully amortised. This allows some part of the plant's revenues to be used to finance the refurbishment, amortised over the remaining lifetime.

O&M costs include all costs that are not considered to be investment or fuel costs, the main elements being the costs of operating and support staff (including training, security, and health and safety), insurance, management and disposal of operational waste, and routine maintenance and inspection. These costs are directly under the control of the operating company and thus represent the main opportunity for cost-reduction in an operating nuclear plant.

Fuel costs include all costs related to the fuel cycle, including the costs of purchasing uranium, its conversion and enrichment where necessary, fuel fabrication, spent fuel conditioning and/or reprocessing, disposal of spent fuel or high-level waste and transport. Fuel costs make up only about 10-15% of the total cost of nuclear-generated electricity, with uranium itself accounting for about half of fuel costs. Hence, the overall cost of nuclear electricity is not sensitive to uranium price fluctuations.

Long-term financial risks and liabilities

A decision to build a nuclear power plant represents a greater commercial risk than is normally associated with other electricity sources, such as coal or natural gas-fired plants, for several reasons:

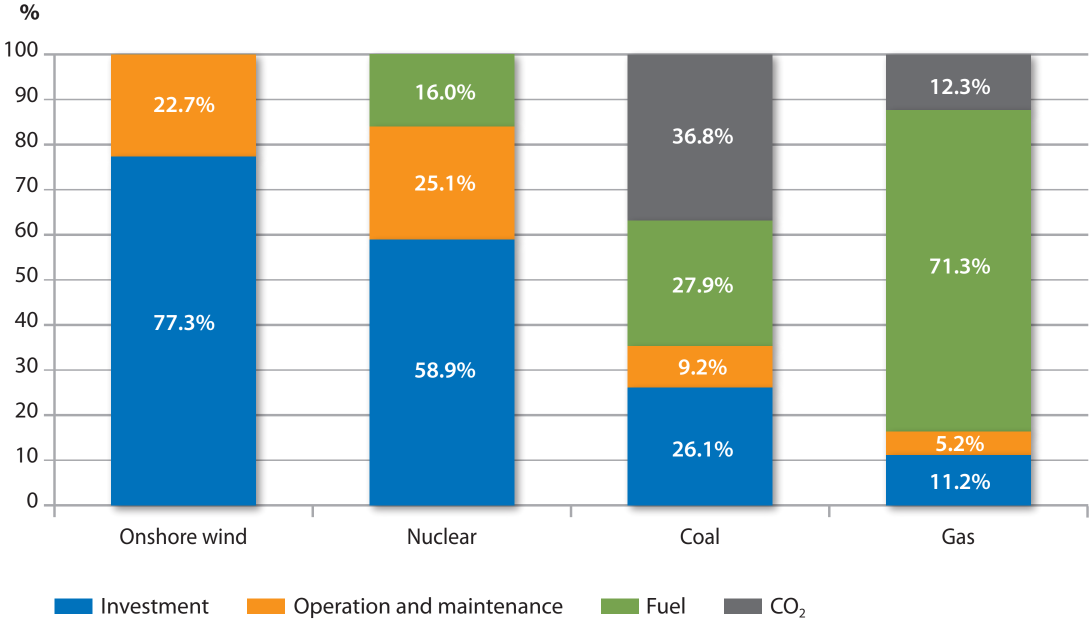
- The technical complexity of nuclear plants has historically led to delays in construction and hence cost overruns.
- Changes in government policy or legislation affecting nuclear energy, or in regulatory requirements, could delay the plant in entering operation, adding to costs.
- Such changes occurring during the plant's operating lifetime could also add to costs and potentially prevent the plant from operating for its full lifetime.
- The long planning and construction timescale and long operational lifetime provide greater potential for long-term changes in the electricity market to impact revenues.
- At the same time, the high proportion of fixed-costs (due largely to high investment costs), results in greater vulnerability to short-term market fluctuations.
- There may be uncertainties about the costs the plant will be required to pay for decommissioning and long-lived waste disposal.

Comparison with other sources of electricity

Compared with nuclear energy, natural gas-fired plants are characterised by low capital investment costs and high 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 generating costs that are, as a result, more 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 marginal production costs per unit of power.

Figure 8.3 gives a comparison of the typical breakdown of electricity costs for nuclear, coal, natural gas and wind generation at a 5% discount rate (a measure of the costs of financing).

Figure 8.3: Typical breakdown of costs of electricity generation from different sources
(5% discount rate and carbon price of 30 USD/tonne CO_2)



Notes: Investment: includes decommissioning costs. Fuel: includes waste management for nuclear.

Source: IEA/NEA, *Projected Costs of Generating Electricity,* 2010.

Competitiveness of existing plants

Given the relatively low cost of nuclear fuel, improvements in operating efficiency over the last 20 years, and the fact that original investment costs are now substantially amortised, the great majority of existing nuclear power plants are very competitive suppliers of electricity. Low fuel costs and moderate O&M costs mean that nuclear plants have low marginal costs of production, and can thus operate profitably even when electricity prices are low (although constant low prices would not allow the recovery of investment costs).

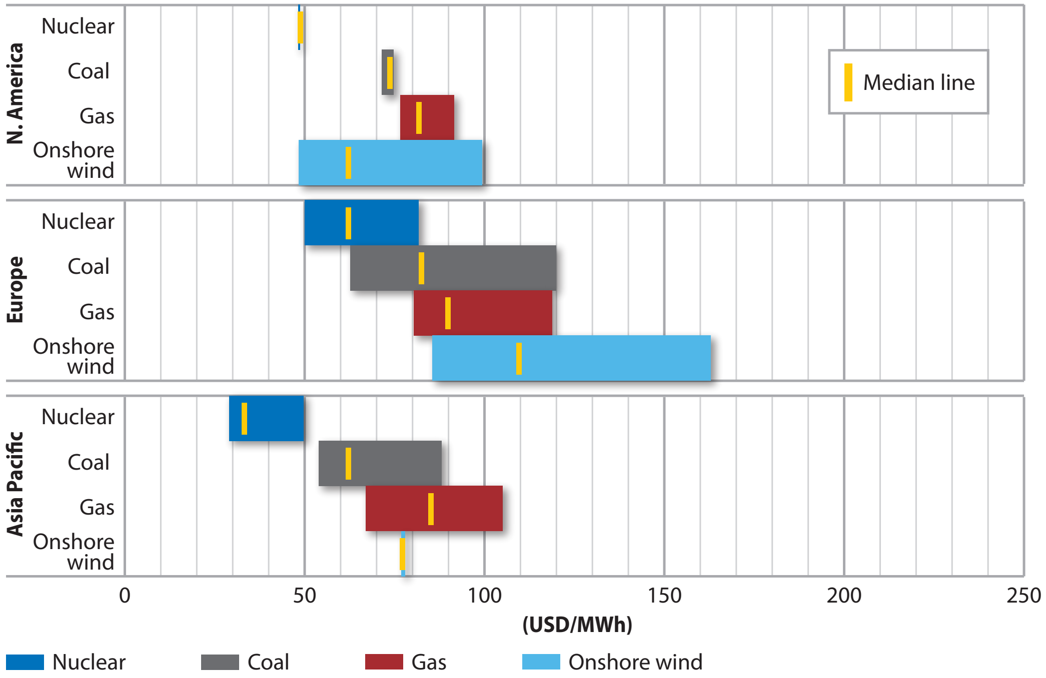
For example, data reported for electricity generating plants in the United States show that in 2009, average operating expenses (O&M plus fuel costs) were about 2.2 US cents/kWh for nuclear, 4.0 US cents/kWh for conventional fossil fuel sources and 0.8 US cents/kWh for hydro.

The outlook for the economic performance of existing plants is that they will continue to provide low-cost electricity and that in many cases it is both technically feasible and economically attractive to invest in upgrading them to extend their operating lifetimes beyond that originally envisaged. In general, upgrading a plant for lifetime extension costs much less than building a new plant, and can also increase power output and improve operating performance.

Comparative costs of new nuclear plants

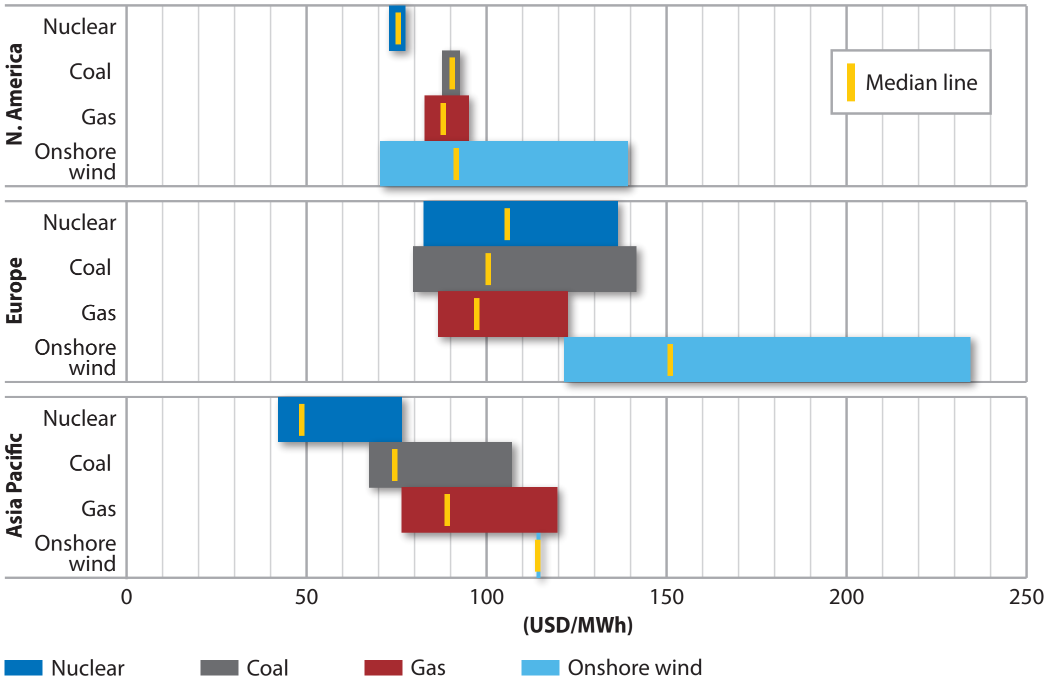
A 2010 study on the *Projected Costs of Generating Electricity* produced jointly by the NEA and the International Energy Agency compares the costs of electricity generated using various technologies, levelised over the estimated plant lifetime (so-called levelised cost of electricity or LCOE). The results show that the relative attractiveness of each technology for new plants is dependent on country-specific factors, including the prevailing discount rate.

Figure 8.4: Regional ranges of LCOE for nuclear, coal, gas and onshore wind power plants (5% discount rate and carbon price of 30 USD/tonne CO_2)



Source: IEA/NEA, *Projected Costs of Generating Electricity,* 2010.

Figure 8.5: Regional ranges of LCOE for nuclear, coal, gas and onshore wind power plants (10% discount rate and carbon price of 30 USD/tonne CO_2)



Source: IEA/NEA, *Projected Costs of Generating Electricity,* 2010.

Figures 8.4 and 8.5 show the ranges of costs reported for three major global regions (North America, Europe and Asia Pacific) for nuclear, coal, natural gas and onshore wind generation, at 5% and 10% discount rates respectively. This indicates that nuclear energy has a clear cost advantage on a levelised cost approach in all regions at the lower discount rate. With a higher discount rate, nuclear loses its cost advantage in Europe, but remains the most competitive option in North America and Asia Pacific. The results assume a cost for carbon dioxide emissions from fossil fuel plants of USD 30 per tonne.

The relatively large investment cost is a major factor in the cost of electricity from nuclear plants, hence the marked impact of the assumed discount rate. To make construction of new plants commercially attractive under competitive conditions, investment costs must be kept as low as possible. New more cost-effective designs, improved construction methods, standardisation and series construction, and multiple unit construction on a single site are all possible means to reduce the investment costs of nuclear power plants.

In a few countries where nuclear development continued without a break during the 1990s and 2000s, improvements in nuclear designs and construction techniques have been achieved, leading to shorter construction times and hence reduced investment costs. China, Japan and the Republic of Korea have all successfully built new nuclear power plants in less than five years. For the latter two, this has been coupled with the introduction of advanced reactor designs, one aim of which is to facilitate the use of more efficient construction techniques.

Nevertheless, the large size of the investment required in a new nuclear power plant, and the risk that costs may escalate due to delays in construction, can make it difficult to obtain private sector finance with attractive financing costs. In some cases, the investment required would be a large proportion of the entire market capitalisation of the electricity company involved, so putting its solvency at risk. Financing may also be more difficult in competitive electricity markets, where the operator has no guarantee of an adequate price for the power produced.

Hence, governments that wish to see additional or replacement nuclear capacity built over the next few years with largely private sector financing may need to provide some form of guarantee and/or other measures to help reduce financing costs. This will allow the risks of nuclear investments to be shared between the government and electricity companies. A leading example of this is the system of loan guarantees introduced by the US government, which is expected to support the financing of at least a few new nuclear plants before 2020.

Carbon emissions and other external costs

An important driver for energy policy is the commitment that most OECD countries have made to reduce their emissions of greenhouse gases, notably carbon dioxide (CO_2) from the burning of fossil fuels. Although this will partly be achieved by the increased use of renewable energy sources, nuclear energy is already a major source of low-carbon electricity and its expansion can make an important contribution to reducing emissions. This is discussed further in Chapter 9.

Measures that governments may take to provide incentives for investment in low-carbon energy sources, including carbon trading systems (where emissions must be covered by tradable permits) or carbon taxes, can help improve the economics of nuclear energy (as well as other low-carbon sources) relative to fossil-fired generation. A recent study published by the NEA in 2011 addresses the competitiveness of thermal power generation technologies under carbon pricing in liberalised electricity markets. The study concentrates on Europe, where there exist both liberalised electricity markets and a carbon price through the European Emissions Trading System, the EU ETS. Based on empirical market data, the study shows that even with modest carbon pricing, competition for new investment in electricity markets will take place between nuclear power and gas-fired power generation with coal-fired power struggling to be profitable. The outcome of the competition between nuclear and gas-fired generation hinges, in addition to carbon pricing, on the capital costs for new nuclear construction, on the level of gas prices as well as on the profit margins in the electricity sector earned due to pricing power. Strong competition in electricity markets also favours the attractiveness of nuclear energy. In this study, carbon pricing enhances the competitiveness of nuclear energy most when prices evolve in a range of USD 40 to USD 70[1] per tonne of CO_2.

Even in the case of low gas prices or high nuclear construction costs, nuclear power may still be attractive to utilities wanting to diversify their power generation portfolio. In this study, the impact of the Fukushima Daiichi accident on the cost of new nuclear plants was taken into account, but was considered not to have a large influence since the new Generation III+ reactor designs that were considered for the study in Europe already incorporate the great majority of enhanced safety systems recommended in the aftermath of the Fukushima Daiichi accident.

More generally, there is a case to be made to internalise the external costs (or externalities) of different energy technologies. Carbon trading or taxes are an example of internalising the external cost of CO_2 emissions in the costs of fossil-fuelled power generation. However, there are also other external health and environmental costs of fossil fuel combustion, corresponding for example to the impacts of particulates and sulphur and nitrous oxides, that are not always internalised [the SO_2 market in the United States or the Large Combustion Plant Directive (LCPD) of the European Union represent exceptions]. Although efforts have been made in some countries to reduce these emissions, they continue to have significant health impacts, in particular in developing countries. In contrast, for nuclear energy the vast majority of the costs of management and disposal of solid and liquid radioactive wastes and of decommissioning are included in the costs of nuclear plant operators and thus in the price of its electricity.

A different form of external effects is constituted by the intermittent nature of some forms of renewable energy, including wind and solar energy. Ensuring a reliable electricity supply means that backup capacity has to be available both for short-term balancing needs and for the long-term provision of adequate capacity. The costs of building and maintaining such capacity, which may only be used occasionally, as well as the costs of the required extension of electricity transmission grids, are currently not incorporated into the costs of electricity from renewable sources. These system costs are very significant for intermittent renewable energies.

Finally, another external cost of nuclear energy relates to the question of the nuclear operators' liability in case of a nuclear accident. National legislations of nuclear power states usually provide that nuclear operators shall be strictly and solely liable for nuclear damage. Even though most nuclear liability legislations limit the liability of the operator in amount, certain countries have opted for unlimited liability. In any event, nuclear operators are usually required by law to maintain insurance or provide other financial security fully covering their liability for nuclear damage and, in case of unlimited liability, up to a legally defined amount. The state may assume responsibility for providing additional compensation in the event that the amount required to compensate nuclear damage caused by a particular accident exceeds the amount of compensation that can be made available by a nuclear operator and its insurers or other financial guarantors (e.g. the 1963 Brussels Convention Supplementary to the Paris Convention mechanism). This potential state intervention has raised some concerns, regarding competition and more specifically state aid rules.

To create a level playing field for different energy sources and to ensure the most cost-effective balance of sources is adopted to meet energy and environmental policy goals, governments and market regulators should aim to internalise all environmental and system costs associated with each energy source.

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[1] The study assumed that unmitigated coal remains in the energy mix. If it does so, coal-fired power plants would set the price of electricity in a liberalised market at higher carbon prices. In this case, both gas and nuclear benefit from high carbon prices, but the profitability of gas increases faster than that of nuclear, making gas the more competitive option at high carbon prices.

References

IEA/NEA (2010), *Projected Costs of Generating Electricity: 2010 Edition,* International Energy Agency and Nuclear Energy Agency, OECD, Paris, France.

NEA (2008), *Nuclear Energy Outlook 2008,* Chapter 6, Nuclear Energy Agency, OECD, Paris, France.

NEA (2009), *The Financing of Nuclear Power Plants,* Nuclear Energy Agency, OECD, Paris, France.

NEA (2011), *Carbon Pricing, Power Markets and the Competitiveness of Nuclear Power,* Nuclear Energy Agency, OECD, Paris, France.

The Future of Nuclear Energy

World energy demand is set to grow rapidly over the coming decades against a background of increasing concern about the environmental implications of energy use, especially the emission of carbon dioxide from burning fossil fuels. Rising demand also means that security of energy supply is becoming a major issue for many countries.

Nuclear energy has certain advantages in addressing both these concerns. It is an established source of low-carbon energy that can add to the diversity and security of energy supplies. This chapter considers the future of nuclear energy in the broader context of energy supply and demand worldwide over the next 40 years and beyond. It concludes with a section looking at present and future non-electric uses of nuclear energy.

World energy demand and security of supply

Growing demand for energy

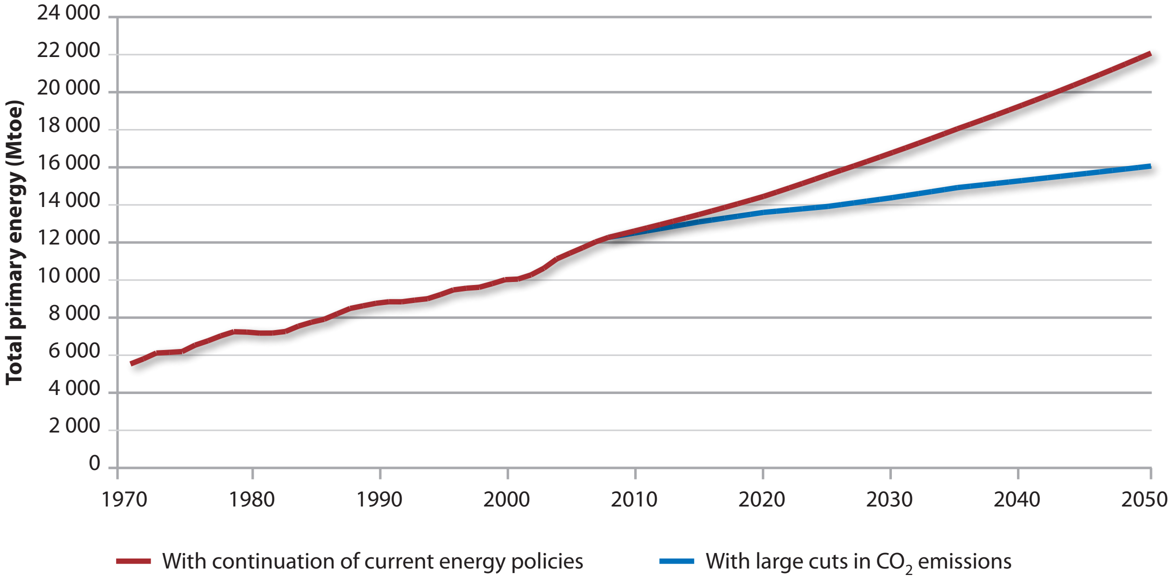
The world's demand for energy will continue to increase as a result of economic development and population growth. Figure 9.1 shows how global energy demand has grown since 1970 as well as two projections of growth to 2050, from the *Energy Technology Perspectives 2010* scenarios of the International Energy Agency (IEA). The upper curve shows the demand growth that can be expected with "business as usual", i.e. if current policies and recent energy use trends continue. This assumes at world level average annual demand growth of 1.4% between 2010 and 2050, giving a cumulative increase of about 75% over the period. For comparison, between 1971 and 2010 the average annual demand growth was over 2%, a cumulative increase of about 120%.

The lower curve shows the potential impact of ambitious policies (so-called Blue Map scenario) to curb energy use and improve energy efficiency, as part of efforts to cut carbon dioxide emissions. In this case it is assumed that annual growth can be cut rapidly over the next few years and that over the next 40 years it will average just 0.6%, a cumulative increase of less than 30% over the period. Achieving this would mean the rapid and widespread introduction of more energy efficient technologies and strong measures to curb unnecessary or wasteful consumption.

The overwhelming share of this energy demand growth will take place in rapidly industrialising non-OECD countries, as they strive to raise the living standards of their growing populations. It can also be expected that the share of this energy that is consumed in the form of electricity will grow as some of the more than 1.4 billion people worldwide currently without electricity in their homes are connected. In addition, new uses of electricity are expected to emerge, for example, the more widespread use of electrically powered vehicles.

The world faces several major challenges over the next four decades and beyond to provide secure and affordable energy supplies to a growing population, while avoiding unacceptable impacts on the environment. Achieving this will involve moderating energy demand growth and greatly improving the efficiency of energy production and consumption, as well as optimising the mix of energy sources and technologies to meet the remaining growth in a socially and environmentally acceptable manner.

Figure 9.1: Historical and projected world primary energy demand (1970-2050)



Sources:
Historical data: *OECD Factbook 2010.*
Projections: Based on IEA Baseline and Blue Map scenarios (*Energy Technology Perspectives,* 2010).

Security of energy supplies

The availability of adequate energy supplies at reasonable prices has long been a concern of many governments, especially where there is a high dependence on imports. Energy shortages and consequent high prices can have a devastating effect on a country's economy. These concerns have, in the past, related primarily to the supply of fossil fuels, oil and natural gas in particular.

One reason for such concerns is that oil and gas resources and production are concentrated in a relatively small number of countries and global regions, some of them politically unstable. In the longer term, there are concerns that as low-cost fossil fuel resources are depleted, extraction will become more costly and potentially more environmentally damaging.

Even if today over 90% of the world's uranium output is produced by only eight countries, resources are widespread across the world. Furthermore, the nature of the nuclear fuel cycle means that nuclear plants are not dependent on continuous deliveries of large quantities of fuel. Nuclear fuel is a very concentrated energy source, and is easy to stockpile. Several years' worth of fuel can be kept in inventory at low cost. About 25 tonnes of fabricated fuel will provide a year's supply for a typical nuclear plant, while a coal-fired plant of similar output requires some three million tonnes of fuel annually.

If increased reliance is to be placed on nuclear energy for the longer term, and given that the operating lifetime of a new nuclear power plant is expected to be around 60 years, then the continued availability of uranium and the adequacy of known uranium resources are important considerations. The very slow growth of nuclear power since 1990 has led to generally low levels of uranium exploration activity over the last 20 years. Despite this, the ratio of known reserves to current consumption represents about 100 years' supply compared to about 40-60 years for oil and gas respectively and about 200 years for coal. Geological information suggests that additional reserves in partially explored regions will increase this ratio to around 300, while so-called unconventional resources (mainly uranium in phosphate rocks) could extend it to around 700 (see Table 9.1).

Taking into account the progressively increasing efficiency with which uranium is being used in reactors and the fuel cycle due to technological advances, it can be concluded that uranium resources are more than adequate to support a significant increase in nuclear capacity by 2050. However, uranium production will clearly need to expand from its present levels, as will the capacity of other nuclear fuel cycle facilities. For the longer term, the recycling of uranium and plutonium in fast reactors could potentially extend the lifetime of existing uranium resources for several millennia; this is discussed further below.

Security of energy supply is also strengthened by increasing the diversity of energy sources, meaning that disruption of one source will have a smaller overall impact. Given most countries' heavy dependence on fossil fuels, nuclear and other alternative energy sources can provide valuable diversification.

For these reasons, many governments view nuclear power as an important component of their strategy to increase the security of their energy supplies.

Table 9.1: Lifetime of uranium resources (in years) for current reactor technology and future fast neutron systems (based on 2006 uranium reserves and nuclear electricity generation rate)

	Identified resources	Total conventional resources	Total conventional and unconventional resources
Present reactor technology	100	300	700
Fast neutron reactor systems	> 3 000	> 9 000	> 21 000

Source: OECD/NEA, *Nuclear Energy Outlook,* 2008.

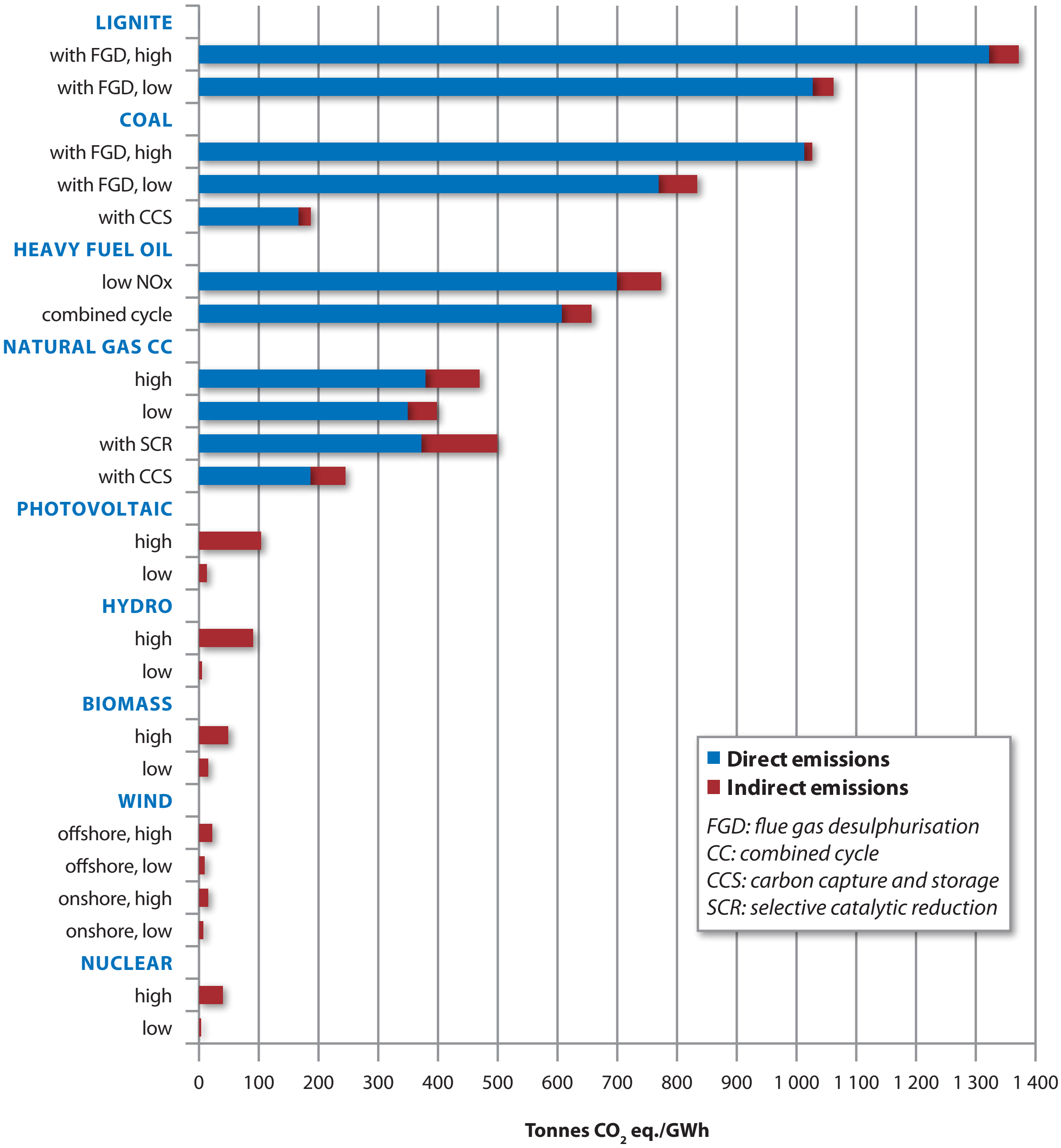
Energy use and climate change

It is widely accepted by the scientific community and by most governments that the increasing concentrations in the atmosphere of carbon dioxide (CO_2) and other greenhouse gases emitted as a result of human activities will, if unchecked, lead to a warming of the global climate. While uncertainties remain over the extent and speed of warming, and over its impacts, a broad global consensus has been reached that future emissions must be significantly reduced from projected "business as usual" levels.

Emissions from the burning of fossil fuels (coal, natural gas and oil) for electricity generation are the largest source of CO_2 from human activities, accounting for about 40% of the total emissions. Fossil-fuelled power plants have also been the fastest growing source of CO_2 emissions over recent decades. Reducing CO_2 emissions from power plants, although challenging, is expected to be less difficult than controlling some other sources of emissions, such as transport and deforestation. Hence, strategies to respond to the threat of global warming invariably include very large reductions in emissions from the power sector, with the goal of its near-complete "decarbonisation" by the middle of this century.

Although nuclear power plants themselves emit essentially no CO_2, some indirect emissions from the complete nuclear cycle can be attributed to nuclear electricity production. Most of these arise from the use of energy from fossil fuels in uranium mining and enrichment. Their size varies considerably depending on the technologies employed and the sources of the electricity used. Figure 9.2 gives high and low estimates for the direct and indirect emissions from a range of electricity generating technologies. This shows that indirect emissions from the nuclear cycle, in common with those from renewable energy cycles, are at least an order of magnitude lower than the direct emissions from burning fossil fuels.

Figure 9.2: Direct and indirect greenhouse gas emissions from various electricity generation systems



Source: Intergovernmental Panel on Climate Change, *Mitigation of Climate Change*, 2007.

The current use of nuclear power avoids the emission of up to 2.6 gigatonnes of CO_2 annually, compared to using coal-fired generation. Only nuclear and hydropower currently provide significant amounts of low-carbon electricity, with over two-thirds of all electricity being produced by burning fossil fuels (see Chapter 1). Nuclear is thus one of very few established low-carbon energy sources and its expansion can make an important contribution to efforts to decarbonise electricity supply.

Nuclear power also avoids the emission of particulates and polluting gases such as sulphur and nitrogen oxides produced by burning fossil fuels, especially coal. These have important local health and environmental effects, such as respiratory diseases and acid rain.

The future role of nuclear power

As noted in Chapter 1, at the end of 2011 world nuclear generating capacity was about 369 gigawatts (GW), providing nearly 14% of global electricity supply. Most of this capacity had already been installed by 1990, with total capacity increasing only slowly since then (see Figure 1.1). However, recent years have seen a significant increase in the construction of new nuclear power plants. Since construction typically takes five to seven years this has yet to feed through to an increase in operating capacity, but by around 2015 capacity will begin to rise more strongly. On the basis of plants under construction and firmly planned, and allowing for the closure of some older units, as well as the phase-out policies of some countries following the Fukushima Daiichi accident, it can be expected that nuclear capacity in 2020 could be between 470 GW and 500 GW. This represents a decrease of about 8% compared to projections made before the Fukushima Daiichi accident, but still a capacity increase of over 25% compared to 2010.[1]

Scenarios for the longer-term future of energy supply take into account population growth, economic growth, technological developments, government energy policies, fossil fuel prices and other factors. Very different scenarios can be produced by changing the assumptions for each of these factors. Scenarios can also be constructed to examine the steps necessary to produce a desired outcome, for example, to achieve a set reduction in CO_2 emissions.

Figure 9.3 shows two scenarios for electricity supply in 2050 prepared by the IEA, compared with actual 2008 supply. The Baseline, or “business as usual”, scenario illustrates the possible outcome if energy policies remain unchanged, given expected population and economic growth. Total electricity supply rises from just over 20 000 TWh to over 46 000 TWh. While use of low-carbon sources (nuclear, hydro, wind, biomass and solar) increases, fossil fuels continue to provide more than two-thirds of all electricity. As a result, CO_2 emissions grow strongly in this scenario.

The second scenario illustrates the electricity supply mix that could contribute to a 50% cut in global CO_2 emissions from energy supply by 2050. In this case, total electricity supply is cut to just over 40 000 TWh through increased efforts on energy efficiency and conservation, with nearly 90% of this provided by low-carbon sources. As well as large increases in nuclear, hydro, wind, solar and biomass, almost all the remaining coal burning is assumed to use carbon capture and storage (CCS) technology, in which CO_2 is liquefied and disposed of underground rather than being released to the atmosphere.

This highlights the fact that many of the low-carbon technologies required to make large cuts in CO_2 emissions still require further technological development if they are to be available for such widespread commercial use by 2050. The scenario is based on achieving reductions in a cost-effective manner, assuming that the cost of each technology will fall as it reaches maturity. However, few low-carbon technologies are yet as competitive as fossil fuels, and CCS remains to be demonstrated on a commercial scale. Nuclear power, on the other hand, is an established technology with over 50 years of development and operational experience.

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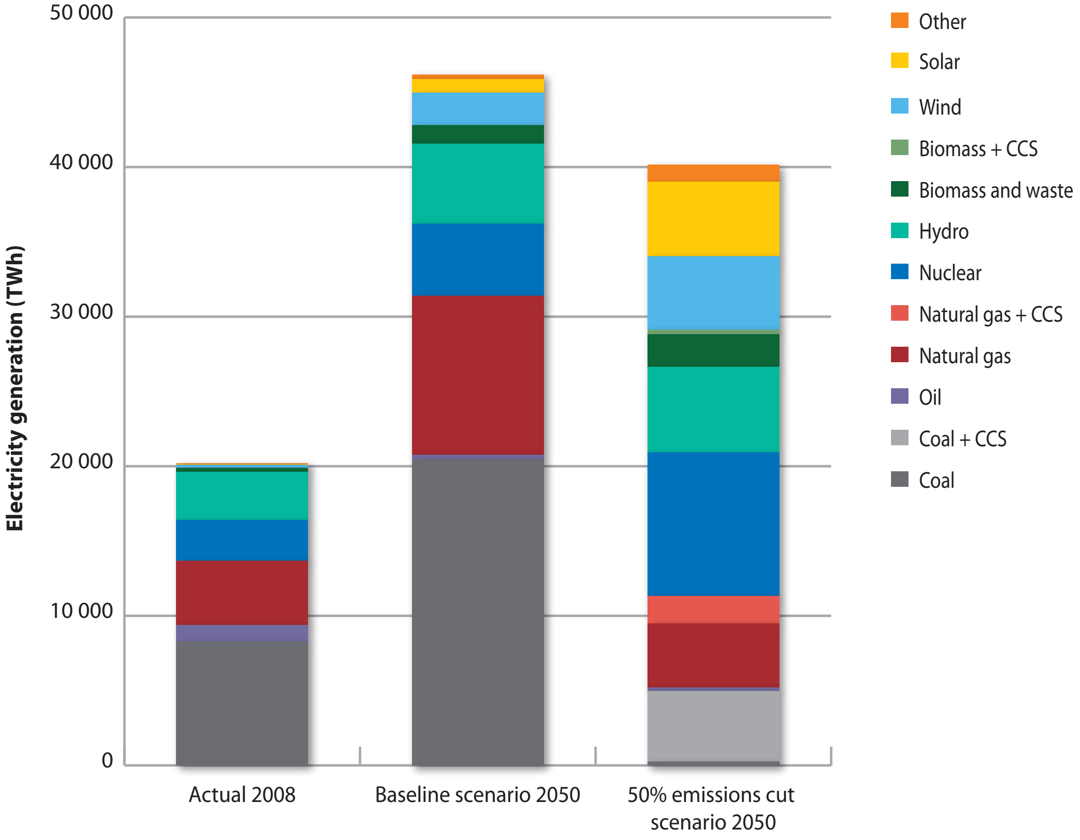
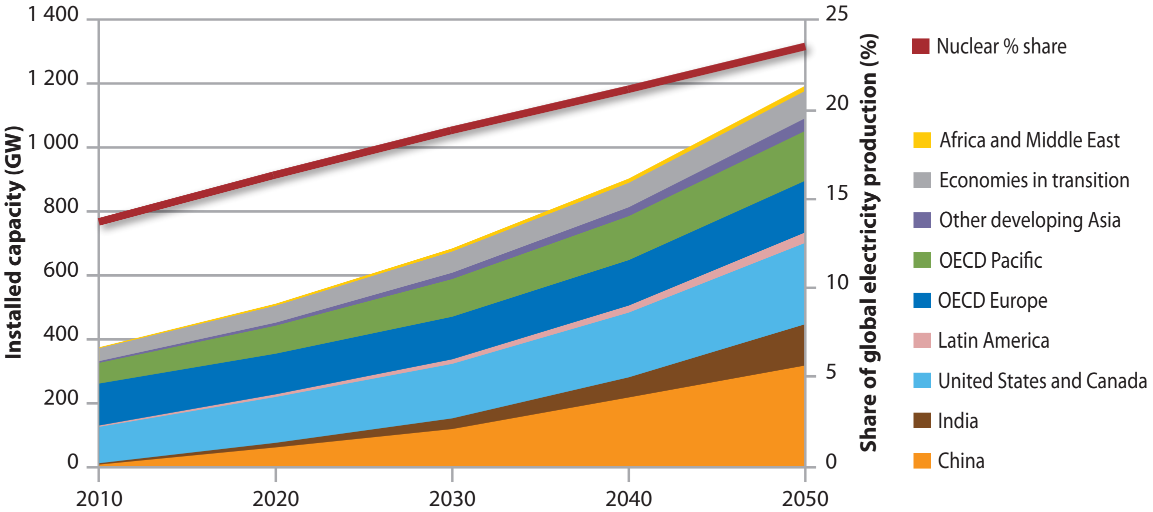
[1] In its *World Energy Outlook 2011,* published in November 2011, the IEA estimated that the total installed nuclear capacity in 2020 would lie between 485 GW (Current Policies scenario) and 519 GW (450 ppm scenario). The New Policies scenario, corresponding to announced but not yet enacted commitments concerning greenhouse gas emissions, sees nuclear representing 495 GW installed capacity.

Figure 9.3: Global electricity production by source in 2008, and in 2050 in baseline and 50% emissions cut scenarios



Note: CCS is carbon capture and storage. "Other" includes geothermal, tidal and wave power.
Source: IEA, *Energy Technology Perspectives,* 2010.

Figure 9.4: Growth in nuclear power capacity and its share of global electricity production



Source: IEA/NEA, *Nuclear Energy Technology Roadmap,* 2010.

The scenario clearly shows the significant role that nuclear power could play in cutting CO_2 emissions. Nuclear capacity would grow from 375 GW in 2010 to around 1 200 GW by 2050, providing almost 25% of all electricity. Figure 9.4 shows the regional breakdown of this growth and the rising share of nuclear power in total electricity production. There is also potential for nuclear to grow even more strongly, if technological development of other low-carbon sources falls short of expectations or their costs remain relatively high.

Achieving such a large expansion of nuclear energy over the next 40 years will depend on successfully addressing issues that could limit its growth, many of which have been discussed in earlier chapters of this report:

- Making available adequate supplies of uranium, and in the longer term introducing advanced nuclear technologies to make more efficient use of the natural resource provided by uranium.
- Fully implementing plans for radioactive waste management and disposal, in particular opening the first deep geological repositories for spent fuel and high-level waste.
- Continuing to improve levels of safety at existing and new nuclear power plants.
- Achieving more widely the shorter construction times and resulting lower investment costs that have been demonstrated in a few countries, thus reducing financial risks and improving overall economics.
- Developing the skilled human resources and industrial capacities needed to build and operate nuclear power plants and fuel cycle facilities.
- Maintaining and strengthening where necessary the international legal framework for nuclear energy, notably the non-proliferation and liability regimes.
- Strengthening acceptance by civil society of nuclear energy as part of an overall strategy to meet energy and environmental goals, based on a balanced assessment of the risks and benefits of different energy sources. This challenge has of course become much more difficult as a consequence of the Fukushima Daiichi accident.

It is clear that a successful nuclear programme requires a clear and stable national commitment over the long term. On a practical level, a country pursuing a nuclear programme needs to develop an effective legal and regulatory framework, as well as its own skilled human resources and industrial capabilities. Even though in many cases the main expertise and components for a nuclear plant will be imported, there is usually significant local content. This has important economic benefits in the country concerned.

Developing nuclear technology for the future

A new generation of reactors and fuel cycles

The present status of nuclear technology is the result of over 50 years of continuous development, making use of experience gained from nearly 15 000 reactor-years of operation. The latest designs of nuclear power plants that are available commercially, known as Generation III or III+ designs, incorporate the lessons learnt from this experience to enable more efficient construction methods, and offer higher levels of safety and performance, improved fuel efficiency and reduced radioactive waste production.

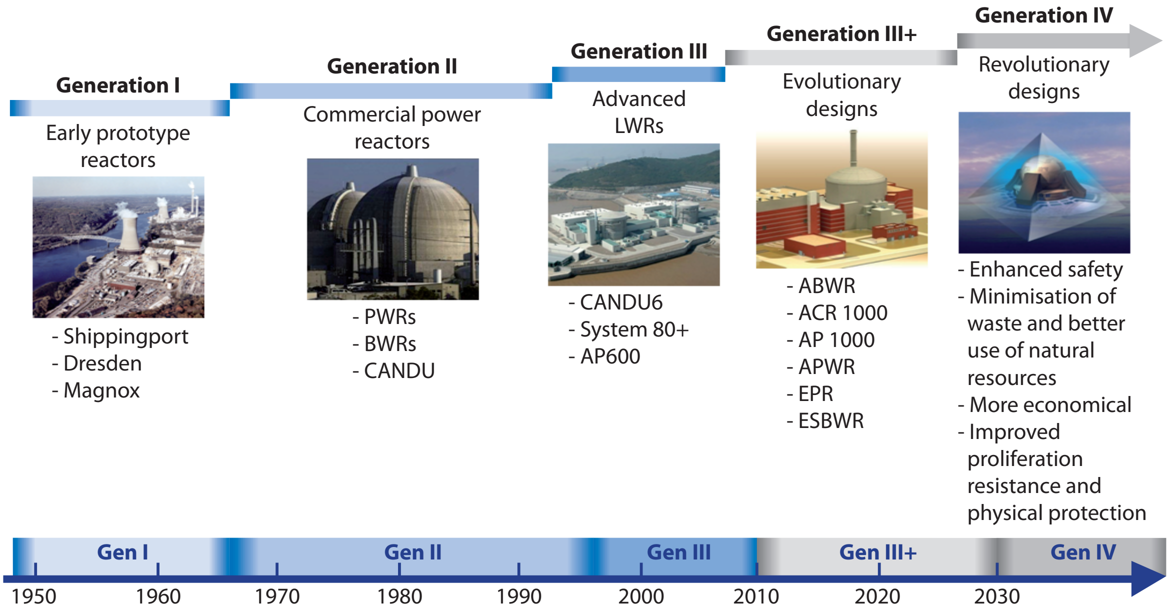
Altogether, several designs for large Generation III/III+ light water reactors have been fully developed, with the first examples of most designs now in operation or under construction in several countries. These designs and others resulting from continuous evolutionary development will be the mainstay of nuclear expansion for the next 20 years and beyond. Small modular light water reactors have also been developed though none has been licensed to this date. As explained in Chapter 2, they compensate in theory for the lack of "economy of scale" characterising large light water reactors by modular design and construction, workshop assembly, faster construction time, and possibly incremental capacity adjustments. More importantly, their lower investment cost would make such reactors attractive to investors not able to finance the high overnight costs of the much larger reactors.

For the longer term, more innovative nuclear energy technologies and fuel cycles, known collectively as Generation IV systems, are being developed through international co-operation. The most important initiative to co-ordinate research and development (R&D) efforts on advanced reactors and fuel cycles is the Generation IV International Forum (GIF). Formed in 2001, GIF brings together the major countries involved, including Canada, China, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland and the United States, plus Euratom. The aim is to develop systems that offer improved sustainability, economics, safety and reliability, proliferation resistance and physical protection.

Six conceptual nuclear energy systems were selected for collaborative R&D, comprising the sodium-cooled fast reactor (SFR), the very-high-temperature reactor (VHTR), the supercritical-water-cooled reactor (SCWR), the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), and the molten salt reactor (MSR). Each of these has reached a different stage of development, depending on the R&D efforts that have been made in the past and the level of commitment each has received from participating countries.

The most mature Generation IV concepts are the SFR and VHTR, which are based on proven technology. These are the leading candidates for large-scale demonstration projects, the first of which could be in operation in the 2020s. The R&D on sodium-cooled reactors draws on a long experience of operation of various prototypes, in the United States, the United Kingdom, France, the Russian Federation and Japan. Many of those are now shut down, but new sodium fast reactors (which are not considered as Generation IV), are being built in the Russian Federation, India and China. Other reactor concepts may require smaller scale prototypes before full-scale demonstration. The first commercial Generation IV systems are not expected to be available before the 2030s, with their full introduction unlikely before the 2040s. Hence, Generation IV reactors are not expected to be a major part of installed nuclear capacity until well after 2050. Figure 9.5 shows the successive generations of nuclear reactors, including their deployment timeline.

Figure 9.5: Reactor generations



As well as the development of reactors, R&D on advanced fuel cycles is an important aspect of the GIF programme. Of the six Generation IV systems, four would use advanced fuel cycles involving the recycling of spent fuel. Their widespread commercial deployment would have important implications for the long-term sustainability of nuclear energy, as it could multiply by between 30 and 60 times the amount of energy extracted from each tonne of uranium, thereby making available uranium resources sufficient to power fast neutron reactors for several thousands of years (see Table 9.1).

Other benefits of advanced fuel cycle technologies could include increased proliferation resistance by avoiding the separation of plutonium, and reduced volumes of long-lived radioactive waste requiring very long-term isolation in a repository. The latter could be achieved by either consuming ("burning") the long-lived isotopes by incorporating them into nuclear fuel, or by separating them chemically and then irradiating them in a nuclear accelerator to transform them into shorter-lived isotopes. The process of separating the long-lived elements of interest (so-called minor actinides such as americium, curium or neptunium) from the rest of the radioactive waste is called partitioning, and the process of transforming these elements into shorter-lived isotopes is called transmutation. Hence the name P&T is given to this advanced fuel cycle research. Recent work on this subject has concluded that:

- P&T and cooling during interim storage prior to disposal can be effectively used to reduce decay heat in the corresponding waste by about a factor of 3 (for a 50-year cooling time) compared to the once-through fuel cycle.
- A more efficient utilisation of repository space is expected, with a reduction of required gallery length of the order of 3.

In addition, the inventory reduction means that uncertainties in repository performance are reduced. Improved public acceptance of geological repositories is therefore expected if P&T can be implemented in future fuel cycles.

Additional uses for nuclear energy, present and future

To date, nuclear energy has been used almost exclusively for the production of electricity. As electricity gradually takes a larger share of final energy consumption, the relative importance of nuclear energy will therefore grow. In particular, the expected rise in the use of electrically powered vehicles over the coming decades will increase its importance in the transport sector.

In addition to its growing importance for electricity supply, there are potential uses of nuclear energy as a source of direct heat. These include:

- supply of process heat for use in industrial plants, including petro-chemical plants;
- production of hydrogen, which could itself then be used as a clean fuel for transport and other purposes;
- desalination of sea water, especially in dry, coastal regions;
- district heating of buildings.

While heat for some of these applications could in principle be supplied from existing reactor designs (this is the case for instance in Switzerland where two nuclear power plants currently provide district heating to the neighbouring communities), the use of advanced reactors specifically designed as dedicated heat producers or as co-generation plants offers the greatest potential. Several of the Generation IV designs mentioned above have the potential to supply heat as well as power, and to offer the higher temperatures required for some potential applications. If these are successfully developed and deployed commercially, nuclear energy could become an important source of heat by 2050. To the extent that it displaces the direct use of fossil fuels, it would further contribute to reducing CO_2 emissions.

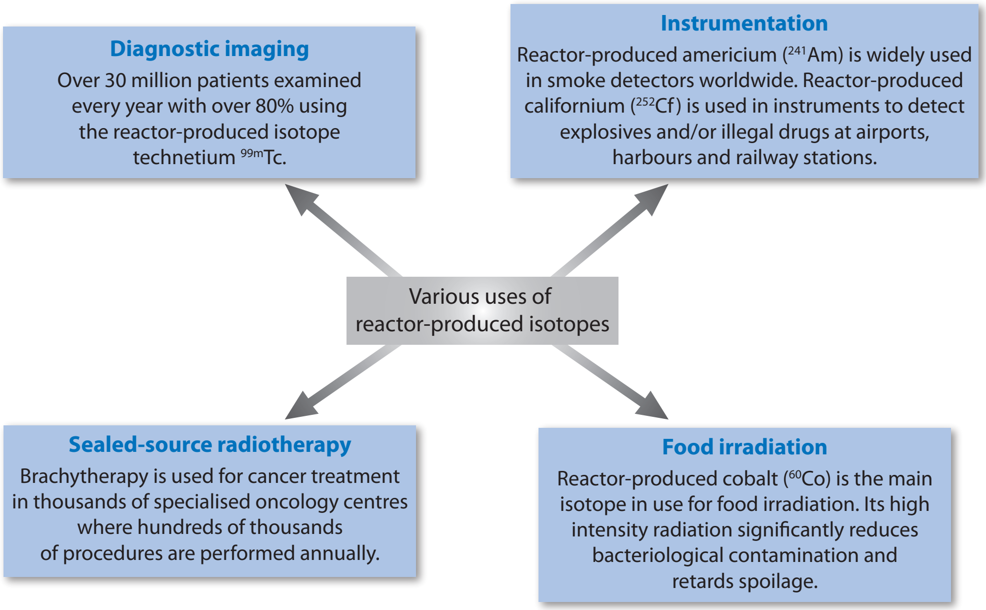
In particular, the VHTR is being specifically designed for heat only or combined heat and power production, offering outlet temperatures of up to 1 000°C and the possibility of large-scale carbon-free hydrogen production. The VHTR is based on high-temperature reactor (HTR) technology, prototypes of which were built in Germany and the United States some decades ago. China is now constructing a pair of demonstration units, and other countries (including Japan, the Republic of Korea and the United States) are working on the technology. Achieving the even higher temperature of the VHTR will require further technological development, especially in high-temperature materials and fuel.

Besides electricity production, an important use of nuclear energy technology today is the production of radioactive isotopes for medical uses, notably diagnostic procedures and cancer treatments, as well as for use in industry, food processing, sophisticated detection systems and environmental and other scientific research (see Figure 9.6). These isotopes are produced by irradiating source material in a research reactor or in a power reactor, then chemically processing the material to separate the required isotopes.

Medical applications include the detection of tumours and other ailments such as cardiological diseases through diagnostic gamma-imaging cameras, substituting for more invasive diagnostic procedures. The primary isotope for these applications is technetium-99m (^{99m}Tc), which is produced in a few research reactors around the world. Recent shortages have shown the importance of ensuring adequate infrastructure to provide a continuous supply of this isotope as it has a very short half-life. Other isotopes such as iodine-125 (^{125}I) and iridium-192 (^{192}Ir) are used in therapy, through implantation in the human body (brachytherapy) to treat cancers of the cervix, uterus, breasts, lung, pancreas, prostate and oesophagus. Radioisotopes also play a very important role in the development process of new drugs, by allowing more efficient ways of assessing their effectiveness.

Further information on these other uses of nuclear energy can be found in the references below.

Figure 9.6: Various uses of reactor-produced isotopes



Diagnostic imaging

Over 30 million patients examined every year with over 80% using the reactor-produced isotope technetium ^{99m}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.

Various uses of reactor-produced isotopes

Sealed-source radiotherapy

Brachytherapy is used for cancer treatment in thousands of specialised oncology centres where hundreds of thousands of procedures are performed 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.

References

GIF (2002), *A Technology Roadmap for Generation IV Nuclear Energy Systems*, Generation IV International Forum, Paris, France. Available at www.gen-4.org/Technology/roadmap.htm.

IAEA (2007), *Advances in Isotope Hydrology and its Role in Sustainable Water Resources Management (IHS-2007), Proceedings of a Symposium Held in Vienna, 21-25 May 2007 (2 volumes)*, IAEA, Vienna, 2007.

IAEA (2009), *Irradiation to Ensure the Safety and Quality of Prepared Meals*, IAEA, Vienna, 2009. Available at www-pub.iaea.org/books/IAEABooks/7906/Irradiation-to-Ensure-the-Safety-and-Quality-of-Prepared-Meals.

IAEA (2009), *Non-electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications, Proceedings of an International Conference, Oarai, Japan, 16-19 April 2007*, IAEA, Vienna, 2009. Available at www-pub.iaea.org/MTCD/publications/PDF/P_1354_web.pdf.

IAEA/NEA (2010), *Uranium 2009: Resources, Production and Demand*, published biennially by the OECD/NEA and the IAEA, OECD, Paris, France.

IEA (2010), *Energy Technology Perspectives 2010: Scenarios and Strategies to 2050*, IEA, Paris, 2010.

IEA/NEA (2010), *Nuclear Energy Technology Roadmap*, jointly produced by the International Energy Agency and the OECD/NEA. Available at www.oecd-nea.org/ndd/reports/2010/nea6962-nuclear-roadmap.pdf.

NEA (2008), *Nuclear Energy Outlook 2008*, Nuclear Energy Agency, OECD, Paris, France.

NEA (2008), *Introduction to Generation IV Nuclear Energy Systems and the International Forum*, available at www.gen-4.org/PDFs/GIF_introduction.pdf.

NEA (2010), *The Security of Energy Supply and the Contribution of Nuclear Energy*, Nuclear Energy Agency, OECD, Paris, France. Executive summary available at www.oecd-nea.org/pub/security-energy-exec-summary.pdf.

NEA (2011), *Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation*, OECD, Paris, France. Available at www.oecd-nea.org/science/reports/2011/6894-benefits-impacts-advanced-fuel.pdf.

NEA (2011), *The Supply of Medical Radioisotopes: The Path to Reliability*, Nuclear Energy Agency, OECD, Paris, France. Available at www.oecd-nea.org/med-radio/reports/med-radio-reliability.pdf.

Conclusions

More than 55 years after the first commercial electricity production by a fission reactor, nuclear energy has come a long way. It developed quickly in the 1970s and 1980s in a large number of OECD countries, as well as in the ex-USSR, as a means to produce electricity on a large scale and with a technology that increased the security of energy supply compared to fossil-based technologies. Over the last two decades, the use of nuclear energy has expanded quickly in Asia, and it is increasingly being considered by several developing countries across the world to meet their rising electricity demand.

As a result of these developments, nuclear energy accounts for about 14% of the world's electricity production, and represents the second largest source of low-carbon electricity after hydroelectricity. But this share has been decreasing recently, and nuclear energy remains a controversial technology, characterised by public concern over its safety (especially after the Chernobyl and Fukushima accidents), the issue of the management of its waste and the risk of proliferation of nuclear material. Although the levelised cost of nuclear electricity generation has been shown to be competitive, especially in the presence of carbon pricing, investors also face the challenge of financing the large upfront construction costs, while seeking long-term stability and political commitment to ensure adequate returns on investment over several decades of operation.

Clearly, nuclear energy is at a new crossroads, with possibilities of the start of a renaissance or a slow decline as existing reactors are gradually retired. Fundamental reasons to support the use of nuclear energy include the following:

- Nuclear technology has evolved continuously and improved from generation to generation. Today's reactors can generate electricity with capacities ranging from several hundreds of megawatts to more than 1 500 MW. The next generation of reactors may also include small modular designs suitable for small electric grids, as well as designs able to produce large quantities of electricity with a higher efficiency than today's reactors.
- Generating electricity using nuclear power is generally cost-competitive, even in liberalised markets.
- Nuclear energy as part of a diversified mix can significantly improve the security of energy supply, since available uranium resources are sufficient to power fission reactors throughout the 21st century at least.
- It is necessary to invest in low-carbon electricity generation technologies, at a time when anthropogenic emissions of greenhouse gases are rising to levels beyond which the consequences of global warming are predicted to be economically and ecologically untenable.
- The technical issues of management of high-level radioactive waste have been solved, with the recommendation to implement deep geological disposal sites. Implementation projects are under way in several countries, after public debates and stakeholder consultation.
- Safety remains the priority of the industry and governments. Lessons learnt from previous accidents and sharing of experience and best practices from regulators and operators across the world will lead to higher levels of safety.
- A framework of national laws and international agreements govern virtually all aspects of the use of nuclear energy, and efficiently address the need for safeguards against the misuse of nuclear technology and materials.

- Research efforts, many of which are performed within international frameworks, are ongoing for the nuclear fuel cycle and reactor technologies, aimed at improving the use of uranium resources and minimising high-level waste, as well as developing non-electric applications of nuclear energy such as process heat, hydrogen production or desalination.
- Nuclear energy is also a key technology for producing isotopes for medical applications (diagnostic and therapeutic), food processing, sophisticated detection devices, and environmental and other scientific research.

In the end, political decision-makers wishing to use this technology have the responsibility to:

- engage in public dialogue about the use of nuclear energy;
- put in place and enforce the regulatory and institutional framework necessary to oversee the safe use of nuclear energy and the appropriate management of waste;
- make long-term commitments and implement energy policies able to provide a stable environment that minimises investment risks for new nuclear build.

The further development of nuclear energy depends on these criteria being met. Doing so will enable nuclear energy to provide electricity in large amounts and at an affordable price, while contributing to the reduction of greenhouse gas emissions from the power sector.

List of figures

List of tables

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 such reactors 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 (^{238}U) can be placed around a fast reactor and it will undergo transmutation to produce plutonium-239 (^{239}Pu) 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 build-up of plutonium isotopes that are unable to fission in the thermal neutron spectrum of a light water reactor and the build-up 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.

Corium

Corium is the lava-like material that results from core melt in a severe accident. The core of a nuclear reactor consists of uranium dioxide in the fuel, zirconium in the fuel rod cladding and carbon steel and stainless steel in other structures. At high temperatures, zirconium is oxidised by steam, so the main constituents of corium are uranium dioxide, zirconium dioxide, zirconium, iron, chromium and nickel.

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 (5 730-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: close-out, 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 (^{235}U) of about 0.71%. 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 interest rate used to convert a future income stream to its present value. It 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

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 (^{235}U) has been increased above the naturally occurring level of 0.71%.

Enrichment

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

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 10 keV and typically about 2 000 000 eV (2 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 is one that is capable of becoming fissile through the capture of a neutron(s), possibly followed by radioactive decay. Important examples are uranium-238 (^{238}U), which can transform into fissile plutonium-239 (^{239}Pu), and thorium-232 (^{232}Tr), which can transform into fissile uranium-233 (^{233}U).

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 (^{233}U), uranium-235 (^{235}U) and plutonium-239 (^{239}Pu).

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 material

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 (^{238}U).

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 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 0.71% 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 includes mining and milling of uranium, conversion, enrichment, fabrication of fuel elements, use in a reactor, possibly reprocessing and finally, 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 radioactive (parent) isotopes in a sample to decay to (or disintegrate into) radiogenic (daughter) isotopes.

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 (HEU)

Uranium enriched to at least 20% uranium-235 (^{235}U).

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 is typically 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) 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 need to 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.

L

Levelised cost of electricity (LCOE)

This cost represents the average price that would have to be paid by consumers to repay exactly the investor/operator for the capital, operation and maintenance and fuel expenses, with a rate of return equal to the discount rate. Thus, the LCOE is the minimum price at which energy must be sold for an energy project to break even. The methodology is often used to help assess economic profitability of a planned electricity generation plant or to compare two or more alternative plant investments.

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.

Long-term operation (LTO)

Long-term operation is the term generally used to describe the operation of nuclear power plants beyond their original design lifetime. It involves specific plant life management issues such as safety upgrades, inspection of critical equipment (for instance the pressure vessel), replacement of large components (for example steam generators or turbine modules) and possibly power uprates.

Low-enriched uranium (LEU)

Uranium in which the isotopic concentration of uranium-235 (^{235}U) 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 (^{235}U).

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) 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), 0.71% ^{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 (^{1}H).

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, 46 as of January 2012, 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 ensuring 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 – ^{243}Am) 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 thousands to several hundreds of years.

Plasma

A state of matter (others are solid, liquid and gas) consisting of an electrically neutral medium of charged particles (ions and electrons) and neutral particles.

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 1×10^{-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. Electromagnetic waves are 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.

Reactivity

The reactivity of nuclear system expresses the departure of that system from criticality, i.e. the state in which each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions. A positive reactivity addition indicates a move towards supercriticality (power increase). A negative reactivity addition indicates a move towards subcriticality (power decrease). Control rods are the main reactivity control systems.

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.

Risk-informed regulation

Risk-informed regulation is an approach which aims to integrate in a systematic manner quantitative and qualitative, deterministic and probabilistic safety considerations to obtain a balanced decision. Both the likelihood of events and their potential consequences together with such factors as good engineering practice and sound managerial arrangements are considered in this approach.

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.

Safety culture

Safety culture is that set 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, to ensure the protection of people and the environment.

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.

Separative work unit (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 (^{235}U) in the waste stream. Typically, about 100 000-120 000 SWU is required to provide the enriched uranium needed to fuel a 1 000 MW light water reactor for one year.

Severe accident

A severe accident in a nuclear reactor is an event which significantly exceeds design basis events and conditions, and is characterised by extensive core damage (molten core) due to a reactivity excursion or the inability to provide adequate cooling to the core.

Sievert (Sv)

The name for the international unit indicating the biological effects caused by an exposure to radiation. The unit is joule per kilogram. The biological effects of radiation exposure vary depending on the type of radiation involved since their ability to penetrate matter varies. 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. One sievert of radiation produces the same biological effect regardless of the type of radiation.

Small modular reactor (SMR)

A new generation of advanced reactors typically in the range of 50-300 MW characterised by modular design and construction. The most mature SMRs which could be licensed in the next decade are light water reactors, but other SMRs based on high-temperature gas-cooled technologies or fast neutron liquid metal cooled technologies are also under development.

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.

T

Technetium-99m (^{99m}Tc)

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.

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.

Thermal neutrons

Thermal neutrons are those with a low kinetic energy, less than 1 electron volt (eV). Thermal neutrons have the greatest probability of causing fission in uranium-235 (^{235}U) and plutonium-239 (^{239}Pu).

Torus

A doughnut-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. Tritium is radioactive and can readily combine with oxygen to form tritiated water, which can penetrate through the skin. It therefore calls for particular radiation protection measures.

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.

List of abbreviations

ALARA	As low as reasonably achievable
BSC	Brussels Supplementary Convention
BSS	Basic Safety Standards
BWR	Boiling water reactor
CANDU	Canadian deuterium uranium reactor (PHWR type)
CCS	Carbon capture and storage
CSC	Convention on Supplementary Compensation for Nuclear Damage
CT	Computarised tomography
CTBT	Comprehensive Nuclear Test Ban Treaty
EDG	Emergency diesel generator
ENSREG	European Nuclear Safety Regulators' Group
ETS	Emissions Trading System
FBR	Fast breeder reactor
GCR	Gas-cooled reactor
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
HEU	Highly-enriched uranium
HLW	High-level waste
HTR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IEA	International Energy Agency
ILW	Intermediate-level waste
INES	International Nuclear Event Scale
ISL	*In situ* leaching
ITER	International thermonuclear experimental reactor
JET	Joint European Torus
LCOE	Levelised cost of electricity
LCPD	Large Combustion Plant Directive
LEU	Low-enriched uranium

LFR	Lead-cooled fast reactor
LLW	Low-level waste
LTO	Long-term operation
LWR	Light water reactor
MOX	Mixed-oxide fuel
MSR	Molten salt reactor
NEA	Nuclear Energy Agency (OECD)
NGNP	Next Generation Nuclear Plant (United States)
NHDD	Nuclear Hydrogen production Development and Demonstration (Republic of Korea)
NPP	Nuclear power plant
NPT	Treaty on the Non-proliferation of Nuclear Weapons
NSG	Nuclear Suppliers Group
O&M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
P&T	Partitioning and transmutation
PET	Positron emission tomography
PFBR	Prototype fast breeder reactor
PHWR	Pressurised heavy water reactor
PSA	Probabilistic safety assessment
PUREX	Plutonium uranium reduction extraction
PWR	Pressurised water reactor
RBMK	Russian abbreviation for graphite-moderated light water-cooled reactors
R&D	Research and development
SCWR	Supercritical-water-cooled reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SNF	Spent nuclear fuel
TMI	Three Mile Island
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
VHTR	Very-high-temperature reactor
VVER	Russian design of pressurised water reactor
WENRA	Western European Nuclear Regulators' Association
WIPP	Waste Isolation Pilot Plant (United States)

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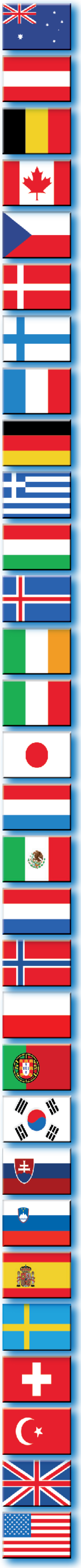

Nuclear Energy Today

Meeting the growing demand for energy, and electricity in particular, while addressing the need to curb greenhouse gas emissions and to ensure security of energy supply, is one of the most difficult challenges facing the world's economies. No single technology can respond to this challenge, and the solution which policy-makers are seeking lies in the diversification of energy sources.

Although nuclear energy currently provides over 20% of electricity in the OECD area and does not emit any carbon dioxide during production, it continues to be seen by many as a controversial technology. Public concern remains over its safety and the management of radioactive waste, and financing such a capital-intensive technology is a complex issue. The role that nuclear power will play in the future depends on the answers to these questions, several of which are provided in this up-to-date review of the status of nuclear energy, as well as on the outcome of research and development on the nuclear fuel cycle and reactor technologies.

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