Australian Government

Department of the Prime Minister and Cabinet
Uranium Mining, Processing and Nuclear Energy Review

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— OPPORTUNITIES FOR AUSTRALIA?

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Summary and looking ahead

On 6 June 2006, the Prime Minister announced the appointment of a taskforce to undertake an objective, scientific and comprehensive review of uranium mining, value-added processing and the contribution of nuclear energy in Australia in the longer term. This is known as the Review of Uranium Mining Processing and Nuclear Energy in Australia, referred to in this report as the Review.[1]

The Prime Minister asked the Review to report by the end of 2006.[2] A draft report was released for public comment on 21 November 2006 and was also reviewed by an expert panel chaired by the Chief Scientist (see Appendix F). The Review is grateful for comments provided on the draft report by members of the public. The report has been modified in the light of those comments.

In response to its initial call for public comment in August 2006 the Review received over 230 submissions from interested parties. It also conducted a wide range of consultations with organisations and individuals in Australia and overseas, and commissioned specialist studies on various aspects of the nuclear industry.

Participating in the nuclear fuel cycle is a difficult issue for many Australians and can elicit strong views. This report is intended to provide a factual base and an analytical framework to encourage informed community discussion.

Australia's demand for electricity will more than double before 2050. Over this period, more than two-thirds of existing electricity generation will need to be substantially upgraded or replaced and new capacity added. The additional capacity will need to be near-zero greenhouse gas emitting technology if Australia is just to keep greenhouse gas emissions at today's levels.

Many countries confront similar circumstances and have therefore considered the use of nuclear power for some of the following reasons:

- the relative cost competitiveness of nuclear power versus the alternatives
- security of supply and independence from fossil fuel energy imports
- diversity of domestic electricity production and reduction in volatility arising from input fossil fuel costs; and
- reduction in greenhouse gas emissions and subsequent effects on global climate.

The world's first civilian nuclear reactor commenced operation in 1955. According to the International Energy Agency (IEA), today there are 443 nuclear reactors operating in 31 countries, producing 15 per cent of the world's electricity.

As a substantial holder of recoverable reserves (38 per cent of known low cost global reserves) and producer of uranium (23 per cent of global production), Australia is well positioned to increase production and export of uranium oxide to meet market demand. There is an opportunity for Australia to be a participant in the wider nuclear fuel cycle given international confidence in the quality of our production processes, our sophisticated technology community (although no longer with a significant presence in the nuclear fuel cycle) and the strength of our commitment to nuclear non-proliferation.

Nuclear power has a much lower greenhouse signature than Australia's current major energy sources for electricity; namely brown and black coal, and gas. Although the priority for Australia will continue to be to reduce carbon dioxide emissions from coal and gas, the Review sees nuclear power as a practical option for part of Australia's electricity production.

1 http://www.pm.gov.au/news/media_releases/media_Release1965.html

2 http://www.dpmc.gov.au/umpner/reports.cfm

Key findings of the Review

- Consultations revealed support for the expansion of Australian mining and export of uranium. Skill shortages, government policies and legal prohibitions restricting the growth of the industry would need to be urgently addressed.
- The rationalisation of uranium mining regulation would ensure a consistent approach to environmental and radiation protection, and the maintenance of high standards throughout the industry.
- Downstream steps of uranium conversion, enrichment and fuel fabrication could add a further $1.8 billion of value annually if all Australian uranium was processed domestically. However, high commercial and technology barriers could make market entry difficult. Current legal and regulatory impediments would need to be removed, but there may be little real opportunity for Australian companies to extend profitably into these areas.
- Nuclear power is likely to be between 20 and 50 per cent more costly to produce than power from a new coal-fired plant at current fossil fuel prices in Australia. This gap may close in the decades ahead, but nuclear power, and renewable energy sources, are only likely to become competitive in Australia in a system where the costs of greenhouse gas emissions are explicitly recognised. Even then, private investment in the first-built nuclear reactors may require some form of government support or directive.
- The earliest that nuclear electricity could be delivered to the grid would be 10 years, with 15 years more probable. At the outset, the establishment of a single national nuclear regulator supported by an organisation with skilled staff would be required.
- In one scenario, deployment of nuclear power starting in 2020 could see 25 reactors producing about a third of the nation's electricity by 2050 (a position already surpassed by France, South Korea, Sweden, Belgium, Bulgaria and Hungary, among others).
- Since Three Mile Island in 1979 and Chernobyl in 1986, the nuclear industry has developed new reactor designs which are safer and more efficient and produce lower volumes of radioactive waste, and has standardised its operating procedures. The future holds the promise of significant further innovation.
- The challenge to contain and reduce greenhouse gas emissions would be considerably eased by investment in nuclear plants. Australia's greenhouse challenge requires a full spectrum of initiatives and its goals cannot be met by nuclear power alone. The greenhouse gas emission reductions from nuclear power could reach 8 to 17 per cent of national emissions in 2050.
- Many countries have implemented straightforward solutions for disposal of low-level radioactive waste. A national repository involving burial of low-level waste from all sources including a future nuclear power industry is logical for Australia.
- Disposal of high-level waste including spent nuclear fuel remains an issue in most nuclear power countries. There is a consensus that disposal in appropriately engineered deep (500–1200 metres underground) repositories is the answer and such facilities are under development in many countries. Australia has areas suitable for such repositories, which would not be needed until around 2050 should nuclear power be introduced.
- Countries with successful nuclear power generation programs have a strong and transparent regulatory environment. Australia starts from a robust, albeit decentralised, framework that would need to be integrated and consolidated into a national structure.
- While proliferation of nuclear weapons remains a critical global issue, increased Australian involvement in the nuclear fuel cycle would not change the risks; nor would Australia's energy grid become more vulnerable to terrorist attack.

Uranium mining and export (Chapter 2)

- Australia has the capacity to expand its production and exports of uranium, and global growth in uranium demand provides a timely opportunity for Australia.
- Skill shortages and restrictive policies (regulation, land access and transport) are the major constraints on industry expansion in Australia.
- Conventional reserves of uranium worldwide are sufficient to meet current demand for 50 to 100 years. There is high potential for future discoveries.

Australia has 38 per cent of the world's low-cost reserves of uranium with most in a small number of deposits. Olympic Dam is the largest deposit in the world and contains approximately 70 per cent of Australia's known reserves.

Little exploration was undertaken in the 30 years to 2003 but from 2004 exploration expenditure has increased dramatically, with dozens of companies now active. Many prospective areas in Australia have the potential to yield further exploitable deposits.

In 2005, Australia's uranium oxide exports earned $573 million with a record production of over 12 000 tonnes. Those exports are enough to generate more than twice Australia's current annual electricity demand. Exports are forecast to increase strongly both from rising prices and rising production, reaching over 20 000 tonnes by 2014–2015.

Australia will increase production over the medium and longer term by expanding existing mines. Each of the three operational mines (Olympic Dam, Ranger and Beverley) can expand production or extend their lives through the discovery of further reserves on already approved mine leases. Many smaller known deposits could be developed relatively quickly, but are currently not accessible under state or territory government policy.

Most analysts predict significantly increased global demand for uranium due to planned new nuclear power plants, increased capacities of existing plants and a reduction in secondary uranium supplies. Demand from India, Russia and China will grow and will add to the existing large demand from the United States, France and Japan.

Canada and Australia produce more than 50 per cent of the world's natural uranium supply, with five other countries accounting for a further 40 per cent. A number of new mines and mine expansions can be expected in the medium term, while increases in uranium production can be expected from Canada, Kazakhstan, Namibia, Russia and the United States. Forecasts show sufficient capacity over the medium term (to about 2015), but after this time there will be greater uncertainty over both supply and demand. On current forecasts, demand exceeds existing capacity. Thus, there is an excellent opportunity for Australia to fill the gap.

Uranium prices are expected to continue to increase in the short term, reflecting strong demand and uncertainties of uranium supply.

The main factors affecting uranium mining in Australia over the past few decades have been historically low prices and restrictive (no new mines) government policies. With a stronger price outlook, impediments to growth are skills shortages (particularly radiation safety officers and geologists with uranium experience), the complexity of the regulatory regime (which differs for each of the three existing mines), access to land for exploration and mining (prohibited by government policies), and restrictions on uranium transport (caused primarily by more stringent constraints than those imposed on other dangerous goods).

Conversion, enrichment and fuel fabrication (Chapter 3)

- Australia's exports of uranium oxide of $573 million in 2005 could be transformed into a further $1.8 billion in value after conversion, enrichment and fuel fabrication. However, challenges associated with the required investment levels and access to enrichment technology are very significant.
- Centrifuge technology will dominate enrichment in the medium term as gaseous diffusion is replaced. SILEX, an Australian developed laser enrichment technology, offers promise, but is yet to be commercially proven.
- Enrichment technology is used for civil and weapons purposes. Any proposed domestic investment would require Australia to reassure the international community of its nuclear non-proliferation objectives.

Uranium oxide must first be converted into uranium hexafluoride (UF_6) for enrichment. The international market for conversion is highly concentrated, with four companies supplying more than 80 per cent of the world's uranium conversion services. The market has not seen new investment or real production expansion and has been characterised by instability on the supply side since 2000. Conversion capacity is adequate to meet demand in the near to medium term. Beyond this, the situation is more difficult to ascertain given the uncertainty surrounding secondary supply.

Enrichment increases the share of U-235 in uranium from its naturally occurring 0.7 per cent to between 3 and 5 per cent. Enrichment is classed as a nuclear proliferation-sensitive technology because of its potential to be used to produce weapons grade material.

As with conversion, the enrichment market is also very concentrated, structured around a small number of suppliers in the United States, Europe and Russia. It is characterised by high barriers to entry, including limited and costly access to technology, trade restrictions, uncertainty around the future of secondary supply and proliferation concerns.

Centrifuge technology currently dominates the industry. While there is potential for General Electric to enter the market with SILEX laser technology within the next 10 years, this technology is still being proven. Given the new investment and expansion plans under way around the world, the market looks to be reasonably well balanced in the medium term. Although capital intensive, the modular configuration of centrifuge technology enables enrichment capacity to be expanded incrementally to meet increases in demand.

The enriched uranium is fabricated and assembled into reactor fuel. The fuel fabrication market is characterised by customisation, with the specifications dependent upon reactor design and the fuel management strategy of each power utility. However, there is a trend worldwide towards standardising around a small number of designs. Currently, three main suppliers provide approximately 80 per cent of the global fuel demand and indications are that capacity significantly exceeds demand.

The possibility of Australia being involved in conversion, enrichment and fuel fabrication presents some challenges. The commercial viability and international competitiveness of new plant will depend on factors such as capital investment cost, operating costs, the ability to access technology on competitive terms, the state of the international market, access to the required skill base and regulatory environment and, in the case of enrichment, nuclear non-proliferation issues.

Electricity generation (Chapter 4)

- Electricity demand in Australia is expected to continue to grow strongly, more than doubling by 2050.
- Nuclear power is an internationally proven technology that is competitive with fossil fuel baseload generation in many parts of the world and contributes 15 per cent of global electricity generation.
- Cost estimates suggest that in Australia nuclear power would on average be 20–50 per cent more expensive to produce than coal-fired power if pollution, including carbon dioxide emissions, is not priced.
- Nuclear power is the least-cost low-emission technology that can provide baseload power, is well established, and can play a role in Australia's future generation mix.
- Nuclear power can become competitive with fossil fuel-based generation in Australia, if based on international best practice and with the introduction of low to moderate pricing of carbon dioxide emissions.
- The cost of nuclear power is strongly influenced by investor perceptions of risk. Risk is highly dependent on regulatory policy and the certainty of licensing and construction timeframes.
- A stable policy environment and a predictable licensing and regulatory regime would be a necessary precursor to the development of nuclear power in Australia.
- Accumulated funds deducted from nuclear power revenues are the best practice method to cover waste disposal and plant decommissioning costs.

Australian electricity consumption has increased more than threefold over the last 30 years and is projected to grow at approximately 2 per cent each year until at least 2030, and to double before 2050. This will require significant additional baseload and peak generating capacity. Projections suggest the need for over 100 GW of capacity by 2050 (compared to the current Australian installed capacity of 48 GW).

Under current policy settings, the Australian generating portfolio is expected to remain dominated by conventional fossil fuel (coal and gas) technologies. If there is a shift to low-emission technologies, nuclear power will compete with other low-emission technologies, some of which are still in the development stage. These include advanced fossil fuel technologies with carbon capture and storage (geosequestration), geothermal (hot dry rocks) and a variety of renewable technologies including wind, hydro, biofuel, solar photovoltaic and solar thermal. The costs and timescales for many of these are more uncertain than for nuclear power and will depend substantially on greenhouse policies. Non-hydro renewables will undoubtedly play an important and growing role in those parts of the overall generation portfolio where they are best suited.

In many countries, nuclear power is already competitive with other baseload technologies, although it is not cost competitive with Australia's very low cost generation from abundant coal reserves. Nevertheless, costs are close enough to indicate that nuclear power will be competitive in carbon constrained electricity supply scenarios. Cost additions to fossil fuel-based generation in the (low to moderate) range of $15–40 per tonne of carbon dioxide equivalent (CO_2-e) would make nuclear electricity competitive in Australia.

Radioactive waste and spent fuel management (Chapter 5)

- Safe disposal of low-level and short-lived intermediate-level waste has been demonstrated at many sites throughout the world.
- There is a high standard of uranium mining waste management at Australia's current mines. Greater certainty in the long-term planning at Olympic Dam is desirable, coupled with guaranteed financial arrangements to cover site rehabilitation.
- Safe disposal of long-lived intermediate and high-level waste can be accomplished with existing technology. The first European repository is expected to commence operating around 2020.
- Reprocessing of spent fuel in Australia seems unlikely to be commercially attractive, unless the value of recovered nuclear fuel increases significantly.
- Australia has a number of geologically suitable areas for deep disposal of radioactive waste.

Radioactive wastes arise from a wide range of uses for radioactive materials as well as from nuclear power generation. They are broadly classified as low, intermediate and high-level wastes, according to the degree of containment and isolation required to ensure human and environmental safety.

Conventional hard rock uranium mining operations generate significant volumes of low-level waste tailings (solid residues from ore processing), which require particular attention in planning the operation and closure of uranium mines.

The strict Australian regulatory regime requires mines to be planned and developed with a view to eventual rehabilitation. This demands very high standards of tailings management. This low-level waste problem is significantly reduced, and indeed virtually eliminated, with in-situ leaching technology where the host rock is barely disturbed.

Australia produces small amounts of low and intermediate-level waste from medical research and industrial uses of radioactive materials. Much of this waste arises from the production of medical radioisotopes by the research reactor of the Australian Nuclear Science and Technology Organisation (ANSTO) at Lucas Heights. ANSTO waste will be managed at the Commonwealth Radioactive Waste Management Facility, to be established in the Northern Territory.

While safe management of all categories of radioactive waste has been demonstrated for decades, no country has yet implemented permanent underground disposal of high-level radioactive waste. The broad consensus of scientific and technical opinion is that high-level waste can be safely and permanently disposed of in deep geological repositories. Several countries are now proceeding with well-developed and thoroughly researched plans for deep geological disposal of high-level radioactive waste.

Should Australia move to nuclear power generation, provision would be needed for management of high-level radioactive waste, including eventual disposal. In line with best overseas practice, radioactive waste management and reactor decommissioning costs would need to be included (ie internalised) in the price of nuclear electricity. Cost estimates for nuclear power in the Review are made on this basis.

Health and safety (Chapter 6)

- Ionising radiation and its health impacts are well understood and there are well established international safety standards that are reflected in Australian practice.
- An efficient, effective and transparent regulatory regime achieves good health and safety outcomes, and provides assurance to the public that facilities are being properly managed.
- The nuclear and uranium mining industries have achieved good performance under these stringent physical and regulatory controls.
- Nuclear power has fewer health and safety impacts than current technology fossil fuel-based generation and hydro power, but no technology is risk free.
- There are legacy problems associated with the nuclear industry. The most significant are the impacts of the Chernobyl accident. However, the Chernobyl reactor is not representative of modern reactor designs.

All human activities, even domestic living, working and travelling, involve risks to health and safety. The whole life cycle of any activity must, therefore, be examined to assess its overall impacts. Any technology choice must inevitably require balancing of the full life cycle costs and the benefits of competing alternatives. The health and safety costs of uranium mining and nuclear fuel use, including waste disposal, are significantly lower, on a unit of energy produced basis, than current fossil fuel-based energy generation when coal mining, preparation and eventual waste disposal are considered.

There are radiation health legacies from the Chernobyl disaster and for some uranium miners who worked underground prior to the 1960s. These will require careful monitoring. As a result of modern operating methods and safety requirements, current uranium mines and the new generation of nuclear power plants pose significantly lower levels of risk.

The health and safety performance of nuclear power facilities has improved significantly over time, and is expected to improve even further with new generation reactors. The current good performance of the nuclear and uranium mining industry is associated with its stringent physical and regulatory control. An efficient, effective and transparent regulatory regime achieves the desired health and safety outcomes and provides assurance to the public that facilities are properly managed.

There is every reason to be confident that Australia's health and safety systems will continue to provide a sound framework for the management of the uranium mining industry and would enable any other parts of the nuclear fuel cycle envisaged for Australia to be equally well regulated, ensuring the highest levels of health and safety.

Environmental impacts (Chapter 7)

- Deep cuts in global greenhouse gas emissions are required to avoid dangerous climate change. No single technology can achieve this — a portfolio of actions and low-emission technologies is needed.
- Nuclear power is a low-emission technology. Life cycle greenhouse gas emissions from nuclear power are more than ten times lower than emissions from fossil fuels and are similar to emissions from many renewables.
- Nuclear power has low life cycle impacts against many environmental measures. Water use can be significant in uranium mining and electricity generation depending on the technology used.
- The cost of reducing emissions from electricity generation can be minimised by using market-based measures to treat all generation technologies on an equal footing.

Greenhouse gas emissions, especially carbon dioxide (CO_2) from fossil fuel combustion, are changing the make-up of the atmosphere and contributing to changing climatic conditions around the world. About 40 per cent of global CO_2 emissions arise from electricity generation. As a result, there is renewed worldwide interest in nuclear power and other low-emission generation technologies.

The Review assesses the environmental impacts of nuclear power on a whole-of-life cycle basis, from uranium mining to final waste disposal and reactor decommissioning, and compares the environmental performance of nuclear with other electricity generation technologies.

Nuclear power plants, unlike fossil fuel plants, do not directly generate greenhouse gas emissions. Nevertheless, some greenhouse gas emissions are generated through mining and processing of the fuel, construction of the plant, waste management and decommissioning activities. On a life cycle basis, greenhouse gas emissions from nuclear power are roughly comparable to renewable technologies, and more than an order of magnitude lower than conventional fossil fuel technologies. Other environmental impacts of the nuclear fuel cycle, including air pollution emissions, land use and water use are either comparable to or significantly lower than conventional fossil fuels.

Australia has a broad range of technology options to cut greenhouse gas emissions from electricity generation. No single technology, nuclear or any other, is likely to be able to meet projected demand and achieve the necessary cuts. Nevertheless, nuclear power could contribute significantly to the overall task.

Non-proliferation and security (Chapter 8)

- Export of Australian uranium takes place within the international nuclear non-proliferation regime.
- Australia has the most stringent requirements for the supply of uranium, including the requirement for an International Atomic Energy Agency (IAEA) Additional Protocol, which strengthens the safeguards regime.
- An increase in the volume of Australian uranium exports would not increase the risk of proliferation of nuclear weapons.
- Actual cases of proliferation have involved illegal supply networks, secret nuclear facilities and undeclared materials, not the diversion of declared materials from safeguarded facilities such as nuclear power plants.

The security threat posed by the proliferation of nuclear weapons has led to the establishment of the multifaceted and evolving international nuclear non-proliferation regime, which comprises a network of treaties, institutions and the safeguards inspection regime. The cornerstone of the international nuclear non-proliferation regime is the Treaty on the Non-proliferation of Nuclear Weapons (NPT), supported by IAEA safeguards inspections. Australia's uranium export/safeguards policy complements the international regime.

Australia's uranium supply policy reinforces the international non-proliferation regime and verifies that Australian obligated nuclear material does not contribute to nuclear weapons programs. The requirement that non-nuclear weapons states receiving Australian uranium have in place an Additional Protocol strengthens the non-proliferation regime by ensuring that the IAEA has broad access and inspection rights in the recipient country. Increasing Australian uranium exports in line with Australia's uranium supply requirements would not increase the risk of proliferation of nuclear weapons. The amount of uranium required for a nuclear weapon is relatively small and, since uranium is ubiquitous in the earth's crust, any country that wished to develop a weapon need not rely on diverting uranium imported for or used in power generation. The greatest proliferation risk arises from undeclared centrifuge enrichment plants capable of producing highly enriched uranium for use in weapons.

Regulation (Chapter 9)

- An efficient and transparent regulatory regime achieves good health, safety, security and environmental protection outcomes for uranium mining, transportation, radioactive waste management, and exports and imports.
- Regulation of uranium mining needs to be rationalised.
- A single national regulator for radiation safety, nuclear safety, security safeguards, and related impacts on the environment would be desirable to cover all nuclear fuel cycle activities.
- Legislative prohibitions on enrichment, fuel fabrication, reprocessing and nuclear power plants would need to be removed before any of these activities can occur in Australia.

The establishment of nuclear fuel cycle facilities — specifically enrichment plants, fuel fabrication plants, power plants and reprocessing facilities — is prohibited under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and the *Australian Radiation Protection and Nuclear Safety Act 1998* (ARPANS Act). Before Australia could consider establishing businesses in uranium conversion, enrichment, fabrication or nuclear power plants these prohibitions would need to be repealed.

There would also need to be a significant investment in an appropriate Australian regulatory system to oversee the establishment of nuclear fuel cycle activities other than mining. The IAEA, the Nuclear Energy Agency (NEA), and countries which have existing regulatory systems could provide valuable guidance in this area.

Once the legal and administrative framework was established, the regulator would need to recruit highly skilled professionals. As Australia has limited experience in some parts of the fuel cycle, additional personnel would need to be trained or recruited from overseas to ensure that the regulator is up to date with international best practice.

Australia currently has several Commonwealth regulatory entities as well as state and territory authorities. Safeguards and security are regulated by the Australian Safeguards and Non-Proliferation Office (ASNO) while health and safety is regulated by state and territory radiation protection authorities or, in the case of Commonwealth entities, by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). Some of these regulatory functions could be consolidated.

While the existing regulation of uranium mining, transportation, radioactive waste disposal and nuclear research facilities in Australia is of a high standard, significant overlaps in regulatory responsibility exist, and reform to streamline existing arrangements would improve regulatory efficiency and transparency.

For Australia to expand its role in the nuclear power industry it is essential that an appropriate and rigorous regulatory framework is established at an early stage. Adequate provision would need to be made for its implementation.

Research, development, education and training (Chapter 10)

- Given the minimal Australian investment in nuclear energy related education or research and development (R&D) over the last 20 years, public spending will need to increase if Australia is to extend its activities beyond the uranium mining sector.
- Significant additional skilled human resources will be required if Australia is to increase its participation in the nuclear fuel cycle.
- In addition to expanding our own R&D and education and training efforts, Australia could leverage its nuclear research and training expertise through increased international collaboration.

Public funding for nuclear energy related research and development in Australia has been very low over the last decade. Nuclear engineering and nuclear physics skills have seriously declined and limited skills in radiochemistry now exist in this country. However, ANSTO remains as a national centre of excellence with an important research program and many relevant skills. Its international connections along with others will need to be exploited and expanded if Australia wishes to be an able, well-educated and well-informed nuclear industry participant.

Given the relatively long lead times to develop an Australian nuclear industry, our own national training and educational resources could be mobilised to provide the next generation of nuclear engineers and technologists in a timely fashion. In doing so, Australia could take advantage of existing opportunities for international collaboration on nuclear education and training. The attraction of interesting, well-paid jobs would encourage universities to create suitable courses and students to enrol in those courses. Increased support for nuclear R&D would undoubtedly also stimulate student enrolments in nuclear energy-related courses.

Looking ahead

Nuclear power has been an important part of the energy supply of 17 out of 24 high income Organisation for Economic Co-operation and Development (OECD) countries over the past 30 years, and represents approximately 22 per cent of OECD electricity generation.

Australia is ranked fourth lowest for cost of electricity generation in the OECD, based on its extensive gas and black and brown coal resources. As a result, Australia is one of the few OECD countries that has not used nuclear electricity as part of its energy mix.

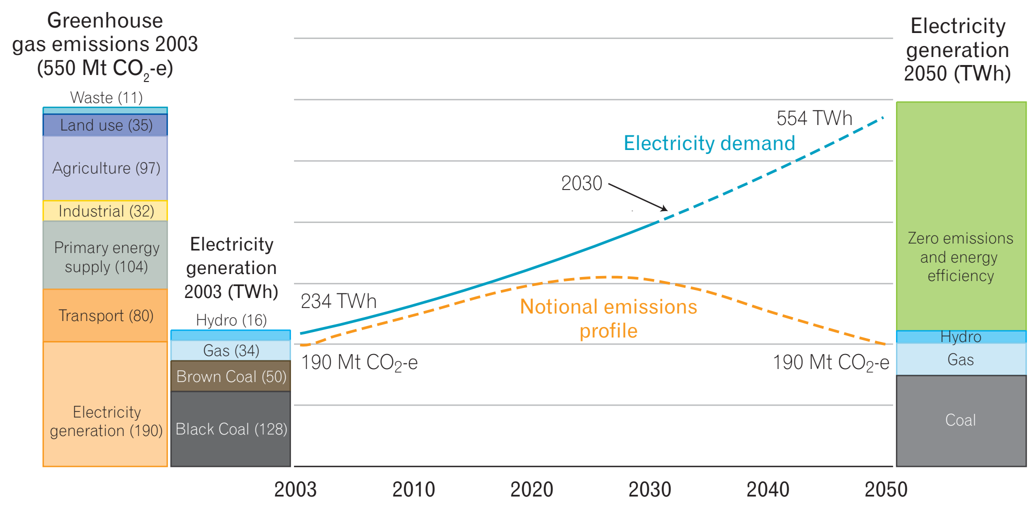
Along with the rest of the world, Australia faces important challenges in climate change. Cutting global greenhouse emissions will be a major national priority. Some of the biggest decisions for Australia will come in relation to the energy sector and electricity generation, although other sectors will need to make similar contributions.

Figure S1 illustrates the challenge for the electricity sector. Just to constrain emissions in 2050 to current levels will require a large share of Australia's electricity to come from zero or low-emission sources. A key question for Australia will be how much of the low-emission electricity will be nuclear power.

For Australia, priority will need to be given to applying the technologies that enable clean and efficient use of our large coal and gas resources (ie without emitting large volumes of greenhouse gases).

However, with electricity demand projected to grow, it is clear that Australia will need to add considerably to current electricity generation capacity, as well as to replace the existing capital stock as it reaches retirement. It is also clear that Australia will continue to rely on an array of electricity generating technologies. This mix of technologies will need to be capable of delivering flexible and reliable power, including large-scale baseload, on a competitive basis and with a much lower greenhouse gas signature.

Figure S1 Electricity generation and greenhouse emissions — a scenario to 2050

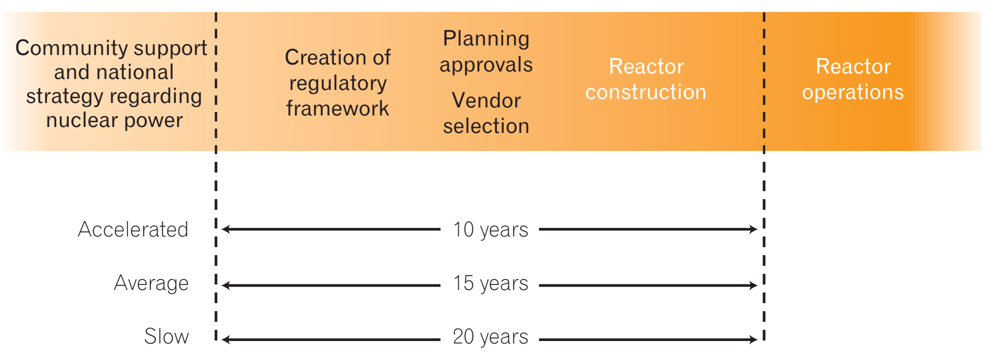


Mt = megatonnes; CO_2-e = carbon dioxide equivalent; TWh = terawatt hours

While established renewable technologies (such as hydro and wind) will continue to contribute, it is expected that other energy technologies will be required. Some of these technologies are promising, but are still in the development phase and have not been proven under commercial conditions.

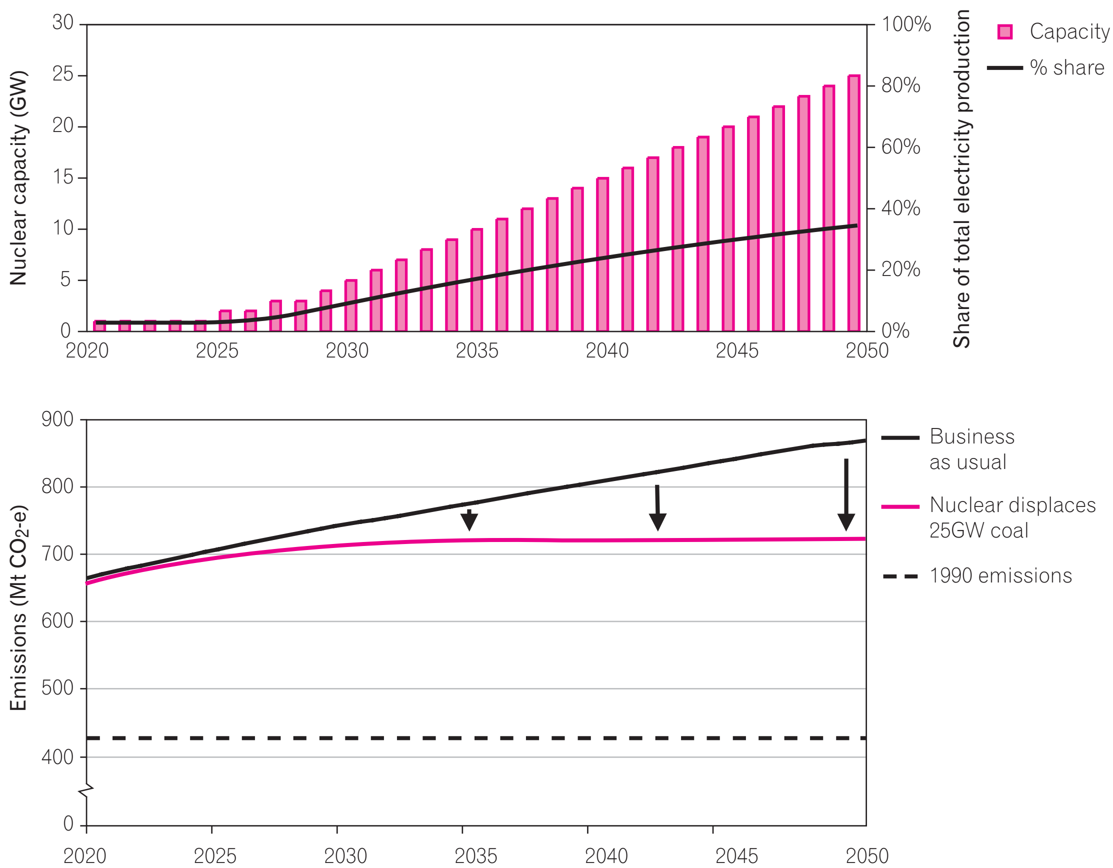
Australia faces a social decision about whether nuclear, which has operated commercially in other parts of the world, would need to be part of the mix. The steps for establishing nuclear power in Australia are reflected in timelines shown in Figure S2. All up, the period for planning, building and commissioning the first nuclear power plant, including establishing the associated regulatory process, is somewhere between 10 and 20 years. On an accelerated path, the earliest that nuclear electricity could be delivered to the grid is around 2016.

Figure S2 Range of timetables for nuclear build in Australia



Under a scenario in which the first reactor comes on line in 2020 and Australia has in place a fleet of 25 reactors by 2050, it is clear that nuclear power could enhance Australia's ability to meet its electricity needs from low-emission sources. By 2050 nuclear power could be delivering about one third of Australia's electricity needs and, if it displaces conventional coal-fired generation, be reducing Australia's total emissions by approximately 17 per cent relative to business as usual. This represents a saving of roughly one-half of the projected emissions from electricity generation (see Figure S3).

Figure S3 Potential emission cuts from nuclear build — illustrative scenario to 2050



Community acceptance would be the first requirement for nuclear power to operate successfully in Australia. This would require informed discussion of the issues involved, including the potential costs and benefits of nuclear power. Important aspects to explain would be the full cost basis for nuclear power, including a suitable mechanism to set aside funds progressively over the life of the operation of a power station, in order to make provision for decommissioning and waste management and disposal.

To address climate change there needs to be a level playing field for all energy generating technologies to compete on a comparable whole-of-life basis. In a world of global greenhouse gas constraints, emissions pricing using market-based measures would provide the appropriate framework for the market and investors to establish the optimal portfolio of energy producing platforms.

Most studies suggest that the current cost gap between conventional fossil fuel electricity generation and nuclear generation would be closed at modest levels of carbon prices. Essentially this would enable nuclear electricity to compete on its commercial and environmental merits.

Legislation would be necessary to establish a reliable and efficient regulatory framework to oversee nuclear fuel cycle activities and nuclear electricity generation in Australia. This would include a national regulatory agency to approve the construction and monitor the operations of nuclear power facilities, and to provide public assurance on health, safety and environment matters. The agency could also monitor and verify compliance with Australia's nuclear non-proliferation safeguards. Based on overseas experience, the agency would need a staff of several hundred.

There is a plethora of overlapping Commonwealth and state regulations covering uranium mine safety and environment conditions. Consideration could also be given to establishing a single national body to regulate the safety and environmental performance of mining operations. This body could be modelled on arrangements for the National Offshore Petroleum Safety Authority (NOPSA).

An efficient and predictable regulatory process is an essential prerequisite for a nuclear power industry. With its high capital costs, nuclear power is very sensitive to delays and uncertainty in obtaining approvals. The United Kingdom government has recognised this and has proposed a streamlined approach to attract investment into nuclear electricity. Similarly, in the United States a streamlined regulatory procedure has been introduced and an incentive package (limited to the first six new nuclear power plants) has been offered to stimulate construction.

If Australia is to extend its nuclear energy activities beyond uranium mining, there would need to be a substantial addition to the education and research skills base. In the short term, most nuclear-specific skills could be acquired on the international market although there is expected to be strong competition for qualified people. International collaboration and sharing of resources would help to establish a nuclear electricity industry.

The expected development of Australia's national electricity network will reduce the business risk associated with investing in large generating assets such as nuclear power stations. The Electric Power Research Institute (EPRI) study commissioned by the Review indicated that the first plants built in Australia could expect to have a higher cost than similar plants built in an established market like the United States. This is because Australia has no physical or regulatory infrastructure for nuclear power. While carbon pricing could make nuclear power cost competitive on average, the first plants may need additional measures to kick-start the industry.

Nuclear power today is a mature, safe, and clean means of generating baseload electricity. Nuclear power is an option that Australia would need to consider seriously among the range of practical options to meet its growing energy demand and to reduce its greenhouse gas signature.

Chapter 1. Introduction

1.1 Context of this review

Australia's electricity demand is expected to continue to grow at an average rate of 2 per cent per year from 2005,[1] more than doubling by 2050. According to the International Energy Agency (IEA), Australia is ranked fourth lowest cost for electricity production among OECD countries due to abundant high-quality coal reserves. Extensive reserves of coal, gas and uranium also make Australia a net energy exporter. However the consumption of fossil fuels (including coal, oil and gas) contributes more than 60 per cent of Australia's greenhouse gas (primarily CO_2) emissions. There is a scientific consensus that greenhouse gas emissions are causing the world's climate to change significantly faster than previously expected.[2]

The 2004 white paper, *Securing Australia's Energy Future*, set out three priorities — prosperity, security and sustainability — recommending policies that aim to:

- attract investment in the efficient discovery and development of our energy resources for the benefit of all Australians
- deliver a prosperous economy while protecting the environment and playing an active role in global efforts to reduce greenhouse emissions
- encourage development of cleaner, more efficient technologies to underpin Australia's energy future
- develop effective and efficient energy markets that deliver competitively priced energy, where and when it is needed into the future
- minimise disruptions to energy supplies and respond quickly and effectively when disruptions occur
- establish an efficient energy tax base, restricting fuel excise to end-use and applying resource rent taxes to offshore projects
- ensure Australia uses energy wisely.

Moreover, the IEA World Energy Outlook 2006[3] described the global energy market in the following terms:

> 'Current trends in energy consumption are neither secure nor sustainable — economically, environmentally or socially. Inexorably rising consumption of fossil fuels and related greenhouse-gas emissions threaten our energy security and risk changing the global climate irreversibly. Energy poverty threatens to hold back the economic and social development of more than two billion people in the developing world.' (page 49)

It is in this context that the Prime Minister established the Taskforce to conduct the Review of Uranium Mining Processing and Nuclear Energy in Australia (the Review). The terms of reference are shown in Appendix A. Overall, the purpose of the Review is to help stimulate and contribute to a wide ranging and constructive public debate on Australia's future energy needs.

1.2 Conduct of this review

The Taskforce members were announced by the Prime Minister on 6–7 June and 28 August 2006 as follows: Dr Ziggy Switkowski (Chair), Prof George Dracoulis, Dr Arthur Johnston, Prof Peter Johnston, Prof Warwick McKibbin and Mr Martin Thomas. Brief biographical details of the taskforce members can be found in Appendix B.

The Review received more than 230 submissions from individuals and organisations (Appendix C). These have been carefully considered and used in formulating the views set out in this report. In addition, the Review conducted numerous consultations with individuals and organisations (Appendix D) and visited a number of sites in Australia, Canada, Finland, France, Japan, South Korea, Ukraine, the United Kingdom and the United States (Appendix E). Three expert studies were commissioned to assist with the Review (Appendixes G, H and I). There are also a number of technical appendixes discussing various aspects of the subject matter of this report in more detail (Appendixes K–S).

1.3 Structure of this report

The structure of this report and the chapter in which each of the terms of reference is discussed is outlined in Table 1.1. Chapters 2 to 5 deal with the nuclear fuel cycle as described in Section 1.5 below. The remaining chapters address important issues of public interest including health, safety and a discussion of nuclear radiation (Chapter 6), environmental impacts including greenhouse gas emissions (Chapter 7), and aspects of security including the prevention of proliferation of nuclear weapons (Chapter 8). Infrastructure matters are discussed in the final chapters — the regulatory regime governing the conduct of uranium mining and nuclear activities in Australia and internationally (Chapter 9) and a discussion of research, development, education and training issues relevant to the industry (Chapter 10).

1.4 Australia's involvement in the nuclear fuel cycle

The nuclear fuel cycle is the term used to describe the way in which uranium moves from existing as a mineral in the earth, through to use as nuclear reactor fuel and final permanent disposal.

Box 1.1 lists Australia's involvement in the nuclear fuel cycle, ranging from uranium mining and milling to the operation of world-class research facilities.[4]

1.5 Introduction to nuclear energy

Nuclear technology has a wide range of peaceful and commercially important uses, including health and medical, environmental and industrial, as well as electricity generation. Current nuclear activities in Australia include uranium mining, health and medical, industrial and scientific research.

This Review examines the potential for Australia to use nuclear energy for electricity generation. It takes into account both economic and social issues raised by nuclear energy, including safety, the environment, weapons proliferation and spent fuel issues. The Review also acknowledges opportunities to reduce greenhouse gas emissions, particularly carbon dioxide.

Nuclear power uses a controlled fission reaction to generate heat. In nuclear power reactors the heat produces steam that drives conventional turbines and generates electricity. Except for the processes used to generate the steam, nuclear power plants are similar to conventional coal-fired generation plants.

Fission occurs when an atom of fissile material (in this case a specific isotope of uranium called U-235) is hit by a 'slow' neutron and divides into two smaller nuclei, liberating energy and more neutrons. If these neutrons are then absorbed by other uranium nuclei, a chain reaction begins. In a nuclear reactor the reaction process is precisely controlled with materials called moderators that slow and absorb neutrons in the reactor core. A controlled chain reaction takes place when approximately 40 per cent of the neutrons produced go on to cause subsequent reactions.

Figure 1.1 shows the steps of the nuclear fuel cycle. Following mining and milling, in the nuclear fuel cycle, uranium goes through production steps of chemical conversion, isotopic enrichment and fuel fabrication. The steps of the cycle are described in more detail below.

1.5.1 Mining and milling

Uranium is a naturally occurring radioactive element and radioactivity is a normal part of the natural environment. Uranium ore is usually mined using open-cut or underground techniques, depending on the location of reserves.

The mineralised rock is ground and leached to dissolve the uranium. That solution is further treated to precipitate uranium compounds which are ultimately dried and calcined to form uranium ore concentrate, conventionally referred to as U_3O_8. Approximately 200 tonnes of concentrate is required annually to produce the fuel for a 1000 MWe reactor (1 MWe is one million watts of electrical power).[5]

An alternative to conventional mining is in-situ leaching, where uranium is brought to the surface in solution by pumping liquid through the ore body.

A more detailed discussion of uranium mining is provided in Chapter 2, which examines the existing resource base and mining capacity, global demand and the scope to expand mining in Australia.

Table 1.1 Report structure

Chapter	Term of reference	Issue
1	–	Introduction.
2	1a	The capacity for Australia to increase uranium mining and exports in response to growing global demand.
3	1b	The potential for establishing other steps in the nuclear fuel cycle in Australia.
4	1c	The extent and circumstances in which nuclear energy could be economically competitive with other existing electricity generation technologies in the long term in Australia, and implications for the national electricity market.
5, 6, 8,10	3a	The potential of 'next generation' nuclear energy technologies to satisfy safety, waste and proliferation concerns.
5	3b	Waste processing and storage issues associated with nuclear activities and current global best practice.
6	3d	Health and safety implications relating to nuclear energy.
7	2a	The extent to which nuclear energy may make a contribution to the reduction of global greenhouse gas emissions.
7	2b	The extent to which nuclear energy could contribute to the mix of emerging energy technologies in Australia.
7	–	Other environmental impacts of the nuclear fuel cycle.
8	3c	Security implications relating to nuclear energy.
9	–	The existing Australian regulatory regime and international regulatory frameworks.
10	1d	The current state of nuclear energy research and development, and potential contributions to international nuclear science in Australia.

Box 1.1 Australia's involvement in the nuclear fuel cycle

1894	Uranium is discovered in Australia.
1944–1964	The UK government asks Australia to help find uranium for defence requirements. Australian Government incentives for the discovery and mining of uranium are announced. Some 400 deposits found in the Mt Isa–Cloncurry region in Queensland and the Katherine–Darwin region of the Northern Territory. Mining begins in the Rum Jungle area, followed by Radium Hill, Mary Kathleen and others. Australia exports approximately 7300 tonnes of uranium ore over this period.
1953	The Australian Atomic Energy Commission (AAEC) is established, with Lucas Heights selected as the site for research facilities.
1958	The high-flux research reactor (HIFAR) is commissioned at Lucas Heights.
1967	Policy for controlling exports of uranium is announced.
1969–1971	A nuclear power plant is proposed at Jervis Bay; plans are abandoned in 1971.
1973	Australia ratifies the Treaty on the Non-proliferation of Nuclear Weapons.
1974	Commercial exports begin. The Australian Safeguards Office is established, which later becomes the Australian Safeguards and Non-proliferation Office (ASNO).
1977	The Ranger Uranium Environmental Inquiry (Fox Inquiry) makes its report and the Australian Government decides to proceed with uranium mining in the Alligator Rivers Region.
1978	The Office of the Supervising Scientist is established.
1983	An Australian Science and Technology Council inquiry reports on the nuclear fuel cycle (*Australia's Role in the Nuclear Fuel Cycle*) and the Australian Government limits uranium mining to three existing sites.
1987	The Australian Nuclear Science and Technology Organisation (ANSTO) is established.
1996	The Australian Government removes restrictions on the number of mines.
1998	The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is established.
2006	A replacement research reactor, the Open Pool Australian Light water reactor (OPAL) is commissioned at Lucas Heights.

1.5.2 Conversion

In order for uranium to be enriched, the U_3O_8 must be purified and chemically converted to uranium hexafluoride (UF_6) gas. This process uses standard industrial chemical steps, some of which use hazardous gases, and the application of moderate heat.

1.5.3 Enrichment

Most nuclear power plants require fissile material that is more concentrated than the level present in natural uranium, in order to sustain a reaction. Natural uranium contains approximately 0.7 per cent of the fissile U-235 isotope, the balance being non-fissile U-238. Enrichment increases this proportion to 3–5 per cent, producing low-enriched uranium (LEU).

Established commercial processes for enrichment include gas centrifuge, the current method of choice, and gaseous diffusion, which is very energy intensive and is being phased out. New technologies under development include laser activated isotope separation.

1.5.4 Fabrication

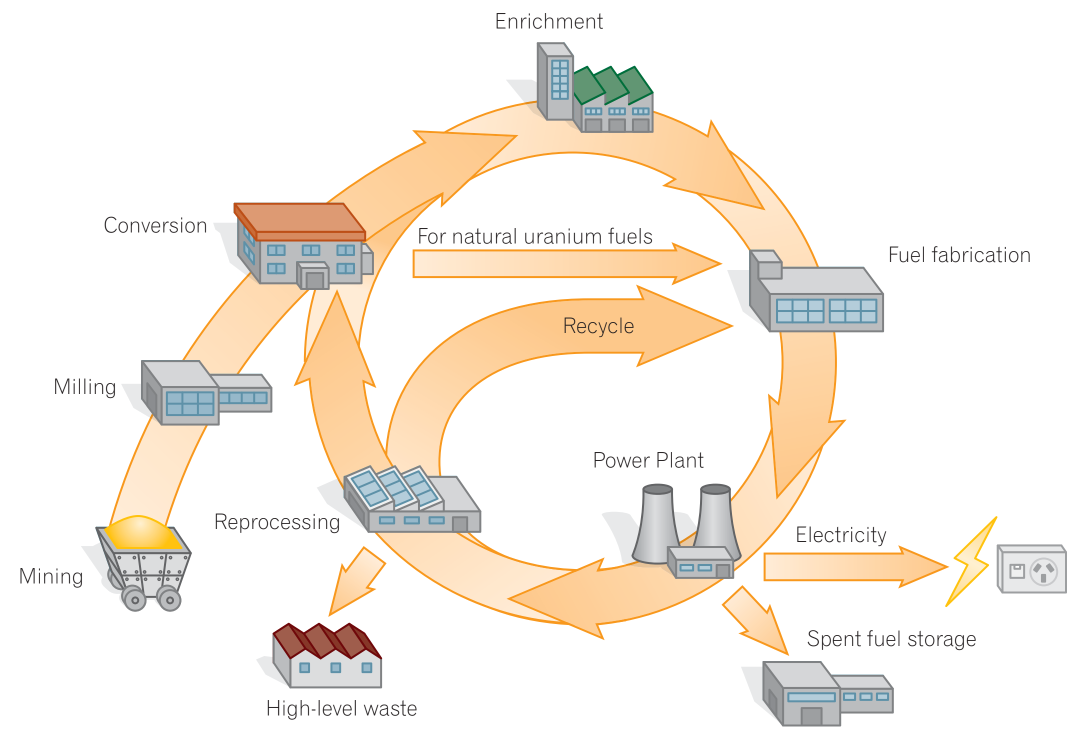
Enriched uranium in the form of UF_6 is transferred to a fuel fabrication plant where it is transformed to another oxide of uranium, UO_2. UO_2 is a black powder that is compressed into small pellets, which are sintered (baked) and then ground to a precise shape and loaded into thin zirconium alloy or steel tubes (cladding) to create fuel rods. These rods are then bundled into fuel assemblies for insertion into the reactor.

A more detailed discussion of uranium conversion, enrichment and fabrication is provided in Chapter 3. Other sections of the nuclear fuel cycle are discussed below.

1.5.5 Fuel cycles

Most current reactors use an 'open fuel cycle' also known as 'once through' cycle. Fuel is used in the reactor to generate power, then removed from the reactor during periodic refuelling. As spent fuel is highly radioactive and self-heating, it is stored in dedicated water ponds for some

Figure 1.1 Schematic of the nuclear fuel cycle



years to allow the radioactivity to decline and the material to cool sufficiently for long-term storage. After a period of three years or more, the spent fuel assemblies may be moved to 'dry storage' to await final deep geological disposal.

The reactor core for a 1000 MWe plant requires approximately 75 tonnes of low-enriched uranium at any one time. Approximately 25 tonnes of fuel is replaced each year, although fuel cycles have been getting longer and are approaching 24 months. Approximately 1 tonne (the U-235 component) of nuclear fuel is consumed during the cycle, with 95 per cent of the remaining spent fuel being U-238 and a small proportion of U-235 that does not fission.

In a 'closed fuel cycle', nuclear fuel is supplied in the same way as in an open fuel cycle, but when the fuel rods are removed from the reactor they are reprocessed. This step involves separating the radioactive spent fuel into two components — uranium and plutonium for re-use and waste fission products. This process leaves approximately 3 per cent of the fuel as high-level waste, which is then permanently immobilised in a stable matrix (eg borosilicate glass or Synroc) making it safer for long-term storage or disposal. Reprocessing spent fuel significantly reduces the volume of waste (compared to treating all used fuel as waste).

Fast breeder reactors have been under development since the 1960s. These reactors have the potential to derive nearly all of the energy value of the uranium mined. Overall, approximately 60 times more energy can be extracted from uranium by the fast breeder cycle than from an open cycle.[6] This extremely high energy efficiency makes breeder reactors an attractive energy conversion system. The development of fast breeder reactors has been a low priority due to high costs and an abundance of uranium, so they are unlikely to be commercially viable for several decades.[6]

1.5.6 Nuclear power plants

Nuclear power plants are used to harness and control the energy from nuclear fission. All plants operate on the same principle, but different designs are currently in use throughout the world. More than 50 per cent of power reactors in use today are pressurised water reactors (PWRs), followed in number by boiling water reactors (BWRs) and pressurised heavy water reactors (PHWRs). The three types vary in operating conditions and fuel mixes used, but the basic principles are similar.

The nuclear power industry has been developing and improving reactor technology for five decades. The next generation of reactors is expected to be built in the next 5–20 years. These so-called third-generation reactors have standardised designs for each type in order to expedite licensing and reduce capital costs and construction time. Many employ passive safety systems and all are simpler and more rugged in design, easier to operate, capable of higher capacity factors, have extended lives of at least 60 years and will have a lower decommissioning burden.

Small, modular high temperature gas reactors are also under development in several countries. Due to the nature of their fuel, they have inherent safety advantages, higher fuel burnup and better proliferation resistance compared with conventional reactors. These reactors have the potential to provide high temperature process heat for hydrogen production and coal liquefaction as well as electricity and their small size makes them suitable for smaller and remote electricity grids, such as in Australia.

The Generation IV International Forum (GIF), representing ten countries, is developing six selected reactor technologies for deployment between 2010 and 2030. Some of these systems aim to employ a closed fuel cycle to minimise the amount of high-level wastes that need to be sent to a repository.

Figure 1.2 shows the basic operation of a standard PWR nuclear power plant. The buildings housing the turbines and the control centre are separate from the reactor containment area. Current and future nuclear power plant technologies are discussed further in Appendix L.

Electricity generation is discussed in Chapter 4, including current electricity demand, projections for future demand, consideration of nuclear energy for electricity generation and cost issues.

1.5.7 Radioactive waste and spent fuel management

All fuels used in the generation of electricity produce wastes and all toxic wastes need to be managed in a safe and environmentally benign manner. However, the radioactive nature of nuclear fission products — in particular long-lived by-products — require special consideration. Principles for the management of potentially dangerous wastes are:

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

The delay and decay principle is unique to radioactive waste strategies.

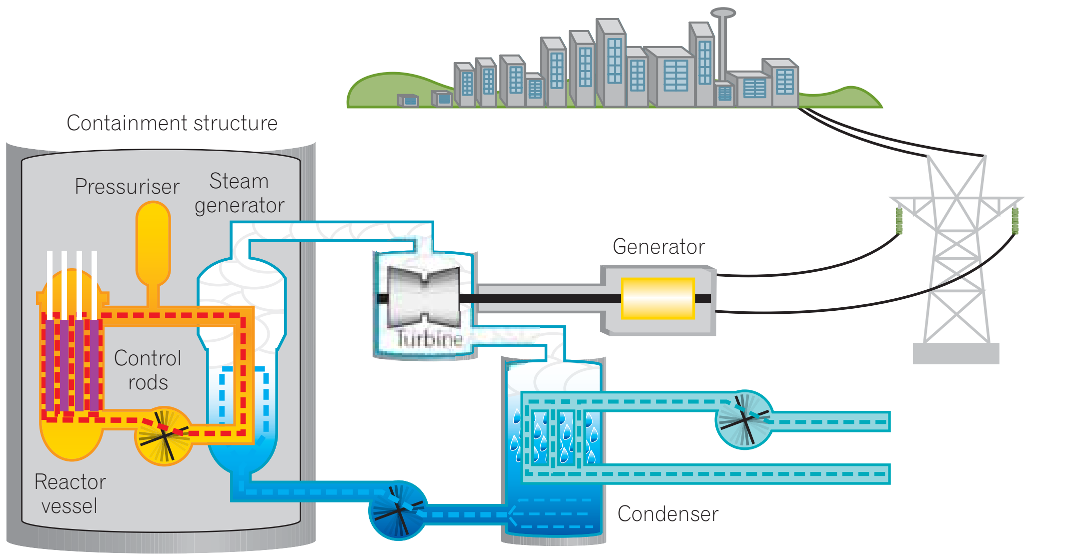
Low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW) are the classifications for nuclear waste. LLW is generated widely in the health and industrial sectors, and comprises potentially contaminated materials such as paper towels, scrap metal and clothing. By far the largest volume of waste materials is LLW, but it is relatively easy to handle due to the very low level of radioactivity.

ILW is more radioactive, but unlike HLW, does not have self-heating properties. ILW includes fuel cladding or reactor components, and is of special relevance in nuclear facility decommissioning. ILW is sometimes categorised according to its half-life.

HLW is normally defined by its self-heating properties caused by radioactive decay. It may consist of spent fuel or liquid products from reprocessing. Spent fuel assemblies from nuclear reactors are extremely hot from decay heat and are still highly radioactive.

Chapter 5 provides further details about radioactive waste and spent fuel management.

Figure 1.2 Schematic of a pressurised water reactor



Source: United States Nuclear Regulatory Commission (NRC)[7]

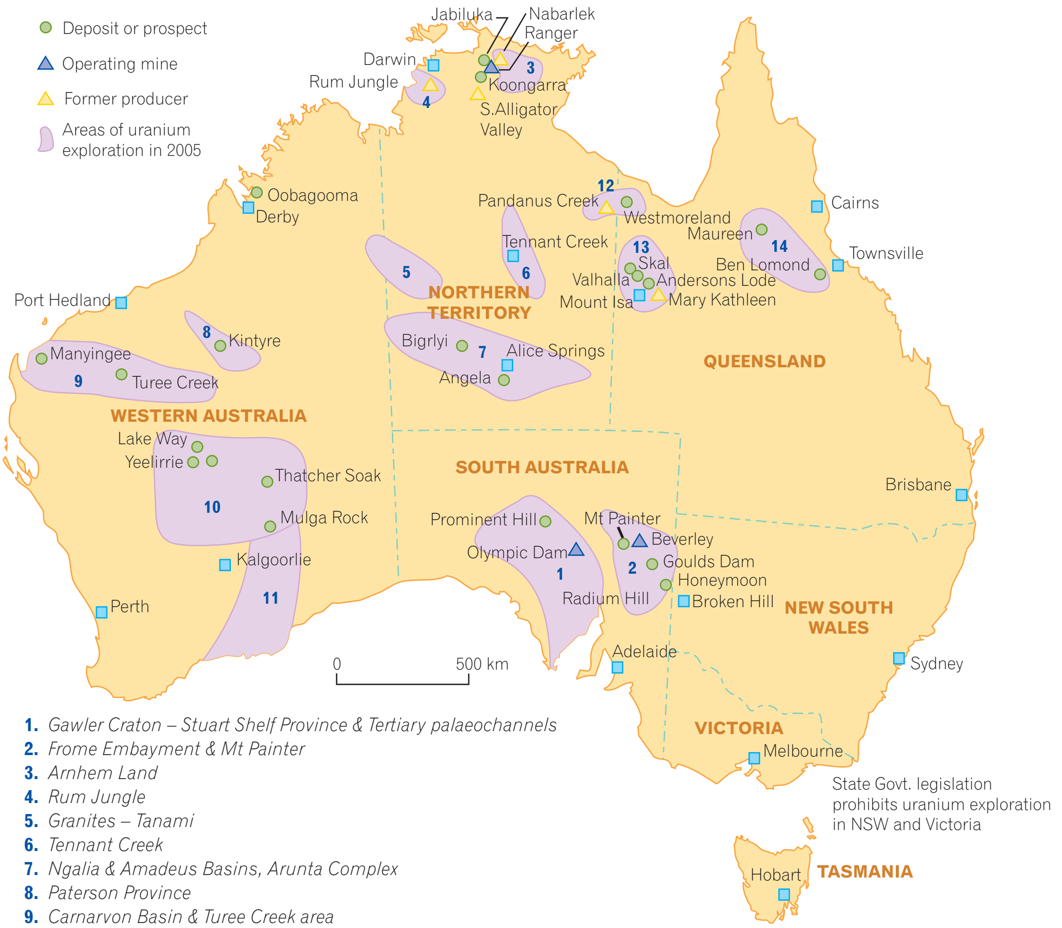
Chapter 2. Uranium mining and exports

- Australia has the capacity to expand its production and exports of uranium, and global growth in uranium demand provides a timely opportunity for Australia.
- Skill shortages and restrictive policies (regulation, land access and transport) are the major constraints on industry expansion in Australia.
- Conventional reserves of uranium worldwide are sufficient to meet current demand for 50 to 100 years. There is high potential for future discoveries.

2.1 Australian uranium mining industry

Australia has a long history of uranium mining — mines at Radium Hill and Mount Painter operated in the 1930s. There are currently three uranium mines in Australia — Ranger in the Northern Territory, and Olympic Dam and Beverley in South Australia. A fourth mine, Honeymoon in South Australia, has all the key approvals and is scheduled to begin production in 2008. Uranium mine locations are shown in Figure 2.1.

Figure 2.1 Uranium mines and areas of uranium exploration, 2005



1. *Gawler Craton – Stuart Shelf Province & Tertiary palaeochannels*
2. *Frome Embayment & Mt Painter*
3. *Arnhem Land*
4. *Rum Jungle*
5. *Granites – Tanami*
6. *Tennant Creek*
7. *Ngalia & Amadeus Basins, Arunta Complex*
8. *Paterson Province*
9. *Carnarvon Basin & Turee Creek area*
10. *Calcrete deposits*
11. *Tertiary palaeochannel sands – Kalgoorlie Esperance and Gunbarrel Basin*
12. *Westmoreland – Pandanus Creek*
13. *Mt Isa Province*
14. *Georgetown – Townsville area*

Source: Geoscience Australia[8]

2.1.1 Uranium exports

Australian uranium exports in 2005 earned a record A$573 million, making uranium the eighteenth largest mineral and energy export by value (2005–2006),[9] as shown in Figure 2.2.

Production in 2005 was also a record 12 360 tonnes U_3O_8.[10],3 In a once-through fuel cycle, this amount of U_3O_8 would generate more than double Australia's current electricity demand.

Uranium export earnings are forecast to increase in the future due to rises in production and average price as new contracts are signed at higher prices. Forecasts suggest that Australian uranium production could increase to more than 20 000 tonnes U_3O_8 by 2014–2015,[11] and may exceed A$1 billion annually before the end of 2010.

In 2005, Australia delivered uranium to ten countries, including the United States (36 per cent), some members of the European Union (31 per cent; including France, 11 per cent), Japan (22 per cent) and South Korea (9 per cent).[10],4 The United States, the European Union, Japan and South Korea have all been long term buyers of Australian uranium. Uranium is sold in accordance with Australia's uranium export policy (see Chapter 8), with eligible countries accounting for approximately 90 per cent of world nuclear electricity generation.5 Contracts for U_3O_8 are between producers and end utilities (see Chapter 3).

2.1.2 Economic benefits

Mining in Australia employs approximately 130 000 people,[12] 1200 in uranium-related jobs. Most of these jobs are in remote areas with limited employment opportunities. Indigenous employment in uranium mining is low at around 100 people. At least 500 people are employed in uranium exploration,[8] and more than 60 people are employed in regulation.

Uranium mines generate approximately A$21.0 million in royalties for state and territory governments and indigenous communities, with different royalty rates in each jurisdiction. Ranger generated A$13.1 million in royalties (A$10.2 million to indigenous groups and A$2.9 million to the Northern Territory Government in 2005),[13] Beverley generated approximately A$1.0 million (2004–2005), and the uranium share of Olympic Dam generated approximately A$6.9 million (2005–2006).[14] Uranium mining companies also contribute taxes and other payments. In 2005, Energy Resources of Australia (ERA), which operates the Ranger mine, paid A$19.7 million in income tax.[15] BHP Billiton's taxation contribution for uranium at Olympic Dam is approximately A$23.0 million.[14]

2.1.3 Uranium reserves

Uranium is a naturally occurring element found in low levels within all rock, soil and water and is more plentiful than gold or silver. It is found in many minerals, particularly uraninite, as well as within phosphate, lignite and monazite sands. Figure 2.3 shows the abundance of various elements in the earth's crust.

Australia has the world's largest low-cost uranium reserves. Geoscience Australia estimates that Australia's total identified low-cost resources (less than US$40/kg, or approximately US$15/lb) are 1.2 million tonnes U_3O_8, which is approximately 38 per cent of the global resources in this category. At recent spot prices, Australia's recoverable reserves increase to 1.3 million tonnes U_3O_8, about 24 per cent of the world's resources (at less than US$130/kg). The lack of mid-cost identified reserves in Australia may reflect the low levels of exploration over the last 30 years.

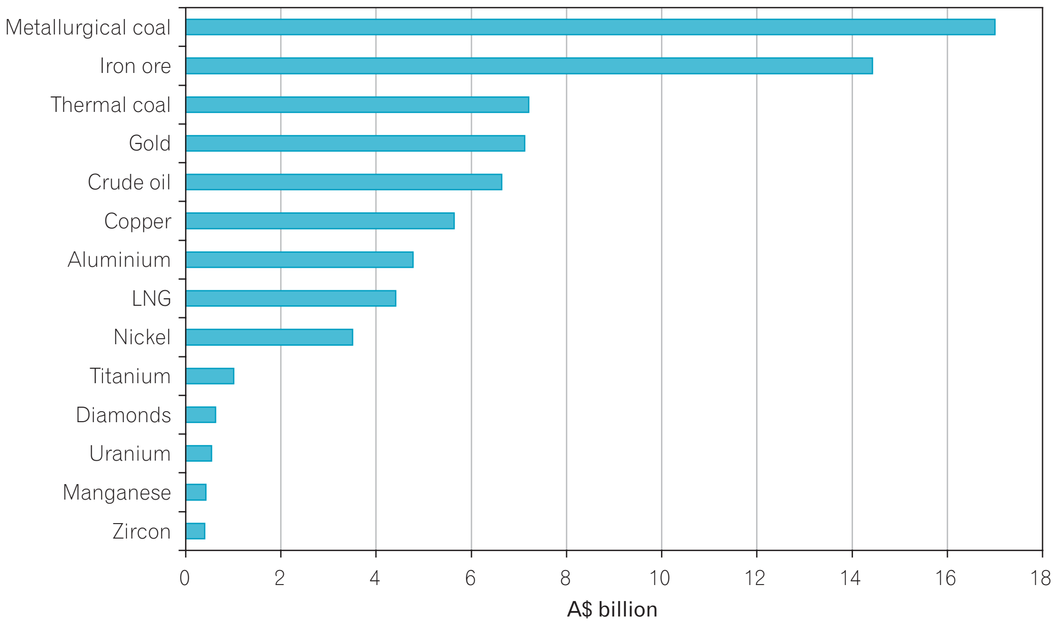
Table 2.1 shows the total identified uranium resources in Australia and the world. Australia's seven largest deposits account for approximately 89 per cent of Australia's total known reserves. Olympic Dam is the world's largest known uranium deposit, containing 70 per cent of Australia's reserves. While Olympic Dam uranium grades are low, averaging 600 parts per million,[17] co-production with copper and gold makes its recovery viable. The other major deposits are Jabiluka, Ranger, Yeelirrie, Kintyre, Valhalla and Koongarra.

3 Note: deliveries do not equal production figures due to a lag between production and when uranium reaches the end user (ie after conversion, enrichment and fabrication into fuel for use by the power plant).

4 Figures are percentages of total exports of uranium.

5 Countries with nuclear power plants that Australia cannot currently sell to include Armenia, Brazil, Bulgaria, India, Pakistan, Romania, Russia, South Africa and Ukraine.

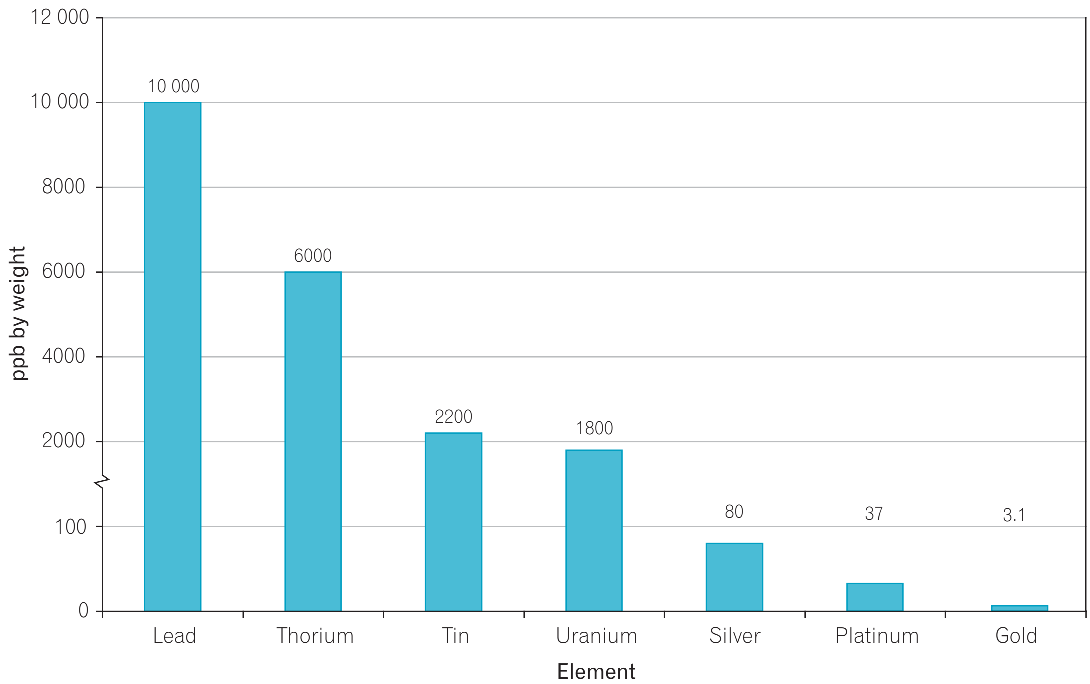
Figure 2.2 Value of selected Australian mineral and energy exports, 2005–2006



Note: Mineral and energy exports were worth more than A$91 billion in 2005–2006.

Source: Australian Bureau of Agricultural and Resource Economics (ABARE)[9]

Figure 2.3 Abundance of various elements in the earth's crust



ppb = parts per billion

Source: WebElements[16]

2.1.4 Outlook for additional reserves to be discovered

Of the 85 currently known uranium deposits and prospects in Australia, approximately 50 were discovered from 1969–1975, with another four discovered from 1975–2003. Little exploration was undertaken in the 30 years until 2003, due to low uranium prices and restrictive government policies. Since 2004, uranium exploration expenditure has increased, with dozens of companies exploring actively. Given the paucity of systematic modern exploration, Geoscience Australia estimates that there is significant potential for the discovery of additional deposits. Modern techniques mean that exploration at greater depths is becoming more comprehensive and less costly. Australia has many areas with high or medium uranium mineralisation potential.

2.1.5 Outlook for Australian suppliers to increase production

Australia is unable to expand uranium production in the short term at existing mines as plant capacity is fully utilised. The new Honeymoon mine is forecast to add only 400 tonnes U_3O_8 in 2008 (or 3 per cent of total production).

Australia can expand production over the medium and long term by increasing output at existing mines and/or by opening new mines. There are opportunities at each of the three current mines to expand production or extend the lives of projects through further reserve discoveries on mine leases. For example, the proposed Olympic Dam expansion (currently subject to a commercial decision by BHP Billiton and government approvals) will increase uranium production from 4300 tonnes per year to 15 000 tonnes per year of U_3O_8 from 2013. In October 2006, the Ranger project life was extended by six years to 2020. The discovery of an adjacent prospect (Beverley 4 Mile) could also increase production at Beverley. Many smaller deposits could be developed relatively quickly, although development would require a change in government policy.

As shown in Figure 2.4, the overall production capability of Australia's existing and approved mines is forecast to increase to more than 20 000 tonnes U_3O_8 by 2015. When new mines from already identified deposits are included in the calculation, the increase may be to more than 25 000 tonnes U_3O_8.[11] Forecasts beyond 2020 do not provide for the commercialisation of new discoveries from current and future exploration activities. (The ABARE forecast to 2015 includes the development of a number of small to medium sized new mines in Western Australia and Queensland, but is reliant on policy changes in those states. Their forecast does not include Jabiluka or Koongarra deposits in the Northern Territory, for which development requires approval by the Traditional Owners.)

Table 2.1 Total identified uranium resources for Australia and the world, 2005[a]

	Total identified resources ('000 tonnes U_3O_8)[b]		
	< US$40/kg	< US$80/kg	< US$130/kg
World	3239	4486	5593
Australia	1231	1266	1348
Australian share	38%	28%	24%

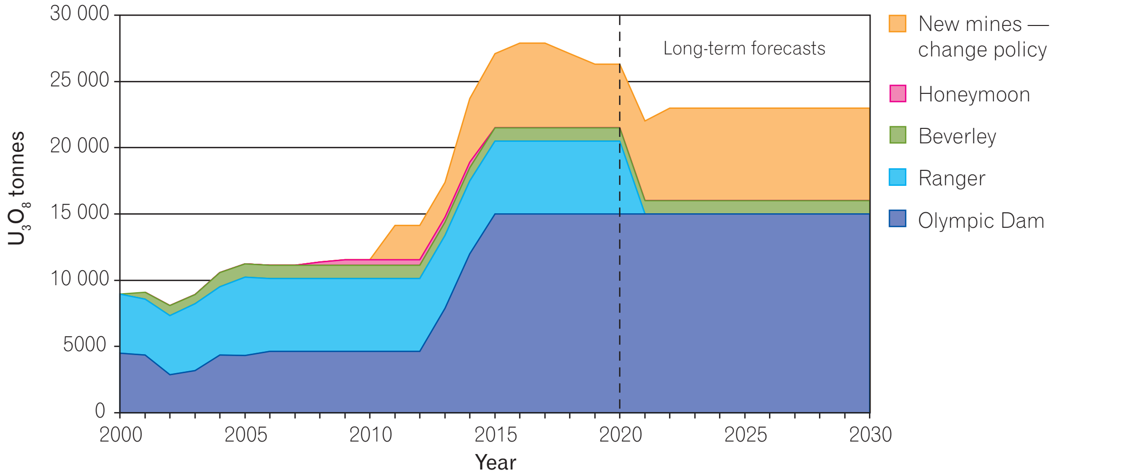
a Resource figures for Australia and the World are as at 1 January 2005; resource estimates are expressed in terms of tonnes of U_3O_8 recoverable from mining ore (ie the estimates include allowances for ore dilution, mining and milling losses).

b Total identified resources = reasonably assured resources + inferred resources (see note).

Note: The international convention for reserve reporting divides estimates into two categories based on the level of confidence in the quantities reported: reasonably assured resources (RAR), which are known resources that could be recovered within given production cost ranges, and inferred resources, which is uranium that is believed to exist based on direct geological evidence. These resources are further divided into categories on the basis of cost of production of U_3O_8 — less than US$40/kg U (approximately US$15/lb U_3O_8), US$40-80/kg U (approximately US$15–30/lb U_3O_8), and US$80-13o/kg U (approximately US$30-50/lb U_3O_8).

Source: adapted from NEA–IAEA.[18]

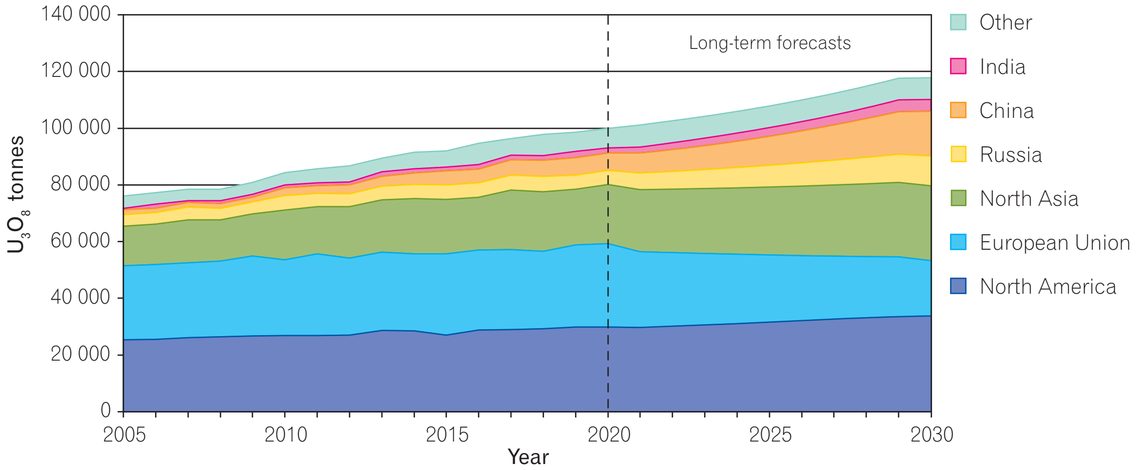
Figure 2.4 Australian uranium production 2000–2005 and forecast production 2006–2030



Note: The 'new mines' forecast is based on a number of assumptions.

Sources: Geoscience Australia,[8], [19] ABARE,[11] World Nuclear Association (WNA),[20] Ux Consulting (UxC),[21] NEA–IAEA,[18] ERA[22]

Figure 2.5 World projected uranium requirements by region, 2005–2030



Source: ABARE,[11] WNA[20]

2.2 World uranium demand and supply

2.2.1 World uranium demand

Forecasts for global uranium demand include those by the WNA,[20] UxC,[21] NEA–IAEA,[18] ABARE[11] and IEA.[3] Most commentators predict an increase in demand due to the construction of new power plants, increased capacity in existing plants and a reduction in secondary supplies (secondary supplies include stockpiles, reprocessing of spent fuel and down-blending of highly enriched uranium (HEU) from weapons. These have accounted for more than 40 per cent of the uranium market in recent years; see Box 3.3). As shown in Table 2.2, new plants are planned in Asia — particularly in China, India, Japan and South Korea, as well as several western countries such as the United States. The current largest uranium users — the United States, France and Japan — are expected to continue to be the major buyers, although India, Russia and China will become larger buyers in the future (Figure 2.5).[6]

Table 2.2 Nuclear power reactors planned and proposed (on available information)

Country/region	Capacity (MW)	No. reactors	Comments
China	48 800	63	The Chinese Government plans to have 40 GW of additional nuclear capacity by 2020.
Russia	31 200	26	The Russian Government plans to have 40 GW of nuclear capacity by 2030.
United States	26 716	23	The US Government is actively pursuing nuclear power for energy security; expect new reactors to 2020.
Japan	16 045	12	The Japanese Government forecast is to maintain or increase the share of nuclear power in electricity generation (30–40 per cent) beyond 2030.
India	13 160	24	The Nuclear Power Corporation of India plans to have 20 GW by 2020.
Western Europe (other)	12 135	13	Turkey (4500 MW), Romania (1995 MW), Bulgaria (1900 MW), Czech Republic (1900 MW), Lithuania (1000 MW) and Slovakia (840 MW).
Middle East/South Asia (other)	9350	11	Iran (4750 MW), Pakistan (1800 MW), Israel (1200 MW), Armenia (1000 MW) and Egypt (600 MW).
South Korea	8250	7	Seven reactors are planned for existing sites and are expected to be operational by 2015.
Asia (other)	6950	7	Indonesia (4000 MW), Vietnam (2000 MW) and North Korea (950 MW).
North and South America (other)	6245	7	Canada (2000 MW), Mexico (2000 MW), Brazil (1245 MW) and Argentina (1000 MW).
South Africa	4165	25	South Africa is developing pebble bed modular reactor (PBMR) technology. If successful, the plan is to commercialise and build plants in coastal regions.
France	3230	2	–
Eastern Europe other	2200	3	Ukraine (1900 MW) and Kazakhstan (300 MW).
Total	**188 446**	**223**	–

Planned = the approvals are in place or the construction is well advanced, but suspended indefinitely.
Proposed = clear intention, but still without funding and/ or approvals.

Note: For further information on nuclear power plans in selected countries see ABARE.[11]

Source: WNA[23]

[6] The United States, Japan and France are important customers for Australian uranium. Australia will shortly finalise a safeguards agreement with China and does not sell uranium to India or Russia.

2.2.2 World uranium supply

Uranium production is concentrated in very few countries. Canada and Australia produce more than 50 per cent of global natural uranium (ie excluding secondary supplies). A second group of countries — Niger, Russia, Kazakhstan, Namibia and Uzbekistan — account for approximately 40 per cent.[18] As shown in Figure 2.6, in the medium term (up to 2015), a number of new mines and expansions to current mines are projected. The increase in uranium production is expected to come from Canada and Australia in particular, but also from Kazakhstan, Namibia, Russia and the United States. Price increases (see Figure 2.7) have encouraged exploration and will lead to more new mines, particularly in existing production centres where they can be brought on line quickly.

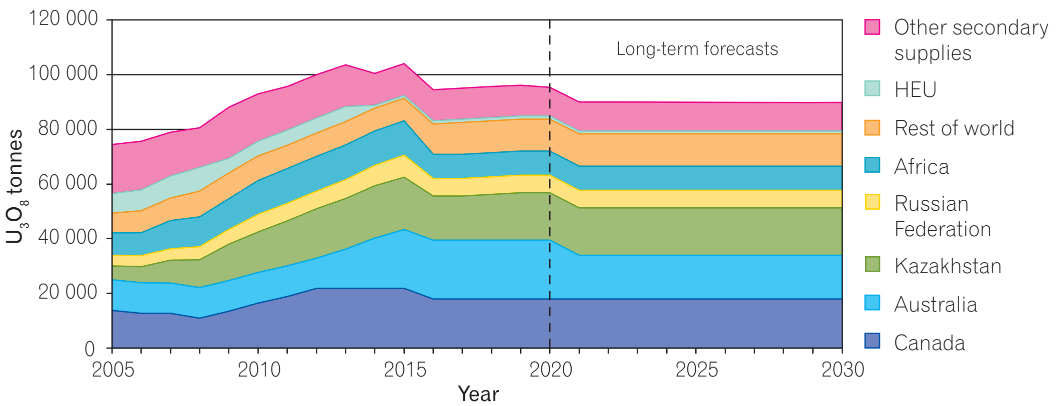
2.2.3 Outlook for uranium prices

As shown in Figure 2.7, over the last two decades the price of uranium has only increased since 2003 — from approximately US$10/lb U_3O_8 (approximately US$27/kg U_3O_8) in early 2003 to more than US$60/lb (approximately US$160/kg) in November 2006. The uranium price is linked to energy prices and the crude oil price was also relatively low over this period.

Forecasts show that supply will meet demand over the medium term and the price is expected to continue to increase in the short term and then stabilise. This projected increase in the short term is being driven by uncertainties over uranium supplies, including secondary supplies and mine production (see Box 3.1 on contractual arrangements). Uranium is mainly sold under long term contracts (90 per cent of the market in recent years) and as new contracts are negotiated, producer prices are expected to increase.

After 2013 when the availability of HEU from Russia is expected to cease, there will be greater uncertainty over both supply and demand, but on current forecasts, demand is expected to exceed supply. Normally this would lead to further increases in price or investment in new capacity. Each of these circumstances represents an opportunity for Australia.

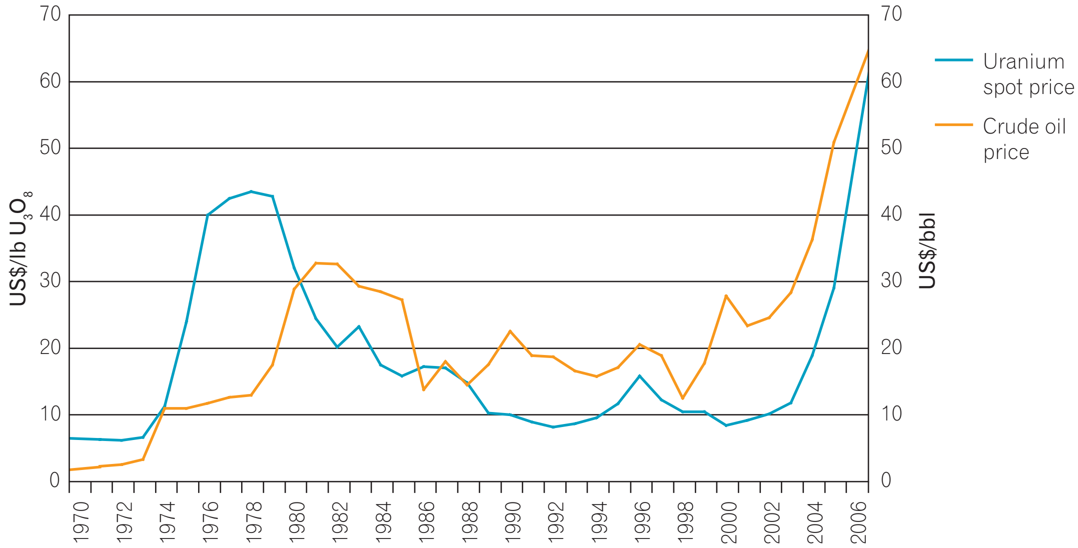
Figure 2.6 Projected uranium supply by country, 2005–2030



Note: Australia only includes current and approved mines (ie excluding the ‘new mines’ in Figure 2.4).

Sources: WNA,[20] ABARE,[11] UxC,[21] NEA–IAEA[18]

Figure 2.7 Uranium and crude oil prices, 1970–2006



Source: UxC,[21] Organization of Petroleum Exporting Countries (OPEC)[24]

2.3 Capacity to expand

The main impediments to the development of Australia's uranium reserves have been low uranium prices and restrictive government policies. Other impediments identified by the Uranium Industry Framework are as follows.[25] These impediments were also identified in the report of the House of Representatives Standing Committee on Industry and Resources Inquiry into developing Australia's non-fossil fuel energy industry.[26]

2.3.1 Skills

In addition to a general nationwide skills shortage faced by the Australian mining industry, the uranium industry faces a shortage of radiation safety professionals required for industry and government regulators, as well as geologists with uranium experience to meet the increased demand for exploration (see Chapter 10 for a discussion of how to address skills shortages).

2.3.2 Regulation

Extensive regulatory requirements apply to uranium mining and milling to meet acceptable community standards on environmental, health and safety issues. In addition to general mining regulations, there are requirements to ensure that radiation risks to workers, the public and the environment are properly managed. Australia's three uranium mines each operate under different regulatory regimes and significant advantages could accrue from rationalising and harmonising regulatory regimes across all jurisdictions (see Chapter 9 for more information on regulation).

2.3.3 Land access

Land access is an ongoing issue for Australian exploration and mining, with uranium mining facing additional restrictions due to government and community attitudes. The governments of New South Wales and Victoria prohibit uranium exploration and mining, while Queensland, Western Australia, South Australia and the Northern Territory still have a 'no new mines' policy.

A number of uranium companies work closely with local communities and have negotiated cooperative agreements. For instance, Heathgate Resources, operator of the Beverley mine, has mining agreements in place with local indigenous groups that provide for benefits including employment and training, royalties and other community payments, as well as protection of cultural sites. Uranium exploration and mining is seen favourably by some communities as a means for economic development, while other communities are not supportive.

2.3.4 Transport

U_3O_8, which is classified as a Class 7 Dangerous Good, is transported by rail, road and sea in 200 litre drums packed into shipping containers (Class 7 is a United Nations classification for Dangerous Goods applying to radioactive materials). Australian regulatory standards for transport meet international standards. However, uranium transport restrictions arise from: negative public perceptions; regulations that exceed international standards; and consolidation in the international shipping industry that limits the scheduled routes and ports where vessels carrying uranium can call (and Australia requires trans-shipment countries to have agreements in place). The effect is to reduce the choice of shipping firms and routes, increasing delays and costs. Higher levels of security in transport modes apply in the current heightened security environment.

Such factors contribute to the reluctance of some transport companies, local councils, and the federal and state governments, to be involved in or allow transport of uranium. For example, governments in New South Wales, Victoria, Queensland and Western Australia have refused permission to allow export of uranium through their ports,[25] leading to scheduling difficulties, higher costs and extended delivery times. Restrictions on transport may limit expansion of Australian uranium exports.

2.3.5 Other impediments

The Uranium Industry Framework also identifies further areas for improvement, including uranium stewardship, indigenous engagement, communication and a uranium royalty regime in the Northern Territory.[25]

Figure 2.8 Drums of U_3O_8 being loaded into a shipping container for transport

Source: Heathgate Resources

2.4 Other nuclear fuel sources

The majority of uranium is the isotope U-238, which does not directly contribute to fission energy in thermal reactors. However, U-238 can produce fissile plutonium, which can be extracted for use as fuel in a nuclear reactor with advanced cycles using reprocessing (for example see Appendix L for a discussion on thermal MOX). Fast breeder reactors have a capability of producing a higher volume of Pu-239 than the volume of U-235 consumed in the original process, allowing the exploitation of much larger reserves of U-238. In an analogous fashion, natural thorium (100 per cent non-fissile Th-232) can be used to breed the fissile isotope U-233, opening up thorium as a potential resource.

The thorium fuel cycle (discussed in more detail in Appendix L) has several advantages including that it does not produce plutonium or minor actinides in significant quantities, thus reducing long lived isotopes in waste. The cycle is potentially more proliferation resistant than the uranium fuel cycle. The disadvantages include the need for reprocessing, which is a proliferation-sensitive technology, and the fact that reprocessing is more difficult than for the uranium cycle. There are several attendant technological difficulties which need to be addressed. No commercial thorium reactor is operating in the world today.

Thorium is contained in small amounts in most rocks and soils and averages 6–10 ppm in the earth's upper crust (three times the average content of uranium).[27] As there is only a very small market for thorium, there are no significant active exploration programs (Australia currently exports thorium in small quantities as a by-product in some mineral sands). Current estimates are 2.4 million tonnes worldwide with a further 1.8–2.3 million tonnes undiscovered.[7] Turkey, India, Brazil, the United States, Australia, Venezuela and Egypt have the largest resources. For countries having limited access to uranium resources thorium-fuelled reactors may be an option.[27] The use of thorium has been a central part of India's nuclear energy strategy.

Uranium is widespread throughout the earth's crust and the oceans. Unconventional reserves are found in phosphate rocks, black shales, coals and lignites, monazite and seawater.[28] The seawater concentration is low — less than 2 parts per billion (ppb). One estimate suggests that approximately 4.5 billion tonnes is contained in seawater. Some research has been done into the extraction of uranium from seawater; however, scaling up may prove impractical.[29] These unconventional sources are estimated to be substantially larger than known reserves.

The NEA–IAEA estimates that there are approximately 22 million tonnes of uranium in phosphate deposits. This estimate is conservative as many countries do not report phosphate reserves. The recovery technology is mature and has been used in Belgium and the United States, but historically this has not been viable economically.[18]

Box 2.1 How long can nuclear last?

Is there sufficient uranium to supply the industry in the long term, given that high-grade uranium ore resources could be limited?

The IEA estimates that at the current rate of demand, known conventional supplies are sufficient to fuel nuclear power for 85 years.[30]

Exploration activity is expected to identify new reserves. In the long term, new fuel cycles using fast breeder reactors could enable the use of the very abundant U-238, increasing the energy value of uranium resources by 30–60 times.[30] This would make known supplies sufficient to fuel nuclear power at current rates of use for thousands of years. This would also allow the exploitation of alternatives such as thorium, which can be used to breed fuel.

By comparison with other energy sources, the world's proven reserves of oil at current rates of production will last 42 years. This has been around the same level for the past 20 years. Proven reserves of gas at current rates of production will last 64 years. Worldwide proven gas reserves have grown by over 80 per cent in the last 20 years.[3]

The IEA concludes that uranium resources are not expected to constrain the development of new nuclear power capacity and that proven resources are sufficient to meet world requirements for all reactors that are expected to be operational by 2030.[3]

[7] Total identified thorium resources at less than US$80/kg thorium; figures in Geoscience Australia,[8] derived from NEA–IAEA.[27]

2.5 Conclusion

Projections for the supply and demand of uranium at a global level over the next 25 years suggest that there is an opportunity for Australia to increase uranium exports significantly. Current Australian ore processing capacity is effectively fully utilised and capacity expansion in the very short term is highly constrained. However a doubling of uranium exports by 2015 is realistic.

Any industry expansion would need concurrent programs to address skills shortages, particularly in relation to radiation protection, and would benefit from a rationalisation of regulatory regimes across all jurisdictions. There is scope for local communities to benefit more from uranium mining, including employment, training and community support. This is particularly important given the location of reserves on indigenous land.

Global uranium reserves at current prices and generating technologies can sustain current power production for 50–100 years. Technology improvements such as breeder reactors would extend this period significantly.

Issues associated with uranium mining, such as environmental impacts, safety, proliferation and waste management are addressed in subsequent chapters.

Chapter 3. Conversion, enrichment and fuel fabrication

- Australia's exports of uranium oxide of A$573 million in 2005 could be transformed into a further A$1.8 billion in value after conversion, enrichment and fuel fabrication. However, challenges associated with the required investment levels and access to enrichment technology are very significant.
- Centrifuge technology will dominate enrichment in the medium term as gaseous diffusion is replaced. SILEX, an Australian developed laser enrichment technology, offers promise, but is yet to be commercially proven.
- Enrichment technology is used for civil and weapons purposes. Any proposed domestic investment would require Australia to reassure the international community of its nuclear non-proliferation objectives.

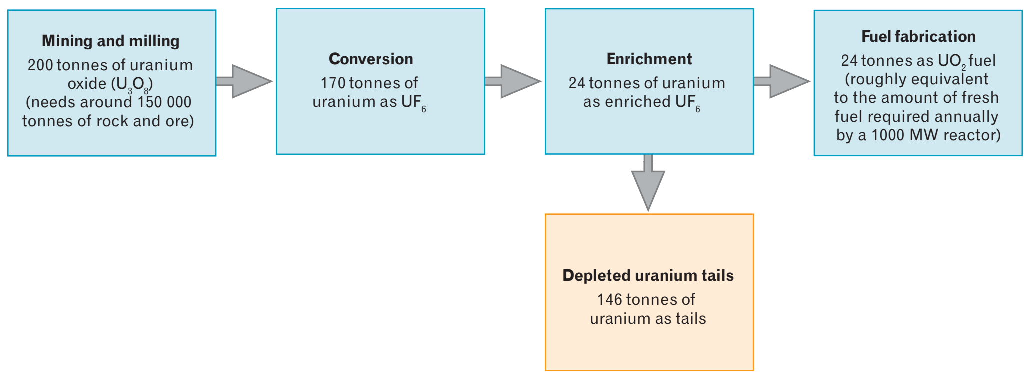
3.1 Value-adding in the nuclear fuel cycle

Unlike coal, natural uranium cannot be fed directly into a power station but must be prepared as special fuel. For the majority of reactors[8], the production steps involved are conversion, enrichment and fuel fabrication. The uranium oxide (U_3O_8) is first purified and then converted into uranium hexafluoride (UF_6), which in gaseous form is required for the enrichment stage. Enrichment increases the proportion of U-235 from 0.7 per cent to between 3 and 5 per cent.[6] The enriched UF_6 is subsequently converted to uranium dioxide (UO_2) and transferred to a fabrication plant for assembly into fuel (commonly pellets and fuel rods).

Figure 3.1 is a diagram showing approximate relative volumes of uranium as it moves through the nuclear fuel cycle.

Additional value-adding can take place in later stages of the fuel cycle such as reprocessing and waste management (Chapter 5).

Figure 3.1 Relative volumes of uranium in the nuclear fuel cycle



[8] Enriched uranium is required for most nuclear power plants, however, heavy water reactors such as CANDU power reactors can use natural uranium as fuel (Appendix L).

Box 3.1 Contractual arrangements in the nuclear fuel cycle

Electricity utilities contract directly with mining companies for the supply of U_3O_8, then contract with other nuclear fuel cycle participants for conversion, enrichment and fuel fabrication.[20]

Typically, each participant in the nuclear fuel cycle organises and pays for transport of the processed uranium to the next participant that has been contracted by the utility.

Contract periods vary in length, but are usually medium to long term (between three and five years), although they can be longer than 10 years.[31]

A diversified set of suppliers is usually preferred by electricity utilities to ensure security of supply. In some cases (eg in the European Union), this is a requirement. As a result no single supplier is likely to dominate the world market for any of the production steps.

The World Nuclear Association (WNA) estimated that in January 2006, the price for 1 kg of uranium as enriched reactor fuel was US$1633 (A$2217)[9].[32] It takes approximately 8 kg of U_3O_8 to make 1 kg of reactor fuel. Conversion, enrichment and fabrication of uranium are included in the cost of the fuel.

WNA figures (January 2006) assumed that 8 kg of U_3O_8 was required at a price of US$90.20/kg, which is below the mid-2006 spot price, but greater than average 2005 contract prices. The U_3O_8 is then converted into 7 kg of UF_6 at US$12/kg and then enriched using 4.8 separative work units (enrichment is measured in separative work units or SWU) at US$122 per SWU. Finally, the uranium is fabricated into 1 kg of fuel at US$240/kg.[10]

The disaggregated cost elements are depicted in Figure 3.2, which shows the January 2006 WNA estimate, the total fuel cost and shares using average 2005 uranium contract prices, and those same shares using mid-2006 spot prices for uranium, conversion and enrichment. At mid-2006 spot prices, Australian miners would have captured more than half of the available value.[11,12]

If all Australian current uranium production (approximately 12 000 tonnes U_3O_8 in 2005) was transformed into fuel, a further A$1.8 billion in export revenue could be derived. The net economic benefit would require a full consideration of costs.

3.2 Conversion

Conversion is a chemical process whereby U_3O_8 is converted into UF_6, which can be a solid, liquid or gas, depending on the temperature and pressure. At atmospheric pressure, UF_6 is solid below 57°C and gaseous above this temperature. It is stored and transported as a solid in large secure cylinders. When UF_6 contacts water, it is highly corrosive and chemically toxic.[33] Transport costs can be up to five times those of transporting natural uranium,[31] and shipping lines tend to be reluctant to carry Class 7 material.

The siting, environmental and security management of a conversion plant is subject to the same regulations as any industrial processing plant involving fluorine-based chemicals.[34] Radiological safety requirements must be met, as with uranium mining and processing.

Conversion comprises only approximately 5 per cent of the cost of reactor fuel (depending on the relative prices of U_3O_8, enrichment and fabrication), which is the lowest fraction of all of the steps in the nuclear fuel cycle. Figure 3.3 shows the conversion plant at Port Hope in Canada.

[9] The WNA updates these figures regularly.

[10] 8 kgs at US$90.20 + 7 kg at US$12 + 4.8 SWU at US$122 + 1 kg at US$240 = US$1633 (may not add up exactly due to rounding)

[11] Average uranium prices in 2005: 8 kg at US$43 + 7 kg at US$12 + 4.8 SWU at US$122 + 1 kg at US$240 = US$1255

[12] Mid-2006 spot prices: 8 kg at US$150 + 7 kg at US$12 + 4.8 SWU at US$130 + 1 kg at US$240 = US$2149

3.2.1 The existing conversion market and outlook

The market for conversion services is highly concentrated with four companies (Tenex, Areva, Cameco and Converdyn) supplying more than 80 per cent of conversion services globally. The main suppliers are shown in Table 3.1. Current suppliers have a capacity of more than 66 000 tonnes per year; however, conversion capacity is difficult to estimate for Russia as Russian conversion services are not directly exported (see Box 3.3 on the United States–Russia HEU deal).

The market has not seen new investment or real production expansion for a considerable period and has been characterised by instability since 2000, due to supply-side factors. Prices have nearly doubled in the last two years. In mid-2006, the conversion price was approximately US$12/kg of uranium as UF_6.[35]

Figure 3.2 Component costs of 1 kg of uranium as enriched reactor fuel

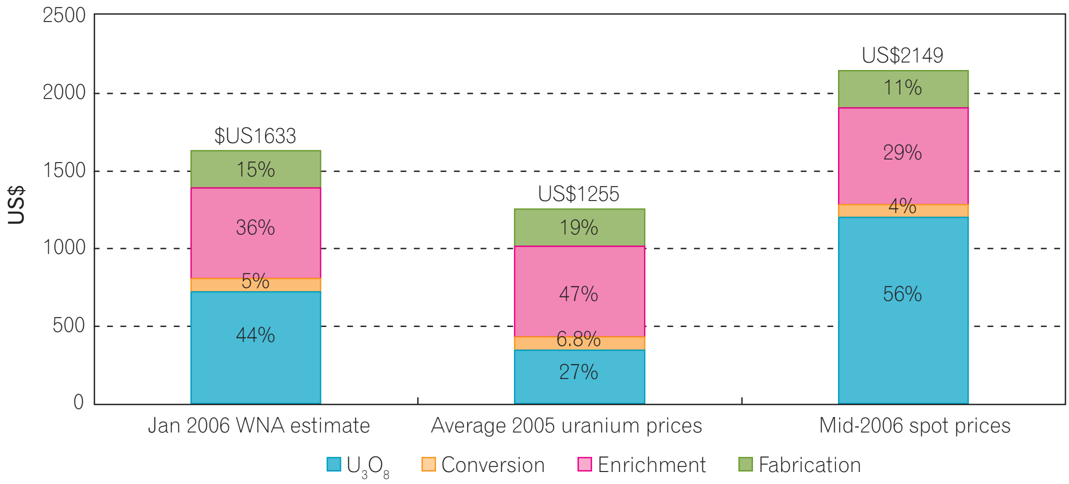


Figure 3.3 The Cameco conversion plant at Port Hope, Canada

Source: Cameco

Table 3.1 Conversion suppliers and capacities

Country	Company	Start of operation	Capacity (tonnes UF_6/year)
Conversion to UF_6			
Russia	Tenex	1954	15 000
France	Comurhex (Areva)	1961	14 000
Canada	Cameco	1984	12 500
USA	Converdyn	1959	14 000
UK	BNFL (Westinghouse)	1974	6000
China	CNNC	1963	1500
Total UF_6			63 000
Conversion to UO_2[a]			
Canada	Cameco	1983	2800
Others (Argentina, India and Romania)	n/a	n/a	762
Total UO_2			3562
Total UF_6 and UO_2			66 562

n/a = not applicable.
a: UO_2 supplies are used in CANDU reactors and other heavy water reactors.
Source: WNA,[20] IAEA[36]

In terms of market outlook, there have recently been announcements for future plant expansion and renewal. These include a toll agreement between Cameco and BNFL, expansion plans by Converdyn and preliminary plans by Areva for a new plant.[20] The expansion plans and possibility of new investment have given the market renewed confidence in the stability of conversion supply.

Analysis of future demand and supply by Ux Consulting (UxC) suggests conversion supply is likely to meet and possibly exceed demand through to 2013.[35] After 2013, the situation is difficult to ascertain given the uncertainty surrounding secondary supply and the Russia–USA HEU deal. Russian suppliers are pushing for direct access to the world (and United States) markets, but this can only take place if trade restrictions are lifted.

Establishment of conversion in Australia is only likely to be attractive if it is associated with local enrichment, partly due to transport costs, the complexity associated with the handling of toxic chemicals and constraints applying to Class 7 Dangerous Goods (which also apply to U_3O_8).[13]

3.3 Enrichment

The enrichment process involves increasing the proportion of U-235 from 0.7 per cent to between 3 and 5 per cent. In the process, approximately 85 per cent of the feed is left over as depleted uranium (tails). Typically, the depleted uranium remains the property of the enrichment plant. While depleted uranium has some industrial uses, most is stored for possible re-enrichment or future use as fuel in fast breeder reactors.[37] Although several enrichment processes have been developed, only the gaseous diffusion and centrifuge processes operate commercially.

[13] Class 7 Dangerous Goods apply to material containing radionuclides above set levels. Examples of items include smoke detectors, isotopes used in nuclear medicine for cancer treatment, U_3O_8, through to spent fuel.

Enrichment is expressed in terms of kilogram separative work units, which measure the amount of work performed in separating the two isotopes, U-235 and U-238 (referred to as SWU, see Appendix K for more detail).[36] Approximately 100 000–120 000 SWU are required to enrich the annual fuel loading for a typical 1000 MW light water reactor (LWR).[34]

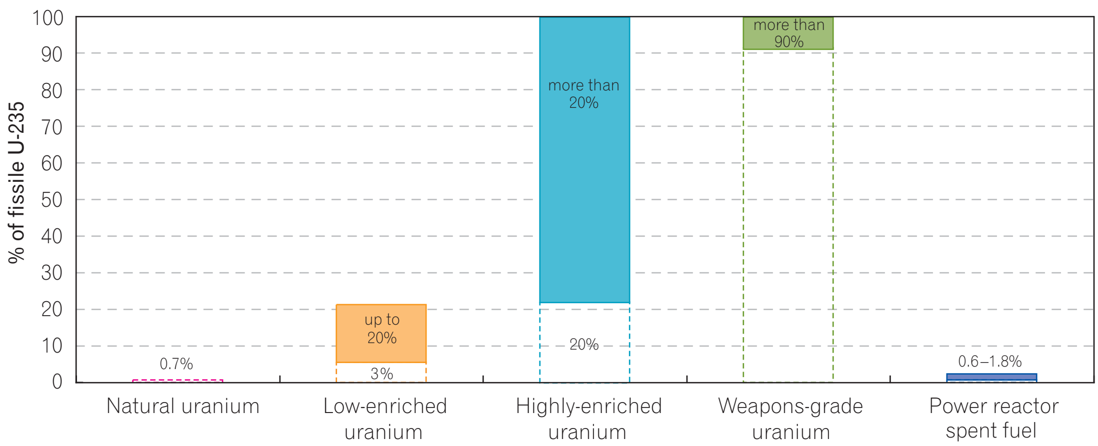
Enrichment adds the largest value to uranium in its transformation into nuclear fuel. Enrichment prices have increased steadily from approximately US$80/SWU in 1999–2000 to approximately US$130/SWU in mid-2006.[38]

Box 3.2 A proliferation-sensitive technology

Enrichment is classed as a proliferation-sensitive technology. Highly-enriched uranium (HEU) is defined as containing 20 per cent or more of U-235 and has research (used in some research reactors) and military uses (such as naval propulsion). Weapons-grade uranium is enriched to more than 90 per cent of U-235 (see Figure 3.4).[39,40]

Special attention is given to enrichment internationally because of the potential for the technology to be adapted to produce weapons-grade materials. The essential ingredients for nuclear weapons can be obtained by enriching uranium to very high levels using the same technology as for low-enriched uranium for electricity generation, with only minor modifications. Thus, vigilance regarding the Treaty on the Non-proliferation of Nuclear Weapons (NPT) is paramount (see Chapter 8).

Figure 3.4 Levels of enrichment

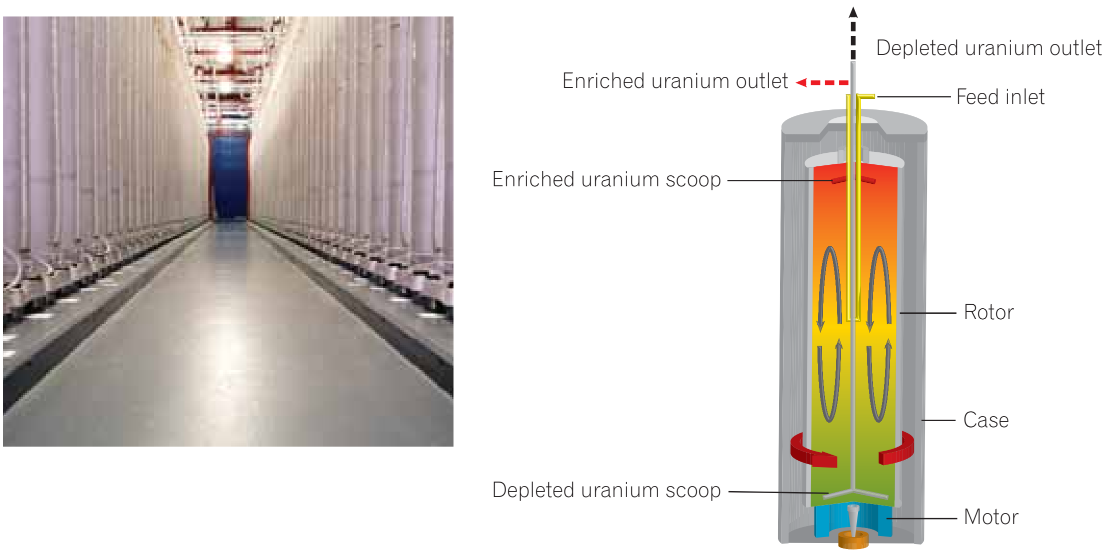


New centrifuge enrichment plants are capital intensive, requiring investment well above A$1 billion. However, the technology is modular in construction, with individual centrifuges arranged in 'cascades' (Figure 3.5). This arrangement enables enrichment services to begin before plant completion, and production capacity to be adjusted incrementally in response to market demand.

Operational enrichment costs are related to plant electrical energy consumption. Gaseous diffusion consumes approximately 2500 kWh/SWU, while centrifuge technology consumes 50 times less at 50 kWh/SWU.[34] For example, at the Areva gaseous diffusion enrichment plant at Tricastin in France, electricity represented approximately 60 per cent of production costs in 2005.[14] Areva provides enrichment services to approximately 100 reactors worldwide and consumes 3–4 per cent of the entire electricity generation in France.[41] Tradetech estimates that electricity consumption is approximately 6–7 per cent of production costs at Urenco's centrifuge plants.[42]

- Areva has been reported as paying Urenco €500 million (A$833 million) for access to Urenco technology through an equity share in the Enrichment Technology Company (jointly owned by Urenco and Areva), plus €2.5 billion (A$4.2 billion) for centrifuges with a capacity of 7.5 million SWU, plus an unknown ongoing royalty amount. This amounts to a total capital investment of approximately €3 billion (A$5 billion).[38,43]
- The National Enrichment Facility (NEF) in New Mexico in the United States is a wholly-owned subsidiary of Urenco. It will have a capacity of three million SWU and is estimated to cost US$1.5 billion (A$2 billion).[44]
- The United States Enrichment Corporation (USEC) American Centrifuge Plant in Ohio in the United States is expected to cost more than US$1.7 billion (A$2.3 billion) and will have a capacity of 3.5 million SWU.[45]

Figure 3.5 Gas centrifuges



Source: Westinghouse presentation to the Review, United Kingdom, 5 September 2006.

[14] Electricity for the Areva gaseous diffusion enrichment plant is provided by nuclear power plants.

In a study on multinational approaches to limiting the spread of sensitive nuclear fuel cycle capabilities, LaMontagne[46] states that, according to USEC officials, high capital costs make small facilities economically unattractive. However data surrounding enrichment economies of scale are closely held within the industry.

There is also potential for a new entrant into the enrichment market with a new technology if General Electric (GE) successfully completes the research and development and commercialisation of the SILEX laser enrichment technology. Although still in development, this technology could reduce capital and energy costs, and has the potential to influence the global enrichment market in the next decade. The SILEX technology is an Australian invention and is the only third-generation laser enrichment process being developed for commercial use. GE owns the exclusive commercialisation rights in return for milestone payments and royalty payments if the technology is successfully deployed.[47]

Box 3.3 The USA–Russia HEU agreement

Since 1987, the United States and former Soviet countries have concluded a series of disarmament treaties to reduce nuclear arsenals. In 1993, the United States and Russian governments signed an agreement known as the Megatons to Megawatts program, designed to reduce HEU from nuclear stockpiles. Under this agreement, Russia is to convert 500 tonnes of HEU from warheads and military stockpiles to low-enriched uranium (LEU) which is bought by the United States for use in civil nuclear reactors.

The United States Enrichment Corporation (USEC) and Russia's Technabexport (Tenex) are executive agents for the United States and Russian governments. USEC is purchasing a minimum of 500 tonnes of weapons-grade HEU (which Russia blends down to LEU) over 20 years from 1999. USEC then sells the LEU to customers.

In September 2005, the program reached its halfway point of 250 tonnes of HEU; at this point it had produced approximately 7500 tonnes of LEU and eliminated approximately 10 000 nuclear warheads.

The United States Government has declared that it has 174 tonnes of surplus military HEU, with about 151 tonnes planned to be blended down eventually for use as LEU fuel in research and commercial reactors, and 23 tonnes for disposal as waste. Approximately 46 tonnes of HEU has been transferred to USEC for down-blending.

The agreement ends in 2013. In the first half of 2006, Russia indicated that it did not wish to enter into a second HEU deal after 2013.

Source: UIC,[48] WNA[49]

3.3.1 The enrichment market and outlook

Similar to the conversion market, the enrichment market is highly concentrated and is structured around a small number of suppliers in the United States, Europe and Russia.

Current suppliers of enrichment services have a capacity of approximately 50 million SWU per year, depending on the estimate of Russian capacity (Table 3.2). A few countries have more limited enrichment capacities or are in the process of developing indigenous enrichment technologies[15] including Argentina, Brazil, India, Iran, Pakistan and North Korea.

The enrichment market is characterised by high barriers to entry, including limited and costly access to technology, trade restrictions, uncertainty due to the impact of secondary supply, security of supply and nuclear non-proliferation issues. It is also undergoing a technology shift as gaseous diffusion technology is replaced by centrifuge technology.

- Restrictions imposed by the United States on the importation of Russian uranium effectively prevents Russia from selling both natural and enriched uranium directly to the United States market. The exception to this is the 5.5 million SWU imported by USEC as part of the HEU agreement (see Box 3.3).
- The diversification of supply policy pursued by the European Union limits the amount of uranium imports per utility from any one source (eg it is limited to approximately 20 per cent for Russian enrichment services).[50]
- The United States–Russian HEU agreement ends in 2013. It is uncertain whether it will be replaced or whether trade restrictions will be lifted to allow Russia direct access to the United States market.

Three major enrichment projects are in early development stages.

- USEC is replacing gaseous diffusion plant technology with indigenous centrifuges, still in development, and is expected to begin in 2010 with an initial capacity of 3.5 million SWU per year.

[15] In the late 1970s, the Uranium Enrichment Group of Australia (UEGA) developed plans for the establishment of enrichment in Australia based on Urenco technology, but the project was terminated.

- Areva is replacing gaseous diffusion plant technology with Urenco centrifuges and will have an initial capacity of 7.5 million SWU by 2013.
- Urenco is building a centrifuge enrichment facility in the United States with a capacity of 3 million SWU by 2013. In addition, Urenco, Tenex and JNFL have plans to expand existing capacity.[20,38]

Table 3.2 Enrichment suppliers and capacity

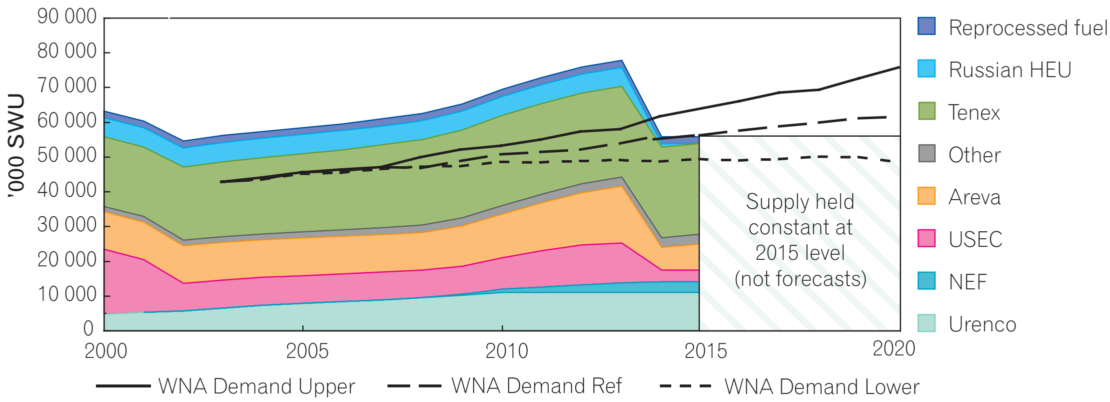
Country	Supplier	Start of operation	Capacity ('000 SWU/year)
Gaseous diffusion			
USA	USEC	1954	11 300
France	Areva	1979	10 800
Centrifuge			
Russia[a]	Tenex	1949–1964	15 000–20 000
Germany	Urenco	1985	1700
Netherlands	Urenco	1973	2500
UK	Urenco	1976	3100
China	CNNC	2002	500
	CNNC	1999	500
Japan	JNFL	1992	600
	JNFL	1997	450
Others (Argentina, Brazil, India & Pakistan)	n/a	n/a	300
Total			46 750–51 750

n/a = not applicable.
a: Russia has enrichment facilities at four sites, each with different start dates ranging between 1949 and 1964.
Sources: WNA,[20] IAEA[36]

As shown in Figure 3.6, supply is forecast to exceed demand until 2014. This forecast includes a build-up of inventory by Areva to facilitate a smooth transition to centrifuge technology,[38] and USEC moving to their own centrifuge technology with a smaller capacity than the current plant. However, enrichment plants do not run at full capacity continuously. Production estimates reduce capacity by between 10 and 25 per cent; the main difference being supply by Tenex and USEC.[38]

Taking into account reduced production estimates, if new investment and expansion plans proceed as expected, the market will be reasonably well balanced in the medium term. However, supply and demand becomes progressively more difficult to ascertain in the longer term. In particular, UxC makes the assumption that the HEU deal is not replaced. While this looks likely, it is not known whether Russia will continue to down-blend HEU, use the down-blending capacity to supply their own internal requirements, or begin to export SWU directly.[323]

Figure 3.6 Forecast world enrichment demand and potential supply



HEU = highly-enriched uranium; NEF = National Enrichment Facility; USEC = United States Enrichment Corporation; WNA = World Nuclear Association

Source: UxC,[38] WNA[20]

3.4 Fuel fabrication

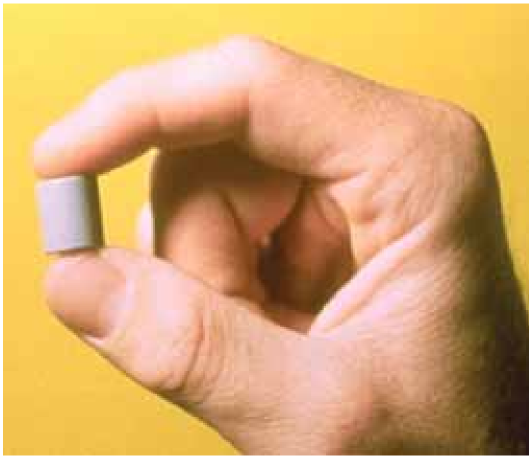
Fuel fabrication is a process by which reactor fuel assemblies are produced. Enriched uranium is manufactured into uranium dioxide (UO_2) fuel pellets (Figure 3.7).

Typically, the pellets are loaded into zirconium alloy or stainless steel tubes to form fuel rods that are then made into fuel assemblies (Figure 3.8) to form the reactor core.

Fuel fabrication comprises approximately 15 per cent of the cost of reactor fuel at a price of approximately US$240 per kg in early 2006 (see Figure 3.2). A 1000 MW reactor operates with approximately 75 tonnes of fuel loaded at any one time, with approximately 25 tonnes replaced each year.[52] However, fuel cycles vary and used fuel may be replaced from every 12 to 24 months.

Five fuel pellets meet the electricity needs of a household for one year. A large Westinghouse pressurised water reactor contains 193 fuel assemblies, nearly 51 000 fuel rods and approximately 18 million fuel pellets.[53]

Figure 3.7 Fuel pellet



Source: Cameco

Figure 3.8 Boiling water reactor fuel assembly[51]

3.4.1 The fuel fabrication market and outlook

The fuel fabrication market differs from the conversion and enrichment markets because each fuel assembly is customised to a specific reactor. There are at least 100 different fuel rod specifications for nuclear reactors around the world. In addition, required enrichment levels can differ within reactor cores, based on the fuel management strategy of each utility.

The fuel fabrication industry has reorganised and consolidated several times over the past few years.[36] As a result, three main suppliers provide 80 per cent of global enriched fuel demand: Areva, BNFL-Westinghouse and Global Nuclear Fuels (GE, Toshiba and Hitachi).[20]

Fuel fabricators are typically associated with reactor vendors, who supply the initial core and in many cases refuel the reactor. Although a highly customised product, LWRs have become increasingly standardised, enabling fabricators to supply fuel assemblies for several LWR designs. Standardisation of reactor design is likely to increase in future.

Fuel fabrication is affected by factors such as fuel assembly design and increased cycle length. Fuel assembly design has improved and the time between refuelling is increasing from 12 months to 24 months. These factors have reduced the number of fuel assemblies required.

The WNA forecasts that global fuel fabrication capacity for all types of LWRs significantly exceeds demand and suggests that industry consolidation and reorganisation will continue.[20]

3.5 Opportunities for Australia

The possibility of Australia becoming involved in one or more of the stages of conversion, enrichment and fuel fabrication presents both significant challenges and some opportunities. The integrated nature of the industry worldwide makes entry difficult. While Australia may have the capability to build an enrichment plant, any such decision would need to be a commercial one. The presumed high returns from enrichment services would need to be balanced against the high barriers to entry and the large technological, economic and political investments required.[16]

Submissions from both BHP Billiton[17] and Rio Tinto[15] state clearly that they are not contemplating entry into the nuclear fuel value-added market and discuss the challenges involved in so doing. BHP Billiton states that the development of a conversion or enrichment capability will need to clear significant regulatory, diplomatic and public perception hurdles, as well as provide a commercial return.

There is no case for the Australian Government to subsidise entry into this value-adding industry. On the other hand, neither is there a strong case to discourage the development of the industry in Australia, and hence, legal and regulatory prohibitions would need to be removed to enable normal commercial decision-making.

3.5.1 Nuclear fuel leasing

Nuclear fuel leasing refers to the supply of fuel to reactors and the subsequent management of reactor spent fuel, essentially a whole-of-life concept.

Proposed scenarios (including those by the Australian Nuclear Fuel Leasing Group)[54] involve the utility leasing the fuel from an internationally-approved source and returning the spent fuel to that source for storage and ultimate disposal after use. In exchange, utilities would be assured of secure fuel supplies and disposal, but ownership of nuclear fuel materials would remain with the leasing company rather than the utility.

[16] Submissions to the Review that noted these challenges included those from Areva, ANSTO, Silex, BHP Billiton and Rio Tinto.

As well as an additional means of value-adding, it has been proposed that nuclear fuel leasing could enhance the international nuclear non-proliferation and safeguards regimes. This proposal is one of several nuclear non-proliferation frameworks discussed in Chapter 8.

The nuclear fuel leasing concept in Australia relies on the appropriate local disposal of high-level waste that would arise from the use of Australian uranium leased by overseas utilities. Regional and international waste repositories are discussed in Chapter 5.

3.5.2 Legal and regulatory regime

Current statutory prohibitions prevent further stages of the nuclear fuel cycle beyond mining being established in Australia. A robust national legal and regulatory framework would need to be established, as discussed in Chapter 9, before any commercial development in the nuclear fuel processing sector.

3.5.3 Employment and skills formation

Entry into the value-added sector will create professional, skilled and unskilled employment, both directly and indirectly. However, it must be noted that companies in the nuclear fuel cycle worldwide are grappling with a shortage of skilled personnel, partly due to the lack of growth in the nuclear industry over the last 20 years (see Chapter 10 for further detail on skills formation).

3.6 Conclusion

Participation in the conversion, enrichment and fuel fabrication industries could significantly increase the value of Australian uranium exports.

The potential for additional export revenues must be balanced against the costs associated with entering and operating in the market. While there are significant challenges associated with entering the value-add industry, the Government would need to remove the legal prohibitions to enable commercial decision-making. The commercial viability and international competitiveness of a new plant in any part of the nuclear fuel cycle will depend on factors such as capital cost, operating costs, the ability to access technology on competitive terms, the state of the international market, access to the required skill base and the regulatory environment. In the case of enrichment, there are also issues associated with the storage of depleted uranium and nuclear non-proliferation. Some or all of these factors may change over the medium term.

Chapter 4. Electricity generation

- Electricity demand in Australia is expected to continue to grow strongly, more than doubling by 2050.
- Nuclear power is an internationally proven technology that is competitive with fossil fuel baseload generation in many parts of the world and contributes 15 per cent of global electricity generation.
- Cost estimates suggest that in Australia nuclear power would on average be 20–50 per cent more expensive to produce than coal-fired power if pollution, including carbon dioxide emissions, is not priced.
- Nuclear power is the least-cost low-emission technology that can provide baseload power, is well established, and can play a role in Australia's future generation mix.
- Nuclear power can become competitive with fossil fuel-based generation in Australia, if based on international best practice and with the introduction of low to moderate pricing of carbon dioxide emissions.
- The cost of nuclear power is strongly influenced by investor perceptions of risk. Risk is highly dependent on regulatory policy and the certainty of licensing and construction timeframes.
- A stable policy environment and a predictable licensing and regulatory regime would be a necessary precursor to the development of nuclear power in Australia.
- Accumulated funds deducted from nuclear power revenues are the best practice method to cover waste disposal and plant decommissioning costs.

4.1 Australian electricity demand

Australian electricity consumption has increased more than threefold over the period 1974–1975 to 2004–2005, to approximately 252 TWh.[17] [55] Consumption in 2004 was just under 1.4 per cent of the world total.[56]

Although energy consumption per unit of gross domestic product (GDP) is declining, economic and population growth are driving up the demand for electricity. With the increasing reliance on electrically powered technologies, consumption is projected to grow at around 2 per cent per year to 2030. The bulk of the electricity will continue to be used in industry and commerce, but domestic consumption is also expected to increase.

Electricity consumption is projected to reach approximately 410 TWh by 2029–2030.[55] Figure 4.1 shows the projection to 2050, with an annual electricity demand of more than 550 TWh. Servicing such demands would require over 100 GW of generating capacity by 2050. Large baseload plant may provide two-thirds or more of this capacity.

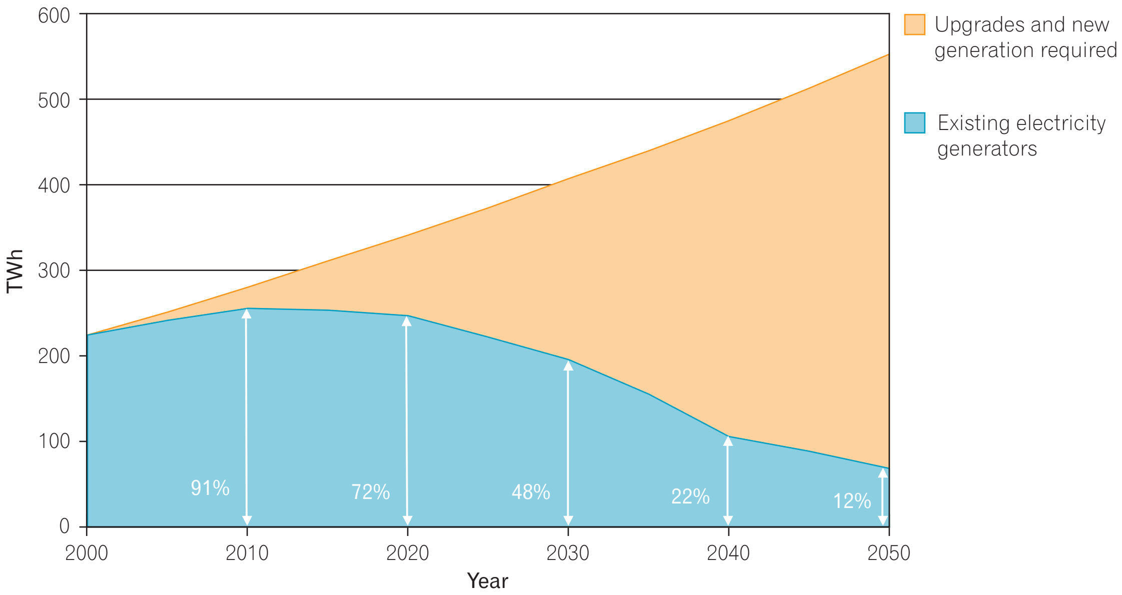
The scenario shown in Figure 4.1 assumes that electricity demand will grow more slowly than total economic output, reflecting relatively faster growth in less energy-intensive sectors and improved energy efficiency.[18] Under-utilised generating capacity exists, but from 2010 growing demand will require significant investment in new capacity.

Peak demand is growing faster than average demand. This is leading to investment in fast-response gas turbine plants where the high fuel cost is not an impediment in meeting system peaks. Under current retail arrangements, electricity prices for most consumers are averaged and regulated, thus providing no incentive to reduce demand when high-cost peak generators are dispatched (supplying). With advanced metering this situation will change.

[17] A TWh is a unit of energy equal to 1000 gigawatt hours (GWh) or 1 million Megawatt hours (MWh). It is equivalent to the energy delivered by a 1000 MW power station operating for 1000 hours.

[18] While improved energy efficiency can delay investment in generation, it also has a rebound effect. The efficiency gain may not result in an equivalent reduction in consumption. Historically, efficiency improvements have been offset by increased electricity use through extended applications and larger appliances.

Figure 4.1 Demand–supply balance for electricity (TWh)



Source: ABARE,[57] Energy Task Force,[58] UMPNER estimates

4.2 Electricity supply in Australia, current and future

4.2.1 The Australian electricity supply industry

Electricity supply contributes approximately 1.5 per cent to GDP. The industry has approximately 48 gigawatts (GW) of installed capacity,[59,60] controls around A$100 billion in assets and employs more than 30 000 people.[1]

Baseload plant capacity comprises approximately 70 per cent of the generating fleet, but supplies 87 per cent of electricity delivered. Baseload plant, with low marginal costs, is generally dispatched for much longer periods than peak and intermediate plant.[1]

Figure 4.2 shows the sources of electricity generation for 2004–2005. Black and brown coals are currently the major fuel sources, contributing approximately 75 per cent of the total. The share contributed by gas has been increasing due to its use in peaking plant, and also the 13 per cent Gas Scheme in Queensland.

Several features define the electricity market. As bulk electricity cannot be stored economically, reliable supply requires generation to match demand. Furthermore, demand varies daily and seasonally (Box 4.1). Thus the system must include some generating capacity able to follow load changes quickly.

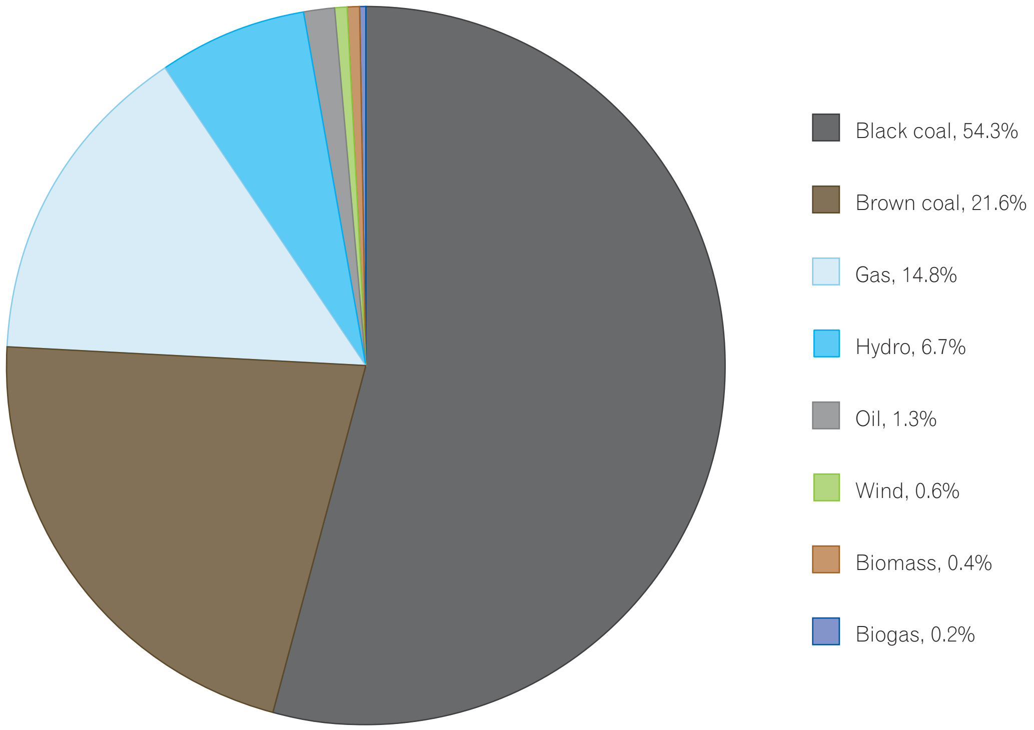
Box 4.1 Variability of electricity demand and supply

As electricity is difficult and costly to store beyond small amounts, once generated it must be delivered and used immediately (although 'pumped storage' hydro-electric plant, where it is available, allows for a modicum of supply/demand flexibility). During demand troughs (notably overnight) significant generating capacity is idle. Figure 4.3 compares electricity demand in the National Electricity Market for a typical summer and winter week.[19]

Depending on location, demand may be highest in summer or winter, corresponding to changing seasonal power requirements, especially heating and airconditioning. Demand also fluctuates throughout the day due to varying industrial and domestic patterns of usage.

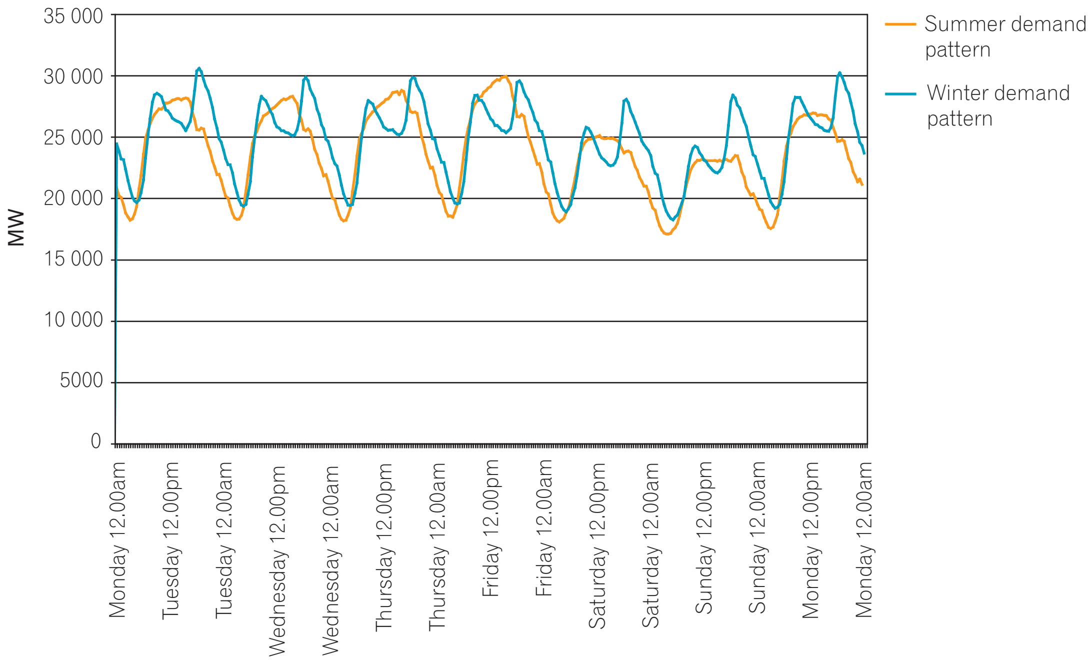
[19] The National Electricity Market (NEM) is a wholesale market where electricity is supplied to electricity retailers in Queensland, New South Wales, the Australian Capital Territory, Victoria, South Australia and Tasmania.

Figure 4.2 Australian electricity generation by fuel, 2004–2005



Source: ABARE[1]

Figure 4.3 Electricity demand over summer and winter days (MW)



Source: National Electricity Market Management Company (NEMMCO)[61]

Intermittent generators (principally wind power and some other renewables) require complementary generation capacity that can be called upon when the intermittent capacity is unavailable.[20] 'Spinning reserve' (provided by conventional power plant) can help to cope with sudden load changes and unplanned loss of generation. Some spare capacity is also required to allow for planned maintenance and outage.

Generating plant with the lowest operating costs (eg coal-fired boiler/steam turbine) is the least responsive to load change, while those that are more responsive (eg open cycle gas turbines) are more expensive to run continuously.[21] Plants with high capital costs generally have low operating costs and vice versa.

Market niches for a wide range of electricity supply technologies are created by differing capital costs, ability to respond to fluctuating demand, location-specific needs, fuel sources, and the need for safety, security and reliability. A comparison of technologies based only on cost per MWh would be misleading, given that a portfolio of generating technologies will form the basis of any national electricity supply system. The most flexible and efficient system is likely to include numerous technologies, each economically meeting the portion of the system load to which it is best suited. In a well-functioning system, a diversity of sources can also provide greater reliability and security of electricity supply. The Australian electricity market provides price signals to help the portfolio evolve towards an efficient solution.[22]

4.2.2 Future prospects for Australian electricity generation

The dynamics for investment in electricity generation capacity are as follows: demand grows; reserve capacity decreases and wholesale electricity price peaks are of longer duration. Peak and intermediate generators are then dispatched for longer periods. Wholesale price increases encourage investment in new baseload (low-cost, large-scale) plant; wholesale prices are driven down; peak and intermediate plants are then dispatched less.

Without a change in emissions policy (see Box 4.2), Australian baseload generation will continue to be dominated by conventional fossil fuel, albeit with progressive technology advances. Figure 4.4 shows fuels and technologies expected to be used in 2029–2030, based on current policies. Black coal will continue to dominate, although natural gas is expected to increase its share by 50 per cent. Renewables will also increase their market share slightly; however, growing off a low base means that even by 2030 they will probably still contribute less than 10 per cent of electricity supply. Wind and biofuel generation are forecast to triple their market share, although the hydro share is expected to decrease. Nuclear power is not shown.

4.2.3 Electricity generating technologies

In Australia, electricity generating technologies include: sub critical pulverised coal, supercritical pulverised coal, open cycle gas turbines (OCGT), combined cycle gas turbines (CCGT), and hydro. Major new technologies still at the demonstration or research and development stage include: integrated gasification combined cycle (black coal), integrated de-watered gasification combined cycle (brown coal), ultra supercritical coal, and fossil fuel generation as above combining geosequestration or carbon capture and storage (CCS). Other promising technologies include geothermal (hot dry rocks) and renewables such as small-scale hydro-electric, wind, biofuel, solar photovoltaic, solar thermal, tidal and wave power.

Coal fired generation is nearly always used in baseload applications due to large thermal inertia. Gas may be used for base, intermediate or peak generation, although the technologies are application specific. With its high cycle efficiency a CCGT plant is best suited for base and intermediate load applications. An OCGT plant provides near instantaneous power but suffers high fuel costs, making it economically suitable only for peak load applications.

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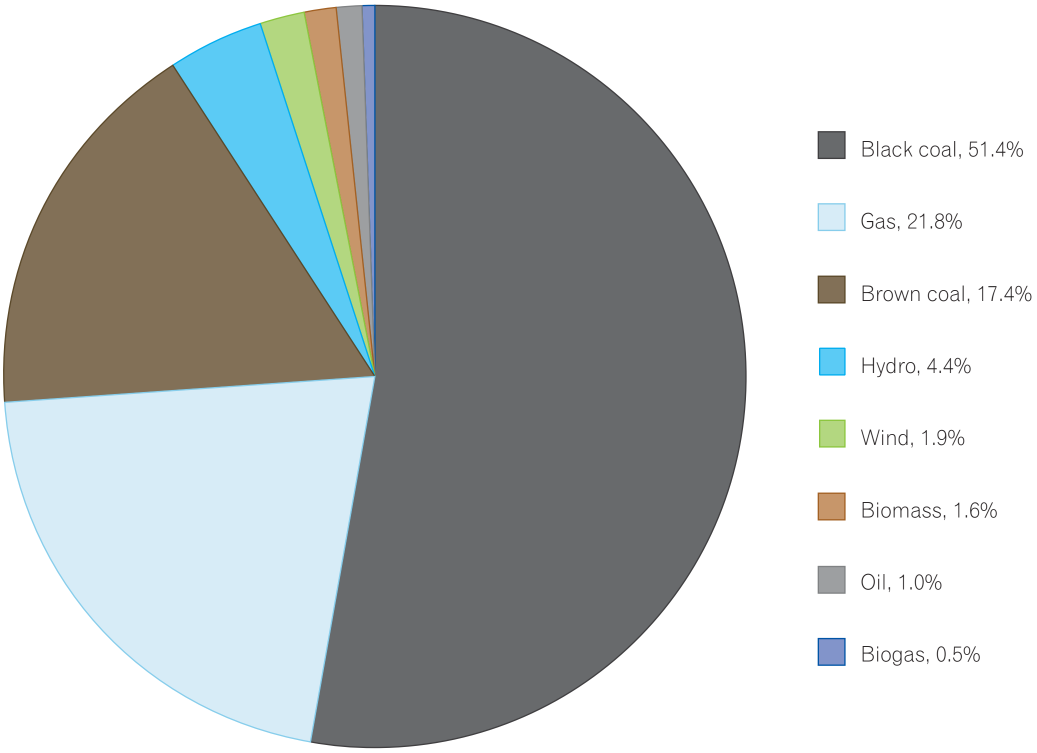
[20] While the inclusion of intermittent sources can increase the need for complementary gas peaking or open cycle gas turbine (OCGT) plants and the requirement for spinning reserve capacity, industry estimates suggest wind could meet up to 20 per cent of demand without undue disruption to the network. As wind power is dispatched first in the merit order and also drives greater uptake of OCGT peaking plants, the net effect of incorporating greater levels of wind power into the system is to displace unresponsive baseload plant, including coal and nuclear power. However, the displacement of baseload plant could raise the average cost of electricity supply.

[21] Hydro-electricity tends to be an exception to this rule, being almost instantly variable but with costs determined almost entirely by capital, rather than operating costs, which are minimal.

[22] See for example, CRA International.[62]

Figure 4.4 Projected Australian electricity generation in 2029–2030 under current policy settings



Source: ABARE[1]

Fossil fuel plants could be combined with CCS. However, CCS remains to be proven except in highly specific applications (notably oil recovery from ageing wells). Uncertainties remain about the cost of CCS, and its reliability and security over the long term. CCS may be less effective in reducing emissions when retrofitted to existing plants.[63,64]

While offering the prospect of lower greenhouse emissions from coal and gas firing, CCS technologies suffer two disadvantages compared to nuclear power. First, CCS uses significant extra energy and additional complex plant. This increases the cost of electricity dispatched.

Second, policies that price greenhouse and other emissions would further reduce the competitiveness of CCS compared to nuclear power because CCS technologies, even on optimistic scenarios, are expected to remain more emissions intensive.[23] (Pricing greenhouse emissions does, however, increase the competitiveness of CCS technology relative to conventional fossil fuel based power.)

Most renewable technologies deliver very low emissions in operation. Over the longer term, some emerging technologies could displace a proportion of fossil fuel based generation. However, even though renewable technologies are competitive in some situations (eg a well-sited wind farm or off-grid applications of solar power) these low emission and less mature technologies are typically not competitive with conventional fossil fuel and are likely to remain so even over the medium to longer term. In the absence of technical breakthroughs or the pricing of greenhouse and other emissions, substantial uptake of renewables will continue to require subsidies.[65–67]

Nuclear power could become less expensive than fossil fuel electricity, should fossil fuel prices rise or nuclear capital costs fall sufficiently through standardised and modular designs.

[23] For further discussion on CCS technologies see Ecofys/TNO.[64]

4.3 The role of nuclear power

4.3.1 Nuclear power in other countries

Nuclear power now supplies 15 per cent of the world's electricity from 443 reactors, which provide 368 GW of generating capacity (ie over seven times Australia's total from all sources).[68] The United States is the biggest user with 104 reactors, followed by France with 59, Japan with 56 and the United Kingdom with 23. 31 countries were producing electricity from nuclear reactors in 2005, according to the IEA. Table 4.1 shows key nuclear statistics.

Approximately 80 per cent of the commercial reactors operating are cooled and moderated with ordinary water and are known as light water reactors (LWRs). The two major LWR types are pressurised water reactors (PWRs) and boiling water reactors (BWRs). Most of the remaining 20 per cent of reactors are cooled by heavy water or gas.[37] Within each type, different designs result from differing manufacturer and customer specifications and regulatory requirements.

Many reactors built in the 1970s and 1980s are expected to continue to operate beyond 2015. Studies reveal no major technical obstacles to long operational lives and operators are finding refurbishment profitable. As of 2006, 44 power reactors in the United States have been granted 20-year licence extensions by the Nuclear Regulatory Commission. Eleven power reactors are being considered for licence extension and others are likely to follow.[69]

According to the World Nuclear Association (WNA) in 2006, 28 power reactors were being constructed in 11 countries, notably China, South Korea, Japan and Russia.[23] No new power reactor has been completed in the past decade in either Europe or North America, but one is being constructed in Finland (for completion in 2010) and construction will soon commence on another in France (for completion in 2012). In the United Kingdom, the government has stated that nuclear power is back on its agenda, but within a policy framework that does not mandate particular technologies. As outlined in Chapter 9, the United Kingdom has begun to reform its nuclear licensing system to facilitate private investment in nuclear power.

Figure 4.5 shows the historical growth of nuclear power from 1965 to 2005 and scenarios of future growth to 2030. Growth has been extended based on the two (hypothetical) scenarios described in the *IEA World Energy Outlook 2006*.[3]

IEA World Energy Outlook 2006 scenarios suggest that in 2030 installed nuclear power capacity worldwide could be between 416 GW and 519 GW.[24]

4.3.2 Characteristics of nuclear power

As a technology, nuclear power is typically characterised by high capital costs, significant regulatory costs, low operational costs, high capacity factors, long operational life and relative insensitivity to fuel price variations. Scale economies dominate and current Generation III technologies do not appear to be economic for power plants of capacities much below 1000 MW.[25] South Korean and French experience suggests that the cost of building nuclear reactors decreases as subsequent plants of standardised design are built.[37,70,71]

Nuclear power also involves decommissioning, and radioactive waste management and disposal. However, these costs are a relatively small component of the total life cycle costs (partly because most are incurred long after reactor construction). Amounts are typically deducted from electricity revenues throughout the operating life of a plant to accumulate sufficient funding for post-shutdown activities. This issue is discussed in greater detail below.

The key advantages of nuclear power include very low greenhouse and other gas emissions and an ability to provide electricity generation on a large scale, at high capacity factors over many years. Nuclear fuel is easy to stockpile, low fuel costs lead to relative insensitivity to fuel price variations and there is a need to refuel only periodically (eg one-third of the reactor core might be replaced every 12–18 months). The ease of fuel management is important to countries concerned with energy security.[26]

[24] The reference scenario assumes that current government policies remain broadly unchanged. The alternative policy scenario assumes the adoption of policies to promote nuclear power.

[25] Small-scale designs (around 200 MW) such as the South African Pebble Bed Modular Reactor or the General Atomics Gas Turbine-Modular Helium Reactor are being developed, but these may not be commercialised for some years.

[26] Australia's coal reserves provide a very high degree of energy security for electricity generation.[56]

Table 4.1 Key nuclear statistics, 2005

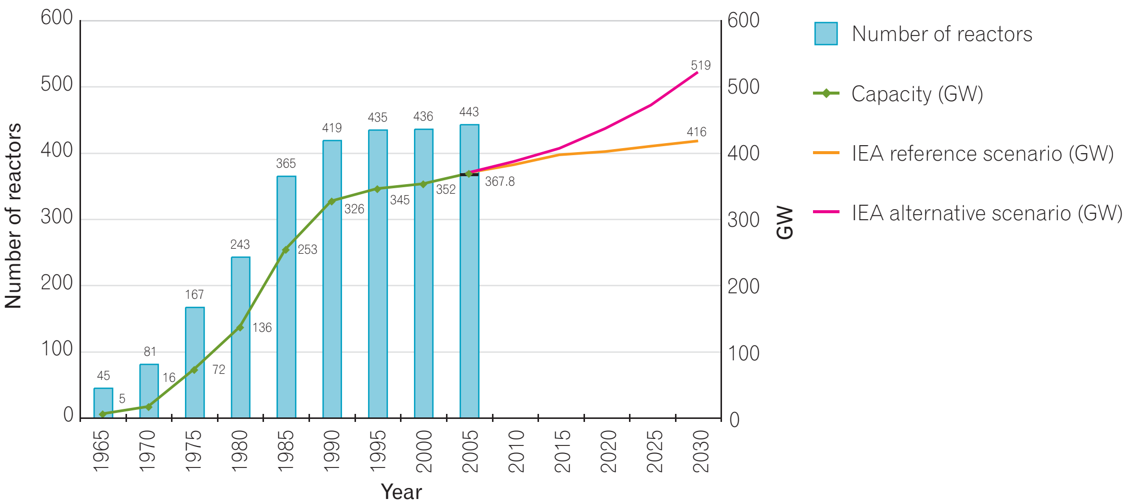
Country	No. reactors	Installed capacity (GW)	Gross nuclear electricity generation (TWh)	Share of nuclear power in total generation (%)	No. nuclear operators
OECD	**351**	**308.4**	**2333**	**22.4**	**68**
Belgium	7	5.8	48	55.2	1
Canada	18	12.6	92	14.6	4
Czech Republic	6	3.5	25	29.9	1
Finland	4	2.7	23	33.0	2
France	59	63.1	452	78.5	1
Germany	17	20.3	163	26.3	4
Hungary	4	1.8	14	38.7	1
Japan	56	47.8	293	27.7	10
South Korea	20	16.8	147	37.4	1
Mexico	2	1.3	11	4.6	1
Netherlands	1	0.5	4	4.0	1
Slovak Republic	6	2.4	18	57.5	2
Spain	9	7.6	58	19.5	5
Sweden	10	8.9	72	45.4	3
Switzerland	5	3.2	23	39.1	4
United Kingdom	23	11.9	82	20.4	2
United States	104	98.3	809	18.9	26
Transition Economies	**54**	**40.5**	**274**	**17.0**	**7**
Armenia	1	0.4	3	42.7	1
Bulgaria	4	2.7	17	39.2	1
Lithuania	1	1.2	10	68.2	1
Romania	1	0.7	5	8.6	1
Russia	31	21.7	149	15.7	1
Slovenia	1	0.7	6	39.6	1
Ukraine	15	13.1	84	45.1	1
Developing Countries	**38**	**19**	**135**	**2.1**	**11**
Argentina	2	0.9	6	6.3	1
Brazil	2	1.9	10	2.2	1
China	9	6.0	50	2.0	5
India	15	3.0	16	2.2	1
Pakistan	2	0.4	2	2.8	1
South Africa	2	1.8	12	5.0	1
World[27]	**443**	**367.8**	**2742**	**14.9**	**86**

GW = gigawatts; TWh = terrawatt hours; OECD = Organisation for Economic Co-operation and Development

Source: IEA[3]

[27] World totals include six reactors in Taiwan with an installed capacity of 4.9 GW, gross nuclear electricity generation of 38 TWh, a 16.9 per cent share of nuclear power in total generation and one nuclear operator.

Figure 4.5 World growth of nuclear power, 1965–2030



Source: NEA[37], IEA[3]

Current disadvantages of nuclear power include investment (financing) risks, long construction times compared with most other electricity generating technologies, persistently negative perceptions, especially regarding the safety of nuclear waste disposal and a possibility of accidents releasing harmful radiation. The nuclear power industry has been working to reduce these disadvantages. (Nuclear reactor technology is discussed in Appendix L) There is also a need to provide specialist regulatory agencies and detailed safety regimes.

Modelling by ABARE and others suggests that the inclusion of nuclear power in the mix of technologies for Australia would reduce the costs of achieving large cuts in greenhouse emissions.[65,67] (Climate change and the role of nuclear power in greenhouse gas abatement are discussed in Chapter 7.)

4.4 Economics of nuclear power

4.4.1 Comparative costs of electricity generation technologies

Electricity generation costs need to be evaluated consistently across all generation technologies, although it is difficult to make precise comparisons among widely-differing alternatives. The magnitude and timing of construction, fuel use, operating and maintenance costs, as well as environmental regulations vary across technologies. Many site-specific factors also affect electricity generation costs. Ultimately, the choice of technology is made by investors looking at a specific opportunity under specific investment criteria. For this Review it is appropriate to compare technologies by considering their costs only within wide ranges.

International evidence confirms that in many countries nuclear power is competitive.[37,72,73] The evidence shows that nuclear power costs have fallen since the 1980s due to increased capacity factors, extended lifetimes and improved reactor designs.[37] Given higher fossil fuel prices in recent years, nuclear power has become attractive in countries lacking access to easily exploitable coal and gas.

While the nuclear power industry has been in a hiatus in the United States and Europe following the accidents at Three Mile Island in the United States and Chernobyl in the former Soviet Union, construction has continued in Asia. Efforts in the United States and Europe have focused on finding ways to reduce costs while improving safety. These efforts have also produced new, standardised, simplified designs, and the development of modular construction techniques to reduce construction times. However, the extent to which a new generation of reactors will reduce the cost of nuclear power remains to be confirmed through experience.[74]

Historical cost overruns and construction delays for nuclear power plants may be attributed, among other things, to:

- 'design as you go' approaches
- delays in approval processes
- 'preference engineering' (ie a regulator's preference for a new system to be similar to a familiar one, rather than assessing a new system against relevant safety criteria)
- a tendency to modify designs with each new plant, reducing the scope for economic prefabrication (modularisation) and perpetuating on-site, 'first of a kind' (FOAK) construction
- a 'cost plus' culture in regulated markets
- changing political, legislative and regulatory requirements.[75]

By contrast, emerging best practice in nuclear power plant construction involves adopting a design approved by international experts and building identical units as a series.

The Taskforce commissioned the Electric Power Research Institute (EPRI) to examine several recent studies that compare the costs of generating electricity using different technologies, including nuclear energy.[74] The studies all used levelised cost of electricity (LCOE) estimates to calculate a constant cost for each generation option. The levelised cost is the constant real wholesale price of electricity that recoups owners' and investors' capital, operating, and fuel costs including income taxes and associated cash-flow constraints. The LCOE approach is widely used and easy to understand, but often produces widely varying results mainly because of differences in the assumptions and inputs used in calculations.

EPRI found that the studies show broad cost ranges for all generating technologies. The studies with very low LCOE estimates for nuclear power use very low discount rates. This may be justified in some cases (eg Tarjanne)[73] because the owners of the plant are also customers and are prepared to finance the plant at low interest rates.[73,74]

In other cases, assuming a lower than commercial discount rate may be justifiable from the utility's perspective if the utility is partly financed by a government, as in the low end scenario of Gittus,[71] or if it is government-owned and operating in a regulated environment, where it can borrow near the government bond rate and pass all costs on to customers through regulated prices. Such an environment does not reduce financial risk, but instead transfers costs from the utility to taxpayers or customers.[28]

Organisation for Economic Co-operation and Development (OECD) (2005) low-end LCOE estimates use a 5 per cent discount rate, which would equate to a government bond rate. At a 10 per cent discount rate, the OECD estimate for nuclear power begins at approximately A$40/MWh.[76]

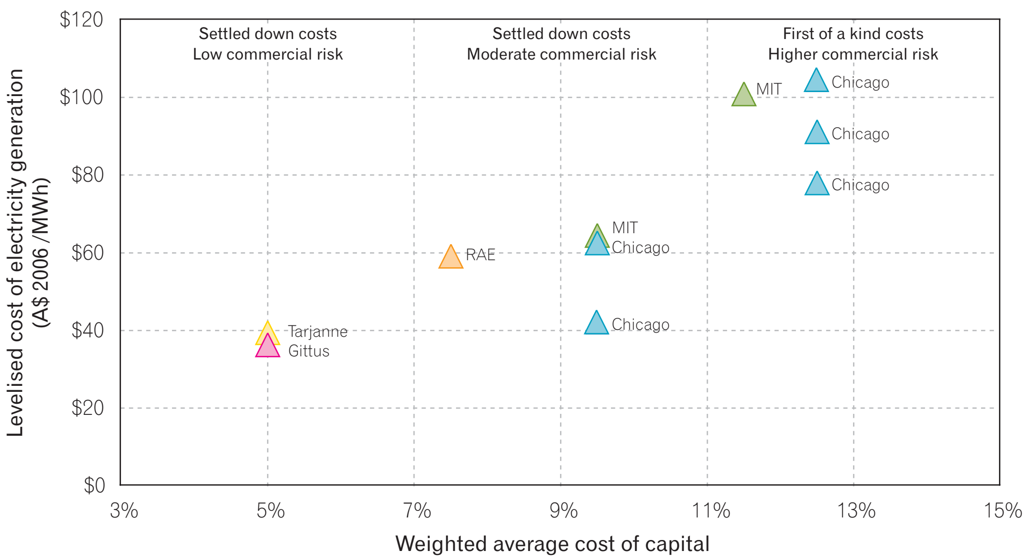
[28] The national electricity market (NEM) is a liberalised wholesale market open to competitive bidding. Prices are not guaranteed to generators. In such a market, the risk surrounding the economics of nuclear power would be borne by investors, not consumers.

The studies more oriented toward a commercial environment for new nuclear builds, according to EPRI, are Massachusetts Institute of Technology (MIT)[77] and University of Chicago[70], where LCOE estimates for nuclear power range from A$75–105/MWh. These numbers are high partly due to assumptions that new plants will suffer from FOAK costs (common in complex engineering projects) and initial learning curves. Both the University of Chicago and MIT illustrate sensitivities where the 'settled down' LCOE could be in the range of A$40–65/MWh, although EPRI notes that such settled down costs are yet to be proven in practice.

There is no reason why Australia could not avoid some FOAK costs if Australia becomes a late adopter of new generation reactors, according to EPRI, but nuclear power plants are initially likely to be 10–15 per cent more expensive than in the United States because Australia has neither nuclear power construction experience, nor regulatory infrastructure. This would put nuclear power in the A$44–70/MWh range for the first Australian plant, assuming it was not FOAK, and that investor perception of commercial risk was akin to the risk perceived for other baseload technologies. In practice, investors may consider nuclear power to be more commercially risky.

Figure 4.6 illustrates the estimates from various studies and shows how costs vary according to perceptions of risk (and therefore the cost of capital) and whether the plant is a FOAK or a settled down build. This shows that for settled down costs and moderate commercial risk akin to other baseload investment, nuclear power could fall within the cost range of A$40–65/MWh.

Figure 4.6 Indicative ranges of nuclear power cost



Source: EPRI study[74], Mayson[78] and Howarth[79]

This cost range would still be uneconomic compared to Australia's cheap coal generation, but overlaps with the higher end of CCGT electricity and would likely be lower on average than CCS cost estimates and renewables. Levelised cost ranges likely to be applicable for Australia for different generation technologies are shown in Figure 4.7.

Nuclear power could become economic even with conventional coal-based electricity at low to moderate prices for carbon emissions — at approximately A$15–40/t CO_2-e.[29]

If investors perceive high financial risk or if FOAK plants were planned, higher carbon prices or other policies would be required before investment in nuclear power would occur. Naturally, projects need to be evaluated on their specific merits and this Review cannot substitute for such an evaluation.

Beyond the costs of production, other features of nuclear power may make it relatively unattractive for Australian investors. The learning by doing that is a feature of complex technologies means nuclear power is most economic if a fleet of several plants is built. Yet a single 1000–1600 MW plant would be a sizeable investment for existing private generating companies in the Australian market (although it would not be a large investment in the context of Australian financial markets). Such investors usually have less than 4000 MW of total generating capacity spread over several units.[30] Private generators in liberalised markets have typically shown a preference for faster lead times and more flexible technologies.

4.4.2 Other considerations for nuclear plants in the Australian market

Other issues raised during the Taskforce's consultations and in submissions include:

- The risk of competing against state-owned generating assets within the national electricity market (NEM) may deter private investment in large power plants (including nuclear).
- A move to larger baseload plants will increase the reserve capacity requirement needed to allow for larger plants being taken off line. (Currently, the largest units in the NEM are approx. 750 MW, although it is not unknown for several of these to go off line at once due to maintenance, plant failure or transmission outage.)
- Australia's transmission network is considered to be 'long and thin', with generators located far from load and links between different regions capacity constrained. Network congestion can occur with large power transfers between regions. This may happen if, for example, excess capacity in New South Wales is needed in Queensland. The network is being progressively upgraded, but the economic case becomes stronger as larger generation plants are built.[31]
- Baseload technologies, including nuclear, typically use large volumes of water for cooling (eg from rivers, estuaries or the ocean), although dry cooling can be used at marginally higher cost if adequate water is not available (as at the large Kogan Creek coal-fired plant).[81] Restrictions on the quantities of water that generators may draw already limit baseload supply in some states during the hotter months.[82] Water use is discussed in Chapter 7.
- There is greater flexibility in siting nuclear plants insofar as they are independent of fuel and waste disposal locations. Plants could be sited near current coal fired plants to use existing transmission networks, or close to demand to minimise transmission costs.

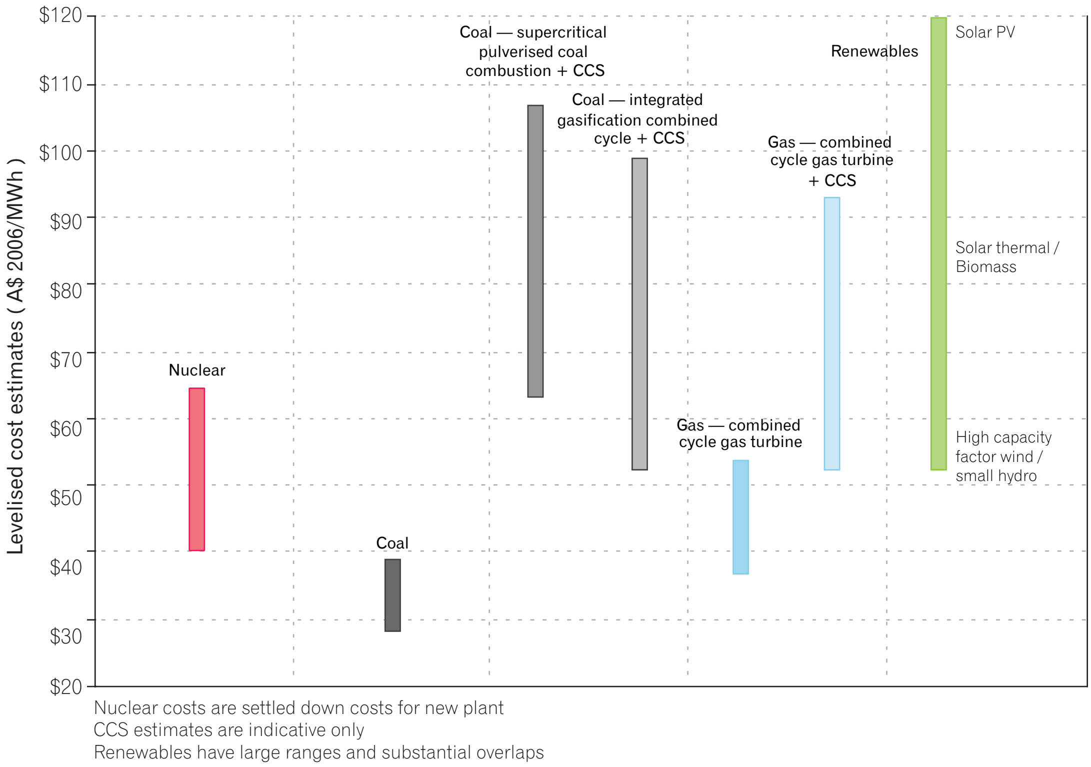
Some of these comments suggest possible impediments to nuclear power in Australian electricity networks, but none would be insurmountable, given the period over which nuclear power may be introduced.

[29] While there is considerable debate about what an appropriate price of carbon should be, a range of A$15–40 CO_2-e is at the low to moderate end of the range commonly used in economic modelling of policy options.

[30] Some of these considerations are likely to apply large scale CCS applications as well.

[31] For further discussion on issues of network congestions see the ACIL Tasman report.[80]

Figure 4.7 Levelised cost ranges for various technologies



MWh = megawatt hours; PV = photovoltaic

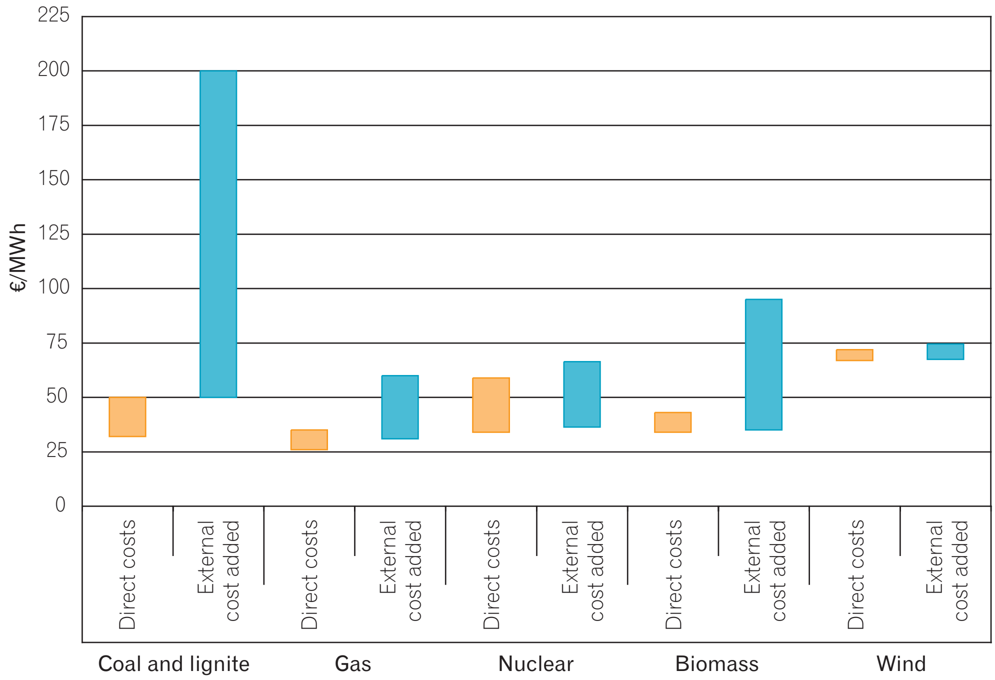
Source: EPRI study[74]

4.4.3 External costs of electricity generation technologies

Externalities are costs or benefits that affect a third party, rather than the immediate participants in a market transaction. All forms of electricity generation involve externalities of one type or another. From a societal point of view, externalities need to be accounted for (internalised) through policy instruments as far as possible so that decisions are made taking into account all the societal costs and benefits. Where externalities are substantial, policies that internalise them can change market decisions.

The external costs of electricity generation in Europe are reproduced from the European Union ExternE report in summary form in Figure 4.8.[83] Other studies on the external costs of nuclear power are reported in Table 4.2. While the cost estimates should not be directly translated to Australia, some general conclusions can be drawn. For fossil fuel powered generation, external costs are around the same order of magnitude as direct costs, principally due to greenhouse emissions. For nuclear power, wind power and solar photovoltaic (not shown), external costs are approximately one order of magnitude lower than the direct costs. Nuclear, solar photovoltaic and wind power produce no direct greenhouse emissions. When measured on a life cycle basis, which takes into account upstream and downstream processes, their emissions are still very low.

Figure 4.8 External and direct costs of electricity generation in the European Union (€/MWh)[32]



Source: ExternE[83]

Table 4.2 External costs of the nuclear fuel cycle

Study	External Cost (A$/MWh)
ORNL[83]	0.33–0.50
Pearce et al[84]	1.33–2.99
Friedrich and Voss[85]	0.17–1.16
PACE[86]	48.3

The relatively low estimates from the ORNL, Pearce et al and Friedrich and Voss studies when compared with the ExternE study can be attributed mainly to narrower definitions of the boundaries of the system.

The very high PACE study estimate of external costs is attributable to a number of factors, including treating decommissioning costs as an external cost (whereas such costs are today usually included in direct generation costs).[4] In addition, the PACE estimate for the cost of nuclear accidents was based on a major core release to the environment, on the scale of Chernobyl, occurring once every 3300 reactor years. This is far higher than the probability that experts consider appropriate for new nuclear plants in the OECD.[87] Worldwide, there are now over 10 000 reactor-years of operating experience and modern nuclear power plants have multiple safety features and employ entirely different designs to that used at Chernobyl.[37,87]

Within OECD countries, the nuclear power industry operates under regulations that set stringent limits for atmospheric emissions and liquid effluents, as well as regulations requiring the containment of solid radioactive waste to ensure its isolation from the biosphere. Thus, nuclear power plants and fuel cycle facilities already internalise the major portion of their potential external costs.

The findings of studies on the externalities of electricity generation support the conclusion that pricing greenhouse emissions would alter the relative competitiveness of generating technologies, with nuclear and most renewables gaining strongly.

[32] €1 = A$1.66, approximately

Box 4.2 Pricing greenhouse emissions

Driving greenhouse emission reductions across the economy is a complex problem. There are many possible ways to encourage abatement, including technical regulation, environmental subsidies, sectoral emissions caps, emissions capping with trading, a carbon tax, or a hybrid of permit trading and emissions charges. Market-based measures such as the latter three are designed to make greenhouse emissions an explicit cost of production.[88]

Once emissions are priced, they become an additional cost of production either directly or through higher prices for emissions intensive goods and services used in production. Emission prices could become a significant cost in generating electricity if carbon emissions are high.

Once emissions become a cost, generators and fossil fuel-intensive industries will have an incentive to reduce emissions or substitute into low-emission technologies wherever possible. A carbon price therefore makes low-emission technologies such as nuclear power and renewables more competitive with energy generated by fossil fuels. It also makes technologies that remove emissions more economically viable. In contrast to subsidising particular technologies, a carbon price will also encourage the development and deployment of clean technologies across the economy, allow the market to find the lowest cost way of doing so, as well as changing the behaviour of individuals and firms throughout the economy to demand less emissions intensive energy, goods and services.

The environmental performance of generating technologies is discussed further in Chapter 7.

4.4.4 Financing waste disposal and plant decommissioning

OECD countries using nuclear power typically establish special accounts or trust funds designed to accumulate sufficient amounts to cover waste disposal and decommissioning costs. Financing systems sometimes involve the collection of fees related to the amount of nuclear electricity generated. In some countries, owners of nuclear facilities need to provide other financial guarantees and give first priority to nuclear waste and decommissioning liabilities. This helps to ensure that producers of nuclear power take into account virtually all life cycle costs.[87]

For example, in Finland nuclear waste management fees are collected from nuclear power producers. These fees cover the costs of spent fuel disposal, operating waste and the management of decommissioning waste. The funds are accumulated in the State Nuclear Waste Management Fund and ultimately reimbursed to meet the costs of waste management as they arise.

Decommissioning programs may have recourse to other funds. The decommissioning of 'legacy' nuclear reactors (eg those used in early R&D and defence activities) is generally funded by governments.

Nuclear decommissioning is costly, but how much so depends on the extent and timing of site restoration, and to a large extent the vintage of the reactors. The United Kingdom Sustainable Development Commission considers that modern reactors will have substantially lower decommissioning costs.[89] Early generation reactors tend to have very large cores and dismantling creates a much larger volume of high and intermediate level radioactive wastes than a modern reactor would create. Modern reactors are also designed from the outset to facilitate decommissioning.

OECD member country estimates suggest that undiscounted decommissioning costs range between 15 and 20 per cent of initial construction. When discounted and amortised over the useful plant life, the cost is typically below 3 per cent.[87]

4.5 Conclusion

This chapter has examined the potential competitiveness of nuclear power in Australia. The technology is well established internationally. Under appropriate policy settings, the inclusion of nuclear power in the portfolio of generating technologies could reduce the economic costs of achieving large scale greenhouse emission cuts. However, a range of technical and policy steps, as well as public confidence and acceptance, would be needed before nuclear power could be introduced.

Chapter 5. Radioactive waste and spent fuel management

- Safe disposal of low-level and short-lived intermediate-level waste has been demonstrated at many sites throughout the world.
- There is a high standard of uranium mining waste management at Australia's current mines. Greater certainty in the long-term planning at Olympic Dam is desirable, coupled with guaranteed financial arrangements to cover site rehabilitation.
- Safe disposal of long-lived intermediate and high-level waste can be accomplished with existing technology. The first European repository is expected to commence operating around 2020.
- Reprocessing of spent fuel in Australia seems unlikely to be commercially attractive, unless the value of recovered nuclear fuel increases significantly.
- Australia has a number of geologically suitable areas for deep disposal of radioactive waste.

5.1 Radioactive waste and spent fuel

Radioactive wastes arise from a wide range of uses of radioactive materials. Those originating from nuclear power production are more significant in terms of volume and concentrations of activity, while medical, research and industrial uses of radioactive materials give rise to relatively small amounts of waste with comparatively moderate levels of activity. A number of countries have a significant legacy of radioactive waste arising from weapons development activities.

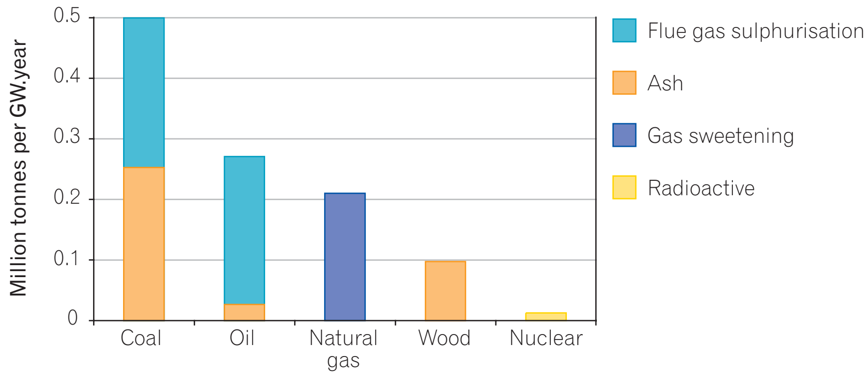
The volume of radioactive waste is small compared with the volume of other industrial waste. Organisation for Economic Co-operation and Development (OECD) countries produce some 300 million tonnes of toxic wastes each year compared with 81 000 m^3 of conditioned radioactive wastes. In countries with nuclear power, radioactive wastes comprise less than 1 per cent of total industrial toxic wastes (Figure 5.1).[90]

Radioactive waste is characterised by its physical, chemical, radiological and biological properties. It is classified to facilitate its safe management, for example, according to the degree of containment and isolation required to ensure that it does not adversely impact on people or the environment. It can be classified in terms of the following.

- Low-level waste (LLW) — the level of radioactivity is sufficiently low that it does not require special shielding during normal handling and transport (it is customary to exclude waste that contains more than very minor concentrations of long-lived radionuclides). LLW comprises materials that may be lightly contaminated, such as paper, glassware, tools and clothing.
- Intermediate-level waste (ILW) — long and short-lived waste, including reactor components, chemical residues, sealed radioactive sources from medicine and industry and used metal fuel cladding. ILW requires special handling and shielding of radioactivity, but not cooling.
- High-level waste (HLW) — contains large amounts of radioactivity and requires cooling and special shielding, handling and storage. HLW includes spent nuclear fuel intended for disposal and the solidified residues from reprocessing spent nuclear fuel.

Radioactive waste management includes all activities, administrative and operational, in handling, treatment, conditioning, transport, storage and disposal. The final step of disposal involves safely isolating waste from people and the environment in purpose-built facilities while it decays to harmless levels.

Figure 5.1 Waste produced in fuel preparation and plant operations (GW.year) for fossil fuels, wood and nuclear[91]



5.1.1 Uranium mining waste

By far the greatest component of nuclear fuel cycle waste is LLW from mining and milling of uranium ores. The most significant wastes are tailings (finely crushed, solid residues from ore processing), liquid waste from the processing plant, and radon gas.

The major task in managing radioactive waste from uranium mining and milling is safe disposal of tailings, since they contain most of the radioactivity originally in the ore. Tailings are significant because of their volume, rather than their specific radioactivity, which is generally low. During the operational phase of uranium mines, tailings are managed to minimise the potential hazard from release of radioactive radon gas into the atmosphere. This often involves deposition under water in tailings dams.

While significant within the nuclear fuel cycle, the volume of tailings is minor in comparison to waste from many other mining and industrial operations that produce materials with the potential to harm health and the environment. These include waste from heavy metal or coal mining, fly ash from coal combustion and toxic industrial waste.

The nature of rehabilitation of uranium mines varies with site and regulatory requirements. Under best practice management, tailings impoundments are covered with earth or rock to prevent dispersal and to reduce release of radon gas. Tailings management is site-specific and involves assessment of ground and surface water movement. Choice of disposal site is aimed at maximum tailings isolation. Some approaches involve returning tailings to the mined out pits (as, for example, at Ranger) or disposal in the stopes of underground mines (as was planned for Jabiluka).

5.1.2 Low and intermediate level radioactive waste

Although it contains only a small fraction of the total activity of all radioactive waste, short-lived low and intermediate level radioactive waste (LILW) is an important category because it represents more than 90 per cent of the global volume (excluding mining and milling waste). The amount of LILW in countries with nuclear power will increase significantly with the growing number of reactors due to be decommissioned.

LILW, with limited amounts of long-lived radionuclides, is disposed of in near-surface repositories. Disposal units are constructed above or below the ground surface up to several tens of metres in depth, depending on site characteristics. Extensive experience in near-surface disposal has been gained from construction and operation of facilities at over

100 sites in more than 30 countries in a range of geographic conditions (Figure 5.2). Repository designs reflect site and waste characteristics and regulatory requirements.

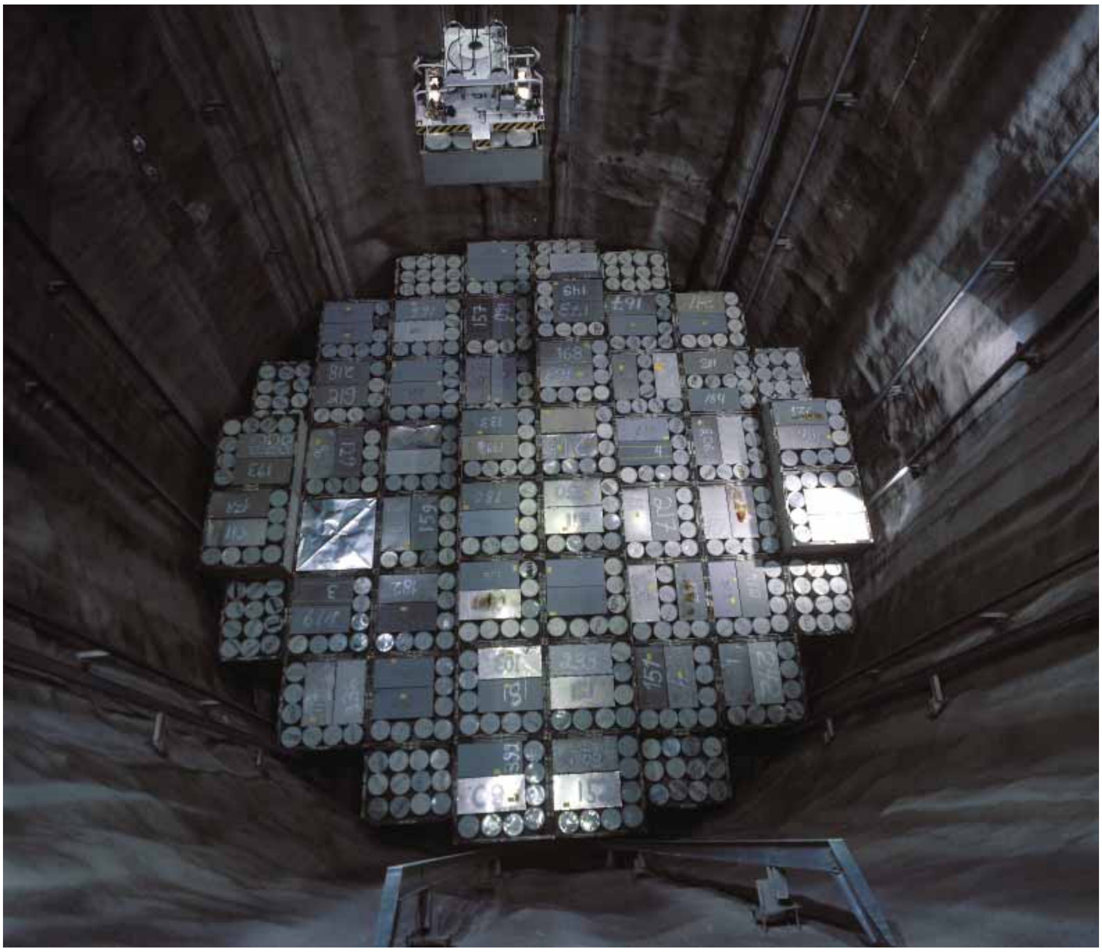
Operating experience has shown that releases of radioactivity from properly sited and constructed LILW repositories are so small that the impact on people and the environment is insignificant. The design goal for these repositories is to isolate and retain radioactive materials so that estimated radiological doses are well below limits set by regulatory authorities; limits which themselves are below normal background radiation.

5.1.3 Spent nuclear fuel

Spent fuel management is an issue common to all countries with nuclear reactors. It has been addressed by the construction of spent fuel stores (Figures 5.3 and 5.4), which have operated safely for decades.

Storage of spent fuel in reactor cooling ponds for several years after its removal from the reactor is necessary to allow residual heat to decline to levels that facilitate handling. This is usually followed by longer term storage away from the reactor, pending reprocessing or eventual disposal. Wet or dry storage is used, but ultimately, spent fuel has to be reprocessed or prepared for disposal.

Figure 5.2 Intermediate waste repository, Olkiluoto, Finland (Markku Korpi-Hallila TVO)



5.1.4 High-level radioactive waste

High-level radioactive waste (HLW) produces considerable heat and contains radioactive isotopes with very long half-lives (see Box 5.1) requiring high management standards. Reprocessing of spent fuel produces a concentrated solution of HLW from which the residual uranium and plutonium have been separated. Alternatively, spent fuel can be disposed of without recovery of uranium and plutonium.

Box 5.1 Half-life

A crucial factor in managing wastes is the time that they are likely to remain hazardous. This depends on the kinds of radioactive isotopes present, and particularly the half-life characteristic of each of the isotopes. The time that radioactive materials take to decay and lose their excess energy is measured in half-lives. One half-life is the average time for half of the atoms in a quantity of a radioactive material to decay. After two half-lives, only one-quarter of the original atoms will remain. After three half-lives, only one-eighth of the original atoms will remain. As time goes on, more and more of the unstable atoms will change into the stable decay product.

The two main characteristics of HLW addressed in its long-term management are the contributions to overall radioactivity of relatively short-lived fission products and long-lived alpha-emitting transuranic elements. During the first few hundred years, as radioactivity levels fall, radioactivity and heat generation are dominated by decay of short-lived fission products, which are effectively eliminated after approximately 600 years. Thereafter, and over a much longer period, radioactivity is largely due to the decay of transuranic elements, although some long-lived fission products continue to contribute to overall radioactivity.

As illustrated in Figure 5.5, fission products that initially dominate activity decay relatively quickly but the decay time for actinides comprised of plutonium (Pu) and minor actinides is long.

As the potential hazard from HLW is greatest in the first few hundred to 1000 years, the geological repository must isolate waste from the biosphere over this period. A geological repository would need to provide complete isolation of waste within the engineered containment until short-lived fission products decay to harmless levels.

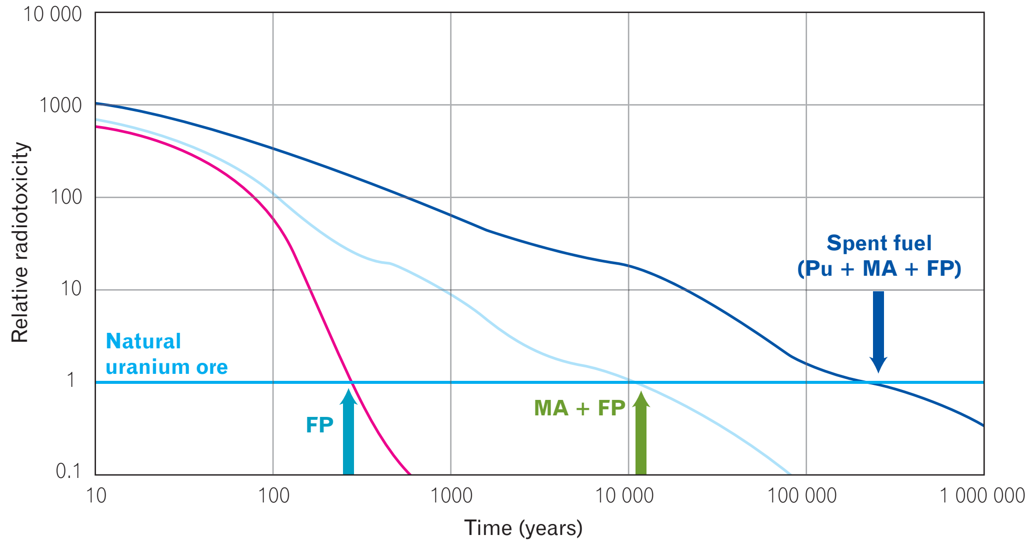
The HLW waste from reprocessing spent nuclear fuel presents a greatly decreased potential hazard beyond 1000 years. At around 10 000 years, the level of activity is approximately the same as that in the original uranium ore body. However, protection is still required from long-lived transuranic elements and actinides. This is provided by engineered multiple barriers to the release of radioactive materials and by the geological environment, which ensure that any released radioactive materials move slowly from the repository. In the more sophisticated fuel cycles incorporating fast reactor systems, the transuranics will not be separated in reprocessing and can be burnt as fuel, thus significantly reducing the long-lived burden.

In spent nuclear fuel radioactivity does not decline to that of the original uranium ore body for about 200 000 years because of the time required for decay of actinides and long-lived fission products in the fuel.

Figure 5.3 HABOG store for spent fuel and reprocessing waste, the Netherlands

Figure 5.4 Dry concrete canister storage of spent nuclear fuel — Wolsong nuclear power plant, Republic of Korea. Eleven canisters are required to store the spent fuel discharged from one reactor over a year

Figure 5.5 Decay with time of radioactivity in high level waste (from Bernard 2004)[92]



FP = fission products; MA = minor actinides; Pu = plutonium

Geological disposal of HLW

There is broad scientific and technical consensus that HLW can be safely disposed of at depths of hundreds of metres in stable geological formations. Reflecting this consensus, the UK Royal Society recently stated: 'it is important to acknowledge that the consensus among the scientific community is that geological disposal is a feasible and low risk option'.[93]

Host geological formations are selected on the basis of long-term stability, capacity to accommodate the waste disposal facility and ability to prevent or severely attenuate any long-term radioactivity releases. The combination of natural barriers and engineered barrier systems provides a long lasting, passively safe system ensuring that significant radioactivity will not return to the surface environment, with no burden of care on future generations.

Ideally, geological repositories will be sited in tectonically stable areas away from the mobile edges of tectonic plates. In such areas the threat of formation of new volcanoes, geothermal activity and large scale uplift or subsidence is very low.

Significant advances are being made towards constructing geological disposal facilities for HLW:

- underground facilities are operating at intermediate depths (more than tens of metres deep) for disposal of low and intermediate level radioactive wastes in Finland and Sweden
- geological disposal of transuranic waste has been demonstrated at the Waste Isolation Pilot Project (WIPP) in the United States
- site characterisation data is being collected and thoroughly analysed at potential repository sites (such as Olkiluoto in Finland, Oskarshamn in Sweden and Yucca Mountain in the United States[33])
- underground laboratories have been constructed in various countries in a range of geological media to obtain data to test models used to assess the performance of potential repository systems
- licensing of deep disposal facilities will commence in the next few years, with the first likely to be established in Finland and Sweden.

[33] Yucca Mountain, the site selected for the first HLW repository in the United States has been the subject of intensive investigation since 1988. The future of the project will depend on legislation currently before the United States Congress.

Assessing the safety of geological disposal

In the licensing of geological repositories, a comprehensive safety case is required by regulatory authorities that includes the results of qualitative and quantitative scientific and technical analyses.

Qualitative arguments in the safety case may refer to natural analogues of radioactive waste repositories such as uranium ore bodies (Figure 5.6). A number of deep uranium ore bodies are so effectively contained by their geological environment that they have no detectable chemical or radiometric signature at the surface. The existence of such ore bodies for over a billion years shows that radioactive materials can be effectively confined in favourable geological environments.

The safety case is supported by quantitative assessments of long-term performance of repository systems, which take into account the probability and consequences of radionuclide releases and compare them with regulatory standards. The safety case evaluates uncertainties in estimates of long-term repository performance.

There is substantial international expert analysis supported by computational models of the long-term performance and safety of geological repositories. Experts in the radioactive waste management community agree that quantitative assessments of repository safety can describe repository performance with sufficient precision.

Figure 5.7 shows how possible exposures from a repository relate to natural background radiation. The units of exposure are millisieverts (mSv), which are a measure of the amount of radiation absorbed, adjusted to take into account different radiation properties and reactions in the body. This is a logarithmic plot with each division of radiation exposure ten times higher than the one to the left.

The overall range of natural background exposures, a more typical range and the global average value can be seen on the right. Ramsar (a town in Iran) has among the highest observed natural background radiation exposures. Calculated impacts from the repositories are tens of thousands of times lower than the doses that people get from natural background radiation. They are also much lower than the radiation dose received by an airline passenger in a long airline trip — something many people do several times a year.

Figure 5.6 A uranium deposit as a natural analogue of a spent fuel repository[94]

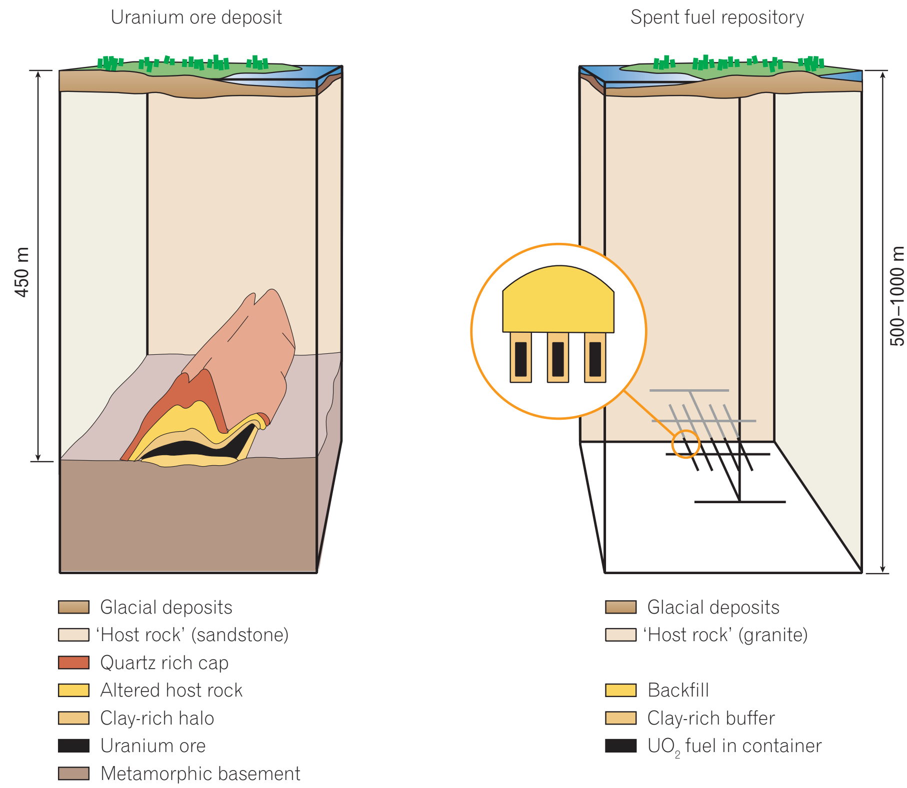
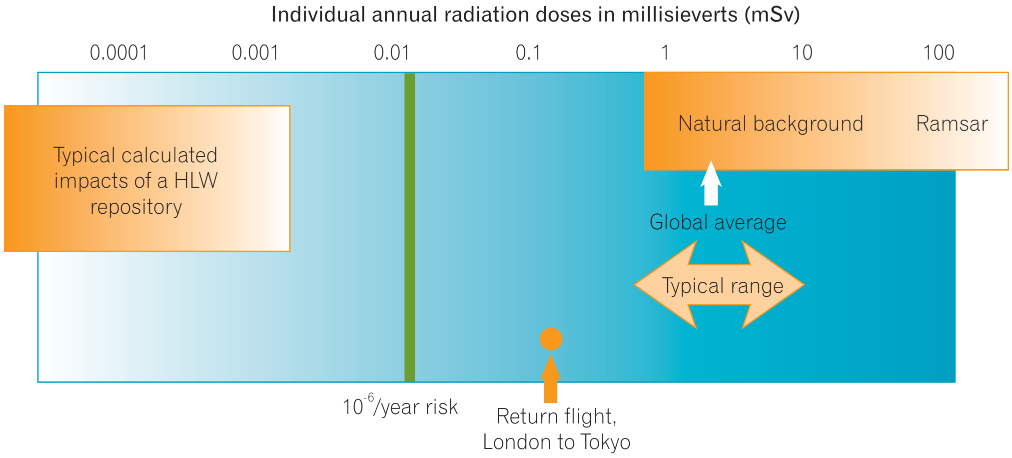


Figure 5.7 Estimated radiological impact of a geological repository compared with background radiation



HLW = high-level waste

Source: modified from Chapman and Curtis.[95]

Progress towards implementation

A recent survey of 39 countries with civil nuclear power or other significant sources of radioactive waste shows that 19 have decided in favour of deep geological disposal and 10 have expressed a preference for this approach.[96] Several have firm plans in place for developing facilities, in some cases supported by national legislation. Some are advanced in establishing facilities and have developed underground laboratories, usually at prospective repository sites.

While there is a strong consensus at the scientific and technical level supporting geological disposal of HLW, surveys of public opinion confirm that this consensus is generally not matched by public perceptions. For example, European Commission surveys show that some Europeans are sceptical about the availability of a safe method of disposing of HLW.[97]

Deep underground disposal in stable geological structures is seen as the most appropriate solution, but one which currently has the support of less than half of the citizens of the European Union. Doubt may arise from the slow pace of development of HLW disposal facilities in some countries. Some European Union citizens believe that because no disposal of HLW has taken place, there is no solution to the problem. Nevertheless, some countries have identified potential disposal sites in regions where there is support for nuclear power. Finland's selection of the Olkiluoto HLW site has been facilitated by positive views based on the safe operation of the Olkiluoto nuclear power plants. In Sweden the two candidate sites are near nuclear power plants.

Effective community engagement is a common element in successful siting of HLW repository investigation sites. In France, identification of the Bure research site followed a consensus with territorial communities. In Sweden, identification of the Oskarshamn investigation site was based on close engagement with communities by the proponent and regulators. The decision to focus siting studies for Finland's HLW repository at Olkiluoto followed interaction between the proponent (Posiva) and local residents, businesses and representatives.[98]

It is widely accepted that a host community should be compensated for accepting a facility which benefits an entire country. This is part of siting strategies in countries including South Korea, France, Sweden, Finland, the United States, Switzerland and Canada.

International HLW repositories

While a number of countries with significant nuclear industries are moving to build national HLW repositories, this may be difficult in countries lacking suitable geology. The high fixed costs of geological repositories for HLW will also make them less attractive for countries with small waste inventories.

These considerations have led to international discussion of multinational or regional repositories. For example, the International Atomic Energy Agency established a working group to examine multinational approaches to the fuel cycle including HLW disposal. This group concluded that multinational repositories offer major economic benefits and substantial nuclear non-proliferation benefits, but raise significant legal, political and public acceptance issues.[99]

At present there is no specific institutional and legal framework for the operation of international repositories and no country has established such a facility. As national governments will have to accept the ultimate responsibility for international repositories, funding arrangements must ensure there is adequate compensation for accepting this liability.

5.1.5 Australia's radioactive wastes

Australia has accumulated approximately 3800 m^3 of low-level and short-lived intermediate level radioactive waste from over 40 years of research, medical and industrial uses of radioactive materials.[34] Over half of this inventory is lightly contaminated soil from research on the processing of radioactive ores by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) during the 1950s and 1960s.

Each year, Australia produces less than 50 m^3 of LILW — approximately the volume of a shipping container. By comparison, Britain and France each produce around 25 000 m^3 of low level waste annually.

Much of Australia's radioactive waste arises from ANSTO's operations (Figure 5.8). This is stored at the ANSTO Lucas Heights site or, in the case of long-lived ILW arising from treatment of Australian research reactor fuel, at overseas facilities pending return to Australia. Australia relies on overseas spent fuel management facilities to convert spent research reactor fuel into a stable waste form suitable for long-term storage in Australia pending ultimate disposal deep underground.

Figure 5.8 Australian Nuclear Science and Technology Organisation low-level waste including lightly contaminated paper and plastic items

[34] This volume of waste would occupy the area of a football field to a depth of less than 1 metre.

Siting radioactive waste management facilities

Since the mid-1980s, successive Australian governments have sought to identify sites for management of Australia's radioactive waste. State and territory governments have welcomed the establishment of national facilities, while generally opposing use of sites in their own jurisdictions.

A siting process initiated in 1992 identified a highly suitable national low-level repository site near Woomera (South Australia). Following legal action in 2003 by the South Australian Government precluding access to the site, the Australian Government abandoned the project. In 2004, the Australian Government announced that it would establish a single facility for safe management of all Commonwealth radioactive waste, leaving the states and territories to make their own arrangements in accordance with Australia's international obligations.

The Australian Government is currently assessing the suitability of three properties in the Northern Territory as the site for the Commonwealth Radioactive Waste Management Facility. This facility will also accept LILW produced by Northern Territory Government agencies. The Western Australian Government operates a LLW disposal facility at Mount Walton East in the Goldfields. The Queensland Government operates a purpose-built store at Esk while other states store LILW in non-purpose built facilities.

Uranium mining

Between 1954 and 1971, Australia produced more than 7000 tonnes of uranium from the Northern Territory (South Alligator Valley and Rum Jungle), Queensland (Mary Kathleen) and South Australia (Radium Hill). Like other mines at this time, these were not subject to formal environmental regulations. Consequently, some left a legacy of environmental damage and physical hazards, which is still being addressed. In contrast, Mary Kathleen in Queensland was the site of Australia's first rehabilitation project. Following completion in 1985, the site was opened for unrestricted use.

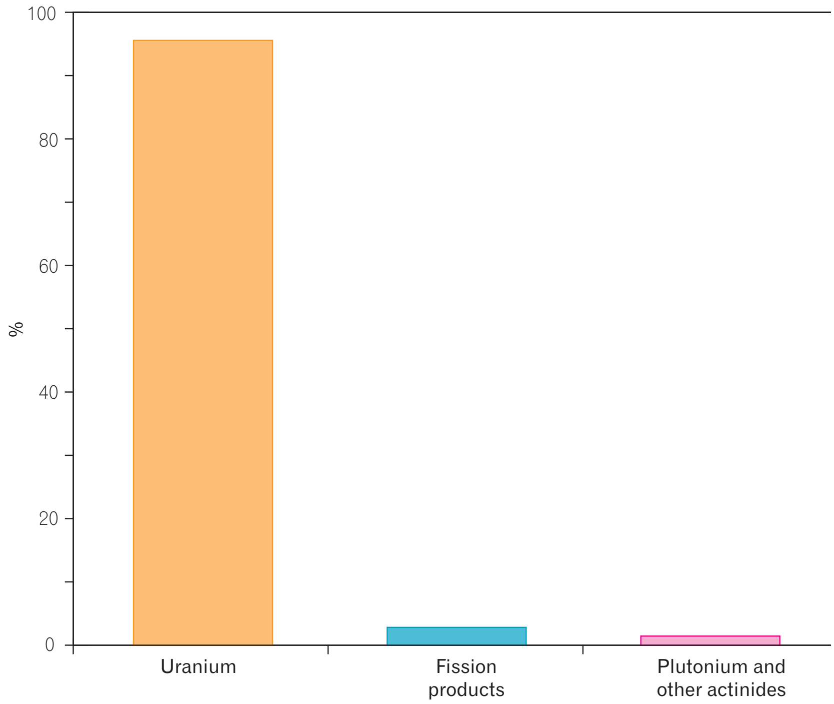
Uranium mining resumed in 1979 under a strict regulatory regime that required mines to be planned and developed with a view to eventual rehabilitation. Nabarlek in the Northern Territory was the first to undergo rehabilitation according to these principles. It operated from 1979 until 1989 and was decommissioned in 1994–1995. Rehabilitation is proceeding and ongoing monitoring will establish when the site returns to the custody of the Traditional Owners.

Plans for final restoration of the Ranger mine are well established, based on a fully costed plan. Mandatory rehabilitation objectives include ecosystem viability, radiological safety, and landform stability. Costings are amended annually to update the guarantee by Energy Resources of Australia, which is held by the Australian Government.

Best modern practice requires a whole-of-life mine plan including proposed plans for rehabilitation. A bank bond is normally required to cover the estimated costs of rehabilitation. Such plans are revised regularly to take into account changing conditions. However, the legislation under which Olympic Dam operates does not put in place an arrangement to guarantee that finance will be available to cover rehabilitation costs.

The Beverley in-situ leach mine in South Australia does not produce conventional tailings or waste rock. The lined evaporation ponds used to dispose of the small volume of waste solids will be closed and revegetated at the end of the life of the mine. This is covered by financial guarantees to the South Australian Government, which will determine the adequacy of rehabilitation plans in consultation with Australian Government agencies.

Figure 5.9 Constituents of spent nuclear fuel



Note: Spent fuel is nearly 96 per cent U-238. Removal of uranium by reprocessing greatly reduces the volume of HLW requiring geological disposal.[100]

5.2 Reprocessing

Reprocessing is the physical and chemical processing of spent fuel to enable the separation of its components (Figure 5.9). The principal reason for reprocessing has been to recover unused uranium and plutonium for use as nuclear fuel, thereby closing the fuel cycle. Reprocessing also reduces the volume of HLW for disposal by a factor of between five and ten, compared to direct disposal of spent nuclear fuel,[101] although it leads to a significant increase in the volume of ILW and LLW.

Commercial reprocessing plants use the PUREX process in which plutonium, uranium and fission products are separated. Thus reprocessing plants, like uranium enrichment plants, are nuclear proliferation sensitive. Other processes (UREX, UREX+), which do not separate out plutonium or other actinides are under development.

For most fuels, reprocessing occurs 5–25 years after its removal from the reactor. The HLW liquid remaining after plutonium and uranium are removed contains approximately 3 per cent of the used fuel as minor actinides and highly radioactive, heat producing fission products.

HLW liquids are conditioned by drying and incorporating the dry material into a durable waste form which is stored pending disposal.

Commercial reprocessing plants operate in France (Cap La Hague), the United Kingdom (Sellafield) and Russia (Ozersk), with a further plant set to commence operation in Japan (Rokkasho) during 2007.

5.2.1 Reprocessing costs

Reprocessing plants have very high capital costs and charges for spent fuel reprocessing are correspondingly high. At present, reprocessing does not appear to be commercially attractive (although mixed oxide [MOX] fuels are used in some countries, eg France and Japan) unless a significantly increased value is given to the recovered plutonium and uranium.

Attributed costs and prices of reprocessing are widely considered to be lower than long-run costs because of the favourable terms under which the two largest plants (THORP and UP3) were financed. Both had pay-ahead contracts with overseas reprocessing customers who were required to reprocess spent fuel in accordance with national policy.

The complexity of reprocessing plants involving remote handling of highly radioactive and corrosive materials requires expensive facilities and many highly trained staff. For example, the UP2 and UP3 facilities at Cap La Hague, the world's largest commercial reprocessing plant, employ up to 8000 people and cost 90 billion francs (over US$16 billion) to build. The only recently constructed commercial-scale reprocessing plant (Rokkasho) is estimated to have cost approximately US$18 billion.[102]

5.3 Future prospects

5.3.1 Impact of 'waste burning' reactors on waste strategies

Current consideration of HLW repositories is based on HLW from the 'once through' nuclear fuel cycle and reprocessing of spent fuel that requires isolation from the biosphere for some thousands of years. This situation would change if development and deployment of Generation IV reactors and advanced fuel processing are successful. There is uncertainty as to the time frame for application of Generation IV technologies and the extent of their adoption. Widespread use of Generation IV fast neutron reactors would dramatically alter the nature and scale of the HLW disposal task, by substantially reducing the volume of HLW and the period over which it requires isolation from the environment, from thousands of years to hundreds of years.[103]

It is not clear what approach will be adopted to managing the shorter-lived HLW arising from Generation IV reactors. Reducing the heat and toxicity of HLW will enable much more effective use of geological repositories in which the waste inventory is limited by heat generation. These technologies could reduce the need for geological repositories, with spent fuel disposed of in near-surface burial facilities or above-ground stores to decay to harmless levels.

A number of countries are interested in using accelerator-driven reactor systems.[35] These produce power and also reduce the actinide and long-lived fission product content of radioactive waste by transmuting much of it into harmless isotopes. While there are technical challenges to be overcome, these technologies could play a useful part in future HLW management strategies.

5.3.2 Managing radioactive wastes from an Australian nuclear industry

Establishing a nuclear power industry would substantially increase the volume of radioactive waste to be managed in Australia and require management of significant quantities of HLW. Based on current light water reactors, for each GW of nuclear power there would be an additional 300 m^3 of LLW and ILW and less than 10 m^3 (30 tonnes) of spent fuel each year.[105]

Assuming an installed nuclear power capacity of 25 GW, a disposal facility would be required for the more voluminous LLW wastes soon after start-up. The much smaller volume of ILW and HLW could be managed initially through interim storage, perhaps for up to 50 years. Assuming a reactor lifetime of 60 years, up to 45 000 tonnes of spent fuel would be produced by a 25 GW nuclear industry in Australia over this period.

Long-term HLW management options for Australia could include disposal in a national geological repository or an international geological repository. Australia has large areas with simple, readily modelled geology in stable tectonic settings and favourable groundwater conditions potentially suitable for nuclear waste disposal. Geoscience Australia identifies the Precambrian granite-gneiss terrain and clay-rich sedimentary strata of Australia as potentially suitable for waste disposal.[8]

Australia's strengths in earth sciences and mining suggest that a geological repository project could be executed with Australian resources. However, some capabilities would need to be scaled up, if Australia were to proceed with a repository. In particular, the number of regulatory staff in the jurisdiction responsible for the project would need to be increased.

The multilateral non-proliferation mechanisms for spent fuel are critical in determining Australia's management arrangements. Should the Global Nuclear Energy Partnership (see Chapter 8) be fully implemented, there may be opportunities for Australia to dispose of its spent fuel in an international repository in a fuel supplier nation such as the United States.

[35] These reactors use a proton accelerator to produce additional neutrons to approach criticality.

5.4 Conclusion

The volume of wastes arising from nuclear power production and other uses of radioactive materials is small compared to wastes produced by many other industrial activities, including coal-fired electricity generation.

Safe management of all categories of radioactive waste has been demonstrated for decades, but no country has yet implemented permanent underground disposal of HLW. There is a scientific and technical consensus that HLW can be safely disposed of in deep geological repositories, and several countries are proceeding with well-developed and thoroughly researched plans for such disposal.

Australia already manages radioactive wastes arising from uranium mining and the medical, research and industrial use of radioactive materials. Australia will soon build a management facility for Commonwealth LLW and ILW and will ultimately require a deep repository. Should Australia move to nuclear power generation, facilities will eventually be required for management of HLW, including its eventual disposal. In line with best overseas practice, radioactive waste management costs would need to be included in the price of nuclear electricity.

Chapter 6. Health and safety

- Ionising radiation and its health impacts are well understood and there are well-established international safety standards that are reflected in Australian practice.
- An efficient, effective and transparent regulatory regime achieves good health and safety outcomes, and provides assurance to the public that facilities are being properly managed.
- The nuclear and uranium mining industries have achieved good performance under these stringent physical and regulatory controls.
- Nuclear power has fewer health and safety impacts than current technology fossil fuel-based generation and hydro power, but no technology is risk free.
- There are legacy problems associated with the nuclear industry. The most significant are the impacts of the Chernobyl accident. However, the Chernobyl reactor is not representative of modern reactor designs.

6.1 Introduction

All industrial activities, including mining and energy production, involve risks to human health and safety. No means of generating electricity is risk free. The choice of any technology or mixture of technologies will inevitably be a matter of balancing different costs and benefits. Operating safely and protecting the health of workers and the public must be a high priority for every industry.

This Chapter examines the whole life cycle of the nuclear energy industry and compares it with other sectors, particularly the fossil fuel energy industry, which could to some extent be displaced by nuclear energy. It considers the risks posed by normal operation of nuclear facilities, and the possibility and consequence of a major accident at a nuclear power plant. The question facing society as a whole is how, based on an objective appraisal of the facts, and in the face of major threats to global climate from fossil fuel burning (described in Chapter 7), do the risks posed by nuclear energy compare with those posed by fossil fuel use, and are they acceptable.

6.2 Health impacts of the nuclear fuel cycle

The European Commission ExternE study examined the external costs of electricity generation using a form of life cycle assessment.[83,106] The study describes the process steps in each energy chain and provides information on material and energy flows, and associated burdens (eg emissions and wastes). This output is then used to estimate the health and environmental impacts and the costs resulting from the burdens. External costs are those incurred in relation to health and the environment that can be quantified, but are not built into the cost of the electricity to the consumer. They include the effects of air pollution on human health, as well as occupational disease and accidents. The study calculates the dispersions and ultimate impact of emissions, and the risk of accidents is taken into account, as are estimates of radiological impacts from mine tailings and emissions from reprocessing.

The ExternE results indicate that the health and safety costs of uranium mining and nuclear fuel use, including waste disposal, are lower than fossil fuel-based energy generation, on a unit of energy produced basis. Comprehensive studies undertaken by Dones et al on the life cycle impacts of energy generation systems in Europe also rate nuclear energy as performing much better in a range of health areas than fossil fuel-based systems.[107,108]

The nuclear fuel cycle produces far lower amounts of greenhouse gas emissions (discussed in Chapter 7) and other pollutants than conventional fossil fuel systems per unit of electricity produced. This includes emissions of air pollutants of major health concern: sulphur dioxide (SO_2), particulate matter (PM) and oxides of nitrogen (NO_x). At concentrations that are common in many parts of the world, these pollutants have significant health impacts.

Globally, an estimated 2 million deaths occur each year as a result of air pollution, indoors and out.[109] In the European Union, the smallest particulate matter (PM2.5), particles 2.5 μm in diameter or less, causes an estimated loss of statistical life expectancy of 8.6 months for the average European.[110] Power generation and the transport sector are major contributors of PM2.5.

The biggest source of emissions of health concern arising from using nuclear power is the burning of fossil fuels to generate electricity used in the fuel cycle, for example, in mining and enrichment. The fundamental reason for the comparatively good life cycle performance of nuclear power is that while a 1000 MW coal plant annually requires approximately 2.6 million tonnes of good-quality black coal (or significantly more brown coal due to its much lower energy content), a comparable size nuclear power plant requires between 25 and 30 tonnes of low-enriched uranium. Taking the Ranger mine as an example, approximately 150 000 tonnes of rock and ore is extracted, moved and/or processed to produce the 25 tonnes of low-enriched uranium. Nonetheless the comparative energy density advantage of uranium remains very high. Coal mining, involving the removal of overburden (the soil and rock overlying the coal seam), and the handling and burning of much larger volumes of material, inevitably leads to greater risk of accidents and health impacts per unit of electricity produced.

6.2.1 Radioactivity measurement and impact

Using uranium to produce electricity involves radioactivity and this has potential health impacts. Ionising radiation is produced when the nucleus of an atom disintegrates, releasing energy in the form of an energetic particle or waves of electromagnetic radiation. Radiation exposure (see Box 6.1) can arise from sources outside the body (external exposure) or from radioactive material inside the body (internal exposure). Radioactive material can enter the body (exposure pathway) by inhalation or ingestion in water or food.

Background radiation

People are continuously exposed to natural background radiation (ie cosmic radiation and terrestrial radiation sources, such as soils and building materials, and radon gas that comes from rocks, soil and building materials). The average natural background radiation at sea level in Australia is approximately 1.5 mSv/year, below the world average of 2.4 mSv/year, because of the relatively low radon exposures.[111] In Denver Colorado, in the United States, the average background radiation dose is approximately 11.8 mSv/year due to local geology and altitude.[112] The average annual individual radiation dose to members of the public from background sources and the nuclear industry are summarised in Figure 6.1. The fact that background radiation varies substantially from place to place provides some reassurance on the risks associated with low doses of radiation, since no study has shown any difference between high and low background radiation areas in terms of impacts on human health.

Box 6.1 Dose and effect

Effective dose
Some parts of the body are more sensitive to the effects of radiation than others, and some types of radiation are inherently more dangerous than others, even if they 'deposit' the same level of energy. To take these characteristics into account, tissue weighting factors and radiation weighting factors have been developed. These can be combined with a measurement of absorbed dose of radiation to give 'effective dose'. The unit of dose is the sievert (Sv). The millisievert (mSv), one thousandth of a sievert, is a more useful unit for the sorts of exposures found in day-to-day life.

Deterministic health effects
Low doses of radiation do not produce immediate clinical effects because of the relatively small number of cells destroyed. However, at high doses, enough cells may be killed to cause breakdown in tissue structure or function. There is a threshold below which deterministic effects do not occur, which varies with the tissues involved.

Stochastic effects
Ionising radiation also damages cells by initiating changes in the DNA of the cell nucleus. If the damage is not repaired and the cell remains viable and able to reproduce, this event may initiate the development of a cancer. If the damaged cell is in the genetic line (egg, sperm or sperm-generating cell) then the damage may result in genetic disease in the offspring. This genetic effect has been seen in animal studies, but there is only limited evidence from studies of humans. These effects — the initiation of cancer or genetic disease — are called stochastic effects. This means that the effect is governed by chance. An increase in the size of the dose will increase the probability of the effect occurring, but not the severity of the effect. Stochastic effects do not generally become apparent for many years after exposure, and in most cases there is no way of distinguishing a particular cancer or genetic effect that might have been caused by radiation from an effect arising for other reasons. Although there is debate on this issue, the International Commission on Radiological Protection (ICRP) recommends the assumption that there is no threshold for stochastic effects as the basis of the system for radiological protection.

Radiation impact
In order to define the impacts of radiation doses, the ICRP recommends the use of a risk for fatal cancer in the whole population of one per 20 000/mSv.[113] In comparison the chance of contracting fatal cancer from all causes is around one in four.

ICRP recommended limits on exposure to ionizing radiation

The following recommended limits on exposure to ionizing radiation have been incorporated into relevant Australian regulations:

- the general public shall not be exposed to more than 1 mSv/year (over and above natural background radiation)
- occupational exposure shall not exceed 100 mSv over 5 years.

These limits exclude exposure due to background and medical radiation. (See Appendix M for further discussion)

Assessing collective dose

The impact of very small doses to many people is often assessed through the use of the concept of collective dose. This tool is frequently used to estimate fatalities by summing small doses over large populations. However the International Commission on Radiological Protection (ICRP) advises that: '…the computation of cancer deaths based on collective doses involving trivial exposures to large populations is not reasonable and should be avoided' (p. 42).[114] (See Appendix M for further discussion.)

6.2.2 Radioactive emissions from the nuclear fuel cycle

An important issue for this Review is to assess the extent to which members of the public and workers could be exposed to radiation during the nuclear fuel cycle.

International guidance

Ionising radiation and its impacts on health are well understood. There is a long-established international system for reviewing the scientific literature on radiation and its biological effects, and for developing and issuing guidelines on relevant matters. Nuclear and radiation safety standards and criteria are recommended by the ICRP. The ICRP is a non-government organisation that has the objective of producing standards for radiation protection and minimising the risks from radiation.

ICRP activities are supported by the work of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which reviews the emerging scientific information on a continuing basis and publishes a major review of the sources of radiation and its effects on health every five years. The recommendations of the ICRP form the basis of safety standards issued by the International Atomic Energy Agency (IAEA), which is the world's major nuclear forum.

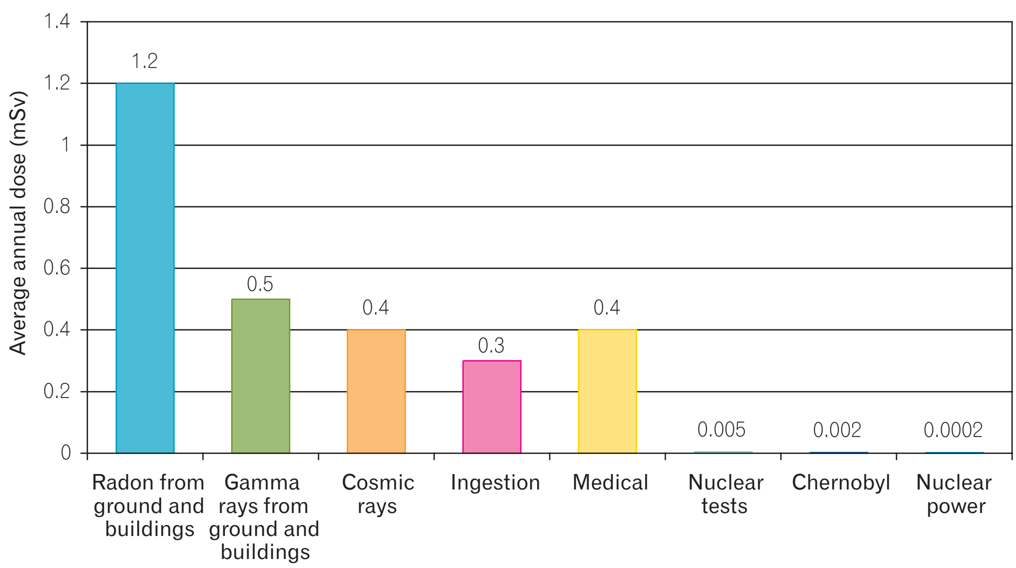
Operational fuel cycle emissions

Radiation exposure at all parts of the nuclear fuel cycle has been assessed in international studies conducted for the United Nations. Dose rates for workers and members of the general public from these UNSCEAR studies can be used to estimate fatality rates.[115]

The estimated fatality rate for workers in the nuclear energy industry based on UNSCEAR radiation dose estimates is approximately 0.06 per 100 000 worker years. By way of comparison, this is far lower than the fatality rate for the coal industry in the United States or for the business sector as a whole in Western Australia.[36]

The dose rate expected for individual members of the public is very low, an average 0.005 mSv/yr for people resident within 50 km of a pressurised water reactor (PWR) power station.[115] To place radiation exposure to the public in perspective, a person taking a return flight from Sydney to London would receive the same dose (approx. 0.25 mSv) as someone living 50 years in the vicinity of such a power reactor.

Figure 6.1 Worldwide average annual radiation dose from natural and other sources, 2000



Source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[115]

[36] The United States coal industry fatality incidence per 100 000 full-time employees was just over 28.7 in 2004. In Western Australia, the fatality incidence across all industries (including education, finance and insurance, retail trade and a range of other activities) in the financial year 2004–2005 was 2.2 per 100 000 workers. The highest fatality incidence was 13.9 per 100 000 workers in the electricity, gas and water supply industry. Figures for one year have to be interpreted with caution as they are based on small numbers. These fatality incidents are actual deaths, not estimates based on modelling as is the case for the nuclear industry.

Radioactive emissions from fossil fuel combustion

It is not widely appreciated that burning coal releases quantities of radioactive materials to the environment that are similar in magnitude to the routine releases from the nuclear industry for comparable electrical output.[116] This is because coal is an impure fuel, containing large amounts of sulphur, significant amounts of aluminium and iron, and trace quantities of many other metals, including uranium and thorium, although the levels vary widely. In the United States, it has been estimated that citizens living near coal-fired power plants are exposed to higher radiation doses than those living near nuclear power plants that meet government regulations. In either case, the amount of radiation released is very small compared to background radiation.[117,118]

6.2.3 Energy industry accidents

As with any human activity such as air, car and rail travel, large scale electricity generation is associated with accidents that cause injury and death to workers and the public. There are mine explosions, dam collapses and fires at gas and chemical plants. The record of such accidents shows that the nuclear power industry is significantly safer than other large scale energy-related industries.

Table 6.1 shows energy industry related severe accidents between 1969 and 2000. The number of deaths caused serves as an indication of the level of impact. In terms of the number of deaths per unit of electricity produced (taking only immediate (also known as prompt or early) deaths into account), nuclear power is less dangerous than all fossil fuel electricity generation systems, and also safer than hydro. Renewable energy sources have a good safety record although wind farms have caused at least 37 fatalities in accidents since 1970.[329]

One notable feature from Table 6.1 is the 31 fatalities attributed to Chernobyl. According to the Chernobyl Forum, immediate and delayed fatalities to date have been less than 100.[119] Further explanation is given in Box 6.2.

Table 6.1 Fatal accidents in the worldwide energy sector, 1969–2000*

	No. accidents	Direct fatalities	Direct fatalities per GWe/year
Coal	1221	25 107	0.876
Oil	397	20 283	0.436
Coal (China excluded)	177	7090	0.690
Natural gas	125	1978	0.093
LPG	105	3921	3.536
Hydro	11	29 938	4.265
Hydro (Banqiao/Shimantan dam accident excluded)[a]	10	3938	0.561
Nuclear reactor[b]	1	31	0.006

[a] The Banqiao/Shimantan dam accident occurred in 1975 and resulted in 26 000 fatalities.

[b] See Box 6.2 for information on long-term impacts of nuclear reactor accidents.

Source: derived from Burgherr et al[120] and Burgherr and Hirschberg.[121]

* These figures do not include latent or delayed deaths such as those caused by air pollution from fires, chemical exposure or radiation exposure that might occur following an industrial accident.

Box 6.2 Chernobyl

The uncontained steam/chemical explosion and subsequent fire at Chernobyl in 1986 released radioactive gas and dust high into the atmosphere, where winds dispersed it across Finland, Sweden, and central and southern Europe.

Within a month, many of those living within a 30 km radius of the plant — approximately 116 000 people — had been relocated. The area remains essentially unoccupied.

Twenty-eight highly exposed reactor staff and emergency workers died from radiation and thermal burns within four months of the accident. Two other workers were killed in the explosion from injuries unrelated to radiation, and one person suffered a fatal heart attack. Nineteen more died by the end of 2004, not necessarily as a result of the accident. More than 4000 individuals, most of whom were children or adolescents at the time of the accident, have developed thyroid cancer as a result of the contamination, and fifteen of these had died from the disease by the end of 2002. Possibly 4000 people in the areas with highest radiation levels may eventually die from cancer caused by radiation exposure. Of the 6.8 million individuals living further from the explosion, who received a much lower dose, possibly another 5000 may die prematurely as a result of that dose.[119] The small increase in radiation exposure caused by the accident for the population of Europe and beyond should not be used to estimate future likely possible cancer fatalities. The ICRP states that this approach is not reasonable. (See discussion 'Collective dose' at Section 6.2.1)

The Chernobyl Forum report in 2006 clearly identifies the extensive societal disruption in the region as the most significant impact resulting from the accident, compounded by the collapse of the Soviet Union in 1989.

As with Three Mile Island, the lack of emergency response planning and preparedness, plus poor communication between officials and the community, added significantly to the social disruption and some of the health consequences of the Chernobyl accident. (See Appendix N for further discussion.)

6.2.4 Accidents at nuclear facilities

The risk of a serious accident at a nuclear power plant is a very important issue for the community. The accidents at Three Mile Island and Chernobyl have come to symbolise the risk of nuclear power.

In fact the health and safety performance of the nuclear industry is good. Apart from Chernobyl (see Box 6.2), there have been few accidents and only minor releases of radioactive elements from civilian nuclear installations, both power plants and fuel cycle installations, since the introduction of nuclear power. The design of the Chernobyl reactor (known as the RBMK) was intrinsically unstable and, unlike most reactors, lacked a massive containment structure. The operators were also attempting an experiment which involved overriding many safety systems including vital cooling pumps, actions completely contrary to the operating procedures laid down for the facility. Such a plant would not have been permitted to operate in the western world and is not representative of modern reactor designs. The Three Mile Island accident, while a large financial cost to the company involved, injured no one and led indirectly to the release of only minor amounts of radioactive elements which, in the opinion of experts, had no measurable impact on health. It demonstrated the robustness of the reactor design and the value of containment structures. (See Appendix N for further discussion of the Three Mile Island and Chernobyl accidents and impacts, and Appendix L for information on nuclear reactor technology.)

There has been comprehensive reporting of incidents at nuclear power plants and other nuclear facilities, although the information from the former Soviet Union was sparse before 1990. Some of the most significant incidents are summarised in Table 6.2. Since 1999 (in August 2004) there has been an accident at the Mihama No. 3 nuclear power plant in Japan involving a steam leak. Neither the reactor nor radioactive materials were involved. There were four fatalities and seven people were injured.

In the nuclear industry, there are risks associated with handling corrosive chemicals and dealing with materials under extremes of pressure or temperature, as is the case in many other industries. In enrichment, reprocessing and fuel fabrication plants handling fissile materials, there is the risk of criticality accidents, which are potential causes of serious radiation-related accidents. To avoid this, plants have physical and administrative controls. A review of all criticality accidents by the Los Alamos

National Laboratory found that the majority (38) occurred at research or experimental facilities such as research reactors, which were purposefully planning to achieve near-critical and critical configurations.[122]

Operating personnel in research facilities are usually expert in criticality physics and experiments are performed under shielded conditions or in remote locations. In these situations, accidents are not totally unexpected and have very limited impacts (confined to the facility and workers in it). The other 22 accidents occurred in commercial process facilities; thus they were unexpected and had generally greater impacts. One resulted in measurable fission product contamination (slightly above background levels) beyond the plant boundary and one resulted in measurable, but low, exposures to members of the public.

6.2.5 Transport risks

The global record of transporting all categories of nuclear materials is good. Very few accidents have involved any release of radioactive material. A recent review of transport accidents involving radioactive materials in the United Kingdom between 1958 and 2004 presents findings that are representative of OECD countries (Figure 6.2).[123] In transporting an average half a million packages per year of all sorts there were 806 incidents of which 19 resulted in individual whole-body doses of over 1 mSv.[37]

6.2.6 Developments in technology and safety culture

International safety guidance

The Three Mile Island accident in 1979 led to a re-examination of reactor design, and more importantly, as the basic design had proved sound, to a review of the operational and training systems, management culture and regulatory regime for nuclear power plants, as well as the need for improved and more transparent community engagement, both in the United States and internationally. The Chernobyl accident added to the impetus for international cooperation in promoting safety performance.

Table 6.2 Significant nuclear facility incidents, 1966–1999

	Country	Year	Fatalities	INES[a] level
Fermi-1	USA	1966	Nil	3
Sellafield reprocessing plant	UK	1973	Nil	4
Three Mile Island	USA	1979	Nil	5
Saint Laurent A1	France	1980	Nil	4
La Hague reprocessing plant	France	1981	Nil	3
Chernobyl 4	Ukraine	1986	31	7
Vandellós 1	Spain	1989	Nil	3
Sellafield reprocessing plant	UK	1992	Nil	3
Tokaimura reprocessing plant	Japan	1997	Nil	3
Tokaimura nuclear fuel conversion plant	Japan	1999	2	4

[a] INES, International Nuclear Event Scale. Events at levels 1–3 are incidents, above level 3 are accidents and level 7 is the most severe. Events with no safety significance (level 0 or below scale) are deviations. Only levels 4 and above involve unplanned radioactive releases off-site above regulated levels.

Source: OECD/IEA[124]

[37] In the worst incident, caused by an improperly shielded source, a radiographer transporting the material received an estimated very serious whole-body dose of 2 Sv (5 Sv would normally be fatal). The estimated worst case dose to any member of the public however was 2 mSv.

Figure 6.2 Transporting spent nuclear fuel in the United Kingdom

Source: photo courtesy of World Nuclear Transport Institute and Direct Rail Services Limited

There is now an international consensus on the principles for ensuring the safety of nuclear power plants and international cooperation through bodies such as the International Nuclear Safety Group established by the IAEA. In addition to publishing safety standard guidance documents, the IAEA provides safety services and runs seminars, workshops, conferences and conventions aimed at promoting high standards of safety. There is also an international regime of inspections and peer reviews of nuclear facilities in IAEA member countries, which has legislative backing through the international Convention on Nuclear Safety which entered into force on 24 October 1996. The Convention on Nuclear Safety aims to achieve and maintain high levels of safety worldwide. All IAEA member states with operating nuclear power reactors are parties to the convention.

Safety assessments and quantified risk

The protective systems of nuclear power plants are required to demonstrate 'defence in depth'. The objective is to ensure that no single human error or equipment failure at one level of defence, or a combination of failures at more than one level of defence, can lead to harm to the public or the environment.[125] Another key element used to demonstrate that operation of a proposed nuclear power plant will not pose significant risk is the preparation of a detailed safety assessment as part of the regulatory licensing process. Safety assessments cover all aspects of the siting, design, construction, operation and decommissioning that are relevant to safety.[126]

A study of reactor safety was published by the US NRC in 1990.[127] Five existing PWR and boiling water reactors (BWR) at nuclear plants were examined using the probabilistic safety assessment (or probabilistic risk assessment) method. The PWR is the most common type of reactor in operation at present with more than 50 per cent of the global fleet.

The study found that the average probability of core damage per plant from all potential internal accident scenarios is 4×10^{-5} per year or one core damage accident in 25 000 years of operation.

The next step in the analysis involved calculating the chances that, if core damage were to occur, could radioactive material escape from the fuel rods into the containment and if so how much. In turn, if this was to occur, the possible routes by which that radioactivity might escape or be released from the containment were examined. The off-site consequences, which depend on weather conditions, surrounding population density, the extent and timing of any evacuation, and the damage to health due to exposure to the various radionuclides that might reach people, were then modelled. The final step involved the assessment of the impacts of radiation on humans including fatal cancer risk using the linear no-threshold model of radiation dose-response.

For a representative PWR the average probability of an individual early direct fatality (or prompt fatality, that is a death directly attributable to the nuclear accident, usually occurring immediately, but including those occurring up to one month after the event) was 2×10^{-8} (1:50 000 000) per operating year. The average probability of an individual latent cancer death from an accident was 2×10^{-9} (1:500 000 000) per year.

A similar probabilistic risk assessment has been undertaken in relation to the likelihood and consequences of a terrorist ground attack on a representative US 1000 MWe nuclear power plant.[128] (See also Chapter 8). It found that the risks to the public from terrorist-induced accidental radioactive release are small. Sixty five per cent of attempted attacks would probably be thwarted prior to plant damage. About 5 per cent of attempted attacks would result in core damage, and about 1 per cent would result in some release of radiation. Overall the chance of one immediate fatality as a result of a terrorist attack was calculated to be below one per 600 000 reactor years. The frequency of events resulting in 20 or more immediate fatalities is less than one per million reactor years. The chance of one latent cancer fatality is less than one in 300 000 reactor years.

The likelihood of any terrorist related accident leading to land contamination beyond the site of the nuclear plant is less than one in 170 000 reactor years. However, if such an event did occur an area of land of up to 208 km^2 could be rendered unusable for agriculture for between one and 30 years, with a further area of around 2 km^2 rendered unusable for farming for more than 30 years. Any other affected land could be decontaminated without significant loss of use.

A more significant accident with a release of radiation sufficient to render a land area of up to 11 km^2 unusable for more than 30 years is expected to occur no more than once in a million reactor years. The areas involved are comparable to the land contamination risk from other types of radiological accidents analysed in the design and licensing of US commercial nuclear plants to date.

The probabilities for events and the associated radiation doses and areas of contamination calculated in these probabilistic risk assessments are very conservative, that is the calculated frequency of accidents is higher than is likely to be the case in reality. Safety analysts make assumptions in creating accident scenarios that assume the worst outcome at every step, and the calculations of the movement of radioactivity to nearby people are precautionary.

These assessments consider only biophysical contamination of land. They do not take into account the likelihood that a much larger area would also probably be effectively unusable because of public perception of contamination, with subsequent economic and social impacts.

As is clear from the discussion above, one of the quantitative safety performance criteria is the frequency of occurrence of severe reactor core damage. The target for existing nuclear power plants built in the 1970s was a frequency of occurrence below 10^{-4} (1 in 10 000) events per plant operating year. Severe accident management and mitigation measures should reduce by a factor of at least ten the probability of large off-site releases, even following such an event. Improvements in design for future nuclear power plants are expected to lead to the achievement of a frequency of not more than 10^{-5} (1 in 100 000) severe core damage events per plant operating year. The certification application for the new Westinghouse AP 1000 nuclear power plant design for example, estimates the risk of core damage to be one in two million (5×10^{-7}) per year and large release frequency to be considerably lower at 6×10^{-8} per year.The new generation reactors are designed to be very safe. They have fewer components than older designs, are more efficient and need less maintenance. All reflect the defence in depth approach and many of them include 'passive safety' features — systems that close down the reactor automatically in an emergency using natural processes such as gravity and convection that need no external intervention or power supplies. This reduces very significantly the probability of core damage or any radioactivity escape from the core, let alone the containment facility.

In one scenario, were Australia to have 25 operating reactors with the above (10^{-5}) design features, then there could be one serious core-damaging incident per 4000 years of operations and a one in 40 000 years event that might see off-site release of radioactive material. Were Australia to comply with the 5×10^{-7} standard, the risks would be lowered further by a factor of 20.

6.3 Acceptable risk?

Hazard and risk assessment is used extensively in Australia and overseas to assist government decision making on major project acceptability. A hazard is an unwanted event that may cause harm to workers, the public or the environment. Risk is the probability of an unwanted event happening and is often expressed as the product of consequence and frequency. Risks can be defined to be acceptable or tolerable if the public will bear them without undue concern.

Regulatory limits are set at points deemed 'acceptable' by the regulator, taking into account objective evidence of harm and the general views of society. Risks are unacceptable if they exceed a regulatory limit, or cannot otherwise be accepted. Negligible risks are those so small that there is no cause for concern, or are so unlikely that there is no valid reason to take action to reduce them.

Humans continually expose themselves to, or have imposed upon them, the risk of injury or fatality. Self-imposed risk is known as voluntary risk and includes everyday events such as smoking, swimming and driving. Each has an associated risk that people voluntarily accept when weighed against the perceived benefits. A range of examples are listed in Table 6.3.

Table 6.3 Examples of everyday risks in Australia

Hazard	Risk of fatality per million person years
Smoking (20 cigarettes/day)	5000
Motoring	144
Accidents in the home	110
Owning firearms	30
Drowning	15
Fire	12
Electrocution	4
Aircraft accident	3
Unexpected reaction to medicine	1
Lightning strike	0.1
Snake bite	0.13
Shark attack	0.065
Nuclear industry contribution to background radiation[a]	0.018

[a] Based on the application of the ICRP risk factor to the contribution of nuclear industry operational emissions, plus those of the Chernobyl accident, to the average annual dose from global background radiation (approx. 0.0022 mSv; see Figure 6.1). This sort of calculation of cancer deaths based on trivial exposures to large populations is questionable and should normally be avoided. (See discussion 'Assessing collective dose' Section 6.2.1 and Appendix M.)

Source: adapted from Environment Australia.[129]

6.3.1 Risk assessment and planning

For formal planning purposes, risks are often assessed through quantified risk-assessment techniques. The acceptability of risk is determined against existing regulatory standards or existing background levels. Most Australian states have set limits on tolerable risk levels based on the frequency of individual death due to an accident (individual fatality risk). For example, New South Wales specifies an individual fatality risk of 1 in 1 000 000 years as being the acceptability limit for industry in residential areas. Risks may also be calculated by aggregating the risk to all individuals who may be affected (societal or collective risk), for example, from explosions, fires or toxic fumes.

6.3.2 Risk perception

Perceptions are important in determining whether risks for hazardous facilities are acceptable. Risks of greatest concern are ones borne involuntarily, especially human activities (rather than natural events) that could have potentially catastrophic consequences. Nuclear accidents are in this category. While risk assessments can help to quantify risk levels, it is a highly subjective issue and the level of risk acceptable to the community or to some individuals may be zero. This is particularly so for a new development that may appear to offer little individual or community benefit. While some risk perceptions are commonly understood, conflicts can arise between 'experts' and the community about acceptability. Research suggests that these arise from differences in the way the public and experts perceive risk.[130] This is of particular concern to policy makers basing decisions on scientific advice.

To determine the acceptable risk level for hazardous facilities, a sound approach is to make a comparison with background exposure levels. Against this measurement, decisions can be made as to the acceptability of additional risks.

6.4 Health and safety performance

Australian industrial experience in the nuclear fuel cycle is limited to uranium mining and milling and the research reactor at Lucas Heights. In these areas the health and safety performance is of a high standard.

For the Australian minerals industry overall, the average fatal injury frequency rate (the number of fatal injuries per 1000 employees for a 12-month period) for the 10-year period 1994–1995 to 2003–2004 was 0.08. This compares well with the United States, which recorded a rate of approximately 0.16 for this period. Lost time injury data are difficult to compare internationally because of the different systems and definitions that are used. Nonetheless, for the past few years the Australian minerals industry performance appears to be comparable with that of the United States.[131]

Uranium mining operations are undertaken under the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores, administered by state and territory governments. Radiation dose records compiled by mining companies under the scrutiny of regulatory authorities have shown consistently that mining company employees are not exposed to radiation doses in excess of the limits. The most exposed group receives doses that are approximately half of the 20 mSv per year limit. Uranium mining does not discernibly increase background levels of radiation for members of the public, including communities living near uranium mines.

At the open cut Ranger mine, because of good natural ventilation, the radon level seldom exceeds 1 per cent of the levels allowable for continuous occupational exposure. In an underground mine, a good forced-ventilation system is required to achieve the same result. At the underground Olympic Dam mine, radiation doses to designated workers in the mine in 2004 averaged 3.7 mSv per year. Strict hygiene standards are imposed on workers handling U_3O_8 concentrate. If it is ingested it has a chemical toxicity similar to that of lead oxide. At Olympic Dam, the packing of uranium oxide concentrate is automated, so no human presence is required. Beverley is an in-situ leach uranium mine so there are no conventional 'tailings', waste rock or similar wastes. This means potential radioactive emissions are very low.

In addition to routine worker exposure, however, there may be incidents at the mines that give rise to non-routine radiation exposure. At Ranger such incidents occurred in 1983 and 2004. There were three incidents at Olympic Dam and four at Beverley in South Australia in 2004–2005 alone, involving spillages of slightly radioactive materials. While all of these incidents could have been avoided, the actual doses received range from trivial to relatively low and are unlikely to have significant long-term health effects.

In common with all workplaces non-radiological accidents have occurred at Australian uranium mines involving vehicles, machinery, explosives and so on. Although there was a fatality in 2005 at Olympic Dam (an explosives accident, the first fatal accident at the site since 1998), and the death of a contractor as a result of an excavator accident in 1996 at the Ranger mine, the overall health and safety performance at uranium mines is at least as good as other mines in Australia.

6.5 Conclusion

Using nuclear energy to generate electricity involves fewer health and safety impacts than current technology fossil fuel-based generation and hydro power, taking into account both emissions during normal operation and the impact of accidents.

As Chapter 7 makes clear, climate change poses a real and grave risk that, if unchecked, would have significant impacts on the world, including Australia. Nuclear energy has the capacity to reduce greenhouse gas emissions globally. The (small) risks associated with Australia having a greater involvement in nuclear energy needs to be considered in the context of the real risks of not taking this action.

There is a long established international system for reviewing the scientific literature on radiation and its biological effects, and for developing and issuing guidelines on relevant matters, key elements in achieving ever safer operation. Australia is already an integral part of this system and our health and safety requirements reflect best international practice (see Chapters 8 and 9). There is every reason to be confident that Australia's health and safety systems will continue to provide a sound framework for the management of the uranium mining industry and would enable any other parts of the nuclear fuel cycle envisaged for Australia to be equally well regulated, ensuring the highest levels of health and safety.

Chapter 7. Environmental impacts

- Deep cuts in global greenhouse gas emissions are required to avoid dangerous climate change. No single technology can achieve this — a portfolio of actions and low-emission technologies is needed.
- Nuclear power is a low-emission technology. Life cycle greenhouse gas emissions from nuclear power are more than ten times lower than emissions from fossil fuels and are similar to emissions from many renewables.
- Nuclear power has low life cycle impacts against many environmental measures. Water use can be significant in uranium mining and electricity generation depending on the technology used.
- The cost of reducing emissions from electricity generation can be minimised by using market-based measures to treat all generation technologies on an equal footing.

7.1 Introduction

Concerns about human-induced climate change are driving renewed worldwide interest in nuclear power and other low-emission technologies. Greenhouse gas emissions, especially carbon dioxide (CO_2) from fossil fuel combustion, are changing the make-up of the atmosphere and contributing to changing weather patterns around the world. It is widely accepted that climate change is real and global greenhouse gas emissions need to be cut dramatically.[132–134] This chapter focuses on the potential of nuclear power to contribute to that task.

This chapter also reviews the non-greenhouse environmental impacts of the nuclear fuel cycle. The analysis is necessarily broadly based, and allows some of the generic impacts of different generation technologies to be compared. It must be stressed that any specific proposal for Australia (eg building an enrichment plant) would be the subject of an environmental impact assessment that would be much more detailed than the assessment presented here.

Emissions and impacts are assessed across the full life cycle of nuclear power, from uranium mining to plant decommissioning and final waste disposal.

Environmental impacts are strongly related to health and safety issues (eg human health is affected by environmental factors, and an accident at a nuclear facility could damage fauna and flora), which are dealt with further in Chapter 6. The risks arising from nuclear waste, and management controls applied to minimise adverse impacts, are addressed in Chapter 5. Regulatory issues are discussed in Chapter 9. A detailed discussion of climate change and greenhouse gas emissions is provided in Appendix O.

7.2 Climate change

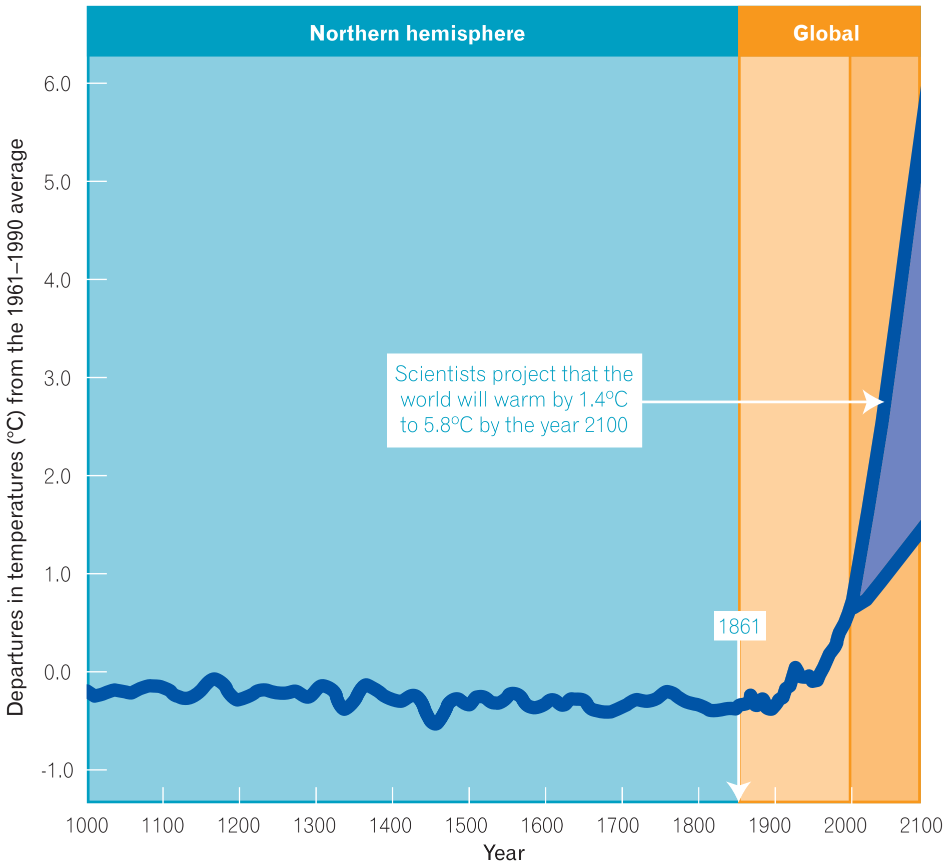
7.2.1 Emissions and projections

Global emissions of greenhouse gases have grown since the beginning of the industrial revolution, driving a rapid increase in the concentration of greenhouse gases in the atmosphere. The pre-industrial atmospheric concentration of CO_2 was 280 ppm. It is now 380 ppm, and rising by approximately 1.8 ppm each year.[135] This is higher than it has been in at least 650 000 (and likely 20 million) years.[2,136,137] While the global climate is naturally variable, this new and rapid increase in atmospheric concentrations could trigger shifts at a scale and rate far beyond natural variation. Indeed, impacts are already observable in rising temperatures and sea levels, loss of ice cover, changing weather patterns and consequent impacts on ecosystems.[134,136]

Scientists project that CO_2 concentrations could grow to between 540 and 970 ppm by the end of the century if the world does not act to cut emissions.[134] Under these conditions, the Earth's average surface temperatures could rise by 1.4–5.8°C and global mean sea levels could rise between 9–88 cm. Changes would vary significantly across regions. For example, it is very likely that nearly all land areas would warm more than the global average, and Australia's annual average temperatures are projected to increase by between 1–6°C by 2070.[135]

Figure 7.1 shows how the surface temperature of the Earth has increased since the mid-nineteenth century and projections for the coming century.

Figure 7.1 Earth's temperature, 1000–2100



Note: Projections for the period 2000–2100 are based on illustrative scenarios.

Source: Australian Greenhouse Office (AGO)[137] adapted from IPCC[2]

Recent research has examined other processes in the climate system that could dampen or amplify climate change. Aerosols in the atmosphere, carbon cycle dynamics and the ice-albedo effect are all associated with feedback loops that affect the degree of warming.[136] Studies of these feedbacks suggest a greater risk of reaching or exceeding the upper end of the 1.4–5.8°C temperature rise by 2100.[136]

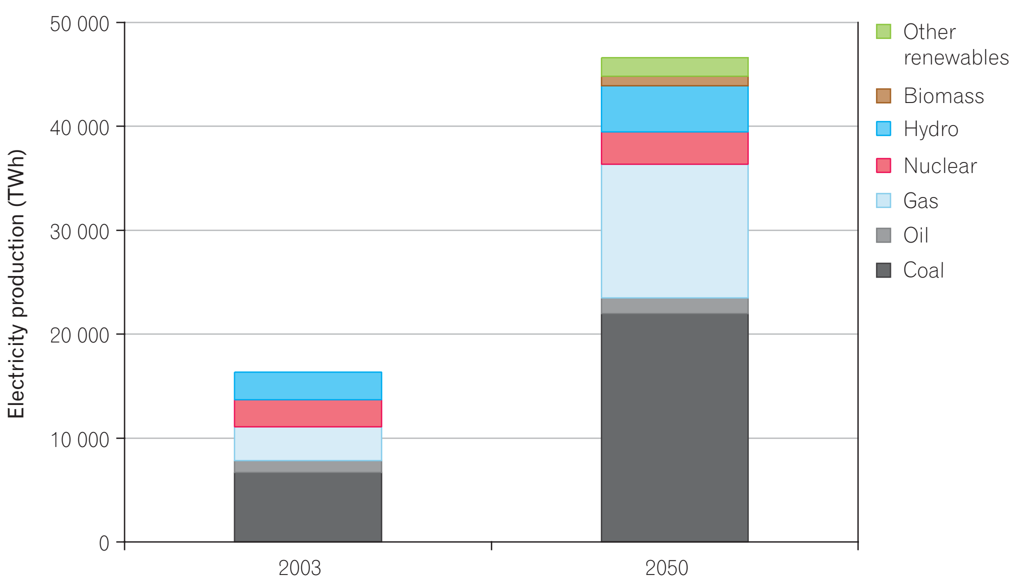
The 0.6°C warming observed over the past 100 years has been associated with increasing heat waves, more intense droughts, coral bleaching and shifts in ecosystems.[137] Additional warming of only 1°C could see 60 per cent of the Great Barrier Reef regularly bleached and cause considerable loss of coral biodiversity.[135,138,139] The larger and faster the change, the greater the risk of adverse impacts. Above 3°C, serious risk of large scale system disruption is more likely, such as destabilisation of the Greenland and Antarctic ice sheets. Collapse of these sheets would lead to centuries of irreversible sea level rise and coastal inundation around the world.[133–135]

7.2.2 Emissions from electricity generation

Globally, approximately 60 per cent of current greenhouse gas emissions arise from the production and use of energy.[140] The electricity sector is a particularly important source. CO_2 emissions from electricity generation have grown by 170 per cent since 1971, and in 2003 electricity generation accounted for 40 per cent of global CO_2 emissions. Of this, coal-fired electricity plants accounted for some 70 per cent, natural gas-fired plants for approximately 20 per cent and oil-fired plants for approximately 10 per cent.[30]

The International Energy Agency (IEA) projects that under current policy settings (ie 'business as usual'), global electricity production will almost triple between 2003 and 2050 (see Figure 7.2). Related CO_2 emissions are projected to rise by more than 2.5 times. The share of fossil fuels increases, eg coal-fired generation is projected to grow from 40 to 47 per cent and gas-fired generation from 19 to 28 per cent of total generation output.[30]

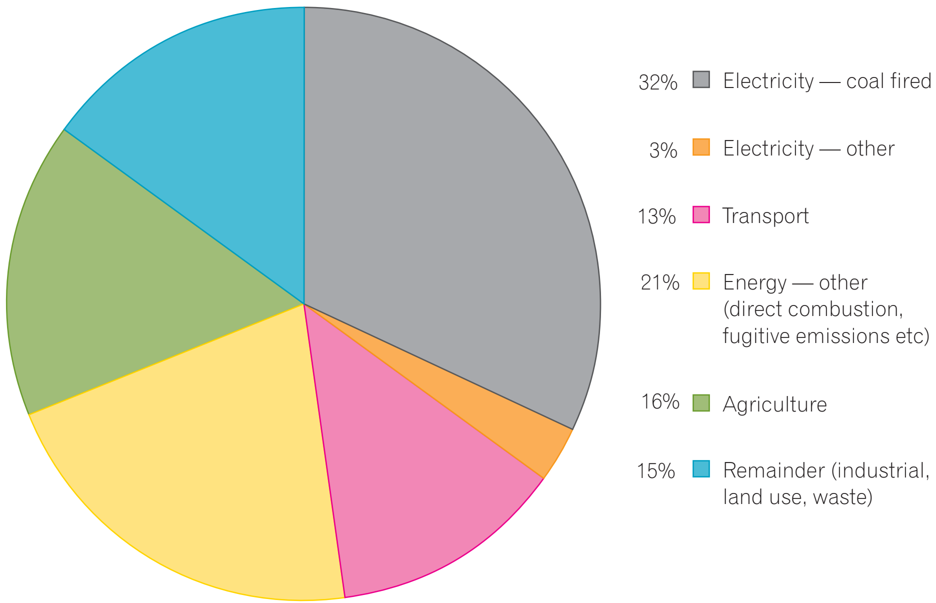
Figure 7.2 Global electricity production by generation type



TWh = terawatt hours

Source: IEA.[30] Projections for 2050 are under current policy settings.

Figure 7.3 Australia's greenhouse gas emissions, 2004



Note: Figures were calculated using the Kyoto Protocol accounting provisions (those applying to the Australian 108 per cent emissions target). Estimate for land use (includes land use change and forestry) is interim only.

Source: AGO[141]

The situation in Australia is similar. Total national emissions in 2004 were 564.7 million tonnes of CO_2-equivalent (CO_2-e).[38] Energy production and use (including electricity generation and transport) was the largest source, accounting for more than 68 per cent. Agriculture was the next largest contributor. The remainder of emissions were from land use, forestry, industrial processes and waste (see Figure 7.3).[141]

Emissions from electricity generation in Australia grew by more than 50 per cent between 1990 and 2004, to approximately 195 million tonnes of CO_2-e. Of this, 92.2 per cent was attributable to coal, 7 per cent to gas, and 0.8 per cent to oil and diesel. As discussed in Chapter 4, demand for electricity is projected to grow over the coming decades. If this demand is met by conventional fossil fuel technologies, Australia's greenhouse gas emissions will also continue to grow.

7.2.3 Abatement task

The scale and pace of emission reductions required to avoid or at least minimise dangerous climate change is vigorously debated. Nevertheless, the balance of scientific opinion is that avoiding dangerous climate change will require deep cuts in global emissions. To avoid more than doubling pre-industrial levels of greenhouse gases in the atmosphere, cuts in the order of 60 per cent are required by the end of the century.[58] Limiting future atmospheric concentrations to this level could limit twenty-first century warming to an estimated 1.5–2.9°C, potentially avoiding the more extreme projected impacts.[135] Deeper cuts are required sooner to achieve lower stabilisation levels.[134]

[38] CO_2-equivalent (CO_2-e) aggregates the impact of all greenhouse gases into a single measure. It adjusts for the fact that each gas has a different global warming potential, for example, 1 tonne of methane has an equivalent effect to 21 tonnes of CO_2.

Climate change is a global problem and emissions arise from everyday activities across all sectors of the economy. As a result, no single country, action or technology alone can deliver deep cuts. An effective response to climate change will require action across the board — by all major emitters, and across all sources of emissions.

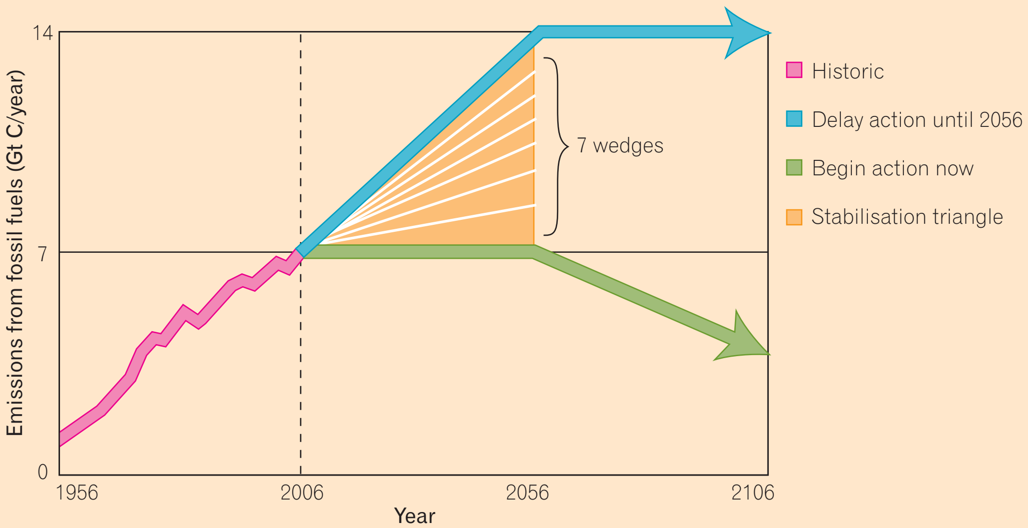
Box 7.1 Stabilisation wedges: a pathway to avoiding dangerous climate change?

The 'stabilisation wedges' concept developed by Princeton scientists Robert Socolow and Stephen Pacala helps to illustrate the overall abatement task.[142,143]

Socolow and Pacala suggest that, at the present rate of growth, emissions of CO_2 from fossil fuels will double by 2056. Even if the world then takes action to level them off, the atmospheric concentration will be headed to more than double pre-industrial levels. But if the world can flatten emissions now and then ramp them down, it should be possible to stabilise concentrations substantially below 560 ppm.

Between the growth and flatline pathways is the 'stabilisation triangle', which represents the minimum emission reductions the world would need to achieve in the coming 50 years. The triangle grows over the next 50 years to a total of 7 billion tonnes of carbon in 2056. The stabilisation triangle is then divided into seven 'wedges'. Each wedge cuts annual emissions by 1 billion tonnes of carbon[39] in 2056. The wedge is a useful unit because its size and time frame match what specific technologies and actions can achieve (Figure 7.4).

Figure 7.4 The stabilisation triangle and wedges



Source: Socolow and Pacala[143]

Socolow and Pacala have identified 15 technologies and actions that could achieve a wedge of abatement, including:

- efficiency improvements (eg double the fuel efficiency for 2 billion cars; cut electricity use in homes, offices and stores by 25 per cent)
- CO_2 capture and storage (eg introduce at 800 GW of coal plants)
- alternative energy sources replacing coal (eg add 700 GW of nuclear; add 2 million 1 MW windmills; add 1400 GW of gas)
- forestry and agricultural practices (eg stop all deforestation; apply conservation tilling to all cropland).

The list is not exhaustive, and not all options would be required to avoid doubling CO_2 concentrations. Many combinations of technologies and practices can fill the triangle. This work makes it clear that substantial reductions are possible, even if some options do not deliver or are excluded.

[39] 1 tonne of carbon is equivalent to 3.67 tonnes of CO_2-e, so 7 billion tonnes of carbon is equivalent to 25.7 billion tonnes of CO_2-e.

Numerous studies have attempted to quantify the cost of stabilising atmospheric levels of greenhouse gases. This is a difficult task, as it is hard enough to forecast the evolution of the global energy and economic system over the coming decade, let alone the coming century. Therefore, projections must be treated with considerable caution. Their value lies more in the insights they provide than the specific numbers.

Overall, the costs of reducing emissions are lower in scenarios involving a gradual transition from the world's present energy system towards a less carbon-intensive one. This minimises costs associated with premature retirement of existing capital stock and provides time for technology development. On the other hand, more rapid near-term action increases flexibility in moving towards stabilisation, reduces environmental and human risks and costs associated with changes in climate, and may stimulate more rapid deployment of existing low-emission technologies.[144]

Delaying emission reductions can result in more rapid warming, increasing the risk of exceeding critical climate thresholds and making dangerous impacts more likely.[145]

At a global economy-wide level, studies suggest deep cuts in greenhouse gas emissions could be achieved while maintaining economic growth over the coming century. A review by the Intergovernmental Panel on Climate Change found that deep cuts could be achieved at a cost of between 1 and 2 per cent of global gross domestic product (GDP) at 2100. Absolute GDP levels would still be substantially higher than today, as a result of the anticipated economic growth.[144] The small fall in future GDP needs to be set against the costs of climate change impacts, which are not factored into these studies.

A major assessment of the costs of climate change impacts was published in October 2006. This review, conducted by Sir Nicholas Stern for the United Kingdom Government, found that if the world does not act to cut emissions, the overall costs and risks of climate change will be equivalent to losing at least 5 per cent of global GDP each year. If a wider range of risks and impacts is taken into account, the costs could rise to 20 per cent of GDP or more, far more than the estimated cost of reducing emissions. The Stern review concluded that urgent and strong action to reduce emissions is clearly warranted.[132]

7.3 Electricity generation technologies compared

7.3.1 Nuclear power

Nuclear power, unlike fossil fuel, does not generate greenhouse gases directly. While nuclear fuels release energy through fission, fossil fuels release energy through combustion: the fuel (eg coal, gas, oil) combines with oxygen, releasing heat and producing CO_2. Nevertheless, greenhouse gases are generated during the nuclear fuel cycle. Emissions arise from mining and processing of the fuel, construction of the plant, disposal of spent fuel and by-products, and waste management and decommissioning.

Emission estimates vary widely due to the plant characteristics (eg type, capacity factor,[40] efficiency, lifetime) assessed. To enable meaningful comparisons, greenhouse gas emissions are expressed relative to the amount of electrical energy generated — either as grams of CO_2-e per kilowatt hour (g CO_2-e/kWh); or (scaled up) kilograms of CO_2-e per megawatt hour (kg CO_2-e/MWh).

[40] The capacity factor of a plant measures its actual electricity output relative to its theoretical maximum output (ie if it ran at full power all the time). In general, intermittent sources such as wind and solar have lower capacity factors (approx. 10–35 per cent), while baseload coal and nuclear plants have higher capacity factors (approx. 80–90 per cent). Peaking plants (typically open cycle gas turbines) tend to have low capacity factors.

Most published studies estimate that on a life cycle basis the emissions intensity of nuclear power is between 2 and 40 kg CO_2-e/MWh.[41] The average for Western Europe is estimated at 16 kgCO_2/MWh for a pressurised light water reactor.[147] Higher estimates generally assume that enrichment is done using diffusion technology, which uses a lot of electricity. If this electricity is generated from fossil fuels, it increases the overall greenhouse gas emissions. As discussed in Chapter 3, diffusion is being progressively replaced by centrifuge technology, which uses much less electricity. Over time this will reduce the emissions intensity of nuclear power.

The Taskforce commissioned the University of Sydney to conduct an independent study of the potential life cycle emissions of nuclear power in Australia.[146] Using a comprehensive methodology and conservative assumptions, this study estimated the life cycle emissions intensity of nuclear electricity in Australia to be between 10 and 130 kg CO_2-e/MWh. The lower end of this range would be seen if only centrifuge enrichment (rather than a mix of centrifuge and diffusion technology) was used, or if the overall greenhouse intensity of the Australian economy was lower. The higher end of this range would only be seen if extremely low grade uranium ores (ie much lower than current grades) were mined.[146]

7.3.2 Fossil fuel and renewables

Generally, fossil fuel technologies have the highest emissions intensity. Of these, natural gas is the lowest, black coal is intermediate and brown coal is the highest. Hydro and wind power, on the other hand, have the lowest greenhouse gas emissions intensity (depending on the technology and location[42]) while solar power is in between.

The University of Sydney developed emission intensity estimates for a range of currently available best practice electricity generation technologies under Australian conditions. These estimates are set out in Table 7.1 and Figure 7.5. As existing technologies improve and new technologies are developed, these figures will change. The efficiency of solar cell manufacturing and performance is improving rapidly; carbon capture and storage could potentially deliver 70 to 90 per cent reductions in emissions to atmosphere from fossil fuel technologies; and geothermal (hot dry rocks), tidal and wave generation technologies show promise.

Table 7.1 Estimated life cycle greenhouse gas emissions intensity of different technologies

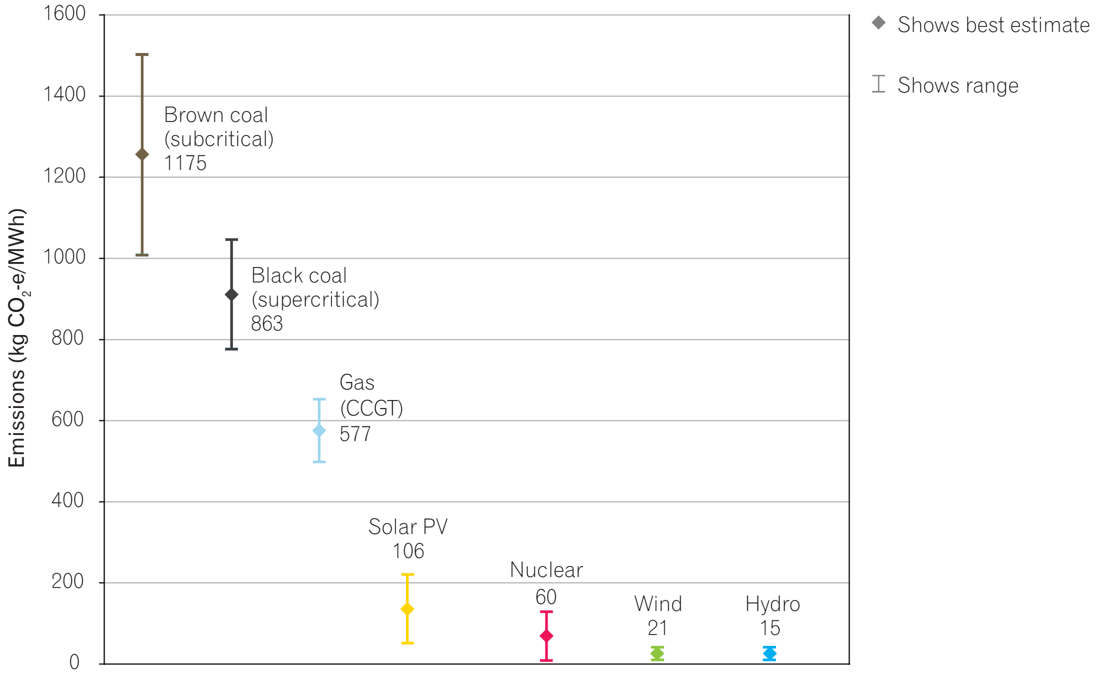
Technology	Emissions intensity (kg CO_2-e/MWh)	
	Best estimate	**Range**
Brown coal (subcritical)	1175	1011–1506
Black coal (subcritical)	941	843–1171
Black coal (supercritical)	863	774–1046
Natural gas (open cycle)	751	627–891
Natural gas (combined cycle)	577	491–655
Solar photovoltaics	106	53–217
Nuclear (light water reactor)	**60**	**10–130**
Wind turbines	21	13–40
Hydro (run-of-river)	15	6.5–44

Source: University of Sydney[146]

[41] See summary of life cycle studies in the University of Sydney report.[146]

[42] Hydro exhibits very low emissions in temperate regions; however, emissions may be much higher in tropical regions due to biomass decay (eg see Dones et al).[108]

Figure 7.5 Estimated life cycle greenhouse gas emissions intensity of different technologies



CO_2-e = carbon dioxide equivalent; MWh = megawatt hour; PV = photovoltaic; CCGT = combined cycle gas turbine. Source: University of Sydney[146]

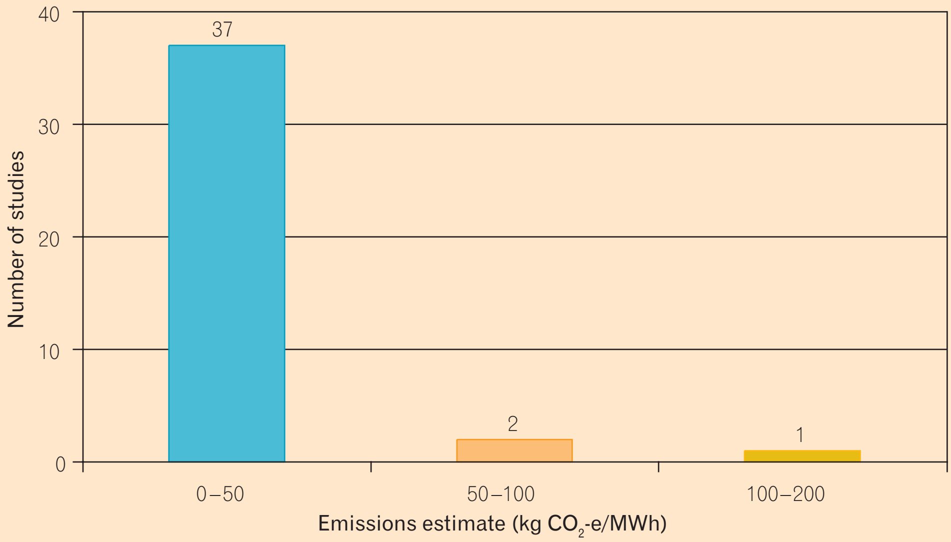
Taking into account full life cycle contributions, greenhouse gas emissions from nuclear power are roughly comparable to renewables and between 10 and 100 times less than natural gas and coal (see Box 7.2). This indicates there is great scope, both domestically and globally, to reduce growth in emissions by replacing fossil fuel plants with lower emission technologies such as nuclear.

Box 7.2 Is nuclear really a low emission technology?

Many submissions to this Review referred to the work of two physicists, Jan-Willem Storm van Leeuwen and Philip Smith, who estimate that life cycle CO_2 emissions of nuclear power in the United States are between 93 and 141 kg/MWh, and claim that nuclear power has limited potential to contribute to global emission reductions.[148,149]

This estimate is significantly higher than other published estimates. The University of Sydney identified 39 other studies with estimates ranging from 2 to 84 kg/MWh. Almost all were below 40 kg/MWh. Unlike Storm van Leeuwen and Smith's estimate, many of these were published in peer-reviewed journals, and some were independently verified. The Storm van Leeuwen and Smith study was the only one exceeding 100 kg/MWh.[146]

Figure 7.6 Estimated emissions for nuclear power



CO_2-e = carbon dioxide equivalent, MWh = megawatt hour

The University of Sydney found that while Storm van Leeuwen and Smith's input data is largely sound, the methodology used is not appropriate and tends to inflate energy use. This is particularly the case for construction and decommissioning; for example their estimate for energy used in construction is many times higher than other studies.

Life cycle emission estimates are strongly affected by the energy source. Fossil fuel energy inputs give higher emissions, while nuclear and renewable energy inputs give lower emissions.[108,146,150] Storm van Leeuwen and Smith assume almost all energy inputs are provided by fossil fuels. While this may be a reasonable assumption for some current operations in the United States, it is not true globally and will change in the future if there is a shift to lower carbon fuels.

Storm van Leeuwen and Smith also draw attention to the energy used to extract uranium from ore. They contend that once high quality uranium reserves are exhausted, it will take more energy to produce uranium than you get from nuclear power. Their calculations for energy use are not based on actual mining operations, rather they estimate energy use for hypothetical mines operating at unnecessarily high standards which are well beyond world's best practice. In addition, they dismiss in-situ leaching mines as wholly unsustainable.

The energy balance of nuclear power is a complex issue, as it is affected by a range of factors including ore grade and location, mining technology and fuel cycle. However it is clear that nuclear power currently produces far more energy than it uses. The University of Sydney, using conservative assumptions, found that nuclear power currently generates at least five times more energy than it uses.[146] The IEA estimates that known uranium reserves — which are of sufficient quality to give a net energy benefit — could fuel nuclear power for 85 years.[30] In contrast, the estimated lifetime of proven oil reserves is 43 years, and proven gas reserves is 64 years.[3] Uranium reserves are discussed further in Chapter 2.

7.3.3 Global abatement potential

By providing 15 per cent of the world's electricity, nuclear is already making an important contribution to constraining global greenhouse gas emissions. The International Atomic Energy Agency (IAEA) estimates that nuclear power annually avoids more than 2 billion tonnes of CO_2 emissions that would otherwise have been produced through burning fossil fuels.[151,152]

Future emissions from electricity generation can be reduced by reducing the amount of electricity used, and by accelerating the uptake of lower-emission generation technologies such as nuclear. Socolow and Pacala estimate that if 700 GW of nuclear power is installed over the next 50 years instead of conventional coal-fired plants, it could deliver a wedge of abatement (ie it could reduce global emissions by 3.67 billion tonnes of CO_2 in 2050).

Globally, the IEA suggests that expansion of nuclear power could reduce greenhouse gas emissions in 2050 by between 1.9 and 2.9 billion tonnes of CO_2.[30] This is based on emission reduction scenarios for the electricity generation sector in which nuclear generation grows by between 18 and 170 per cent (to 3100–7300 TWh) by 2050. In the most optimistic scenario nuclear provides 22 per cent of total electricity generation in 2050.

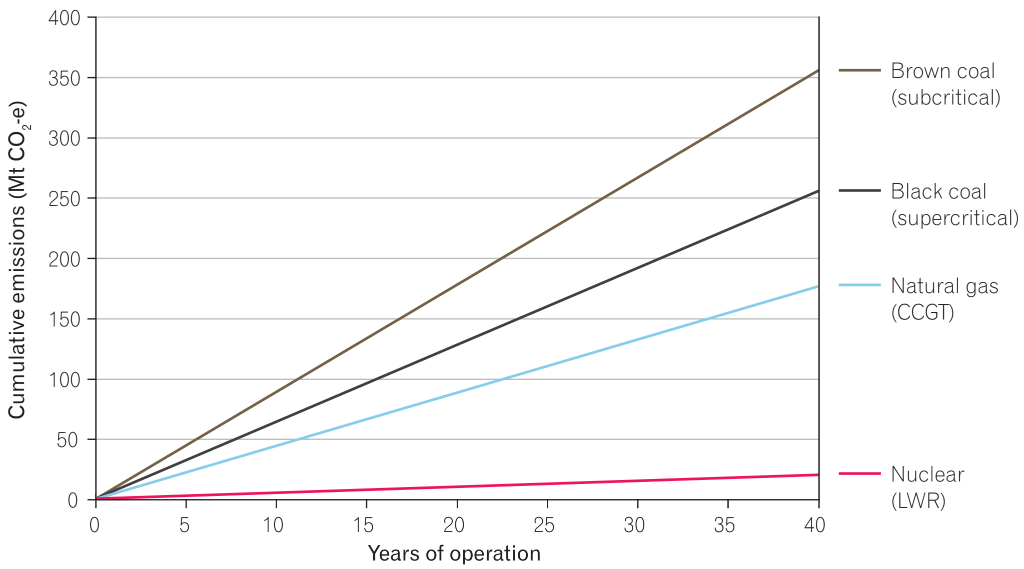
The IEA analysis indicates that nuclear could make an important contribution to the global abatement task in the energy sector — it delivers between 6 and 10 per cent of the total abatement achieved under the scenarios analysed to 2050. In combination with other measures it could help achieve deep cuts in emissions over the longer term.

It is generally accepted that no single technology or action can deliver the emission cuts required to avoid dangerous climate change. There is no 'silver bullet'. In the IEA scenarios, energy efficiency improvements make the greatest contribution (one-third to half of total abatement achieved). Carbon capture and storage technologies make a major contribution (more than 20 per cent of total abatement in most scenarios), while renewable energy, fuel switching, biofuels and nuclear also make significant contributions.[30]

7.3.4 Potential contribution in Australia

If Australia was to use nuclear power rather than conventional fossil fuel technologies to meet future electricity demand, then nuclear power would help reduce emissions growth. Figure 7.7 plots the total greenhouse gas emissions from different generation technologies and fuels over time. This illustrates how the greenhouse gas advantage of nuclear power grows over time.

Figure 7.7 Cumulative emissions from different generation fuels and technologies



CCGT = combined cycle gas turbine; LWR = light water reactor; Mt CO_2-e = megatonnes of carbon dioxide equivalent

Note: Assumes 1000 MW plant and 85 per cent capacity factor for all plants.

Source: UMPNER analysis based on University of Sydney life cycle emission estimates in Table 7.1.[146]

Emissions for a subcritical brown coal-fired power plant would be approximately 8.7 Mt CO_2-e/year, and for a supercritical black coal plant approximately 6.4 Mt CO_2-e/year. Combined cycle gas turbine (CCGT) plant emissions would be approximately 4.3 Mt CO_2-e/year. In contrast, nuclear power emissions would be less than 0.5 Mt CO_2-e/year.

Over a lifetime of 40 years, the emissions savings from nuclear power would be 332 Mt CO_2-e relative to a brown coal plant, 239 Mt CO_2-e relative to a black coal plant, or 154 Mt CO_2-e relative to a CCGT plant. As a reference point, Australia's total electricity sector greenhouse gas emissions in 2004 were 195 Mt CO_2-e.

The potential contribution of nuclear power to Australia's overall abatement task depends in part on our 'business as usual' emissions trajectory and desired level of emission reductions. For the purpose of this analysis the business as usual case is taken from projections by the Australian Bureau of Agricultural and Resource Economics (ABARE).[55] Using this data, in 2050 under current policy settings Australia's total emissions (excluding land use change and forestry) are projected to be 869 Mt CO_2-e (ie more than double 1990 levels). Electricity generation is projected to contribute 320 Mt CO_2-e in 2050, 37 per cent of the total.

Figure 7.8 shows the business as usual case (black line) and 1990 emissions (dotted line).

Figure 7.8 also illustrates two alternative scenarios to business as usual. In the 'fast build' case (represented by the red line), the first nuclear plant comes on line in 2020. Additional plants are added from 2025, growing to total capacity of 25 GW by 2050. This reduces annual emissions by almost 150 Mt CO_2-e in 2050, as indicated by the red arrow.

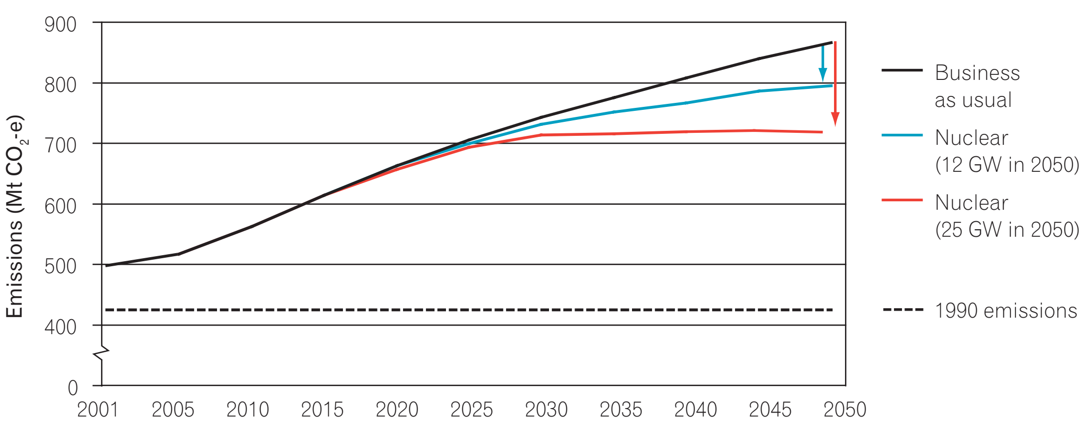
In the slow build case (blue line), the first nuclear plant comes on line in 2025, additional capacity is added from 2030, and total capacity is 12 GW in 2050. This reduces emissions by over 70 Mt CO_2-e in 2050, as indicated by the blue arrow.

These two scenarios reduce Australia's total emissions in 2050 by between 8 and 17 per cent relative to business as usual. This represents roughly one-fifth to almost one-half of the projected emissions from electricity generation. The estimates assume that nuclear displaces supercritical black coal generation and are based on current performance figures, so each 1 GW nuclear plant reduces annual emissions by approximately 6 Mt CO_2-e. If nuclear displaces gas, emission savings would be lower.

A number of recent studies examine the potential costs of cutting greenhouse gas emissions in Australia, and how costs vary under different policy approaches and technology mixes.[65,153,154] While the results of these studies are affected by the particular scenarios, assumptions and input data used, they provide some useful insights.

A report by CRA International which focused on the electricity generation sector found that the cost of reducing emissions from this sector are significantly lower if nuclear technology is available. Under one scenario, in which emissions were reduced to 25 per cent below 1990 levels by 2050, adding nuclear to the technology mix reduced total capital expenditure between 2010 and 2050 by 15 per cent (from $150 billion to $128 billion).[154] Similarly, ABARE modelling found that economy-wide costs are lower if a wider range of generation technologies is available. Under a scenario with quite limited deployment of nuclear, in 2050 costs were reduced by $2 billion (0.1 per cent of GDP) and annual emissions were cut by an additional 4 Mt of CO_2-e.

Figure 7.8 Potential to reduce Australia's emissions — illustrative scenarios to 2050



GW = gigawatts; Mt CO_2-e = megatonnes of carbon dioxide-equivalent

Note: Emissions exclude land use change and forestry.

Source: UMPNER analysis, based on ABARE projections[55] and University of Sydney emission intensities.[146]

CRA also analysed a number of carbon price, technology benchmark and mandatory emission limitation policies. It found that policies that expose all emissions to the same incentives for reduction (eg carbon price) provide the most efficient means to reduce emissions.[154] A report by Allen Consulting showed that to achieve the same climate outcome, early introduction of policies to reduce emissions was less costly than later action which required more abrupt reductions.[153]

These studies show that no single technology can alone deliver deep cuts in emissions and highlight that a broad suite of technologies and actions will be required to stabilise and then reduce Australia's emissions by 2050. They demonstrate that technology-neutral policy approaches can stimulate cost-effective action on both the demand and supply side of electricity generation. As a result, these approaches have great scope to stimulate emission reductions at least cost.

7.4 Other environmental impacts

7.4.1 Resource use and emissions

Comparisons of the impacts of electricity generation technologies indicate that the life cycle environmental impacts of nuclear power are significantly less than conventional fossil fuel technology, and on many measures similar to renewable energy.[108,155,156]

Energy density and land use

A key determinant of overall life cycle impacts is the energy density of different sources. Nuclear fission generates very high amounts of energy compared to fossil fuel combustion (over a year, a 1 GW nuclear plant would use approx. 1 tonne of U-235, while an equivalent coal-fired plant would use approx. 3 million tonnes of black coal). Both nuclear and fossil fuels have high energy densities relative to renewables.

While precise numbers depend on the specific technology, location and fuel source, studies indicate that over the full life cycle nuclear power and fossil fuel technologies use significantly less land than renewable technologies. Wind and biomass technologies have larger land requirements — 10 to 100 times more than nuclear power.[157]

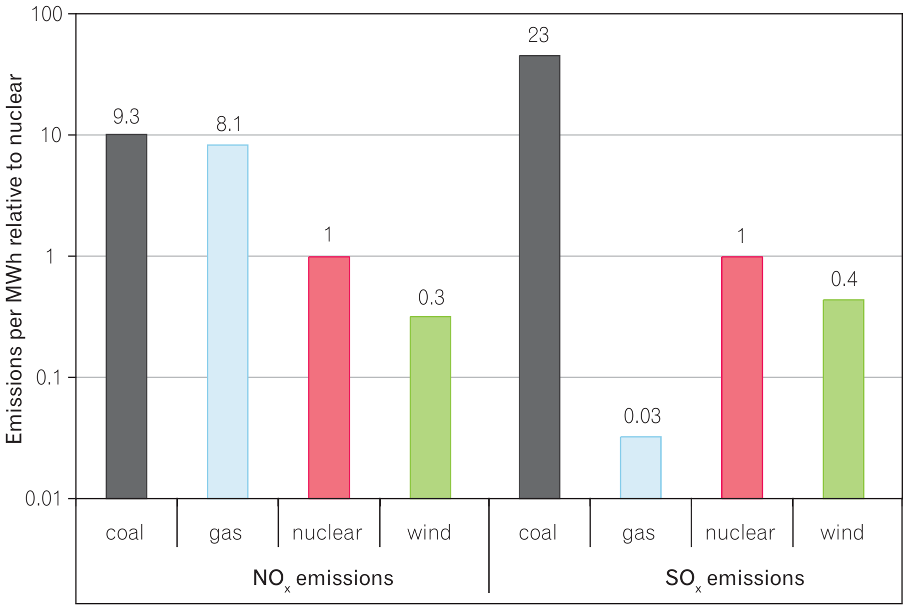
However simplistic comparisons may overstate the land requirements for renewables, many of which allow multiple concurrent uses of the land (eg wind turbines can be located on agricultural land, and solar photovoltaic cells can be installed on building roofs and facades). In addition, land area is just one aspect of location-related impacts. The value of a particular site — in environmental, aesthetic, cultural and economic terms — is also important. These values were at the forefront of concerns regarding the proposed Jabiluka mine in the Northern Territory.

Air pollution

In terms of air pollution, the performance of nuclear power and renewable technologies is significantly better than that of conventional fossil fuel plants. Fossil fuel combustion produces pollutants with environmental and health impacts, including sulphur oxides (SO_x), nitrogen oxides (NO_x) (which also contribute to climate change) and particulate matter (eg droplets or particles from smoke and dust). At high concentrations, these pollutants have significant health impacts, and some contribute to acid rain. These problems are generally less significant in Australia because of our relatively low population density, low sulphur content in coal, and greater distances between power stations.

Figure 7.9 illustrates the estimated relative levels of emissions of SO_x and NO_x from nuclear, fossil fuel and wind generation technologies from an Australian study. Emissions from nuclear power generation are substantially lower than coal, and somewhat higher than wind. In this study, SO_x emissions from natural gas were very low.

Figure 7.9 Estimated life cycle air pollution from different technologies



SO_x = Sulphur oxides; NO_x = nitrogen oxides; MWh = megawatt hour

Note: This graph uses a logarithmic scale, so each point on the vertical scale is ten times more than the last.

Source: Australian Coal Association[155]

Water

Water use is of particular interest in Australia, given the limited availability of water in many regions. The main uses of water in the nuclear fuel cycle are in mining and milling of uranium and for nuclear power plant cooling. However, it is important to note that many of these processes do not require potable (ie drinking) water and only a small fraction of the water used is actually consumed in the process. In addition, water use is not unique to nuclear activities and generic approaches to water resource management, such as allocation through licences, can be readily applied.

Water requirements and management issues are technology and location-specific. In uranium mining, underground and open-cut methods generally require more water than in-situ leaching (ISL). Overall, the process of ISL mining has considerably less environmental impact than other conventional mining techniques. While re-injection of the leach solution and liquid waste into the aquifer at the Beverley mine in South Australia increases the concentration of soluble ions, the groundwater affected is not potable and has no other apparent beneficial uses. In addition, it is widely believed that the water chemistry will return to pre-mining conditions within a timeframe of several years to decades.[158]

The proposed expansion of the Olympic Dam mine would increase annual water use four-fold from 12 000 to 48 000 megalitres. BHP Billiton is investigating the use of a coastal desalination plant to meet these needs, given the limited availability of water from the Great Artesian Basin.[17] The potential impacts of the desalination plant will be investigated in detail as part of the environmental impact assessment of the proposal.[159]

Nuclear power plants have similar water requirements to fossil fuel plants using steam turbine generators. Large volumes of water are used to cool the turbine condensers. The water can either be recirculated through evaporative cooling towers or drawn from and released to a large body of water (eg a river, lake or ocean).[160] Releases are typically regulated to minimise adverse heat-related impacts on the environment. In addition, nuclear and other steam turbine plants use small volumes of purified water to generate the steam. Water in the steam loop is continuously recycled.[161]

Access to water is therefore an important factor in site selection, both to ensure supply and to minimise any environmental impacts of the discharged warm water. If freshwater is not available, nuclear plants can use sea water for cooling. Sea water cooling is common in many countries, including Finland and Korea, and is also used in fossil fuel power stations such as the Gladstone power station in Queensland. Dry-cooling systems are also available, although these designs increase costs by up to 2 per cent. These use air as a coolant (like a car radiator), cutting water consumption by approximately 95 per cent.[161]

7.4.2 Radiation impacts

International radiation protection standards are primarily designed to protect human health. Until recently it has been assumed that these standards would incidentally protect flora and fauna as well. However, it is now agreed that additional standards and measures are required to protect other species, and a number of international organisations including the International Commission on Radiological Protection and the IAEA have established new work programs to this end.

Studies of the impacts of various stages of the nuclear fuel cycle on biota have generally concluded that effects on biota are very small.[162] A specific assessment of the impacts of Australia's Ranger mine concluded that it is highly unlikely that the operation of the mine has resulted in harm to aquatic biota arising from exposure to ionising radiation.[163]

Nuclear safety issues and the potential impacts of nuclear accidents are discussed in Chapter 6.

7.4.3 Environmental performance of Australian uranium mines

The environmental performance of the three current Australian uranium mines — Ranger, Olympic Dam and Beverley — has generally been of a high standard. While there have been a number of incidents at each mine involving spills of mildly radioactive fluids and leaks at tailings facilities, none have had a significant impact beyond the mine site.

Perhaps the most contentious environmental issue is the potential impact of the Ranger mine and possible future developments at Jabiluka. These ore deposits are surrounded by the World Heritage-listed wetlands of the Kakadu National Park (Figure 7.10) and so generate considerable public concern about possible contamination of surface and ground water. As a result, Ranger is one of the most highly scrutinised mines in the world. The Australian Government, through the Supervising Scientist Division, conducts ongoing monitoring and research programs to assess the mine's impact on the surrounding environment and oversees the regulatory regime implemented by the Northern Territory.

Figure 7.10 Ranger uranium mine, Northern Territory

Source: Skyscans/Energy Resources of Australia Ltd.

A large number of incidents have been reported at the Ranger mine over the period of its operation. This is often cited as evidence that the mining has had significant environmental impacts. However, the Supervising Scientist has analysed each of these incidents and concluded that, out of a total of 122 incidents reported since 1979, only one had been assessed as being of moderate ecological significance and one other had a significant impact on people working at the mine.[164] The large number of incidents reflects the rigour of the reporting framework, rather than the standard of environmental performance. Two further significant incidents occurred at Ranger in 2004 and led to the successful prosecution of Energy Resources of Australia, the company that runs Ranger. Nevertheless, the Supervising Scientist concluded that no harm had resulted to the environment and no significant long-term health effects would be expected from these incidents.

Assessment of environmental performance in the region has not been restricted to Australian authorities. In 1998, the World Heritage Committee requested a report from the Supervising Scientist on the risks associated with the proposed development of mining at Jabiluka. The Committee later established an Independent Scientific Panel (ISP) to assess the Supervising Scientist's report. The conclusion of the ISP was:

> 'Overall the ISP considers that the Supervising Scientist has identified all the principal risks to the natural values of the Kakadu World Heritage site that can presently be perceived to result from the Jabiluka Mill Alternative [JMA] proposal. These risks have been analysed in detail and have been quantified with a high degree of scientific certainty. Such analyses have shown the risks to be very small or negligible and that the development of the JMA should not threaten the World Heritage values of the Kakadu National Park.'[165]

Legacy issues, tailings management and provision for mine rehabilitation are discussed further in Chapter 5.

7.5 Conclusion

The world's energy systems face the twin challenges of accelerating climate change and growing demand for energy. Electricity generation therefore needs to move to a low emission footing. Nuclear power has a smaller environmental footprint than electricity from conventional fossil fuels, generating much lower greenhouse gas and air pollutant emissions and using comparable land and water resources. These impacts can be managed in the same way as for other industrial activities. If all generation technologies compete on a level playing field, nuclear could make an important contribution to the future generation mix, both globally and in Australia.

Chapter 8. Non-proliferation and security

- Export of Australian uranium takes place within the international nuclear non-proliferation regime.
- Australia has the most stringent requirements for the supply of uranium, including the requirement for an International Atomic Energy Agency (IAEA) Additional Protocol, which strengthens the safeguards regime.
- An increase in the volume of Australian uranium exports would not increase the risk of proliferation of nuclear weapons.
- Actual cases of proliferation have involved illegal supply networks, secret nuclear facilities and undeclared materials, not the diversion of declared materials from safeguarded facilities such as nuclear power plants.

Box 8.1 Nuclear proliferation

Nuclear proliferation is defined as an increase in the number of nuclear weapons in the world. Vertical proliferation is an increase in the size of nuclear arsenals of those countries that already possess nuclear weapons. Horizontal proliferation is an increase in the number of countries that have a nuclear explosive device.[28]

Typically, power reactors operate on low-enriched uranium (LEU, 3–5 per cent U-235), which is not suitable for use in nuclear weapons, and the plutonium contained in spent fuel from the normal operation of power reactors is not weapons grade. In order to produce weapons grade plutonium, a nuclear power plant would have to be run on short cycles or with continuous on-load refuelling, both of which are readily detectable under IAEA safeguards procedures. Fissile material for nuclear weapons can be obtained either by enriching uranium to high levels (90 per cent of U-235 or above is favoured for use in nuclear weapons [167]) or by reprocessing spent nuclear fuel to extract plutonium. Enrichment and reprocessing are therefore proliferation-sensitive technologies. While all activities in the nuclear fuel cycle are monitored by safeguards, enrichment and reprocessing are given special attention.

The prevention of nuclear war is of utmost importance. More states acquiring nuclear weapons would destabilise regional and international security and undermine global restraints on nuclear proliferation. The security threat posed by the proliferation of nuclear weapons has led to the establishment of the multi-faceted and evolving international nuclear non-proliferation regime, which comprises a network of treaties, institutions and the safeguards inspection regime.[166] To guard against their use for nuclear weapons, civilian nuclear programs and uranium trade are subject to international controls. Stringent safeguards are applied to ensure that Australian uranium is not diverted from peaceful purposes to weapons or other military purposes.

The cornerstone of the international nuclear non-proliferation regime is the Treaty on the Non-proliferation of Nuclear Weapons (NPT), supported by International Atomic Energy Agency (IAEA) safeguards. International instruments and organisations that complement the NPT and IAEA include: the United Nations Security Council, the Nuclear Suppliers Group, the Comprehensive Nuclear-Test-Ban Treaty and Nuclear Weapon Free Zones. There are a number of proposals to strengthen the regime by limiting the spread of proliferation-sensitive enrichment and reprocessing technologies.

8.1 Treaty on the Non-proliferation of Nuclear Weapons

The NPT aims to prevent the spread of nuclear weapons, advance and eventually achieve nuclear disarmament and facilitate the peaceful use of nuclear energy. The five recognised nuclear weapon states (the United States, Russia, the United Kingdom, France and China) and all NPT parties commit to reduce and ultimately eliminate nuclear weapons. The NPT nuclear weapon states still possess nuclear weapons, although most have substantially reduced their arsenals. Non-nuclear weapon states forgo nuclear weapons and accept IAEA safeguards to verify this commitment. The NPT has been central in ensuring that only nine countries are believed to possess or claim to possess nuclear weapons. A total of 189 countries have joined the NPT.[168]

Figure 8.1 IAEA safeguards inspector checking fuel rods

Source: IAEA

Australia signed the NPT in 1970 and ratified it in 1973. In the 1950s and 1960s, prior to the NPT, Australia was one of a number of countries which had not ruled out the option of developing nuclear weapons. An important factor in Australia deciding against the nuclear weapons option was the strong support the NPT was attracting. Ratification of the NPT represents an international legal commitment by Australia that it will not acquire a nuclear weapon. The assurance provided by the NPT and IAEA safeguards that nuclear activities are peaceful provides the foundation for responsible trade and cooperation in the peaceful uses of nuclear energy, including Australia's uranium exports.[169]

The NPT is the most widely supported arms control treaty — only India, Pakistan and Israel have never joined. India and Pakistan have developed nuclear weapons. Since 1998, India and Pakistan have maintained a moratorium on nuclear testing. North Korea joined, but claims to have withdrawn, and in October 2006 announced it had conducted an underground nuclear test.[170] Israel has nuclear activities that are not safeguarded and there is speculation that it is nuclear weapons capable.[169] South Africa developed nuclear weapons outside the NPT but relinquished these in 1991 when it joined the NPT as a non-nuclear weapon state. IAEA inspectors subsequently verified its nuclear dismantlement.

8.2 Other elements of the non-proliferation regime

Nuclear Suppliers Group (NSG)

The NSG was created in 1974. Operating by consensus, the NSG establishes guidelines that harmonise conditions of supply to prevent civil nuclear trade contributing to nuclear weapons. The NSG now comprises 45 states, including all the major suppliers of uranium, nuclear fuel cycle services and nuclear technology. Australia is a member of the NSG. The NSG is working toward establishing criteria to determine eligibility for the receipt of proliferation-sensitive equipment and technology.[171]

Nuclear Weapon Free Zones (NWFZ)

NWFZ contain a more comprehensive commitment to forgo nuclear weapons than the NPT. Not only do the parties reject the acquisition or use of nuclear weapons themselves, they also preclude others from producing, storing, installing, testing or deploying nuclear weapons on their territories. Australia is a party to the South Pacific Nuclear Free Zone (Treaty of Rarotonga), which was established in 1986. The Southeast Asia Nuclear Weapon Free Zone entered into force in 1997 covering countries in Southeast Asia.[169]

United States–India civil nuclear cooperation

United States President Bush and Indian Prime Minister Singh on 2 March 2006 announced agreement on a plan to separate India's civil and military nuclear facilities, which will allow for the United States to supply India with nuclear fuel and resume civil nuclear cooperation with India.[172] The agreement is seen by some as potentially damaging the nuclear non-proliferation regime, while others point to the proliferation benefits because of India's commitment to place 14 of its 22 thermal power reactors under permanent IAEA safeguards and align its export control policies with international standards.[173] Before the agreement takes effect, it must be approved by the United States Congress and the NSG must agree to create an exception to its guidelines.

8.2.1 Nuclear energy and proliferation

Most nuclear power plants present a low proliferation risk, although on-load refuelling reactors and fast breeder reactors present a higher risk (see Appendix P). Typical reactors produce plutonium in spent fuel,[43] although reactor-grade plutonium is not favourable for use in nuclear weapons.[28,174] While plutonium from spent power reactor fuel could theoretically be used to develop a crude nuclear device such as a dirty bomb (see Box 8.4), there has been no known successful nuclear explosion using reactor-grade plutonium from light water reactor spent fuel.[44] To produce weapons-grade plutonium in a typical power reactor would require abnormal operation (a much shorter operating cycle), which would be apparent under IAEA safeguards. Further, the reactor spent fuel must be reprocessed before use in a nuclear weapon, a significant technical hurdle.[175]

[43] The isotope Pu-239 is a key fissile component in nuclear weapons. The build up of the heavier isotope Pu-240 when fuel is left in reactors undermines the suitability of the material for use in weapons.

[44] In 1962, the United States conducted a nuclear test using what was thought to be 'fuel-grade' plutonium, an intermediate category between weapons-grade and reactor-grade, but the results of this test are not publicly available.

Table 8.1 Nuclear weapons technology development[175]

Countries with nuclear weapons	Nuclear Weapons Technology and Nuclear Energy
China, France, Russia, UK, US	The NPT nuclear weapon states developed nuclear weapons before they developed nuclear energy programs.
India	India completed its first energy reactor in 1969, and conducted its first nuclear explosion in 1974 using plutonium produced in a research reactor, which commenced operation in 1960.
Pakistan	Pakistan developed its KANUPP energy reactor at about the same time as the development of its uranium enrichment program. Pakistan's nuclear weapons were based on HEU, while the KANUPP reactor operates on natural uranium.
Israel	Israel's possession of nuclear weapons has never been officially confirmed. Israel does not have a nuclear energy program.
North Korea	North Korea has tested a nuclear weapon. North Korea does not have an operational nuclear energy industry, but does have a research reactor.

The absence of a civil nuclear industry is not likely to affect a decision to develop nuclear weapons. As outlined in Table 8.1, countries thought to currently possess nuclear weapons developed them separately from civilian power programs.

8.3 Challenges to the non-proliferation regime

The nuclear non-proliferation regime has come under challenge by countries developing secret weapons programs while party to the NPT.[169] IAEA inspections have found that Romania,[45] Iraq, North Korea, Libya and Iran have been in non-compliance with their IAEA safeguards agreements. Libya subsequently renounced nuclear weapons, which was verified by the IAEA.[179] A nuclear weapons program in Iraq was discovered after the first Gulf War. In 2004, the United States Central Intelligence Agency Iraq Survey Group confirmed that Iraq had effectively ended its nuclear program.[180,181]

In 2003, North Korea announced its withdrawal from the NPT. This highlighted the risk of states acquiring or developing sensitive nuclear technology for ostensibly peaceful use on the basis of being an NPT member, and subsequently withdrawing from the NPT to develop nuclear weapons. Since 1993, the IAEA has drawn the conclusion that North Korea is in non-compliance with its safeguards obligations.[182] In February 2005, North Korea first claimed that it had produced nuclear weapons. The six-party talks, comprising North Korea, the United States, China, South Korea, Japan and Russia, were established to find a peaceful resolution to the North Korean nuclear weapons issue.[183] In October 2006, North Korea announced that it had conducted an underground nuclear test.[170] The test was confirmed by the United States Government.[184]

In November 2003, the IAEA reported that Iran's nuclear program consisted of 'a practically complete front end of a nuclear fuel cycle.'[185] The IAEA found that in pursuing these activities in secret, Iran had failed to meet its obligations under its safeguards agreement. These sensitive nuclear activities, which Iran has admitted conducting in secret for nearly two decades, have raised international concerns that it may be seeking to develop nuclear weapons.[186] Iran has also pursued other activities relevant to the production of nuclear weapons. In February 2006, the IAEA referred Iran to the United Nations Security Council. On 31 July 2006, the Security Council passed a resolution mandating the suspension of all uranium enrichment activities in Iran.[187]

[45] In 1992, 470 g of plutonium were discovered in a secret laboratory of the Atomic Energy Institute in Romania. The IAEA was invited to conduct a special inspection to resolve the matter, which had taken place some years earlier under the previous Romanian regime. Romania is now in compliance with IAEA safeguards.[176,177] One significant quantity of nuclear material is the amount for which manufacture of a nuclear device cannot be excluded. The IAEA defines this as 8 kg of plutonium or 25 kg of U-235 in HEU.[178]

In 2004, Abdul Qadeer Khan, the architect of the nuclear weapons program in Pakistan, admitted that he had organised a clandestine network to supply Iran, Libya and North Korea with uranium enrichment technology. Khan used his senior position to develop his illegal network, which exploited weak enforcement of export controls in several countries. The Pakistani Government has stated that Khan acted independently and without the knowledge of authorities (more detail in Appendix P).[188]

8.4 Expanding the non-proliferation regime

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) reinforces other elements of the nuclear non-proliferation regime by banning all nuclear explosions. By December 2006, the CTBT had been signed by 177 countries and ratified by 137 countries, including Australia. However, 10 of the 44 specified countries which must ratify the CTBT to trigger its entry into force have yet to do so. All nuclear weapon states have signed, but the United States and China are yet to ratify. While the Treaty is yet to enter into force, the Treaty's International Monitoring System is in the process of being installed and is partly operational.[169,189]

A Fissile Material Cut-off Treaty (FMCT) would strengthen the non-proliferation regime by banning the further production of fissile material for nuclear weapons as a means of capping the amount of fissile material available for nuclear weapons use. The negotiation of an FMCT has been blocked for years by deadlock in the United Nations Conference on Disarmament.[169]

8.4.1 Limiting the spread of proliferation-sensitive nuclear technologies

The proliferation cases outlined in 8.3 underscore the dangers of inadequate controls on international trade and technology transfers, and the challenge to the NPT posed by the spread of proliferation-sensitive enrichment and reprocessing technologies. There are a number of proposals that aim to limit the spread of sensitive technologies. These seek to remove the need for countries to develop sensitive nuclear technologies by ensuring the supply of low-enriched nuclear fuel. In 2005, an IAEA report outlined possible multilateral approaches to the fuel cycle: multilateral fuel leasing and spent fuel take-back, a fuel bank under multilateral control, fuel supply assurances and conversion of existing proliferation-sensitive facilities to multilateral control.[99,166]

United States policy opposes the supply of enrichment and reprocessing equipment and technology to countries which do not already possess 'full scale, functioning enrichment and reprocessing plants'. [190] In 2006, the United States proposed the Global Nuclear Energy Partnership (GNEP), which envisages a fuel leasing system where fuel supplier nations that hold enrichment and reprocessing capabilities would provide enriched uranium to conventional light water nuclear power plants located in user nations. Used fuel would be returned to a fuel supplier nation and recycled using a proposed technology that does not result in separated plutonium, therefore minimising the proliferation risk. The Generation IV Forum (GIF) also proposes the development of more proliferation-resistant nuclear technologies.[166,174]

In 2004, G8[46] leaders called for a moratorium on the export of proliferation-sensitive nuclear technologies to additional states until criteria 'consistent with global non-proliferation norms' were developed by the NSG.[191] G8 leaders agreed in 2005 and again in 2006 to extend the moratorium. Separately in 2005, IAEA Director General ElBaradei called for a five year moratorium on all new enrichment and reprocessing facilities.[166,192]

Russia has proposed a network of multination centres to provide nuclear fuel cycle services on a non-discriminatory basis and under the control of the IAEA. The Nuclear Threat Initiative, an independent organisation based in the United States, has pledged US$50 million towards an IAEA-managed fuel reserve. In June 2006, a group of fuel suppliers (France, Germany, the Netherlands, Russia, the United Kingdom and the United States) proposed a mechanism for the reliable access to nuclear fuel.[173] Separately, Japan has proposed a mechanism for increased transparency in the international nuclear fuel market and Germany has proposed a multination fuel cycle service in a neutral state, which would guarantee supply of nuclear fuel.

Nuclear fuel assurance proposals date back to the 1970s, but none have come to fruition due to legal, diplomatic and technical hurdles. Some countries have concerns about restrictions on enrichment and reprocessing technology that infringe on what they claim to be a 'right' under the NPT to nuclear technologies for peaceful purposes.[193] Others argue these rights are not unqualified and do not automatically extend to proliferation-sensitive technologies.[166]

8.5 Safeguards

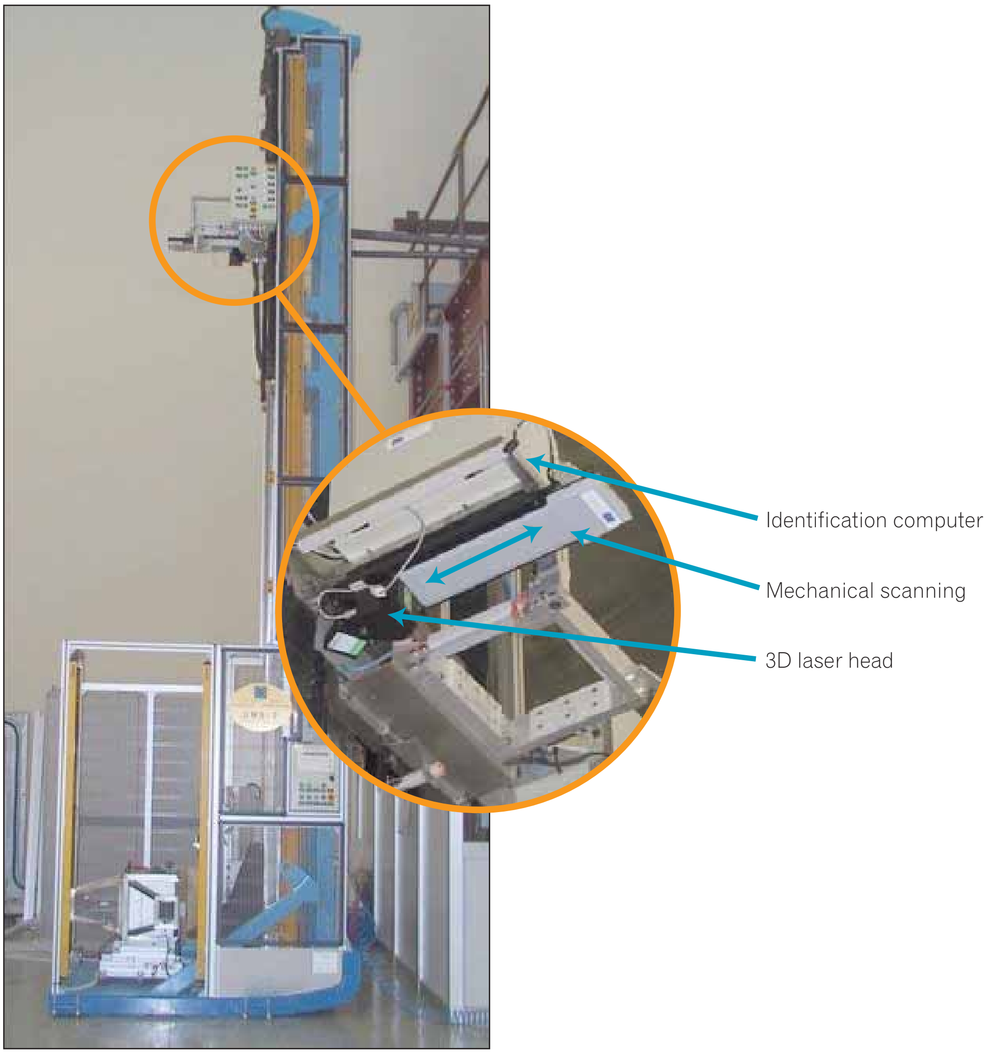
Safeguards are a system of technical measures — including inspections, measurements and information analysis — through which the IAEA can verify that a country is following its international commitments to not use nuclear programs for nuclear weapons purposes.

For the period from the early 1990s to 2003 the IAEA operated under a zero real growth budget, in line with other United Nations bodies. In 2003, the IAEA increased the regular safeguards budget by about 22 per cent over 4 years. Savings in safeguards costs are expected from the introduction of 'integrated safeguards', which allow the rationalisation of safeguards activities in states where the IAEA has concluded there is no undeclared nuclear material or activity. These savings will be available to offset increasing costs in other areas of safeguards implementation.[169]

Weaknesses in the safeguards system identified by the clandestine nuclear weapons program in Iraq were addressed by the introduction of new safeguards methods and technologies and the Additional Protocol. This extends IAEA inspection, information and access rights, enabling the IAEA to provide assurance not only that declared nuclear activity is peaceful, but also on the absence of undeclared nuclear materials and activities (Figure 8.2).

[46] The Group of Eight (G8) is an unofficial forum of the leaders of large industrialised democracies (Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, the United States and the European Union).

Figure 8.2 Unattended monitoring stations are designed to provide continuous monitoring of fresh fuel assemblies in a nuclear fuel fabrication plant



Source: European Commission — Joint Research Centre, Institute for the Protection and Security of the Citizen, Nuclear Safeguards Unit, Ispra, Italy.

Adoption of an Additional Protocol is now a condition for the supply of Australian uranium to non-nuclear weapon states. No other uranium exporter has this requirement. Safeguards measures, including under Additional Protocols include:[194]

- inspections to confirm that nuclear material holdings correspond to accounts and reports provided to the IAEA
- short-notice (from 2 to 24 hours) access to all buildings on a nuclear site
- examination of records and other visual observation
- environmental sampling (including beyond declared locations)
- radiation detection and measurement devices
- application of seals and other identifying and tamper-indicating devices
- unattended and remote monitoring of movements of nuclear material
- transmission of authenticated and encrypted safeguards-relevant data
- the right to verify design information over the life cycle of a facility, including decommissioning.

While all fuel cycle activities are covered by Australia's safeguards agreement with the IAEA, a decision to enrich uranium in Australia would require the management of international perceptions, given that enrichment is a proliferation-sensitive technology.

Box 8.2 Uranium

Uranium is an abundant mineral in the earth's crust and oceans (see Figure 2.3) and is available to any country willing to meet the cost of extraction. Only relatively small quantities are required to produce nuclear weapons. The minimum quantity of uranium ore concentrate as U_3O_8 required for the production of a nuclear weapon is 5 tonnes. By contrast, approximately 200 tonnes are required to operate a 1000 MW nuclear power plant for one year.[195] All nuclear weapon states have enough indigenous uranium for their military programs. A country could develop nuclear weapons irrespective of uranium supplied for electricity.[28] Publicly available information states that all the NPT nuclear weapons states ceased production of fissile material for nuclear weapons in the 1980s or 1990s.[175]

8.6 Australia's uranium export policy

Australian uranium exports may be used only for peaceful, non-weapons and non-military purposes. For the supply of Australian uranium and nuclear material derived from its use — Australian obligated nuclear material (AONM)[47] — receiving states must:[196]

- be party to and comply with the NPT
- have a bilateral safeguards agreement with Australia
- in the case of a non-nuclear weapon state, have an Additional Protocol with the IAEA.

These requirements are verified through IAEA safeguards inspections. In addition to IAEA safeguards, Australia's bilateral safeguards agreements apply specific conditions to AONM, such that it:

- may be used only for exclusively peaceful non-military purposes
- is covered by IAEA safeguards for the full life of the material or until it is legitimately removed from safeguards
- is covered by fallback safeguards in the event that IAEA safeguards no longer apply for any reason

[47] Depleted uranium sourced from Australian uranium is covered by Australia's safeguards requirements and cannot be used for any military application.

- cannot be transferred to a third party for enrichment beyond 20 per cent of U-235 and for reprocessing without prior Australian consent
- can only be received by countries that apply internationally accepted physical security standards.

Bilateral safeguards treaty parties are carefully selected. A breach of Australia's safeguards conditions by a recipient state would result in international condemnation and the loss of commercial supplies of Australian uranium, which would have an impact on nuclear energy infrastructure. While future diversion might occur, Australia's policy and practice on uranium supply seeks to minimise this risk.[159]

While Australian uranium is fully safeguarded, it is impossible to track individual atoms of uranium through the fuel cycle. Australia is able to verify that its exports do not contribute to military applications by applying safeguards obligations to the overall quantity of material it exports. Tracking quantities rather than atoms is established international practice, known as the equivalence principle (Box 8.3).

Box 8.3 Equivalence

Atoms of uranium supplied to conversion, enrichment and reprocessing plants are not separately tracked through the facility. Batches of material supplied from different sources are co-mingled inside the plant during processing. An equivalent amount of the plant's output is then allocated to particular customers on an accounting basis. This takes into account the quality of nuclear material. A simple banking analogy illustrates these principles — bank notes and coins given to a customer making a withdrawal are not physically those previously deposited by the same customer.[197] Australian uranium must be covered by the recipient's safeguards agreement with the IAEA. In the case of non-nuclear weapon states, all nuclear material in the country is required to be subject to safeguards. Therefore Australian uranium will only be mixed with safeguarded material, and all facilities are safeguarded.

8.6.1 Fuel leasing

Proponents of nuclear fuel leasing suggest that in order to enhance safeguards on Australian uranium exports, some Australian uranium could be leased to user utilities, with the spent fuel being returned to Australia for disposal.[54,174] They argue that this would reduce the incentives to build additional uranium enrichment and plutonium reprocessing plants as Australian ownership would ensure the use of existing safeguarded facilities. The Australian Safeguards and Non-proliferation Office (ASNO) considers that nuclear fuel leasing does not strengthen current safeguards arrangements because it does not '… address the real proliferation risk. Actual cases (Iraq, North Korea, Libya, Iran) show the danger lies, not with diversion of declared materials from safeguarded facilities, but with clandestine nuclear facilities and undeclared materials. IAEA safeguards have been demonstrated to be highly effective in deterring diversion of declared materials.' ASNO also argues that if it is acceptable to have our uranium processed at the 'front end' by countries we trust, then this should also be acceptable at the 'back end' (eg for spent fuel).[174]

The non-proliferation credentials of the nuclear fuel leasing concept need to be tested in the context of proposals for multilateral approaches to the nuclear fuel cycle as discussed in section 8.4. The nuclear fuel leasing framework typically requires the return of spent fuel rods for long term storage in a host country. Proponents see significant commercial appeal in providing such a global repository. However, whether as part of a leasing model, or simply the presumed commercial merits of Australia providing a regional or global nuclear waste repository, this idea remains contentious.

8.7 Nuclear security

According to the IAEA, possible terrorist scenarios in relation to nuclear material are: theft of a nuclear weapon, theft of nuclear or radiological material and sabotage.[198] There are, however, technical and regulatory obstacles to terrorists obtaining nuclear materials or weapons. The ASNO submission states that ‘it is highly unlikely that al-Qa’ida or other terrorist organisations have stolen or purchased a nuclear weapon or the combination of fissile material, physical infrastructure and technical expertise necessary to build their own improvised nuclear device’.[174]

Uranium ore concentrate (such as yellowcake) is of low security concern due to its low levels of fissile U-235. The nuclear materials used in uranium mining, conversion, enrichment and fuel fabrication present minimal risk to public health and safety. The consequences of sabotage on these facilities would be low when compared to a similar act against other industrial facilities, which often use larger quantities of hazardous materials.

Spent fuel poses a greater potential risk because it contains highly radioactive fission products — although this gives it a high degree of self-protection against theft. Spent fuel is present in reactor cores, reactor storage ponds, storage facilities and reprocessing plants.[174] Over the past 35 years there have been more than 20 000 transfers of spent fuel worldwide, by sea, road, rail and air, with no significant security incident. Spent fuel containers are designed to withstand accidents or attack. An Electric Power Research Institute (EPRI) evaluation showed that the container body withstands a direct impact from an aircraft engine strike without breaching.[199] This conclusion is supported by other studies.[174,200]

The key for security at a nuclear reactor is robustness and defence in depth that requires redundant, diverse and reliable safety systems (Figure 8.3). Security measures include:

- physical barriers and isolation zones
- well-trained and well-equipped guards
- surveillance and patrols of the perimeter fence
- search of all entering vehicles and persons
- intrusion detection aids, such as closed-circuit television and alarm devices
- bullet-resisting barriers to critical areas
- coordinated emergency plans with police, fire, and emergency management organisations
- regular drills
- staff security clearances.[201]

Studies carried out for the Sizewell B public inquiry in the United Kingdom concluded that in a worst case scenario, if a military aircraft were to strike the reactor building, there would be a 3–4 per cent chance of significant release of radioactive material.[202] The United States Nuclear Energy Institute rule out breach of US-style reactor containment structures by large aircraft because an aircraft would be unlikely to strike at the angles and speeds necessary to cause sufficient damage. A study by EPRI using computer analyses found that robust containment structures at modern US power reactors were not breached by the impact of the largest commercial airliner. Modern power plant reactor structures are similarly resistant to rocket, truck bomb or boat attack.[128,174,199] A new build of reactors in Australia would incorporate robust physical protection measures to mitigate against an attack.

Figure 8.3 Security features at the new ANSTO Open Pool Light water (OPAL) research reactor in Sydney

To counter terrorist and other security threats, international standards of physical protection are applied to nuclear material and facilities in Australia. Australia's bilateral safeguards agreements include a requirement that internationally agreed standards of physical security are applied to nuclear material in the country concerned. International standards of security for nuclear facilities are established by the Convention on the Physical Protection of Nuclear Material (CPPNM) and IAEA guidelines. These standards are administered in Australia through the permit system under the *Nuclear Non-Proliferation (Safeguards) Act 1987*. Ratification of amendments broadening the coverage of the CPPNM from international transport to domestic use, storage and transport is under consideration by the Australian parliament.

Box 8.4 Dirty bombs

Radioactive sources are used widely for a range of peaceful purposes. While they cannot be developed into nuclear weapons, some radioactive sources could be attached to conventional explosive devices to create radiological weapons or 'dirty bombs'. There has been no known use of a dirty bomb. Australia has strong domestic measures to secure its radioactive sources.[169,203]

Because dirty bombs seek to disperse radioactive material, rather than relying on nuclear chain reactions, the impact would be minor when compared with a highly destructive nuclear weapon. In most instances, the conventional explosive itself would have more immediate lethal impact than the radioactive material, and would be localised. The Australasian Radiation Protection Society (ARPS) has determined that the likely health impacts of the airborne radioactive dust from a dirty bomb would be minor. However, there could be significant disruption to the community and costs associated with decontamination.[169,204]

8.7.1 Critical infrastructure

A secure, reliable supply of energy to industry and households is central to economic development and community wellbeing. Australia has taken steps to identify and protect critical infrastructure, including existing energy infrastructure. The baseload of a typical nuclear power plant is similar to that of a typical coal or gas power plant and there is reserve capacity to take into account unexpected outages for any of the power stations in the network. In terms of maintaining critical energy infrastructure, the removal from the power grid of a nuclear power plant for whatever reason would be no different than the removal of a coal or gas power plant.

8.8 Conclusion

Australia's uranium supply policy reinforces the international nuclear non-proliferation regime and verifies that Australian obligated nuclear material does not contribute to nuclear weapon programs. The requirement that non-nuclear weapon states receiving Australian uranium have in place an Additional Protocol strengthens the non-proliferation regime by ensuring that the IAEA has broad access and inspection rights in the recipient country. The amount of uranium required for a nuclear weapon is relatively small and, since uranium is ubiquitous in the earth's crust, any country that wished to develop a weapon need not rely on the import of uranium. Increasing Australian uranium exports in line with Australia's uranium supply requirements would not increase the risk of proliferation of nuclear weapons. The greatest proliferation risk arises from undeclared centrifuge enrichment plants capable of producing HEU for use in weapons.

Chapter 9. Regulation

- An efficient and transparent regulatory regime achieves good health, safety, security and environmental protection outcomes for uranium mining, transportation, radioactive waste management, and exports and imports.
- Regulation of uranium mining needs to be rationalised.
- A single national regulator for radiation safety, nuclear safety, security, safeguards, and related impacts on the environment would be desirable to cover all nuclear fuel cycle activities.
- Legislative prohibitions on enrichment, fuel fabrication, reprocessing and nuclear power plants would need to be removed before any of these activities can occur in Australia.

9.1 Australia's international commitments

Australia is a party to the international legal instruments relevant to its current nuclear activities and is implementing all current international obligations through domestic law and administrative arrangements.[166]

Under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), Australia has undertaken to accept International Atomic Energy Agency (IAEA) safeguards set out in the Agreement between Australia and the IAEA for the Application of Safeguards in Connection with the NPT. Australia has also ratified the Additional Protocol to its safeguards agreement with the IAEA (see Chapter 8).

As a member of the Zangger Committee and the Nuclear Suppliers Group (NSG), Australia has agreed to export controls over nuclear material, equipment, technology, and dual-use items and technology. Australia has parallel export control commitments under the South Pacific Nuclear Free Zone Treaty.

Australia is a party to the Convention on the Physical Protection of Nuclear Material (CPPNM).[48] The Convention establishes the standards for the physical protection of nuclear material and nuclear facilities. The IAEA Information Circular INFCIRC/225/Rev.4 provides detailed guidance on the physical security standards applicable to nuclear material and facilities. Australia implements the standards in the CPPNM and INFCIRC/225/Rev.4.[49]

Australia is a party to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The Joint Convention establishes a harmonised approach to national waste management practices and standards. Australia is also a party to the Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter[50] and the Convention for the Protection of the Natural Resources and Environment of the South Pacific Region.[51]

International transport of radioactive material is subject to two sets of rules: transboundary movement rules and technical standard rules.[52] The IAEA Transport Regulations reflect international best practice and are incorporated into Australian domestic legislation (see Appendix Q for more detail on Australia's international commitments).

[48] Australia is in the process of ratifying the Amendment to the Convention on the Physical Protection of Nuclear Material that will strengthen the Convention.

[49] Although IAEA Information Circulars are not directly binding on countries, the standards outlined in INFCIRC/225/Rev.4 have been widely implemented among IAEA member states.

[50] Also known as the London Convention.

[51] Also known as the SPREP Convention.

[52] For example, the standard of packaging for the transportation of radioactive material.

9.2 Australia's existing regulatory regime

Australia's existing regulatory regime extends to uranium mining and transportation, radioactive waste management, nuclear research, and export and import control (Table 9.1).

Table 9.1 Regulatory responsibility across levels of government for nuclear activities in Australia

Activity	Regulatory responsibility	Key Legislation/Regulations
Uranium Mining	Commonwealth	*Safeguards Act 1987* *Atomic Energy Act 1953* *Environment Protection and Biodiversity Conservation Act 1999* *Environment Protection (Alligator Rivers Region) Act 1978* *Aboriginal Land Rights (Northern Territory) Act 1976*
	Northern Territory (mining permitted only at existing uranium mines)	*Mining Act 1980* *Mining Management Act 2001*
	South Australia (mining permitted only at existing uranium mines)	*Mining Act 1971* *Development Act 1993* *Radiation Protection and Control Act 1982* *Roxby Downs (Indenture Ratification) Act 1982* *Environmental Protection Act 1993*
	New South Wales & Victoria (exploration and mining prohibited)	*Uranium Mining and Nuclear Facilities (Prohibitions) Act 1986 (NSW)* *Nuclear Activities (Prohibitions) Act 1983 (Vic)*
	Queensland & Western Australia (exploration permitted, government policy prohibits new uranium mines)	
	Tasmania (no legislative prohibitions on exploration or mining)	
Conversion, enrichment, fabrication and nuclear power generation	Commonwealth (prohibited)	*Environment Protection and Biodiversity Conservation Act 1999* *Australian Radiation Protection and Nuclear Safety Act 1998* *Safeguards Act 1987*
	New South Wales & Victoria (prohibited)	*Uranium Mining and Nuclear Facilities (Prohibitions) Act 1986 (NSW)* *Nuclear Activities (Prohibitions) Act 1983 (Vic)*
Transportation	Commonwealth	*Safeguards Act 1987*
	Northern Territory, South Australia, Queensland, Western Australia, New South Wales, Tasmania & Victoria (transportation of radioactive material permitted, comply with the ARPANSA Transport Code)	*Radioactive Ores (Packaging and Transport) Act (NT)* *Radiation Protection and Control Act 1982 (SA)* *Radiation Safety Act 1999 (Qld)* *Radiation Safety (Transport of Radioactive Substances) Regulations 1991 (WA)* *Radiation Control Regulations 1993 (NSW)* *Radiation Protection Regulations 2006 (Tas)* *Radiation Act 2005 (Vic) (to come into force September 2007)*

Activity	Regulatory responsibility	Key Legislation/Regulations
Waste Management	Commonwealth	*Commonwealth Radioactive Waste Management Act 2005*
	States and Territories	*Radiation Safety Act 1975 (WA)* *Radiation Control Act 1977 (Tas)* *Radiation Safety Act 1999 (Qld)* *Radiation Protection and Control Act 2004 (SA)* *Radiation Act 1983 (ACT)* *Radiation Control Act 1990 (NSW)* *Radiation Protection Act 2004 (NT)* *Radiation Act 2005 (Vic)*
	Western Australia, South Australia & Northern Territory (transport and storage of nuclear waste prohibited)	*Nuclear Waste Storage and Transportation (Prohibition) Act 1999 (WA)* *Nuclear Waste Storage Facility (Prohibition) Act 2000 (SA)* *Nuclear Waste Transport, Storage and Disposal Prohibition Act 2004 (NT)*
Nuclear Research[53]	Commonwealth	*Australian Nuclear Science and Technology Organisation Act 1987* *Australian Radiation Protection and Nuclear Safety Act 1998* *Safeguards Act 1987*
Export and Import Control	Commonwealth	*Customs Act 1901*[54]

9.2.1 Regulation of uranium mining

Regulatory arrangements applying to mining operations are complex and vary from site to site, and across states and territories. The regulation of mining operations remains a state and territory government responsibility. However, certain aspects of uranium mining involve Australian Government regulation.

Commonwealth legislation

A party seeking to mine uranium must obtain a permit from the Australian Safeguards and Non-Proliferation Office (ASNO) under the *Safeguards Act 1987*. New uranium mines or significant expansion of existing mines require assessment and approval under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).[55] Under the *Environment Protection (Alligator Rivers Region) Act 1978*, the oversight of environmental aspects of uranium mining operations in the Alligator Rivers Region in the Northern Territory is a Commonwealth responsibility, carried out by the Supervising Scientist. A mine operator must have a license issued under the Commonwealth *Customs Act 1901* to export uranium ore.

Each state and territory has its own radiation protection authority. The Commonwealth, state, and territory governments have moved towards harmonisation of radiation safety regulation by developing the National Directory on Radiation

[53] Radioactive material generated by ANSTO that is used in medical, research and industrial applications is regulated by state and territory legislation.

[54] As outlined in Customs (Prohibited Exports) Regulations 1958 and the Customs (Prohibited Imports) Regulations 1956.

[55] Prior to the enactment of the EPBC Act, mining proposals were assessed under the *Environmental Protection (Impact of Proposals) Act 1974*.

Protection (National Directory) and the Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005) (Mining Code).

Compliance with the Code of Practice for the Safe Transport of Radioactive Material (2001) and the Recommendations for Limiting Exposure to Ionising Radiation (1995), both promulgated by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), are requirements for Authorisations issued by the Northern Territory Government and licenses issued by the South Australian Government to mine uranium.

Mining in the Northern Territory

A mine operator requires four approvals to carry out mining activities in the Northern Territory:

- a mineral lease under the *Mining Act 1980 (NT)*[56]
- if on Aboriginal land, an Agreement specifying the conditions for access to the land with the relevant Land Council under the Commonwealth *Aboriginal Land Rights (Northern Territory) Act 1976*
- an Authorisation under section 35 of the *Mining Management Act 2001 (NT)*
- an Approval under the *EPBC Act*.

Under the *Mining Act 1980*, the Northern Territory Minister for Mines must consult and give effect to any advice of the Commonwealth Minister for Industry, Tourism and Resources, before issuing a mining title.

The Authorisation for mining activities is issued subject to the mine operator complying with a current mine management plan that includes particulars of the implementation of the management system to address safety and health issues, environmental issues, a plan and costing of closure activities, particulars of the organisation's structure and plans of current and proposed mine workings and infrastructure.[205]

The *Mining Management Act 2001* mandates a regime of audits, inspections, investigations, monitoring and reporting to ensure compliance with agreed standards and criteria at mines.[25]

Under the Commonwealth–Northern Territory Working Arrangements for the regulation of uranium mining, the Northern Territory Minister for Mines must consult with the Supervising Scientist on environmental matters under the *Mining Management Act* for mines in the Alligator Rivers Region.

Mining in South Australia

Mine operators require four approvals to mine uranium in South Australia:

- a mining lease under the *Mining Act 1971* (SA), that considers the results of an environmental assessment and satisfactory resolution of native title
- a license to mine and mill radioactive ores under the *Radiation Protection and Control Act 1982* (SA), which includes conditions attached to the licence requiring uranium mining operators to comply with the requirements of the four Codes promulgated by ARPANSA[205] (discussed in section 9.2.1)
- a permit under the *Water Resources Act 1997* (SA) for the drilling of well holes
- an Approval under the *EPBC Act*.

An environmental impact statement is required as a precursor to any new uranium mine development.[57] Past practice has been to prepare a joint environmental impact statement for the purposes of approval under Commonwealth environmental protection legislation.[25]

Parties that hold licences to mine or mill radioactive ores (uranium or thorium) are required, under conditions on the licences, to report annually on radioactive waste production and management.

[56] The Australian Government has retained ownership of uranium in the Northern Territory and all discoveries of uranium must be reported to the Australian Government authorities within one month.

[57] Section 75 of the South Australian *Development Act 1993*.

The operation of mines and management of radioactive wastes on site also involves approval of facilities such as tailings dams and evaporation ponds, waste management plans, and releases of radionuclides into the environment.[205]

In conjunction with obtaining a mining lease, an operator must develop a mining and rehabilitation program to minimise the environmental effects of mining and milling and ensure adequate rehabilitation of mining sites. Under the *Mining Act 1971*, the South Australian Minister for Mineral Resources Development may require a miner to enter into a bond to cover any civil or statutory liability likely to be incurred in the course of carrying out the mining operations, and the present and future obligations in relation to rehabilitation of land disturbed by mining operations.

The South Australian *Radiation Protection and Control Act 1982* and the Radiation Protection and Control (Ionizing Radiation) Regulations (2000) provide controls for the safety of radioactive waste management.

All mines in South Australia are also subject to the *Mines and Works Inspection Act 1920* (SA) and the *Occupational Health, Safety and Welfare Act 1986* (SA).

Mining in other states

New South Wales and Victoria prohibit uranium exploration and mining.[58] Western Australia and Queensland have policies prohibiting uranium mining, but allow exploration. There is no restriction on uranium exploration and mining in Tasmania.

9.2.2 Transport regulation

Commonwealth legislation

The transportation of nuclear material is regulated by ASNO,[59] which issues permits to transport nuclear material under specified restrictions and conditions. The permits specify the requirements to be met to ensure that nuclear material is secure at all times when in transit. The permit holder may be required to have a transport plan detailing the security procedures to be observed.

State and territory legislation

With the exception of Victoria, all states and territories have adopted the Code of Practice for the Safe Transport of Radioactive Material (2001).[25] However, there is inconsistency in the application of uranium transport standards across jurisdictions and there is regulation in force that exceeds the standards specified in the Code, without improved health and safety outcomes.[25]

9.2.3 Management of radioactive waste

Radioactive waste comes from two main sources in Australia, mining activities and radionuclides used in research, medicine and industry. Management of radioactive waste is the responsibility of the government in whose jurisdiction it is produced.[206]

In December 2005, the Australian Parliament enacted the *Commonwealth Radioactive Waste Management Act 2005*. The law confirms the Commonwealth's power to establish the Commonwealth Radioactive Waste Management Facility in the Northern Territory. A number of states and territories prohibit the construction and operation of nuclear waste storage facilities (see Table 9.1).

There are three national codes regulating radioactive waste management: the Code of Practice for the Disposal of Radioactive Wastes by the User (1985), the Code of Practice for the Near Surface Disposal of Radioactive Waste in Australia (1992) and the Mining Code.

[58] Uranium Mining and *Nuclear Facilities (Prohibitions) Act 1986* (NSW) and the *Nuclear Activities (Prohibitions) Act 1983* (Vic).

[59] Section 16 of the *Safeguards Act 1987*.

9.2.4 Exports and imports regulation

The export of uranium, thorium, monazite and certain fissionable materials requires a permit issued by the Australian Minister for Industry, Tourism and Resources.[60] Before permits are issued, safeguards clearances from ASNO must be obtained. Export permits for 'high activity radioactive sources' are issued by ARPANSA. Nuclear equipment and facilities that are on the Defence and Strategic Goods List require export approval from the Minister for Defence.[207]

Safeguards requirements on imports ensure that nuclear material is not imported without being added to the inventory of safeguarded material in Australia. A permit issued by ARPANSA is also required for the importation of medical and non-medical radioactive substances.[61]

9.2.5 Regulation of nuclear research reactors

Australia has two nuclear research reactors, the High Flux Australian Reactor (HIFAR) and the Open Pool Australian Light-Water reactor (OPAL) at the Australian Nuclear Science and Technology Organisation (ANSTO).[208] OPAL is a multipurpose facility for radioisotope production, irradiation services and neutron beam research.[209] HIFAR has operated for over 40 years and is due for closure in February 2007.[210]

ARPANSA regulates the safe use of nuclear material by Commonwealth entities, including ANSTO. ARPANSA is prohibited from licensing specified nuclear activities: a fuel fabrication plant, a power plant, an enrichment plant or a reprocessing facility.[62] Commonwealth entities are prohibited from undertaking these activities. ASNO issues permits and authorities to ANSTO covering safeguards (accounting and control) and security.

9.3 Overseas regulatory experience

Through the IAEA and the Nuclear Energy Agency (NEA), there is a high degree of cooperation between countries on matters relating to the regulation of nuclear energy. Australia would be able to draw on this expertise to develop a regulatory framework, if it decided to undertake additional nuclear fuel cycle activities.

United States: Nuclear Regulatory Commission (NRC)

The NRC regulates the civilian use of nuclear material in the United States. The Commission develops policies and regulations governing nuclear reactor and materials safety, issues orders to licensees, and adjudicates legal matters brought before it. Regional Offices of the NRC implement NRC decisions.[69]

The NRC regulates to protect public health and safety, and the environment, from the effects of radiation from nuclear reactors, materials and waste facilities. This includes licensing or certifying applicants to use nuclear materials or operate nuclear facilities. The public provide input into all aspects of the licensing process.[211]

Among other functions, the NRC is responsible for licensing the following:

- design, construction, operation and decommissioning of nuclear plants and other nuclear facilities, such as nuclear fuel facilities, uranium enrichment facilities, test reactors and research reactors
- possession, use, processing, handling and exportation of nuclear materials
- siting, design, construction, operation, and closure of low-level radioactive waste disposal sites under NRC jurisdiction and the construction, operation, and closure of a geologic repository for high-level radioactive waste
- operators of civilian nuclear reactors.

[60] Regulation 9 in the Customs (Prohibited Exports) Regulations 1958.

[61] Regulation 4R in the Customs (Prohibited Imports) Regulations 1956.

[62] Section 10 of the *ARPANS Act*.

Canada: Canadian Nuclear Safety Commission (CNSC)

The CNSC is the leading federal regulator in Canada. The CNSC regulates almost all uses of nuclear energy and nuclear materials in Canada through a licensing process. Interested parties are given the opportunity to be heard at public CNSC licensing hearings.[212]

The CNSC regulations apply to nuclear research and test facilities, nuclear reactors, uranium mines and mills, processing and fabrication facilities, waste management facilities, transportation of nuclear substances, and imports and exports of nuclear material.

The CNSC is updating its regulatory framework for nuclear power plants. The updated framework is intended to align the CNSC regulatory framework for new nuclear power plants with international standards and best practice. The regulatory framework is intended to ensure that the regulations do not inappropriately limit the choice of nuclear energy technologies.[212]

Separate licences are required for each of the five lifecycle phases of a nuclear power plant, specifically to:

- prepare a site
- construct
- operate
- decommission
- abandon.

The CNSC assessment of information submitted by applicants is carried out with input from other federal and provincial government departments and agencies responsible for regulating health and safety, environmental protection, emergency preparedness, and the transportation of dangerous goods.

In addition to the five licensing steps, an environmental assessment (EA) must first be carried out to identify whether a project is likely to cause significant environmental effects before any federal authority issues a permit or licence or approves the project. If the decision on the EA is negative, the project will not proceed. Both federal and provincial governments require an EA to be completed.

Finland: Radiation and Nuclear Safety Authority (STUK)

STUK is the regulator of radiation and nuclear safety in Finland. STUK regulates the use of radiation and nuclear energy, conducts radiation research, monitors environmental radiation and provides commercial radiation services. It issues regulations for the safe use of nuclear energy and for physical protection, emergency preparedness and safeguards.[213]

The decision-making process for the construction of a nuclear facility[63] follows the following steps:

- the proponent carries out an environmental impact assessment on the construction and operation of a proposed nuclear facility
- the operator files an application to the government to obtain a decision-in-principle on a new nuclear facility
- the government requests a preliminary safety appraisal from STUK and a statement from the municipality intended to be the site of the planned nuclear facility, the municipality has a right to veto the approval of a new facility
- the government makes a decision-in-principle on the construction
- if the decision-in-principle is positive, the operator applies in due time for a construction licence from the government
- towards the end of the construction, the operator applies for an operating licence for the facility.

[63] Nuclear facilities include power plants and final waste disposal facilities.

United Kingdom: Health and Safety Executive (HSE)

There are a number of nuclear regulators in the United Kingdom. The HSE and the Scottish Environment Protection Agency are responsible for regulating nuclear safety. The Environment Agency is responsible for regulating discharges to the environment and disposal of radioactive waste. The Department of Transport is responsible for regulating the transport of radioactive matter, while the Office for Civil Nuclear Security, is the security regulator for the civil nuclear industry. The UK Safeguards Office facilitates EURATOM safeguards activities in the United Kingdom.[214-217]

The HSE licenses each nuclear site. Prior to the construction of a nuclear facility, a licence from the HSE is required to provide the necessary checks and controls for the design, construction, commissioning and operational stages of installation and decommissioning.[218]

The HSE is working on a pre-licensing design acceptance system. The HSE has proposed a two-phase approach: a reactor design authorisation process based on a generic site concept and a site and operator-specific assessment on which to grant a nuclear site licence. Phase 1 would focus on safety and take some three years, phase 2 would take less than a year, (apart from planning permission).[219] This process is intended to provide a more transparent, rigorous and robust regulatory approach to the safety of any new nuclear reactors.[220]

9.3.1 Drawing on international experience

If Australia were to pursue additional nuclear fuel cycle activities, overseas regulatory systems could provide a useful starting point to develop its regulatory regime.

The United States Nuclear Regulatory Commission provides advice and assistance to foreign countries and international organisations to help them develop effective regulatory systems. For example, the NRC is currently working with regulatory authorities in Finland and France on the Multinational Design Approval Program (MDAP). The later stages of the MDAP are intended to foster the safety of reactors in participating nations through convergence of safety codes and standards, while maintaining full national sovereignty over regulatory decisions.

The IAEA helps countries to comply with international standards by providing technical support to develop necessary standards and regulatory regimes. The NEA, a specialised agency of the OECD, also assists member countries to develop effective and efficient regulation and oversight of nuclear installations.

Australia has strong relationships with many of the countries using nuclear energy. During its consultations the Review found a willingness to provide technical support to Australia to develop a regulatory system for further nuclear fuel cycle activities.

9.4 Regulatory reform in Australia

Australia's three uranium mines all operate under different regulatory regimes, for historical and jurisdictional reasons. Extensive and at times duplicative regulatory requirements apply to uranium mining.[25] Adding to this complexity, across the states and territories the regulatory responsibility for health and safety, and environmental standards, is housed in different agencies, and in some cases across agencies.[25] There are significant advantages in rationalising and harmonising regulatory regimes for uranium mining across jurisdictions.

One option to streamline regulatory arrangements would be to channel mining proposals and operations through a single regulator for mine safety compliance. The Council of Australian Governments (COAG) has committed to the reduction of the regulatory burden in occupational health and safety. The COAG National Mine Safety Framework Steering Committee is considering the option of having a single national authority for mine safety. This model could be extended to environmental assessment and approvals processes for uranium mining. In practice, environmental assessments and approvals are conducted in a joint process between agencies. However, there is uncertainty as to which regulatory authority is appropriate on any matter, because of the overlaps in regulatory responsibility between authorities.

The regulatory responsibilities assigned to ASNO and ARPANSA are another example of overlap between authorities. While working arrangements exist between these bodies to delineate regulatory responsibilities between them,[64] the existence of such overlaps causes uncertainty and unnecessary regulatory burden on those subject to regulation, and is not consistent with international best practice.[221]

A number of authorities perform a regulatory function, as well as undertake other functions. For example, ARPANSA provides services on a commercial basis, undertakes research, promotes national uniformity of radiation protection and regulates the Australian Government's use of sources of radiation and nuclear facilities.[222] Similarly, the Office of the Supervising Scientist conducts environmental audits and technical reviews of uranium mining operations while the Environmental Research Institute of the Supervising Scientist conducts research on the environmental impacts of uranium mining.[223] The separation of the regulatory function from other functions performed by authorities could improve transparency and would be consistent with international best practice.

Under the *Environment Protection and Biodiversity Conservation Act 1999*, enrichment, fuel fabrication, reprocessing facilities and nuclear power plants are prohibited in Australia.[65] These prohibitions would need to be removed before any of these activities can be pursued.

[64] Memorandum of Understanding between ASNO and ARPANSA Covering Evaluation of Physical Protection and Security Arrangements for the Replacement Research Reactor at Lucas Heights and the Protection of Associated Information 2001.

[65] New South Wales and Victoria also have legislative prohibitions on these activities *Uranium Mining and Nuclear Facilities (Prohibitions) Act 1986 (NSW)* and *Nuclear Activities (Prohibitions) Act 1983 (Vic)*.

9.5 Conclusion

The regulation of uranium mining and transportation, radioactive waste management and nuclear research facilities in Australia is of a high standard. However, there are opportunities for reform that would streamline existing arrangements.

Before nuclear fuel cycle activities can be established in Australia, the existing legislative prohibitions would need to be removed.[66] Australia would also need to establish an appropriate body to license and monitor the construction and operation of nuclear facilities to ensure that high standards in health, safety and environmental performance are maintained.

Should Australia choose to pursue nuclear energy, there is a clear case for better integration of health, safety and environment assessment and licensing processes. The regulation of nuclear power facilities would require inputs from a variety of disciplines. Codes and standards would need to be developed in relation to nuclear safety, environmental protection, operational radiation protection, auditing and inspections of facility operations, physical protection, civil liability arrangements and waste management. To set up regulatory authorities with the requisite expertise in each jurisdiction would be inefficient.

It would be desirable to establish a national regulator to regulate nuclear fuel cycle activities. The Australian Government and the states and territories could establish such a national regulator. Australia could draw on other countries' experiences and the support provided by the IAEA to build an effective national regulator. Successful regulation would require a significant increase in the number of qualified and trained regulators. (Capacity building needs in relation to nuclear regulation are discussed in Chapter 10.)

In summary, the regulation of uranium mining and transportation, radioactive waste management and nuclear research facilities in Australia is of a high standard. However, there are opportunities for reform that would streamline existing arrangements. If Australia were to undertake nuclear fuel cycle activities a significant investment in new regulatory arrangements would be required.

[66] Section 140 A in the *EPBC Act 1999.*

Chapter 10. Research, development, education and training

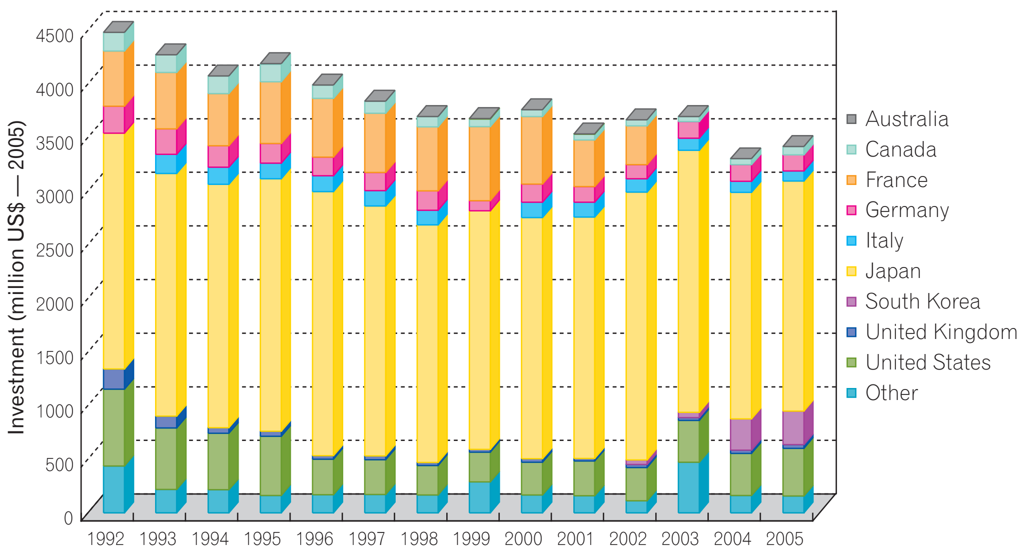
- Given the minimal Australian investment in nuclear energy related education or research and development (R&D) over the last 20 years, public spending will need to increase if Australia is to extend its activities beyond the uranium mining sector.
- Significant additional skilled human resources will be required if Australia is to increase its participation in the nuclear fuel cycle.
- In addition to expanding our own R&D and education and training efforts, Australia could leverage its nuclear research and training expertise through increased international collaboration.

10.1 International and Australian nuclear research and development

The term nuclear R&D can refer to a wide range of basic and applied activities, including research related to the production of nuclear energy (in Australia such activities are largely related to uranium mining). However nuclear R&D can also be conducted in areas that are not related to energy production, such as nuclear medicine.

Nuclear R&D is vitally important to all countries involved in aspects of the nuclear fuel cycle. Government spending on nuclear R&D among Organisation for Economic Cooperation and Development (OECD) countries was almost half of total energy R&D spending in the period 1992 to 2005. Absolute funding for nuclear R&D did fall slightly over the decade to 2001, but has since begun to increase.[67]

Figure 10.1 Spending on nuclear R&D by OECD countries, 1992–2005



Source: IEA Statistics[224]

[67] The nuclear R&D spending data for France for 2003–2005 is currently being revised.

The level and nature of a country's nuclear R&D activities vary with its involvement in the fuel cycle. Countries with significant nuclear energy programs have large R&D efforts in place. However, even countries with smaller nuclear energy programs can and do support significant R&D efforts.

International Energy Agency statistics show that most publicly funded nuclear R&D is on reactor safety, radioactive waste management and next-generation technologies, such as Generation IV reactors and fusion power. The first two are particularly important because of their contribution to public confidence and acceptance of nuclear energy, whereas the latter is part of many governments' efforts to secure long term energy supply options to 2050 and beyond.

Companies in the nuclear industry are mainly large global firms. While it is more difficult to obtain information on investment in R&D by these firms, the amounts involved are likely to be significant.[68] Nuclear R&D is essential both for maintaining the safe and efficient operation of existing nuclear power stations and fuel cycle facilities and for promoting the discovery and development of new and innovative nuclear energy systems in the future.

The role of R&D in the nuclear industry is more important than in many other industries because the implications of technology failure relate not only to operational costs of the industry, but also to safety and ultimately the industry's 'license to operate'.

The Australian Bureau of Statistics (ABS) collects data on public spending on energy-related R&D. Survey respondents can allocate their nuclear related R&D across four categories of activity, namely:

- exploration for uranium
- mining and extraction of uranium
- preparation and supply of uranium as an energy source material
- nuclear energy.

However, these categories do not capture all of the significant R&D that occurs at universities and organisations such as the Australian Nuclear Science and Technology Organisation (ANSTO).

For example, research in health and safety, radiation physics and nuclear physics[69] is an important means for ensuring the availability of appropriately trained people for a range of policy and regulatory functions, including health and safety regulators such as the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)[70] and the Australian Safeguards and Non-Proliferation Office (ASNO).

Australian nuclear energy R&D tends to focus on exploration and mining of uranium.[71] There has been very little R&D spending on the other two ABS categories since 1994–1995.[72] Notwithstanding these low levels of funding, Australia has developed research excellence in several areas, including the following.

- Waste conditioning — Synroc (synthetic rock) technology, invented in 1978 by Professor Ted Ringwood at the Australian National University (ANU), is an advanced ceramic that can immobilise most elements present in high-level radioactive waste in its crystal structure.[73]
- Laser enrichment — in May 2006 the private firm Silex signed an exclusive Commercialisation and License Agreement for their uranium enrichment technology with the United States General Electric Company.
- High performance materials — the ANSTO Advanced Nuclear Technologies Group and various Australian universities have skills that could contribute to international research efforts into high-performance materials. The Generation IV Forum (GIF) and the International Thermonuclear Experimental Reactor (ITER) project have identified this as an area where more R&D is required.

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68 For example, in 2005 the French firm Areva invested €582 million (approx. A$910 million) in R&D. This was equivalent to 5.7 per cent of the sales revenue of the group.

69 The ABS energy R&D statistics do not capture research activity in these areas as it is not energy-related research.

70 The ARPANSA submission to the Review identified their ongoing interest in R&D directed towards nuclear safety.

71 Funding by mining firms for R&D by the ANSTO Minerals Group increased fourfold between financial year 1999–2000 and financial year 2005–2006 and is estimated to increase by a further 50 per cent in financial year 2006–2007.

72 There is a lack of reliable information on Australia's existing skills base. An audit would help identify areas of both expertise and shortfall.

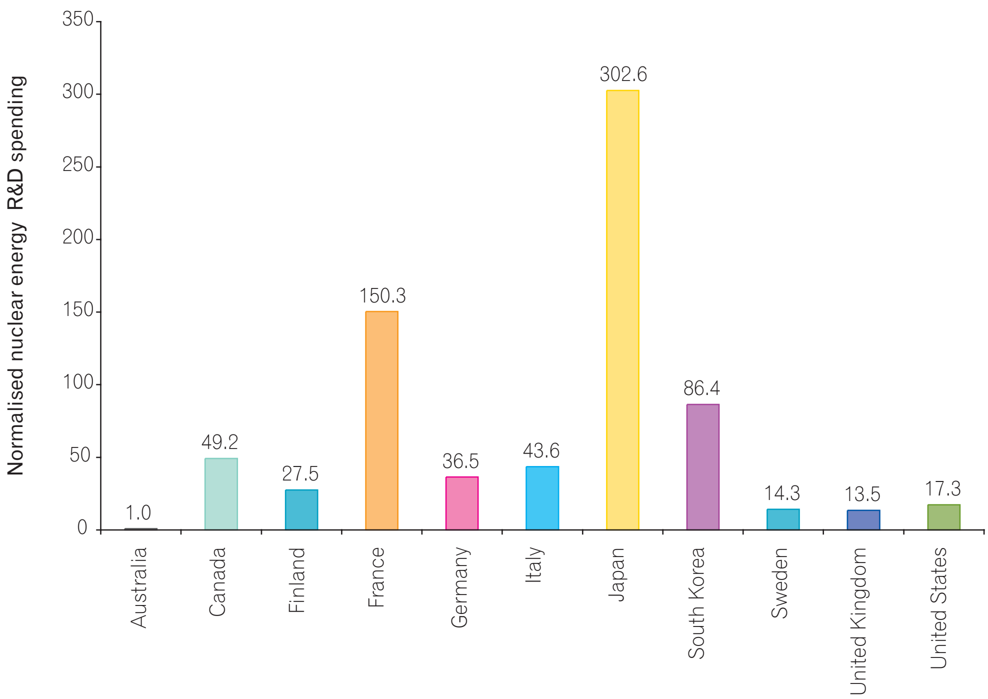
73 Synroc R&D continues at ANSTO, including collaboration with several overseas partners. See also discussion in Appendix R.

- Environmental toxicology — the research programs of the Environmental Research Institute of the Supervising Scientist and of Earth, Water & Life Sciences, a subsidiary of Energy Resources of Australia (ERA), have been essential to achieving a very high level of environmental protection during the operational stage of mining at Ranger and Nabarlek and also to the planning of rehabilitation of these mine sites.

In addition, Australia has research capacity in areas such as the analytical tools used in risk assessment, the modelling of severe accidents, and human and organisational performance. The Nuclear Energy Agency (NEA) has argued that research in these areas has spin-off benefits in that it supports efficient and effective regulation across a broad spectrum of nuclear activities.[225]

Figure 10.2 shows the nuclear energy R&D effort relative to GDP by selected countries, normalised to that of Australia over the period 1992–2005. Australia's relative R&D effort is well below that of all other countries shown. For example, in relative terms, Sweden spent approximately fourteen times more than Australia.[74] This difference is not surprising as all the other countries shown, apart from Italy, have active nuclear power programs. However, if Australia moves beyond uranium mining, then public spending on nuclear energy-related R&D will need to increase significantly.

Figure 10.2 Spending by selected countries on nuclear energy R&D relative to GDP and normalised to Australian effort, 1992–2005



Source: IEA Statistics[224]

[74] Note: these spending figures have been expressed as a proportion of 2005 GDP.

Any increase in R&D spending is likely to be on topics similar to those pursued overseas. This suggests that Australia would need to seek to utilise existing international collaborative agreements as far as is possible. The already established expertise of Australian scientists should make Australia an attractive research partner.

10.1.1 Opportunities for international collaboration on nuclear R&D

The resources required for nuclear R&D are considerable. Therefore, it is not surprising that collaborative R&D partnerships are common. The NEA and International Atomic Energy Agency (IAEA) have both established mechanisms that support international research collaboration. Australia already participates in a number of these.

Another example of multilateral collaboration is the GIF,[75] created to support the development of next-generation nuclear energy systems. The GIF partners selected six reactor concepts judged to be the most promising. A 2002 technology roadmap estimated the cost of required R&D to 2020 at approximately US$5.8 billion.[226] Australia's research and development, particularly in materials science and waste management, could make a valuable contribution.

Another major international collaborative research effort is the experimental fusion reactor ITER.[76] ITER aims to develop the technologies essential for a future fusion reactor for power production. The total cost of the ITER project, to be built at Cadarache in France, is in the order of €10 billion, half to construct the reactor over the next seven years and the remainder to operate it for 20 years and then decommission the facility.

The United States Department of Energy (DOE) International Nuclear Energy Research Initiative (I-NERI) encourages collaborative R&D with international partners in advanced nuclear energy systems development.[77] I-NERI provides a vehicle for cost-shared international R&D collaboration into the DOE Generation IV Nuclear Energy Systems Initiative, the Advanced Fuel Cycle Initiative (AFCI)[78] and the Nuclear Hydrogen Initiative (NHI).[79] The contribution by I-NERI participants to research over the period 2001–2006 was almost US$152 million.

I-NERI also promotes the education of future nuclear scientists and engineers. In 2005, 85 students from undergraduate, graduate, and doctoral programs participated in I-NERI research projects at 12 universities in the United States. This illustrates how R&D collaboration can also help address education and training issues (see discussion in section 10.2).

There are undoubtedly many opportunities for Australian scientists to contribute to international research programs, and for overseas scientists to contribute to Australian programs. It may be necessary to negotiate new bilateral or multilateral agreements for research collaboration with international partners. However, adequate resources must be provided to enable such collaboration and to support local research programs.[80]

[75] The current GIF members are Argentina, Brazil, Canada, Euratom, France, Japan, South Korea, South Africa, Switzerland, the United Kingdom and the United States. China and Russia are expected to join by the end of 2006.

[76] The ITER partners are the European Union, Japan, Russia, the United States, China, South Korea and India.

[77] Current collaborating countries and international organisations include: Brazil, Canada, the European Union, France, Japan, South Korea, and the OECD/NEA.

[78] AFCI aims to develop proliferation resistant spent nuclear fuel treatment and transmutation technologies in order to enable a transition from the current once through nuclear fuel cycle to a future sustainable closed nuclear fuel cycle.

[79] NHI aims to develop the technologies and infrastructure to economically produce, store, and distribute hydrogen.

[80] The House of Representatives Standing Committee on Industry and Resources inquiry into developing Australia's non-fossil fuel energy industry made a number of recommendations aimed at encouraging increased collaboration between international and Australian researchers.[26]

10.2 Education and training

Nuclear education and training provides science, engineering and technology (SET) skills needed for activities ranging from radiation safety and regulation, through to aspects of the mining industry, spanning vocational training to postdoctoral studies relevant to research and policy development.

10.2.1 Nuclear skills needs

The number of personnel required to participate in various stages of the nuclear fuel cycle are similar to those needed for many other industrial processes (Table 10.1). Although the required skills sets are not unique to the nuclear sector, their area of application is. Issues such as quality control and stringent safety standards also create a need for additional training.

The slow down in nuclear power programs worldwide since the 1980s, coupled with the global decline in funding for nuclear R&D, led to a worldwide drop in the number of students pursuing nuclear-related courses.

However, the revival of interest in nuclear energy with significant extensions in the lives of existing nuclear power plants, and the ageing of the existing workforce, are ensuring that the training and retention of an appropriate skills base has become an increasingly important concern for policy makers in countries with nuclear power.

In Finland, the adequacy of human resources had to be demonstrated before approval could be given for the construction of the third reactor at Olkiluoto. One of the main mechanisms for ensuring that the skills base was available was the Finnish national research program for the operational and structural safety of nuclear power plants (SAFIR).[227] SAFIR courses have trained approximately 150 young experts over the period 2003–2006.

A draft report from the United Kingdom on future nuclear skills needs found that the industry was currently recruiting about half the number of SET graduates needed to maintain its existing strength.[228]

Table 10.1 Overseas examples of employment in various nuclear fuel cycle activities

Activity	Workforce (approx. numbers)
US Nuclear Regulatory Commission (NRC)[81]	3270
UK Nuclear Safety Directorate (NSD)[82]	250
Conversion facility, 13 000 tonnes/year (Areva, France)	1600
Enrichment facility, 10 million SWU/year (Areva, France)	1500
Nuclear power plant operation (800 MW, PWR USA)[229]	500
Nuclear power plant operation (1600 MW, PWR Finland)[230]	150–200
Reprocessing facility (similar scale to plant at La Hague)[231]	3900
Central spent fuel storage facility (CLAB, Sweden) [232]	70
Swedish Nuclear Fuel and Waste Management Co. (SKB, Sweden)[232][83]	230
Posiva Oy (Finnish Nuclear Fuel and Waste Management Co, Finland)[233]	60
Construction and operation of HLW disposal facility (UK)[228]	275

Note: The history, size and scope of each country's nuclear industry varies considerably and these factors will affect workforce needs. See Table 4.1.

[81] US NRC personnel ceiling for the 2006 financial year.

[82] Sixty per cent are technical staff qualified to honours degree level or above and most of them will have ten or more years of industry experience.

[83] In addition, approximately 300 university researchers and consultants are contracted for various research projects and studies.

A nuclear industry survey from the United States found that nearly half of the current nuclear industry workforce was over 47 years old, and approximately 40 per cent of the total workforce (23 000 workers) may leave over the next five years.[234] The United States NRC has called for a major industry effort to bring the supply of scientists and engineers into equilibrium with the escalating demand. The NRC expects to hire some 300 engineering and science graduates during 2006. The minimum requirements for these positions were a bachelors degree plus at least three years of fulltime professional engineering or physical science experience.

10.2.2 Response of the international education and training sector

The revival of interest in nuclear energy will make the industry a more attractive career option. However, a career in the nuclear energy sector will only become an option if universities and other educational establishments have the facilities and places available to provide relevant nuclear skills and training. Some overseas initiatives are described below.[84]

The Dalton Nuclear Institute (DNI), United Kingdom

The DNI was established to implement the aim of the University of Manchester to become a leading domestic and international player in nuclear research and education.[85]

The DNI coordinates a consortium of universities and research institutes to address the nuclear skills shortage in the United Kingdom. As one component of this initiative, in 2005 the Nuclear Technology Education Consortium began a Masters program in nuclear science and technology. The program is designed to meet the future nuclear skills needs in the United Kingdom in areas such as decommissioning, reactor technology, fusion and nuclear medicine. The DNI expressed interest in collaborating with appropriate Australian institutions during discussions with the Review.

The World Nuclear University (WNU)

The WNU was founded by the IAEA, the NEA, the World Association of Nuclear Operators and the World Nuclear Association, in September 2003. Its main function is to foster cooperation among its participating institutions. This includes facilitating distance learning so that courses at any WNU university are available to students throughout the network. The WNU network consists of 30 nations represented by universities and research centres with strong programs in nuclear science and engineering.[86]

United States Department of Energy (DOE)

The number of United States institutions offering nuclear engineering courses fell 50 per cent between 1975 and 2006. However, since 1997 enrolments have begun to increase. One reason for increased enrolments is the improving outlook for employment in the nuclear sector.[87] Another reason is the introduction of various United States DOE programs to expand nuclear training opportunities for students. Figure 10.3 illustrates the lead time between United States government investment in programs to encourage nuclear engineering studies and increasing enrolments.

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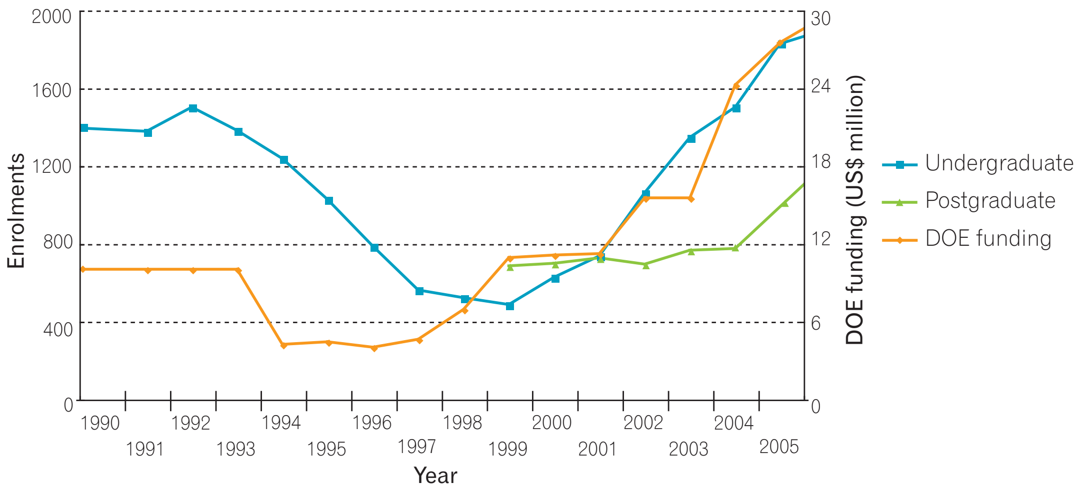
84 Other collaborative efforts include the European Nuclear Education Network (ENEN) and the Asian Network for Education in Nuclear Technology (ANENT).

85 The DNI has strategic collaborative linkages with leading nuclear countries including Canada, the United States (Battelle), South Africa (North-West University), France, India, China (Tsinghua University) and other Asian networks.

86 Australia is represented by ANSTO and an ANSTO employee attended a six-week course in 2006.

87 For example, the United States NRC is hiring staff to prepare for an expected increase in reactor license applications.

Figure 10.3 Nuclear engineering enrolments and US DOE funding in the United States



Source: Presentation by Dr José N Reyes Jr to the American Nuclear Society Meeting, June 2006.[235]

10.2.3 Existing Australian human resources and potential future requirements

The uranium exploration and mining industry faces similar human resource needs as other resource sectors. BHP Billiton estimates that the proposed Olympic Dam mine expansion could increase employee numbers by one-third (or approximately 1000 people).[17] In addition, some 5000 construction jobs could be associated with the expansion.[88] However, the industry also faces some unique skills requirements relating to the specific characteristics of uranium mining, including:

- Radiation Safety Officers (RSO) — the 2005 Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing requires the operator and employer to appoint a qualified and experienced RSO.[89]
- specialised skills in relation to the operation of the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves.[90] Under the Code, uranium exploration results must be reported by persons with at least five years relevant experience.
- persons with highly specialised skills related to in-situ leaching of uranium.

Australia currently has no (non-R&D) involvement in other components of the nuclear fuel cycle. The submission to the Review by ANSTO[101] argued that overseas experience has shown that between 50 and 100 appropriately qualified professionals are needed during the pre-project and early implementation phases of any nuclear power program. This figure was supported by information gathered by the Review from the DNI.

88 On the basis of revenue, it is estimated that approximately 25 per cent of the workforce is connected with the mining of uranium.

89 The 2006 Uranium Industry Framework report identifies skills shortages in this area as being among the main factors influencing the international competitiveness of the industry.

90 Often referred to as the JORC Code after the Australasian Joint Ore Reserves Committee.

The construction of the new ANSTO OPAL research reactor at Lucas Heights provides an insight into the capabilities of Australian industry in such projects. Design, construction and commissioning was done by a joint venture between the Argentine company INVAP SE and its Australian partners, John Holland Construction and Engineering Pty Ltd and Evans Deakin Industries Limited (JHEDI).

The JHEDI consortium had no major difficulties in obtaining appropriately skilled personnel for the project, although some additional research and training was needed to ensure that the higher standards associated with reactor construction were met (for example in areas such as welding and preparation of high density concrete). Other issues specific to the OPAL project included the significantly higher degree of planning required (approximately twice as many planning days per construction day as would be required for a more conventional project). Quality control and audit trail requirements were also much higher.

The regulatory sector

ARPANSA currently has 125 full time equivalent staff, eight of whom are committed to the regulation of nuclear installations. Staff have been obtained through a mixture of international recruitment and on the job training. Any decision to expand Australia's role in the nuclear fuel cycle would require an early investment in training and recruiting substantially more human resources with skills in a wide range of nuclear related areas, including radiation protection and nuclear safety.[174,222] The challenge of doing so in a timely fashion is considerable. An early step might include measures to facilitate the training of Australian regulators through staff exchanges with their overseas counterparts.

10.2.4 Existing Australian training and education capacity

Australia's only School of Nuclear Engineering was operated by the University of New South Wales between 1961 and 1986. A 2006 survey found a lack of tertiary education in nuclear science and technology in engineering departments in Australian universities,[236] although a number of courses deal with nuclear physics and radiation safety.

The ANU plans to offer a Masters of nuclear science course, with an initial intake of five to ten students in 2007 and growth anticipated in subsequent years. The Australian Technology Network[91] identified courses relating to the reliability, safety, economics and environmental and societal effects of nuclear energy systems as an area where they are well placed to provide education and training.

The Council of the Australian Institute of Nuclear Science and Engineering (AINSE), a body that has a mandate to train scientific research workers and award scientific research studentships in nuclear science and engineering fields, has decided to facilitate the formation of an Australia-wide nuclear science and technology school. The intention is to provide education in a wide range of nuclear-related matters from technical aspects of the fuel cycle and reactor operation through to nuclear safety, public awareness, and other matters of interest to policy makers.[92]

Australia's existing and proposed nuclear training and education capacity is also discussed in Appendix R.

[91] The Australian Technology Network is an alliance of Curtin University of Technology, the University of South Australia, RMIT University, the University of Technology Sydney and Queensland University of Technology.

[92] Participants in the discussions included the ANU, a consortium of universities in Western Australia, the Universities of Wollongong, Newcastle, Sydney and Melbourne, Queensland University of Technology and RMIT University.

The 2006 SET Skills Audit

The 2006 SET Skills Audit examined trends in the demand and supply of SET skills in Australia and the factors affecting this balance.[237] Audit modelling estimated a cumulative shortfall of some 20 000 people with SET skills by 2012–2013. More than 95 per cent of this shortage is in science professionals, with the remainder in engineering professionals.

The SET Skills Audit also highlights the strong link between SET skills and associated R&D expenditure. The existence of this link is supported by the NEA.[238] This is not surprising as the brightest minds will tend to be attracted to research areas where there is the opportunity to do leading edge research.

Analysis of unpublished ABS data shows that the role of the higher education sector in nuclear energy-related R&D is small and declining. Annual spending by this sector averaged around $150 000 in the decade to 2004–05. This low activity level is reflected in a lack of higher education opportunities specifically related to the nuclear fuel cycle. See also discussion in Appendix R.

10.2.5 Training and educational implications of an expansion in nuclear-related activity

Although lead times for the construction of nuclear fuel cycle facilities could be several years, it would be important to establish the appropriate skills for planning, regulation and design at an early stage. The establishment of a skilled workforce, including local training of personnel and international recruitment, would need to be considered at the same time that Australia's policy decision about the nuclear fuel cycle is determined.

People employed in the uranium mining industry come from diverse backgrounds, ranging from hard rock mining to specialist health and environment areas. At present, the necessary skills are developed through a combination of specialist courses and on the job training. While the industry faces a skills shortage, large international firms have the capacity to draw on worldwide resources to manage their development priorities. Smaller local companies may have no option but to attract skilled staff away from other firms.

One submission to the Review argued that expanding the Australian nuclear industry beyond mining may require approximately 20 graduates per year.[101] However, the Chief Scientist's Review Panel believes that this number would be insufficient. While the number of graduates needed per year will depend upon the nature and level of Australia's involvement in the nuclear industry, the Review notes that, given the low starting point, the education and training task for Australia could be considerable.

The Review expects that nuclear education and training providers will respond to market signals such as increased funding and employer demand. Proposals for new nuclear training courses at the ANU and ANSTO lend some support for that view. It may be necessary to encourage Australian educational and training institutions to coordinate their responses and to increase collaboration with their overseas counterparts. In particular, growing a local nuclear industry will require a full range of education and research activities to be developed and supported in Australia. Having a broad range of groups providing these services will also help maintain a diversity of research capability, knowledge and independent opinion as Australia moves forward in what is likely to be a very complex and challenging debate.

Direct industry involvement through measures such as cadetships and joint development of programs would be a means of ensuring that the education and training sector meets the needs of the industry.

Local demand is initially unlikely to be sufficient to sustain the re-establishment of a university school of nuclear engineering in Australia. As a first step it might be more appropriate to develop an educational network involving Australian universities and colleges, industry and ANSTO. Such a network could build on the role of AINSE[93] and also take advantage of overseas training opportunities, such as those available through the WNU and the European Nuclear Education Network. There may also be a role for the learned Academies and professional organisations, such as Engineers Australia, in developing such an educational network.

10.3 Conclusion

Many nations are moving to boost education and training activities to overcome nuclear skills shortages. Australia will also need to do this if it decided to expand its role in the nuclear fuel cycle. Australia should aim to link in with and take advantage of international opportunities to supplement its own nuclear education and training. With the appropriate educational policies in place, there is little doubt Australian educational institutions and students will respond to any increased demand for skills.

Government support for nuclear energy-related R&D will likewise need to increase significantly if Australia expands its nuclear fuel cycle activities. Again, there are significant opportunities for Australia to leverage its research expertise through various existing international forums for R&D collaboration. Increased support for nuclear R&D will undoubtedly stimulate student enrolments in nuclear energy-related courses.

[93] The House of Representatives Standing Committee on Industry and Resources inquiry into developing Australia's non-fossil fuel energy industry recommended that university research into aspects of nuclear energy and the nuclear fuel cycle be encouraged through the allocation of research grants awarded by AINSE.[26]

Appendix A. Terms of reference

The Terms of Reference were announced by the Prime Minister on 6 June 2006.

The Review will consider the following matters:

1. Economic issues

(a) The capacity for Australia to increase uranium mining and exports in response to growing global demand.

(b) The potential for establishing other steps in the nuclear fuel cycle in Australia, such as fuel enrichment, fabrication and reprocessing, along with the costs and benefits associated with each step.

(c) The extent and circumstances in which nuclear energy could in the longer term be economically competitive in Australia with other existing electricity generation technologies, including any implications this would have for the national electricity market.

(d) The current state of nuclear energy research and development in Australia and the capacity for Australia to make a significantly greater contribution to international nuclear science.

2. Environment issues

(a) The extent to which nuclear energy will make a contribution to the reduction of global greenhouse gas emissions.

(b) The extent to which nuclear energy could contribute to the mix of emerging energy technologies in Australia.

3. Health, safety and proliferation issues

(a) The potential of 'next generation' nuclear energy technologies to meet safety, waste and proliferation concerns.

(b) The waste processing and storage issues associated with nuclear energy and current world's best practice.

(c) The security implications relating to nuclear energy.

(d) The health and safety implications relating to nuclear energy.

Appendix B. Taskforce Members

Chairman

Zygmunt (Ziggy) Switkowski

Dr Switkowski, formerly the Chief Executive Officer of Telstra Corporation (1999–2005), is a director of Tabcorp, Healthscope Ltd, Opera Australia and Suncorp-Metway. Dr Switkowski holds a PhD in nuclear physics from the University of Melbourne. Ziggy Switkowski previously held the position of Chief Executive Officer of Optus Ltd. Prior to that he worked for Kodak (Australasia) for eighteen years, serving as the Chairman and Managing Director from 1992–1996.

Members

Professor George Dracoulis

Professor George Dracoulis is Professor and head of the Department of Nuclear Physics in the Research School of Physical Sciences and Engineering at the Australian National University. Professor Dracoulis is an internationally renowned expert on nuclear physics. He is a Fellow of the Australian Academy of Science and a Fellow of the American Physical Society. He was awarded a Centenary Medal in 2003 and was the recipient of the Lyle Medal for distinguished research in physics in 2003 (Australian Academy of Science) and the Walter Boas Medal for excellence in research in Physics in 2004 (Australian Institute of Physics).

Dr Arthur Johnston PSM

Dr Johnston was a research scientist in nuclear structure physics at the University of Glasgow and the Australian National University from 1966 until 1982. Over the past 25 years he has become internationally recognised as an expert on the effects of uranium mining on people and the environment through his leadership of the Environmental Research Institute of the Supervising Scientist. As Supervising Scientist from 1999 to 2005 he was responsible for the supervision of the environmental regulatory regime for uranium mining in the Northern Territory. In 2003, he was awarded the Public Service Medal for his contribution to the protection of Kakadu National Park.

He is an Adjunct Professor at the University of the Sunshine Coast, a member of the Australian Radiation Health and Safety Advisory Council and a member of the Environment Committee of the International Commission on Radiological Protection.

Professor Peter Johnston

Professor Peter Johnston is Head of Physics within the School of Applied Sciences, RMIT. He is the Registrar and a member of the National Executive of the Australian Institute of Physics and a Councillor of the Association of the Asia Pacific Physical Societies and of the Australian Institute of Nuclear Science and Engineering. He is a member of the Radiation Health and Safety Council and the Nuclear Safety Committee, and a former member of the Radiation Health Committee. He is also an independent member of the Alligator Rivers Region Technical Committee. Professor Johnston has had considerable experience in health and safety associated with environmental radioactivity especially through his involvement with rehabilitation of the former British nuclear test site at Maralinga.

Professor Warwick McKibbin

Professor Warwick McKibbin is currently Director of the Centre for Applied Macroeconomic Analysis and Professor of International Economics in the Research School of Pacific and Asian Studies at the Australian National University. He is a Professorial Fellow at the Lowy Institute for International Policy, a Senior Fellow at the Brookings Institution in Washington, a member of the Board of the Reserve Bank of Australia and a member of the Prime Minister's Science Engineering and Innovation Council. Professor McKibbin is an internationally renowned economist with a deep understanding of the economics of energy and issues relating to climate change.

Mr Martin Thomas, AM

Mr Martin Thomas is the Chairman of Dulhunty Power Limited. He was Deputy Chairman of Australian Inland Energy and Water and a non-Executive Director of the Tyree Group of companies from 1993 until 2001. Mr Thomas was the President of the Institution of Engineers Australia in 1991, Vice President of the Australian Academy of Technological Sciences and Engineering from 1996 to 2000, Chairman of the NSW Electricity Council from 1988 to 1995 and has held a number of other senior positions within the energy sector, concluding his professional career as a Principal of Sinclair Knight Merz, one of Australia's leading consulting engineers. Mr Thomas has experience in the energy, science and commercial sectors.

Secretariat

The Review was supported by a secretariat headed by Mr John Ryan, Deputy Secretary, Department of Industry, Tourism and Resources, with staff drawn from the following departments and agencies:

The Department of the Prime Minister and Cabinet

The Department of the Treasury

The Department of Foreign Affairs and Trade

The Department of Industry, Tourism and Resources

The Department of the Environment and Heritage

The Department of Education, Science and Technology

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Australian Nuclear Science and Technology Organisation (ANSTO)

Appendix C. Submissions received by the Taskforce

Individual submissions

- Aldrick, Robyn
- Alexander, Karen
- Atkinson, Bernardine
- Barnes, Julie
- Blair, David
- Blyth, Judy
- Bohnet, Gabriele
- Boulton, Liz
- Bradbury, David
- Brier, David
- Broinowski, Richard
- Bruinstroop, Frank
- Bunch, Enid
- Burgess, Michael
- Bussenschutt, Joseph
- Byass, Rosalind
- Byrne, Aiden
- Callaghan, Andrea
- Cusack, Mary
- Daly-King, Betty
- Deblaquiere, Julie
- Deeley, Diana
- Delaney, Craig
- Diesendorf, Mark
- Dixon, Lorraine
- Edwards, S
- Faulkner, Peter
- Finegan, Pat
- Finkel, Alan
- Fisher, William
- Foster, Jean
- Furuno, Shin
- Gambotto, Daniela
- Gates, Steve
- Gellatly, Peter
- Giles, Nick
- Glover, Simon
- Goldschlager, Les
- Gordon, Anna
- Green, Dot
- Greenhill, John
- Grierson, Ian
- Hagen, Hans
- Harrington, Geraldine
- Hassett, Michael
- Higson, Don
- Holmes, HR
- Horner, Pen
- Houston, Michael
- Humphris, Peter
- Hungerford, Keith
- Jennings, Philip
- Johnson, M
- Johnson, Wendy
- Jones, Chris
- Keeffe, Lisa
- Kemeny, Leslie
- Keough, Kris
- Kerjman, Michael
- Kirchhoff, Alana
- Kline, Colin
- Koch, Cecilie
- Laird, Philip
- Law, Valerie

- Lawrence, Barry
- Le Couteur, Caroline
- Lichacz, Wieslaw
- Lock, Nicholas
- Mabb, John
- MacDonald, David
- Mackle, Pat
- Madigan, Michele
- Maiden, Pepita
- Malcolm, Clive
- McCarthy, Lance
- McCarthy, Sidrah
- McCormack, John
- McDarmont, Ben
- McGrath, Michael
- McHugh, Gerard
- McHugh, Ian
- Mehta, Fred
- Miller, Joel
- Morris, Louise
- Mushalik, Matt
- Nichols, Kenneth
- O'Kelly, Peter
- Owen, John
- Palmer, Lucille
- Parkinson, Alan
- Paterson, Duncan
- Peters, Donella
- Pinkas, Joanna
- Pollard, Alex
- Rainbird, Wendy
- Reid, Don
- Ross, Donald
- Rowland, Phillipa
- Sanders, George
- Schardijn, Irene
- Schnelboegl, Peter
- Sharp, Nicholas
- Smalley, Chris
- Smith, Rebecca
- Smith, Zane
- Stephen, Wendy
- Stephens, Irving
- Stevenson, Hayley
- Suehrcke, Harry
- Surveyor, Ivor
- Swinton, Richard
- Taylor, Daniel
- Thomas, Geoff
- Thornber, Mike
- Thummel, Cindy
- Tilbrook, Challis
- Tomlinson, Alan
- Turtle, Robert
- Tutty, Justin
- Van Zonneveld, Samantha
- Ward, John
- Ward, K
- Webb, Mandy
- Whelan, Cedar & Aja
- Wilcox, Michael
- William, Lisa
- Wood, Peter
- Wood, Tony
- Wright, William
- Wrigley, Derek

Submissions received from organisations

- Academy of Technological Sciences and Engineering
- Alice Action Group
- Alternative Technology Association
- Anti-Nuclear Alliance of Western Australia
- ANU Environment Collective Office
- AREVA
- Australian Academy of Science
- Australian Business Council for Sustainable Energy
- Australian Conservation Foundation (Sydney Branch)
- Australian Conservation Foundation
- Australian Greens
- Australian Institute of Nuclear Science and Engineering
- Australian ITER Forum
- Australian Nuclear Association
- Australian Nuclear Forum Inc
- Australian Nuclear Science and Technology Organisation
- Australian Radiation Protection and Nuclear Safety Agency
- Australian Safeguards and Non-Proliferation Office
- Australian Strategic Policy Institute
- Australian Student Environment Network
- Australian Technology Network
- Australian Union of Students
- BHP Billiton
- Canberra Region Anti Nuclear Campaign
- Chamber of Commerce and Industry (WA)
- Conservation Council of Western Australia
- CSIRO
- Demand Manager Pty Ltd
- Department of Foreign Affairs and Trade
- Docklands Science Park Pty Ltd
- Doctors For the Environment Australia
- Energy Networks Association
- Energy Resources of Australia
- Energy Supply Association of Australia
- Engineers Australia
- Environment Business Australia
- Environment Centre NT
- Everyone for a Nuclear Free Future — Lismore
- Food Irradiation Watch
- Fremantle Anti-Nuclear Group
- Friends of the Earth
- Friends of the Earth Adelaide
- Friends of the Earth Brisbane
- Gecko — Gold Coast and Hinterland Environment Council
- Geoscience Australia
- Glen Haven Consulting
- Greenpeace Australia Pacific
- Hunwick Consultants
- Institute of Public Affairs
- Katherine Nuclear Dump Action Committee
- Kim Stephan Consulting
- Medical Association for the Prevention of War
- Medical Association for the Prevention of War (NT)
- METTS Pty Ltd
- Minerals Council of Australia
- Musgrave Design and Engineering Pty Ltd

- National Civic Council (SA)
- National Generators Forum
- National Toxics Network
- NEMMCO
- Northern Territory Government
- Nuclear Engineering Panel of the Institute of Engineers Australia
- Nuclear Free Queensland and the Queensland Conservation Foundation
- Nuclear Fuel Leasing Group
- Nu-Power Green
- Peace Organisation of Australia
- People for Nuclear Disarmament NSW Inc
- Prospect Residents' Energy Forum (SA)
- Queensland Resources Council
- Renewable Energy Generators Australia
- Rio Tinto
- Rylstone District Environment Society
- Scientists and Technologists Against Nuclear Dumping
- Silex
- Submarine Institute of Australia
- Sunshine Coast Environment Council
- Sutherland Shire Environment Centre Inc and People Against Nuclear Reactor Inc
- UNSW Environment Collective
- Uranium Information Centre
- Victorian State Government
- Western Australian Sustainable Energy Association
- Women's International League for Peace and Freedom

Appendix D. Consultations

- ABN Amro
- Alinta
- Andra (France)
- Areva (France)
- Association of Mining and Exploration Companies
- Australian Academy for Technological Sciences and Engineering
- Australian Academy of Science
- Australian Conservation Foundation
- Australian Council for Infrastructure Development
- Australian Council of Trade Unions
- Australian Nuclear Science and Technology Organisation
- Australian Radiation Protection and Nuclear Safety Agency
- Australian Safeguards and Non-Proliferation Office
- Australian Technology Network
- Australian Vice-Chancellors' Committee
- BHP Billiton
- British Energy
- British Nuclear Fuels and British Nuclear Group
- Broinowski, Adjunct Prof Richard
- Business Council for Sustainable Energy
- Caldicott, Dr Helen
- Cameco (Canada)
- Chamber of Minerals and Energy of Western Australia
- Cooperative Research Centre for Greenhouse Gas Technologies
- CSIRO Energy Transformed Flagship
- Dalton Nuclear Institute (United Kingdom)
- Department of the Environment and Heritage Office of the Supervising Scientist
- Department of Trade and Industry (United Kingdom)
- Duncan, Dr Ian
- Eléctricité de France
- Energy Supply Association of Australia
- Engineers Australia
- Environment Centre Northern Territory (ECNT)
- Exelon (United States)
- Flannery, Dr Tim
- Fortum (Finland)
- Friends of the Earth (Australia)
- General Atomics (United States)
- General Electric
- Goldman Sachs JBW
- Heathgate Resources
- International Atomic Energy Agency
- International Energy Agency
- Japan Atomic Power Company
- Kansai Electric Power Company (Japan)
- Korea Hydro and Nuclear Power
- McKinsey and Company (Australia)
- Medical Association for Prevention of War (Australia)
- Minerals Council of Australia
- Ministry of Economy, Trade and Industry (Japan)
- Ministry of Education, Culture, Sports, Science and Technology (Japan)
- Ministry of Trade and Industry (Finland)
- Morgan, Mr Hugh
- National Generators' Forum

- National Security Council (United States)
- Northern Land Council
- Northern Territory Government
- Nuclear Energy Institute (United States)
- Nuclear Fuel Leasing Group
- Nuclear Industry Association (United Kingdom)
- Nuclear Regulatory Commission (United States)
- Organisation for Economic Cooperation and Development Nuclear Energy Agency
- Pacific Basin Nuclear Conference meetings
- Paladin Resources
- Posiva (Finland)
- Rio Tinto
- Silex Systems Limited
- South Australian Government
- State Nuclear Regulation Committee of Ukraine
- Teollisuuden Voima Oy (TVO) (Finland)
- Tokyo Electric Power Company
- Uranium Information Centre
- Urenco (United Kingdom)
- United States Department of Energy
- United States Department of State
- VTT Technical Research Centre of Finland
- Wesfarmers Energy
- Western Australian Government
- World Nuclear Association
- World Wildlife Fund Australia

Appendix E. Site visits

- AREVA NC La Hague reprocessing plant, La Hague (France)
- Australian Nuclear Science and Technology Organisation Lucas Heights facilities (New South Wales)
- Beverley in-situ leach uranium mine (South Australia)
- Capenhurst uranium enrichment facility (United Kingdom)
- Chernobyl (Ukraine)
- Dalton Nuclear Institute, Manchester (United Kingdom)
- European Underground Research Infrastructure for Disposal of nuclear waste In Clay Environment (EURIDICE) High Activity Disposal Experimental Site, Mol (Belgium)
- General Atomics R&D facilities, San Diego (United States)
- JAEA Tokai-mura R&D facilities (including spent fuel reprocessing centre) (Japan)
- Meuse/Haute-Marne Underground Research Laboratory (France)
- Olkiluoto nuclear power plants and waste repository (Finland)
- Olympic Dam copper and uranium mine (South Australia)
- Port Hope fuel fabrication facility (Canada)
- Port Hope uranium conversion facility (Canada)
- Ranger uranium mine (Northern Territory)
- Sellafield nuclear facility (United Kingdom)
- Springfields fuel fabrication facility (United Kingdom)
- Three Mile Island nuclear power facilities (United States)
- Tokai nuclear power facility (Japan)
- Wolsong nuclear power facility (Korea)
- Yucca Mountain geological waste repository (United States)

Appendix F. Chief Scientist's Expert Panel

Role and operation of the Expert Panel

On 6 June 2006 the Prime Minister announced the appointment of a Taskforce to undertake an objective, scientific and comprehensive review into uranium mining, processing and the contribution of nuclear energy in Australia in the longer term. The Prime Minister also announced that the Chief Scientist, Dr Jim Peacock, would chair an Expert Panel that would review the scientific aspects of the Uranium Mining, Processing and Nuclear Energy Review (UMPNER).

The Expert Panel met in Canberra on 21–22 November. During that time the Expert Panel met with members of the UMPNER Secretariat and the Review Panel and provided their comments on the draft report.

Chair

Dr Jim Peacock, Australian Chief Scientist

Dr Jim Peacock was appointed Australian Chief Scientist in March 2006. Dr Peacock is an outstanding scientist with a record of academic excellence and is highly respected by the science, engineering and technology community.

Dr Peacock is an award winning molecular biologist and fervent science advocate. He is recognised internationally as an eminent researcher in the field of plant molecular biology and its applications in agriculture.

In 1994, he was made a Companion of the Order of Australia for outstanding service to science, particularly in the field of molecular biology and to science education. Dr Peacock is a Fellow of the Australian Academy of Science, Fellow of The Royal Society of London, the Australian Academy of Technological Sciences and Engineering, a Foreign Associate of the US National Academy of Sciences and a Foreign Fellow of the Indian National Science Academy.

In 2000 he was a co-recipient of the inaugural Prime Minister's Science Prize, for his co-discovery of the Flowering Switch Gene — a key gene that determines when plants end their vegetative growth phase and begin flowering. This discovery will help boost the productivity of the world's crops by billions of dollars each year and could also help increase the nutritional value of crops eaten by billions of the world's poorest people.

He was also awarded the BHP Bicentennial Prize for the pursuit of excellence in science and technology and the Australian Academy of Science's Burnett Medal for distinguished contributions in the biological sciences.

Dr Peacock has gained valuable experience working in industry having founded the Gene Shears biotechnology company and instituted the GrainGene initiative and the HRZ Wheat Company — linking research with the production of new wheat varieties for Australia. He played a key role in the establishment of cotton as Australia's first highly successful biotech crop.

Dr Peacock is a strong advocate for the integration of science and global business. He drives innovative communication efforts to inform the general public as to the outcomes and value of modern science. He has brought the excitement of science to a broad cross-section of the community and to Australian school students.

International review panel members

Dr Christine Brown, Head of Strategy, MOX, British Nuclear Fuels PLC.

Dr Brown joined the United Kingdom Atomic Energy Authority at Dounreay in 1971 after completing BSc and PhD degrees at Glasgow and Oxford Universities. During her early career she specialised in electron optics methods to study the effects of irradiation damage on reactor core structural and fuel materials, in particular, plutonium containing fuels. In 1992 she was awarded the Charles Eichner Medal by the Materials and Metals Society of France for her contribution to Fast Reactor materials studies.

From this pure research background, Dr Brown's career moved into the more industrial applications area of nuclear reactor systems, including fuel fabrication and performance, plant operations and decommissioning. By leading development programmes on advanced fuels for future nuclear fuel cycles and advanced reactor systems, Dr Brown enjoys an international reputation for providing technical support and advice. She was a member of the US DOE Blue Ribbon Committee reporting to Nuclear Energy Research Advisory Committee (NERAC) on the proliferation resistance of recycled nuclear fuels and was technical advisor to the UK Department of Trade and Industry on future Generation IV reactors. She was a member of the BNFL/ Westinghouse team appointed to review the South African Pebble Bed Moderated Reactor and for 4 years was technical advisor and participant in the BNFL National Stakeholder Dialogue process.

Dr Brown retired as Head of Strategy, MOX in July 2006 but continues as technical advisor to British Nuclear Fuels PLC and to other government organisations.

Professor Gordon MacKerron, Director, Sussex Energy Group, SPRU, University of Sussex.

Professor MacKerron has been Director, Sussex Energy Group, SPRU (Science and Technology Policy Research), University of Sussex since April 2005, following four years as Associate Director, NERA Economic Consulting and an earlier career for over 20 years at SPRU, University of Sussex. He is an economist working in energy and environmental economics and policy. After early work in Malawi, Nigeria and as a lecturer at Griffith University, Brisbane, his academic career has specialized in the economics and policy issues of electricity and especially nuclear power.

He has frequently been Specialist Adviser or invited witness before UK House of Commons Select Committee inquiries on energy subjects. In 2001 he worked for the UK Cabinet Office as Deputy Leader of the UK Government's Energy Review team.

He has advised a wide range of public and private sector bodies including the European Commission, the European Parliament, the European Court of Auditors, the UK National Audit Office, the Parliamentary office of Science and Technology, the Brazilian Government, PowerGen (E.On), and Friends of the Earth. He has published widely on nuclear economics and policy, regulatory economics in electricity, energy security of supply and energy policy as a whole. Professor MacKerron has also been the expert witness on economic issues for the Irish Government in its two international court cases on the subject of Sellafield before the Permanent Court of Arbitration in the Hague in 2002 and 2003.

Professor MacKerron chaired the Energy Panel, Department of Trade and Industry/Office and Science and Technology (DTI/OST) Technology Foresight Programme (1995–98) and in December 2003 became the Chair of the Committee on Radioactive Waste Management, an independent body charged with recommending the best approach to long-term radioactive waste management to the UK Government.

Dr Richard A. Meserve, President, Carnegie Institution of Washington.

Dr Meserve became the ninth president of the Carnegie Institution in April 2003, after stepping down as chairman of the US Nuclear Regulatory Commission (NRC). Dr Meserve had been a member of Carnegie's board of trustees since 1992.

As Chairman of the NRC, Dr Meserve served as the principal executive officer of the federal agency with responsibility for ensuring the public health and safety in the operation of nuclear power plants and in the usage of nuclear materials. Before joining the NRC, Dr Meserve was a partner in the Washington, D.C., law firm of Covington & Burling, and he now serves as Senior Of Counsel to the firm. With his Harvard law degree, received in 1975, and his Ph.D. in applied physics from Stanford, awarded in 1976, he devoted his legal practice to technical issues arising at the intersection of science, law, and public policy.

Dr Meserve currently serves as Chairman of the International Nuclear Safety Group, which is chartered by the IAEA. Dr Meserve serves on the Board of Directors of the Universities Research Association, Inc. and on the Council of the American Academy of Arts and Sciences. He is a member of the National Academy of Engineering and the American Philosophical Society and is a Fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the American Physical Society.

Australian review panel members

Professor Kurt Lambeck, President, Australian Academy of Science.

Professor Lambeck is Distinguished Professor of Geophysics at the Australian National University. His research interests range through the disciplines of geophysics, geodesy and geology with a focus on the deformations of the Earth on intermediate and long time scales and on the interactions between surface processes and the solid earth. Past research areas have included the determination of the Earth's gravity field from satellite tracking data, the tidal deformations and rotational motion of the Earth, the evolution of the Earth-Moon orbital system, and lithospheric and crustal deformation processes. His recent work has focussed on aspects of sea level change and the history of the Earth's ice sheets during past glacial cycles, including field and laboratory work and numerical modelling.

Professor Lambeck has been at the Australian National University since 1977, including ten years as Director of the Research School of Earth Sciences. He is currently also strategic science advisor to the National Geospatial Reference System of Geoscience Australia. Before returning to Australia he was a Professor at the University of Paris. He has also worked at the Smithsonian and Harvard Observatories in Cambridge, USA. He has studied at the University of New South Wales, the Technical University of Delft, Netherlands, the National Technical University of Athens and Oxford University from which he obtained DPhil and DSc degrees. He has held visiting appointments in France, Netherlands, Belgium, Britain, Norway and Sweden. He was elected to the Australian Academy of Science in 1984 and to the Royal Society in 1994. He is a foreign member of the Royal Netherlands Academy of Arts and Sciences (1993), Norwegian Academy of Science and Letters (1994), Academia Europaea (1999), and the Académie des Sciences, Institut de France (2005). He has received a number of international prizes and awards including the Tage Erlander Prize from the Swedish Research Council (2001), the Prix George Lemaître from the Université catholique de Louvain (2001), and the Eminent Scientist Award from the Japan Society for the Promotion of Science (2004).

Mr David Murray, Chairman, Future Fund.

David Murray has 39 years experience in banking. He retired from the Commonwealth Bank in 2005 having served 13 years as Chief Executive, he joined the Commonwealth Bank in 1966.

In November 2005 the Australian Government announced that Mr Murray would be Chairman of the Future Fund. The Fund's objective is to invest budget surpluses to meet the long term pension liabilities of government employees.

Mr Murray holds a Bachelor of Business from the NSW Institute of Technology and a Master of Business Administration, commenced at Macquarie University and completed at the International Management Institute, Geneva. He holds an honorary PhD from Macquarie University and is a Fellow of the University of Technology, Sydney.

As part of his interest in education Mr Murray chairs the Business Industry Higher Education Collaboration Council, is a benefactor of Schools and a member of Tara Anglican School for Girls Foundation in Sydney and a life member of the Financial Markets Foundation for Children. He is Chairman of the Global Foundation and is a non-executive director on the Board of Tenix Pty Ltd.

Dr Leanna Read, Managing Director, TGR BioSciences Pty Ltd.

Dr Read is a founder of TGR and has been Managing Director and CEO since the Company's incorporation in June 2001. She is a physiologist by training with over 90 scientific papers and more than 20 years experience in biotechnology research.

Dr Read has been a private member of the Prime Minister's Science, Engineering and Innovation Council for four years, has chaired two PMSEIC working groups and serves on the SA Premier's Science and Research Council as well as the boards of Novogen Ltd and the Australian Proteome Analysis Facility.

Prior to her current position, Dr Read was CEO of the commercially successful CRC for Tissue Growth and Repair, a position she took up after 10 years as the inaugural director of the Child Health Research Institute in Adelaide.

Dr Read is also a member of the National Collaborative Research Infrastructure Scheme (NCRIS) Committee. From 1995–2002 she was a member of the IR&D Board and chaired the IR&D Board Biological Committee.

Appendix G. Electric Power Research Institute* — commissioned study

Review and comparison of recent studies for Australian electricity generation planning

Summary

Australia's future economic growth and prosperity depend on having ample supplies of affordable energy. Currently, Australia relies on coal and natural gas to generate more than 90 per cent of its electricity.

Even though Australia holds 40 per cent of the world's known, low-cost, recoverable uranium reserves, nuclear power has never been a part of the nation's power supply portfolio.

Growing concern over the contributions of fossil fuel combustion to climate change is one of several factors compelling policymakers, energy companies, nongovernmental organisations, and other stakeholders to look at nuclear energy from a different perspective: around the world, nuclear power plants are generating large quantities of reliable, cost-competitive electricity without releasing greenhouse gases.

On June 6, 2006, Prime Minister Howard appointed a taskforce to undertake an objective, scientific, comprehensive, and long-term review of uranium mining and processing and of the possible contribution of nuclear power to Australia's energy future.

The merits, hazards, and relative economic costs of various technologies for baseload electricity generation have been analysed in many previous studies. The Prime Ministerial Uranium Mining, Processing and Nuclear Energy Review (UMPNER) Taskforce engaged the Electric Power Research Institute (EPRI) to conduct an independent review and analysis of selected studies to provide baseline information on whether nuclear energy could — in the longer term — be economically competitive with other electricity generation technologies in Australia. This report presents the results of EPRI's analyses.

Approach

This report compares and contrasts the results of recent studies examining the economic costs and other impacts of using nuclear, coal, natural gas, and renewables for electricity generation.

The previous studies largely address the future of power generation technologies in the United States, Australia, United Kingdom, Finland, other European Union nations, and other Organisation for Economic Co-operation and Development (OECD) nations. They also consider the status and cost-performance potential of carbon capture and sequestration technologies, the economic and non-economic (external) costs associated with current generation options, and the possible effect of climate policies and other government interventions on technology choice. The studies were conducted by highly regarded institutions and are widely referenced in the literature and in debates regarding governmental policies on energy and the environment.

This report analyses the findings from these studies — and how the results were derived — to provide insights on the possible competitiveness of nuclear generation in Australia. It incorporates a summary-level comparison of the costs of similar coal-fired plants in Australia and the south-central United States to illustrate the use of scaling factors in transferring cost data from one country to another. It also employs available data to examine the current and future competitiveness of existing fossil and renewable generation options within Australia. In lieu of making the many specific and detailed assumptions required to develop accurate cost estimates for a nuclear power plant in Australia, EPRI identified fundamental differences between establishing a commercial nuclear program in Australia and adding to the nuclear capacity in the United States, as has been intensively examined in previous studies for specified or implied locations. Based on these differences, scaling factors were developed for issues relating to regulatory

* Full report available at http://www.pmc.gov.au/umpner/docs/commissioned/EPRI_report.pdf

capabilities; design, engineering, and licensing; siting; financing; construction; construction duration; production; capacity factor; and spent fuel, waste, and decommissioning. These scaling factors were then combined to assess the potential competitiveness of nuclear power in Australia.

Findings and recommendations

The previous studies all used the same general methodology to calculate a levelised cost of electricity (LCOE) cost for each generation option within a specified geographical region. The levelised cost is the constant real wholesale price of electricity that recoups owners' and investors' capital costs, operating costs, fuel costs, income taxes, and associated cash flow constraints. The LCOE approach is widely used and easy to understand, but the previous studies arrived at very different conclusions because they employed different algorithms, assumptions, and inputs.

In two studies, for example, nuclear power was the least expensive option, while in two others it was the most expensive. This variability is illustrated in Figure ES-1 (*in the EPRI report*), which shows base-case findings from five previous studies and sensitivity studies for a sixth, with all LCOE values reported in year 2006 Australian dollars.

Appendix H. Australian Bureau of Agricultural and Resource Economics (ABARE)* — commissioned study

Uranium: global market developments and prospects for Australian exports

Summary

World uranium requirements are projected to increase in the period to 2030:

- This projected increase reflects the expected construction of new nuclear reactors and extensions to the operating lives of a number of existing reactors.
- The strongest growth in nuclear capacity is expected to be in China and India, where rapid economic expansion has led to a strong increase in demand for electricity. The expansion of nuclear capacity in China and India is seen as a measure to address electricity supply concerns in areas that are experiencing rapid economic growth but are located far from lower cost domestic fossil fuel supplies.
- In other countries, the promotion of nuclear power also seeks to address energy security considerations and in some cases environmental issues including localised pollution and greenhouse gas emissions. Uranium demand growth in countries with the largest installed nuclear capacity, including the United States, France, Japan and the Russian Federation, is likely to be supported by increased load factors and operating life extensions at existing nuclear power plants, as well as new and replacement reactor builds.
- The longer term outlook for global enrichment capacity will have an important influence on the demand for uranium.
- Enrichment capacity is expected to remain reasonably steady over the medium term as approximately 13 million separative work units (SWU) of gaseous diffusion capacity is phased out between 2010 and 2015 and replaced with centrifuge technology.
- Beyond 2015, the outlook for global enrichment capacity is significantly more difficult to ascertain. One of the characteristics of centrifuge enrichment is the ability to allow incremental expansion of enrichment capacity. Accordingly, global enrichment capacity is likely to expand in line with global enrichment demand.

World uranium mine production is projected to increase in the period to 2030:

- Global mine production is expected to increase substantially over the period to 2015 as increases in the uranium price encourage the development of new mines and prolong the operating lives of existing mines.
- Over the period 2006 to 2015, global mine production is projected to increase by 77 per cent to just under 84 400 tonnes U_3O_8, with the major increases in global uranium mine production expected to occur in Canada, Kazakhstan, the Russian Federation and Africa.
- Beyond 2015, based on uranium resources, countries that have the potential to significantly increase uranium mining capacity include Australia, Kazakhstan, Canada, the United States, South Africa, Namibia, Niger, Brazil and the Russian Federation.

Secondary supplies of uranium are projected to decline in the period of 2030:

- Secondary supplies of uranium are expected to decline over the period to 2015. The assumed commencement of sales from US government uranium stockpiles in 2009 is expected to be offset by the completion of the US–Russian HEU purchase agreement in 2013.
- Therefore, given the forecast growth in uranium requirements over the outlook period, an increase in uranium mine production will be required to meet demand.

* Full report available at http://www.abareconomics.com/publications_html/energy/energy_06/uranium.pdf

Australia will lose significant uranium mine production share over the period to 2030 if the 'no new mines' policy is maintained:

- Australia has the potential to significantly increase uranium mine production over the longer term. It has the world's largest resources of low cost uranium and there has been a substantial rise in domestic exploration of uranium.
- Government policy regarding mine development, rather than resource availability, is expected to be the major factor in determining growth in Australia's uranium production and exports.
- The outlook for Australia's exports of uranium will largely depend on whether or not the 'no new mines' policy is maintained.
- Should there be no change to this policy, Australia's market share of global uranium production is expected to decline over the period to 2030 as countries such as Kazakhstan, Canada, Namibia and the Russian Federation substantially increase production.
- If the 'no new mines' policy is overturned, Australia's mine production to 2015 and beyond is forecast to be substantially higher in volume terms than under the 'no new mines' scenario.

Appendix I. ISA, The University of Sydney* — commissioned study

Life cycle energy balance and greenhouse gas emissions of nuclear energy in Australia

Summary

This report distils in a condensed yet comprehensive way a large body of previous work and knowledge about the energy balance and life cycle greenhouse gas emissions associated with the nuclear fuel cycle. For comparison, a summary of the energy balance and life cycle emissions for a range of non-nuclear electricity generation technologies is also presented.

Certainly, every practical life cycle assessment is undertaken for particular circumstances, that is particular locations, ores, or reactor types. Results from the literature must therefore be interpreted as valid primarily under these circumstances. Changing critical parameters and assumptions will lead to variations of the results.

Also, every practical life cycle assessment leaves out some more or less important part of a theoretically 'true' life cycle, be it parts of the fuel cycle processes, indirect, upstream inputs into components, or parts of the material fuel and waste stream.

In bringing together analyses that are all incomplete with regard to a different aspect of the nuclear fuel cycle, and in extrapolating the results from these analyses towards a more complete 'integrated' assessment, this work has achieved comparisons between nuclear energy systems that are very different in terms of a large number of critical technical parameters, operate in low- and high-carbon economies, and are assessed using different methods.

This study has also provided an example that demonstrates both the strength of state-of-the-art life cycle methods for informing national policy, and the need for quality data underpinning this method.

Assumptions and scope of this life cycle analysis of nuclear energy in Australia

The assumptions outlined below form the base case of our assessment. In a sensitivity analysis, these assumptions were varied, and the energy balance and greenhouse gas emissions recalculated.

A spreadsheet calculator was developed which allows these parameters to be set to any desired scenario.

An Australian nuclear fuel cycle is — except for mining and milling — hypothetical, and has been constructed based on the best knowledge and overseas experience available. Ideally, a more detailed **life cycle assessment** than the one carried out in this work would exploit detailed planning and engineering data for concrete Australian facilities, in conjunction with an Australian input–output database.

The energy requirements for **mining and milling** as well as the **recovery rate** depend critically on the grade of the uranium-bearing ore, and on whether uranium is mined together with other products. In this study we have assumed that uranium is recovered from ore of 0.15 per cent grade (typical grade for Ranger and Beverley mines), and that no other product is mined, so that the full energy requirement is attributable to uranium. This is a conservative assumption, because had we assumed conditions as in the Olympic Dam mine, the ore grade would have been lower (around 0.05 per cent), however most energy requirements would have been attributable to the recovered copper.

The energy requirements for **enrichment** depend critically on which enrichment method is employed. In this study we have assumed the present mix of diffusion and centrifuge plants (30/70 per cent). For future scenarios this is a conservative assumption, because it is expected that in the future centrifuge plants will substitute diffusion plants.

* Full report available at http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf

The energy requirements for the **construction, operation and decommissioning** of nuclear facilities depend critically on what method is used for their enumeration. We have based this study on input–output hybrid life cycle assessments.

The energy requirements for **mine clean-up, intermediate storage and long-term disposal** of nuclear waste depend critically on which procedures are deemed acceptable for sufficiently isolating radioactivity from the natural and human environment. At present, there is no operating final disposal facility, and hence limited practical experience of containing radioactivity for very long periods. This study does not comment on the adequacy of existing and planned mine clean-up, storage and disposal procedures, because these aspects fall outside this study's scope.

The **lifetime of uranium resources** for supplying the world's nuclear power plants depends critically on assumptions about future electricity demand, recoverable resources and ore grade distributions, by-products of uranium in mines, future exploration success, the exploitation of breeder reactors and plutonium in MOX fuels, and market conditions. These aspects are outside the scope of this study.

Results for the nuclear fuel cycle in Australia

The energy balance of the nuclear fuel cycle involves trade-offs between material throughput and fissile isotope concentration at various stages in the cycle. For example, there are trade-offs between:

- using less but enriched fuel in Light Water Reactors, versus more but natural fuel in Heavy Water or Gas-cooled Graphite Reactors
- applying more enrichment work to less fuel, versus less enrichment work to more fuel, and
- investing more energy into uranium and plutonium recycling, versus higher volumes of fuel uranium mining, throughput, storage, and disposal.

The overall **energy intensity of nuclear energy** depends critically on:

- the grade of the uranium ore mined
- the method for enrichment
- the conversion rate of the nuclear fuel cycle (ie fuel recycling).

The energy intensity will increase:

- with decreasing uranium ore grades
- with increasing proportion of diffusion plants, and
- with decreasing fuel recycling.

Notwithstanding these variations, it can be stated that:

- accepting the qualifications and omissions stated
- for grades of average ore bodies mined today, and
- for state-of-the-art reactors and uranium processing facilities

the energy intensity of nuclear power:

- is around 0.18 kWh_{th}/kWh_{el} for light water reactors, and around 0.20 kWh_{th}/kWh_{el} for heavy water reactors
- is slightly higher than most figures reported in the literature, because of omissions in the nuclear fuel cycle and upstream supply-chain contributions
- varies within the range of 0.16–0.4 kWh_{th}/kWh_{el} for light water reactors, and within 0.18–0.35 kWh_{th}/kWh_{el} for heavy water reactors
- is lower than that of any fossil-fuelled power technology.

The **energy payback time of nuclear energy** is around 6½ years for light water reactors, and 7 years for heavy water reactors, ranging within 5.6–14.1 years, and 6.4–12.4 years, respectively.

The **greenhouse gas intensity of nuclear energy** depends critically on:

- the energy intensity
- the proportion of electric versus thermal energy in the total energy requirement
- whether electricity for enrichment is generated on-site (nuclear), or by fossil power plants, and
- the overall greenhouse gas intensity (ie fuel mix) of the economy.

The greenhouse gas intensity will increase:

- with increasing energy intensity
- with increasing proportion of electricity in the energy requirement
- with increasing proportion of electricity for enrichment generated by fossil power plants, and
- with increasing greenhouse gas intensity of the economy.

Similarly,

- accepting the qualifications and omissions stated
- for grades of average ore bodies mined today, and
- for state-of-the-art reactors and uranium processing facilities

the greenhouse gas intensity of nuclear power is:

- around 60 g CO_2-e/kWh_{el} for light water reactors, and around 65 g CO_2-e/kWh_{el} for heavy water reactors
- slightly higher than most figures reported in the literature, because of omissions in the nuclear fuel cycle and upstream supply-chain contributions
- varies within the range of 10–130 g CO_2-e/kWh_{el} for light water reactors, and within 10–120 g CO_2-e/kWh_{el} for heavy water reactors
- lower than that of any fossil-fuelled power technology.

Sensitivity analysis

Significant parameters and assumptions influencing the energy and greenhouse gas intensity of nuclear energy are:

- the grade of the uranium ore mined
- the enrichment method and product assay
- the nuclear power plant's load factor, burn-up, and lifetime
- the greenhouse gas intensity and electricity distribution efficiency of the background economy.

In a sensitivity analysis, these parameters were varied and the energy and greenhouse gas intensity of nuclear energy recalculated. This sensitivity explains the ranges of both the energy and greenhouse gas intensity of light water reactors and heavy water reactors.

Other electricity technologies

A comparable analysis has been undertaken for a number of conventional fossil-fuel and renewable electricity technologies. As with the methodology for the nuclear case, a range of literature values and current estimates have been used to examine the performance of these technologies in an Australian context, assuming new capacity is installed at close to world's best practice. These results, together with a summary of the nuclear energy results, are presented in the table below. The figures in parentheses represent the likely range of values. It is clear from the results that the fossil-fired technologies have significantly higher energy and greenhouse intensities than the other technologies.

Methodology and data

Hybrid input–output-based life cycle assessment is the most appropriate method to use for the analysis of energy and greenhouse gas emission balance of nuclear energy.

A comprehensive life cycle assessment of the nuclear fuel cycle in Australia requires:

- cost specifications and engineering data on the mining, milling, enrichment, power generation, storage and disposal facilities, and
- data on the background economy supporting such a nuclear industry indirectly.

The reliability of an input–output-based life cycle assessment relies critically on the quality of the underpinning input–output data. In particular, given that hybrid input–output-based life cycle assessment is an internationally accepted standard for investigating resource issues, it is essential that Australia possesses a detailed and complete input–output database.

Electricity technology	Energy intensity (kWh_{th}/kWh_{el})	Greenhouse gas intensity (g CO_2-e/kWh_{el})
Light water reactors	0.18 (0.16–0.40)	60 (10–130)
Heavy water reactors	0.20 (0.18–0.35)	65 (10–120)
Black coal (new subcritical)	2.85 (2.70–3.17)	941 (843–1171)
Black coal (supercritical)	2.62 (2.48–2.84)	863 (774–1046)
Brown coal (new subcritical)	3.46 (3.31–4.06)	1175 (1011–1506)
Natural gas (open cycle)	3.05 (2.81–3.46)	751 (627–891)
Natural gas (combined cycle)	2.35 (2.20–2.57)	577 (491–655)
Wind turbines	0.066 (0.041–0.12)	21 (13–40)
Photovoltaics	0.33 (0.16–0.67)	106 (53–217)
Hydroelectricity (run-of-river)	0.046 (0.020–0.137)	15 (6.5–44)

The need for further analysis

Energy and greenhouse gas emissions analyses of energy supply systems are not a substitute for, but a supplement to economic, social, and other environmental considerations. If an energy supply system can be shown to a clear energy loser, then energy analysis is sufficient to argue that the program should be abandoned. If, on the contrary, the system appears to be an unambiguous energy producer, the decision whether or not to proceed with the program must also be based on other economic, social and environmental criteria.

The project team makes the following observations:

1. Further analyses of energy scenarios for Australia would benefit from an extended multi-criteria life cycle analysis incorporating additional **social, economic and environmental indicators spanning the entire Triple Bottom Line (TBL)**.
2. Most previous life cycle studies documented in the literature use static methods that do not take into account temporal profiles of energy sources and sinks occurring in the full energy cycle, and the temporal interplay of net supply and demand for electricity.

   The current study could be enhanced by:

   - developing a **dynamic formulation** of a time-dependent future profile of energy supply from a mix of sources, and
   - undertaking a **long-term forecasting exercise** of the transition of Australia's electricity generating system to a new mix of nuclear, advanced fossil, and renewable technologies, and the economy-wide TBL implications thereof.
3. In order to enable sound life cycle assessments of the implications of energy systems for our environment, our physical resource base, and our society, it is essential that these assessments are underpinned by a **detailed and complete information base**. Australian life cycle assessment capability would benefit from an enhanced data collection effort at the national level, in particular with view to creating a seamlessly aligned input–output database.

Appendix J. Frequently asked questions

1. Are nuclear reactors safe?

The civilian nuclear industry is more than 50 years old and Chernobyl is the only accident with serious health and safety impacts. This accident involved a reactor design not used outside the former Soviet system. The current nuclear power industry, with more than 440 reactors currently operating safely in over 30 countries, is mature, safe and sophisticated and compares favourably with all other forms of electricity production on key health and safety measures.

Of course, no industrial process is risk-free, but modern reactor designs aim to contain the impact of any accident and to prevent the release of radiation.

2. Can there be another Chernobyl-like accident?

The Chernobyl reactor lacked many of what are now regarded as basic safety design systems. Since that accident in 1986, the nuclear energy industry has developed and adopted safety and training practices that have helped achieve thousands of reactor years of safe operations.

Some current reactor designs use passive safety systems (where safe shutdown happens without the need for human intervention). Current estimates suggest a core meltdown event would be less than one in a hundred thousand years in a typical Australian scenario. Well-engineered containment systems, a standard feature of modern reactors, further reduce the risk to the population. The lack of injury or radiation exposure resulting from the accident at Three Mile Island showed that this approach works.

3. If Australia had nuclear power, would the reactors become attractive targets for terrorists?

To the extent that a nation's energy system is a possible terrorist target, then any electricity generator shares that risk. However, the designs of nuclear reactors are specially strengthened against any unauthorised intervention and those physical protection measures have been demonstrated to be effective.

4. Will increasing Australian uranium production and exports add to the risks of proliferation of nuclear weapons?

Proliferation remains a serious global issue and one where Australia has played a positive leadership role.

Australia's uranium supply policy, supported by International Atomic Energy Agency safeguards inspections, ensures that Australian obligated nuclear material does not contribute to nuclear weapons programs. Actual cases of proliferation have involved illegal supply networks, secret nuclear facilities and undeclared centrifuge enrichment plants, not the diversion of declared materials from safeguarded facilities such as nuclear power plants.

As the global nuclear industry grows, any increased role for Australia would be a positive force for the non-proliferation regime.

5. Will the world run out of uranium?

With present levels of use and current technologies, existing economic reserves of uranium are sufficient to produce nuclear fuel for 50–100 years. Moreover, uranium is a relatively abundant element in the earth's crust and further discoveries of recoverable ore bodies are highly likely to extend this time. The development and deployment of breeder reactor technology in the decades ahead could provide sufficient fuel for potentially thousands of years.

6. Where would nuclear reactors be located?

There are a number of criteria used for power plant site selection: proximity to the source of electricity demand, access to the transmission grid, access to cooling water, special applications (eg desalination, mining operations), and so on. Frequently, new plants are co-located near existing baseload generators.

The Review did not consider possible locations for nuclear power plants.

7. Can the radioactive waste be safely managed and where would it be located?

There is an international consensus at the scientific and engineering level that high-level radioactive waste, including spent nuclear fuel can be safely disposed of in suitable deep geological formations.

A number of countries are developing such facilities. The first European facility is likely to come on stream around 2020.

Australia has significant areas where the geology is favourable for long-term disposal of high-level waste in deep repositories, enabling its radioactivity to decay to harmless levels.

Were Australia to deploy nuclear reactors, a high-level waste repository would not be needed before 2050.

8. Isn't the requirement to store spent fuel for thousands of years an unreasonable burden upon future generations?

An important and widely adopted principle is that current users should pay the full costs of the use of nuclear power and thus avoid any intergenerational cost transfers.

The need to contain radioactive waste for thousands of years is recognised in regulatory standards specifying the design life of repositories. For example, the United States EPA recently set an exacting design life standard for the Yucca Mountain high-level waste repository. The lifetime costs of waste disposal at this facility will be met from funds being raised from current users.

Spent fuel is highly radioactive but the volume of waste is comparatively small, and well established processes exist for its safe handling.

After a sufficient time in a storage or disposal facility, radioactive materials will decay back to background levels. Furthermore, it is reasonable to expect that research into advanced fuel cycles will develop technologies to render harmless these by-products of the nuclear fuel cycle.

9. Might Australia become a dump for the world's radioactive waste?

Australia's large land area and geology combine to suggest that it could provide highly suitable sites for national, regional or even global radioactive waste disposal facilities, if it were deemed to be in the national interest.

In reality, there have been few instances of countries accepting the waste from the nuclear industries of other countries for disposal, and there are no agreed mechanisms for operation and control of multinational repositories.

There are advocates of a significant international waste facility in Australia, citing commercial and geopolitical benefits. The Review found such proposals still need to resolve a number of questions.

10. If Australia 'goes nuclear' will this increase tensions in our region, or even start a nuclear arms race?

Typical nuclear power plants represent a low proliferation risk. Many countries in our region plan to deploy civil nuclear energy.

Enrichment is a more proliferation-sensitive nuclear technology. The Review considered that there should be no unnecessary regulatory impediments to commercial involvement in the nuclear fuel cycle. Any extension by Australia into enrichment or reprocessing will require careful explanation to many constituencies including countries in our region.

Australia has well-accepted non-proliferation credentials and the transparency of our processes is excellent.

11. Will investment in nuclear power reduce the flow of funds into renewables such as solar and geothermal?

No single energy technology can meet Australia's forecast growth in electricity demand and also meet environmental objectives. A mix of technologies, including renewables, will be required.

Even if our national energy strategy were to include nuclear as an option, contributions from other low-emission sources would probably still be needed for Australia to achieve its economic, energy, environmental and climate objectives.

All energy technology alternatives should have the opportunity to compete on a level playing field and decisions should be market driven. If a carbon price was introduced then this would have a favourable impact on all low-emission technologies (including renewables), and research into energy technologies that reduce emissions would become more attractive.

12. Can Australia achieve greenhouse emission goals without nuclear power?

The scale of greenhouse gas emission reductions required is so great that a portfolio of low-emission technologies together with widespread efforts to use energy more productively is needed. The availability of a wider range of technology options can minimise the cost of achieving greenhouse gas emission reduction goals.

Nuclear power supplies baseload electricity — something that key renewables like wind and solar energy cannot do economically until practical and affordable energy storage systems are available.

The Review concluded that the lowest cost pathway to achieve our greenhouse emission goals is likely to include nuclear as part of the future generation mix in Australia.

13. What is the cost of nuclear electricity versus Australia's current electricity costs?

Nuclear power is competitive with fossil fuels in many countries already.

Based upon full costing (which includes the cost of waste management and plant decommissioning), nuclear electricity generation would be about 20–50 per cent more expensive. If, as happens in some parts of the world, power plants using fossil fuels are required to pay for their emissions, this cost differential disappears.

A 20–50 per cent higher cost to generate electricity does not translate into an equivalent increase in price at the household or retail level. This is because the cost of generation accounts for only around one third of the total retail/household electricity price. The cost of other significant elements such as transmission and distribution would be unaffected.

14. Will household electricity costs inevitably go up in the decades ahead?

The rebalancing of Australia's energy platforms to low-emission technologies is a journey of many decades, notwithstanding the urgency of the climate change issue.

All low-emission technologies are currently more expensive than our low-cost coal and gas. Various models of emission abatement have been proposed, all of which entail some increase in electricity costs.

Pollution problems are typically solved through either regulation, market-based schemes and/or technological improvements. These usually involve some additional cost.

15. Does nuclear power require extensive government subsidies to be cost competitive?

Many civilian nuclear industries abroad have started with government support either through their original nuclear defence programs, or subsequently via government owned utilities. A current example is the US Government subsidy for the first six nuclear plants based upon next generation technology.

Nuclear power is defined by high upfront capital costs, long lead times, and in the case of first time deployment, a number of other risks. Countries relying on nuclear power have adopted a variety of approaches to deal with these challenges.

At the end of the day, a level playing field needs to be created so that all energy technologies can compete on an equal footing.

16. How much does nuclear power help to reduce greenhouse gas emissions?

Life cycle studies show that nuclear power is a low-emission technology.

Greenhouse gas emissions from nuclear power across the full life cycle, from uranium mining to final waste disposal, are at least ten times lower than from conventional fossil fuels, and are similar to those from many renewables.

Under one scenario considered by the Review, adoption of nuclear power in Australia in place of coal could reduce national greenhouse gas emissions by 17 per cent in 2050.

17. Would nuclear power be an additional user of water?

All thermal power stations (including coal and nuclear) require cooling either by water or air cooling systems.

No thermal power station is 100 per cent efficient at converting heat to electricity and so all require cooling to remove the excess heat. Nuclear plants typically operate at lower steam temperatures than coal-fired plants. This makes them somewhat less efficient and so they require more cooling. Either fresh or salt water or air (as with a car radiator) can be used for this purpose.

Most power stations are water-cooled and withdraw water from a river or lake or the ocean and discharge it a few degrees warmer after use. Sometimes cooling towers are used and water is evaporated into the atmosphere and not returned to the waterway. Nuclear power plants are frequently located on the coast and in such cases would use sea water for cooling.

No matter which cooling system is used, cooling water is isolated from the radioactive core of the reactor and cooling water discharges do not contain any radioactivity.

18. What is the timetable for building a nuclear industry?

Most estimates suggest that were a decision taken to introduce nuclear power in Australia, it would be 10 to 15 years before the first nuclear power plant could be operating.

One scenario would see 25 reactors in place by 2050 and generating about a third of Australia's electricity.

19. What about thorium as an alternative nuclear fuel? Should Australia be developing reactors based on thorium rather than uranium?

Thorium is a naturally occurring element which is about three times more abundant in the earth's crust than uranium. However, thorium is not a fissile material (although like U-238 it is *fertile*) and so needs to be used in conjunction with small amounts of fissile material — usually enriched uranium or plutonium. Reactors based on thorium signal some advantages over uranium, namely, fewer long-lived actinides and claims for improved proliferation resistance. (There is more information on thorium in Appendix L.)

The disadvantage of the thorium fuel cycle lies in the need to produce the initial fuel by incorporating a fraction of fissile material such as highly enriched uranium or plutonium, both of which pose a proliferation risk, as well as complicating the process of fuel fabrication. Subsequent use of the fissile isotope U-233 produced from the thorium also implies the need for a reprocessing cycle.

Another variant of the thorium based reactor is the accelerator driven system (ADS) where the need for fissile material is partly replaced by using a spallation source of neutrons (see Appendix L).

Currently, commercial thorium based systems are not available. Considerable development would be required to engineer and qualify such systems to the standards required.

20. Do operators of nuclear power stations have insurance coverage and what compensation would be available in the event of an accident?

Private insurance coverage is available for nuclear power utilities. An international nuclear insurance pool structure is used by insurers to obtain large amounts of private capacity to cover the risk of nuclear accidents. Insurance markets and private markets in general have substantial capacity for covering risk. Governments might be called upon to provide funds if the amount of damages from an accident exceeded the covered amount, or for exclusions that might apply to the private coverage.

Countries that have nuclear power generally require their nuclear operators to obtain nuclear liability insurance. Although not a party to the international nuclear liability regime, the United States requires its nuclear operators to maintain nuclear liability insurance as well as to contribute to a mutual fund to cover damage from a major accident. Some other countries are members of the Paris Convention which will require nuclear operators to obtain minimum financial coverage of €700 million, under an Amending Protocol. Nuclear liability is discussed further in Appendix Q.

Appendix K. Enrichment

K1 What is a SWU?

The enrichment process involves separating the two isotopes U-235 and U-238 and increasing the proportion of U-235 from 0.7 per cent to between 3 and 5 per cent for use as fuel in nuclear power plants.

The output of an enrichment plant is expressed as 'kilogram separative work units', or SWU. It is indicative of energy used in enrichment and measures the quantity of separative work performed to enrich a given amount of uranium when the feed and product quantities are expressed in kilograms.

In the enrichment process, approximately 85 per cent of the feed is left over as depleted uranium or tails. The amount of U-235 left in these tails is called the tails assay.

The U-235 tails assay can be varied. The lower the tails assay, the greater the amount of U-235 that has been separated in the enrichment process and the greater the amount of energy or SWU needed. A lower tails assay means that less natural uranium is required but more enrichment effort, or SWU is required. A higher tails assay requires a greater amount of natural uranium but less SWU.

It takes approximately 8 kilograms of uranium oxide (U_3O_8) and 4.8 SWU to produce one kilogram of enriched uranium fuel (enriched to 3.5 per cent) at 0.25 per cent tails assay.[32,52]

Table K.1 below shows the natural uranium and enrichment effort (SWU) required to produce one tonne of 4 per cent enriched uranium at various tails assays.

As the tails assay decreases, separating the two isotopes becomes more difficult and requires more and more energy or SWU. The SWU formula is complex[322] but calculators are readily available.

The primary factors in determining the tails assay are the relative prices paid for uranium and enrichment. An increase in the price of uranium will make lower tails assays attractive as less uranium is required (unless this is offset by an increase in the price of enrichment) and vice versa. Given the trend of uranium and enrichment prices in recent years, Western enrichment companies have chosen to re-enrich depleted uranium (or tails) resulting from previous enrichment processes.[20]

Table K.1 Required natural uranium and enrichment effort for 1 tonne of 4 per cent enriched uranium

Tails assay (% U-235)	Natural uranium requirement (tU)	Enrichment requirement (SWUs)
0.35	10.11	4825
0.30	9.00	5276
0.27	8.45	5595
0.25	8.13	5832
0.20	7.44	6544
0.13	6.66	8006

Source: WNA[20]

K2 Enrichment technologies

Gaseous diffusion was the first enrichment method to be commercially developed. It takes advantage of the difference in atomic weights between U-235 and U-238 to separate the two isotopes.

It involves forcing UF_6 gas through a series of porous membranes. The lighter U-235 molecules move faster and are better able to pass through the membrane pores. The UF_6 that diffuses through the membrane is slightly enriched, while the gas that does not pass through the membrane is depleted in U-235. This process is repeated many times in a series of stages called a cascade. Around 1400 diffusion stages is needed to produce low-enriched uranium. Gaseous diffusion technology is energy intensive and consumes approximately 2500 kWh/SWU. [34,41]

Gaseous centrifuge technology is classified as a second-generation enrichment technology. It also uses the difference in atomic weights between U-235 and U-238, however the approach is different.

UF_6 gas is fed into a vertical cylinder which spins in a vacuum at very high speed. The centrifugal force propels the heavier U-238 molecules to the outer edge, separating them from the lighter U-235 molecules. The gas enriched with the lighter U-235 flows towards the top of the centrifuge and the gas with the heavier U-238 flows towards the bottom. Centrifuge stages typically consist of a large number of centrifuges in parallel and are arranged in a cascade, similar to gaseous diffusion. However, the number of stages may be only 10 to 20 instead of around 1400 for gaseous diffusion. Centrifuge technology consumes 50 times less energy than gaseous diffusion, at 50 kWh/SWU.[34,41]

Laser enrichment processes are a third-generation enrichment technology that has the potential to deliver lower energy inputs, capital costs and tails assays.

Most laser enrichment research and development programs have ceased and the only remaining laser process being developed for commercial deployment is SILEX (Separation of Isotopes using Laser EXcitation), an Australian innovation. In May 2006, General Electric (GE) acquired the exclusive rights to complete the research and development as well as the commercial deployment of the SILEX technology in the United States. This includes building a demonstration facility in the US and possibly proceeding to full scale commercial production. If successful, a commercial scale deployment would take around a decade.[34,47]

Appendix L. Nuclear Reactor Technology

Nuclear reactors exploiting the energy released from nuclear fission for production of electricity were first built in the 1950s, with a commercial-scale plant, Calder Hall in the UK, commencing operation in 1956. A number of early designs (Generation I) evolved into five (Generation II) which today are the basis of most of the nuclear power plants now operating. New reactor build is presently a mix of Generation II and III designs, although construction has commenced on the first Generation III+ reactor in Finland in 2006. Generation IV designs have been chosen and are under development, with the first expected to be deployed sometime after 2015. This timeline is illustrated in Figure L1 below.

In section L1 below the present day reactor designs and their evolution are discussed, information on the current and planned deployment for the various reactor types is given in section L2, and current ideas for designs of future nuclear power plants are presented in section L3.

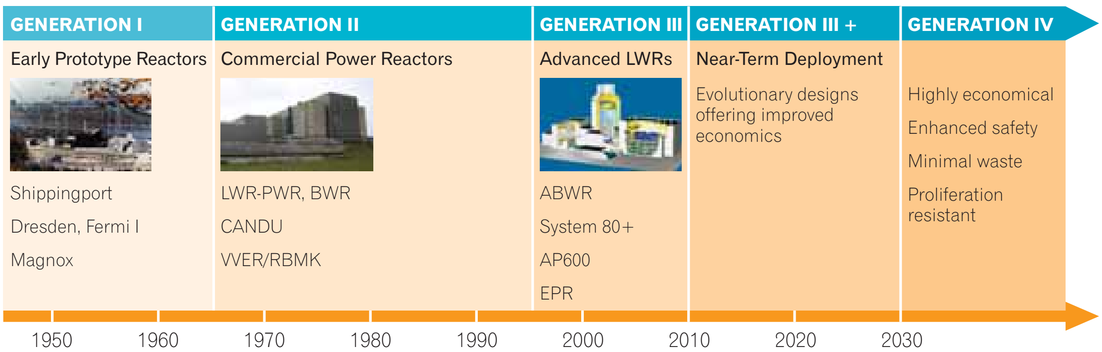
L1 Nuclear reactor designs

There are essentially five reactor systems that have been used for electricity production around the world, the most common being the pressurised water reactor, or PWR. It accounts for about 60 per cent of the world's current power reactors. Each of these reactor types is briefly described below.

L1.1 Pressurised Water Reactor (PWR)

PWRs use ordinary water as both coolant and moderator in the reactor core. The water is held at pressures around 160 bar[94] to prevent boiling and is heated to 320–330˚C by the fission process as it passes through the core. It transfers energy to a secondary loop, producing steam, which drives the steam turbine and, in turn, a generator to produce electricity. The overall steam cycle (often referred to as a Rankine cycle), is typically 33 per cent efficient.

Figure L1 Diagram illustrating the evolution of nuclear power plant designs



Source: USDoE/GIF[239]

[94] One bar is equal to approximately one atmosphere pressure (1 bar = 0.98692 atm).

The second generation PWR that was developed by the US firm Westinghouse[95] in the 1960s formed the basis for numerous international designs. These can now be found in operation in the United States, France, Japan, South Korea, the Ukraine, Russia, Germany, Spain, Belgium and 15 other countries. Following this wave of PWRs, built mostly in the 1970s, evolutionary third generation PWR designs have been developed in Korea and Japan and are scheduled for new build in those countries. These are the Korean APR-1400[240] and the APWR, a 1500 MWe design by Mitsubishi Heavy Industries and Westinghouse. Mitsubishi has submitted a pre-application for licensing of the APWR design in the US.[241]

A new PWR design, the European Pressurised Reactor (EPR), promoted by French nuclear vendor Areva, incorporates improved safety features, better fuel utilisation and other features for improved economics that characterise so-called Generation III+ designs.[242] The EPR has an electrical output of 1600 MWe and an expected overall efficiency of 37 per cent.[230] The design was developed jointly by the French company responsible for the French nuclear fleet, Framatome, and the German reactor manufacturer, Siemens, both of which are now incorporated into Areva. The design was carried out in collaboration with the French and German regulators to ensure its licensability. The first EPR is currently under construction at Olkiluoto in Finland and is the first Western European build for more than 15 years. France has announced that it will construct a second EPR at Flamanville in Normandy which is scheduled for completion by 2012[243].

The EPR is being considered for pre-licensing in the USA[244] and internationally under stage two of the new, Multinational Design Evaluation Program (MDEP). MDEP is a program that aims to pool regulatory information in order to facilitate standardised designs and expedite their licensing in many countries.

In the USA, Westinghouse has developed its own third generation pressurised water reactor, the AP-1000. It has a simplified design[96], passive safety systems[97], improved fuel utilisation and an electrical output of 1170 MWe. The design received US Nuclear Regulatory Commission certification in January 2006. The simplified design and increased use of modular construction means that planned build time for an AP-1000 is now much reduced from previous generation reactors to only five years, with only three years from first concrete on site to completion.

Figure L2 The Areva 1600MWe EPR nuclear reactor; computer generated photomontage of the Olkiluoto site in Finland with the two existing nuclear power plants

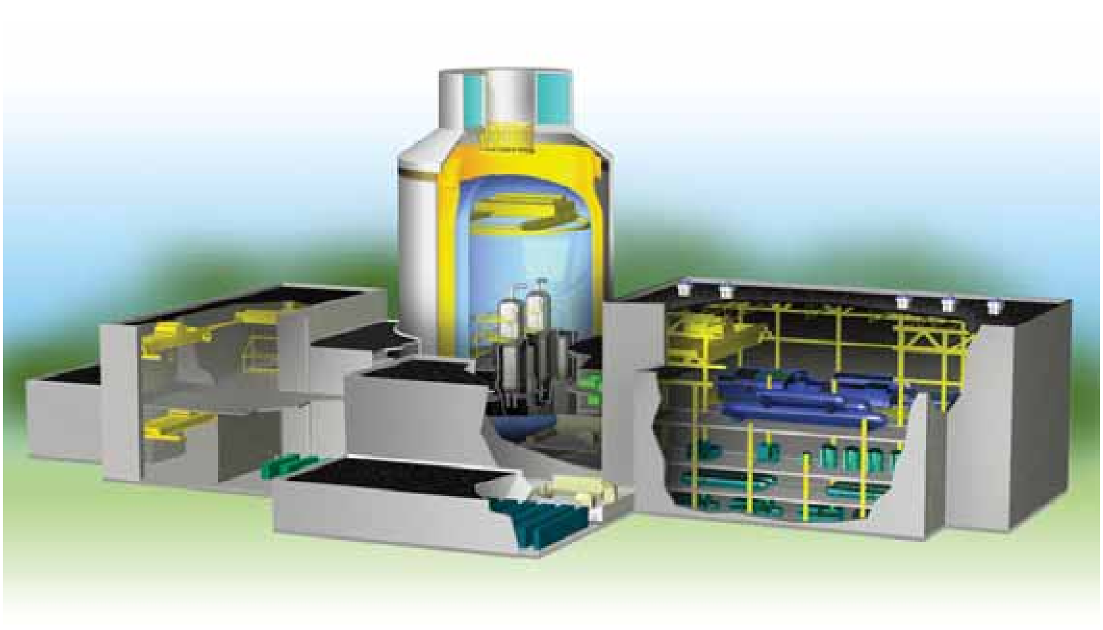
Source: Innovarch/TVO

[95] Toshiba of Japan purchased Westinghouse from BNFL for US$5.4 billion in February 2006.

[96] With reduced numbers of pumps, safety values, pipes, cables and building volume relative to a standard PWR.

[97] These systems rely on natural forces such as gravity, natural circulation and compressed gas for the systems that cool the reactor core following an accident. No pumps, fans, chillers or diesel generators are used in safety systems.

Figure L3 The Westinghouse 1170 MWe AP-1000 nuclear reactor



Source: Westinghouse[245]

L1.2 Boiling Water Reactor (BWR)

Boiling water reactors which, like PWRs, use ordinary water as the coolant and moderator, were developed in the United States by General Electric in the 1950s. In a BWR, water is constantly fed into the bottom of the primary vessel and boils in the upper part of the reactor core. The steam generated, at a pressure of 70 bar and temperature around 290°C, is routed directly to the turbine. Fuel load and efficiency are similar to the PWR.

BWRs are the second most common nuclear reactor in commercial operation today, accounting for 21 per cent of nuclear reactors installed. BWRs built to several proprietary designs are in operation in United States, Japan, Germany, Sweden, Finland, Switzerland, Spain, Mexico and Taiwan. Of the twelve reactors commissioned in Japan since the mid-1990s, ten are of the BWR or ABWR design.

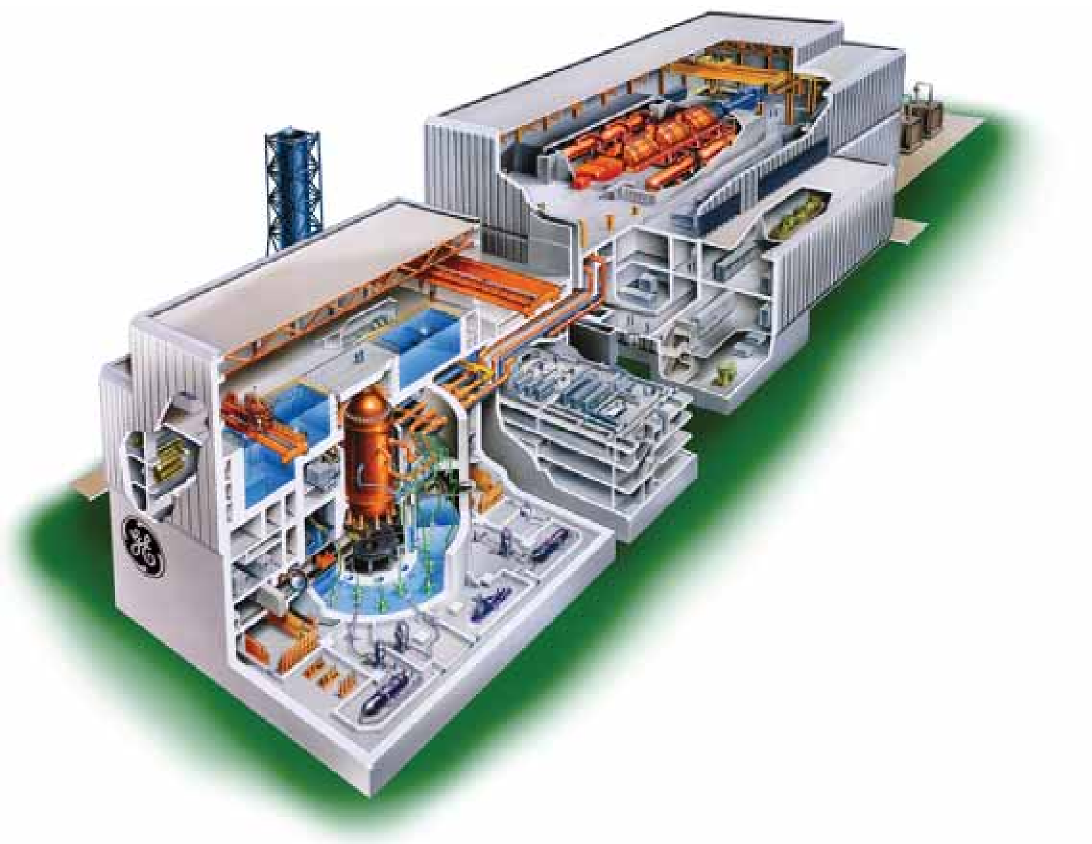
The BWR design has a number of advantages over the PWR: it does not require separate steam generators and has reduced reactor vessel wall thickness and material costs owing to its lower primary pressure. However, the BWR primary circuit includes the turbines and pipework and these components become radioactive through exposure to small quantities of activated corrosion products and dissolved gases over the lifetime of the reactor. This complicates plant maintenance and increases the costs of decommissioning. Also, the reduced power density means that for a given power output a BWR unit is significantly larger than a similar PWR unit.

The Advanced BWR (ABWR) was developed in the 1990s by General Electric, Hitachi[98] and Toshiba[99]. This third generation BWR is claimed by the manufacturers to have improved economics, passive safety features, better fuel utilisation and reduced waste.

[98] On 13th Nov 2006, Hitachi and General Electric signed a letter of intent to form a global alliance to strengthen their joint nuclear operations.[246]

[99] These three companies signed an agreement to develop, build and maintain Japan's Generation II BWR fleet in 1967.

Figure L4 The Advanced Boiling Water Reactor (ABWR)



Source: General Electric[247]

Japan has four 1300 MWe ABWR units in operation. Another three units are under construction in Taiwan and Japan, and a further nine are planned for Japan.

General Electric later re-directed its development program to design a larger reactor to take advantage of economies of scale, proven technology and ABWR components to reduce capital costs. The resulting 1560 MWe design, known as the Economic Simplified BWR (ESBWR), relies upon natural circulation and passive safety features to enhance plant performance and simplify the design.[248] It is currently undergoing NRC design certification.[244]

As with PWR, a Generation III+ BWR has been proposed in Europe by Areva, namely the SWR 1000 of 1250 MWe capacity.[249] The design is an evolution of the German Siemens-designed BWRs that have been in operation for more than 20 years and uses a combination of proven components and additional passive safety features, as well as an increase in fuel enrichment to 5 per cent, to reduce capital and operating costs. The design was developed in cooperation with the French and German regulators and so would likely be readily licensed for construction in those countries.

Figure L5 AECL Advanced CANDU Reactor (ACR)

Source: AECL[250]

L1.3 Pressurised Heavy Water Reactor (PHWR/CANDU)

The Canadians developed a unique design in the 1950s fuelled with natural uranium and cooled and moderated by heavy water (the CANada Deuterium[100] Uranium (CANDU) reactor). Forty one CANDU units are in operation[101] with a combined capacity of 21.4 GW, some 9 per cent of global nuclear capacity.

The PHWR/CANDU design is similar to the PWR in that fission reactions inside the reactor core heat coolant — heavy water in CANDU and normal (light) water in PWR — in the primary loop. This loop is pressurised to prevent boiling and steam formation. As in a PWR, steam is generated in a secondary coolant loop at reduced pressure to drive the turbine and generator. CANDU overall thermal efficiency is typically about 31 per cent. A major difference is that, whereas the core and moderator of a PWR are in a single large, thick-walled steel pressure vessel, the CANDU fuel bundles and coolant are contained in some hundreds of pressure tubes penetrating a large tank of heavy water moderator. Pressure tube reactors are inherently safer in so far as they don't have the possibility of a single-point failure of the large pressure vessel.

The key differentiating feature of the CANDU design is its neutron economy and hence its ability to use natural uranium dioxide containing 0.7 per cent U-235 as fuel. This provides strategic and economic advantages because it enables the use of indigenous uranium feed-stocks and independence from international and potentially expensive uranium enrichment. These advantages are partially negated by the increased cost of the moderator (heavy water is expensive to produce) and the faster consumption of the non-enriched fuel.

A further advantage of the pressure-tube design is that it can be re-fuelled while operating at full power. In contrast, PWRs and BWRs use batch refuelling and need to shut down for 30–60 days every 18–24 months to replace approximately one third of the fuel load. On-load refuelling improves CANDU availability, capacity factor and economic performance, although in practice modern PWRs and BWRs have reduced their refuelling downtime and have improved to similar or better levels of performance. On the other hand, the ability to remove nuclear material readily from the reactor gives rise to proliferation concerns[102] and has contributed to a downturn in the projected uptake of the design.

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[100] Deuterium is a stable isotope of hydrogen that forms the basis of 'heavy water'. Its mass is twice that of normal hydrogen and is present naturally in one in every 6500 hydrogen atoms. Heavy water is used because it absorbs fewer neutrons and therefore offers better neutron economy than light water.

[101] With 18 units in Canada, 13 in India, 4 in South Korea, 2 in both China and Argentina and 1 in both Pakistan and Romania.

Atomic Energy of Canada Limited (AECL) is currently developing a Generation III+ Advanced CANDU Reactor (ACR).[250] The ACR-1000 is an evolutionary, 1200 MWe pressure tube reactor that departs from previous CANDU designs by using slightly-enriched fuel and light water in the primary cooling loop. It is currently undergoing pre-licensing in Canada. The first of its kind is expected to be operation in 2016, although its US NRC certification is currently believed to be on hold.[244]

The CANDU design was appropriated by the Indian nuclear industry following purchase of an initial reactor from AECL in the late 1960s. The initial unit of 202 MWe formed the basis of a series of 10 power plants. The design has been developed indigenously and two larger units of 490 MWe capacity have been built, with further units planned to have 700 MWe capacity.

L1.4 Gas Cooled Reactors (GCR)

Gas-cooled reactors have an inherent safety feature that the cooling properties of the gas do not change with increasing temperature. In water-cooled reactors great care must be taken with design and operation to ensure that there is no phase change, that is the cooling water does not turn to steam in the reactor core. This is because the moderation properties are affected and, since steam has much poorer cooling properties than liquid water, the reduced cooling capability could cause the fuel to overheat and be damaged.

In the 1950s the United Kingdom chose and developed the carbon dioxide-cooled graphite-moderated reactor design. They built two generations of the GCR. The first of these designs, known as Magnox after the magnesium alloy cladding used to contain the natural uranium metal fuel, became the world's first commercial nuclear power station when it was introduced at Calder Hall in 1956.

The Magnox design was not static but was continuously refined, with coolant pressures ranging from 7–27 bar, coolant gas outlet temperatures of 336–412°C and power outputs from 50–590 MWe.[251] All versions used on-load refuelling and were a proliferation concern — earlier units were used to produce weapons-grade plutonium in the UK. A total of 28 units at 11 sites was constructed in the UK and a further two were built and operated in Italy and Japan. Eight units are still operating in the UK, with a combined capacity of 2284 MWe. The robust nature of the design and the inherent safety features meant that a secondary containment vessel was not required at the time.

The Advanced Gas-cooled Reactor (AGR) was the second generation British gas-cooled design. It aimed for higher gas temperatures, improved thermal efficiencies and power densities in order to reduce capital costs. This in turn led to the use of oxide fuel enriched to 2.5–3.5 per cent U-235. The carbon dioxide coolant gas is pressurised to 40 bar and is able to reach temperatures of up to 640°C, well in excess of that achievable with water. As a result, the system thermal efficiency of 41 per cent is considerably higher than that of conventional light water reactors and most coal-fired plant. However, the physical size of an AGR is larger than a comparable PWR or BWR reactor because graphite is a less efficient neutron moderator than water. The UK has 14 operating AGR units each with a power output in the 555–625 MWe range.

The large physical size and issues with chemical contamination of the graphite used has resulted in much larger volumes of intermediate and low-level waste in decommissioning, than would be required for modern PWR reactors.

In the mid 1980s, with the success of LWRs elsewhere, Britain's nuclear industry made the decision to adopt LWR technology and gas cooled reactors were no longer built.

[102] Early removal of fuel maximises the proportion of fissile Pu-239 isotope that is desirable for weapons production. Longer irradiation times, such as the 12–24 month refuelling cycles in LWRs, increase the amount of the non-fissile isotope Pu-240 and make weapons production more difficult.

L1.5 RBMK (Chernobyl Type Reactor)

The Soviet designed RBMK[103] (high power channel reactor) uses light water as coolant and graphite as its moderator. The RBMK was the reactor type used at the Chernobyl power plant, which was the site of the world's worst nuclear accident in April 1986.[104]

The RBMK was one of two Soviet designs. It evolved from earlier plutonium production reactor technology in the mid 1960s and 1970s and allowed on-load refuelling. While the technology evolved over time, a typical reactor uses slightly enriched uranium dioxide fuel (1.8 per cent U-235) and generates 700–950 MWe. The design uses vertical fuel channels through which light water is pumped at a pressure of 68 bar. The water boils in the top part of the channels and steam at a temperature of 290°C is then separated in a series of steam drums for conventional power generation.

Since the Chernobyl accident, the three remaining Chernobyl reactors have been shut down, and the one Lithuanian and eleven remaining Russian RBMK units have been extensively retrofitted with safety upgrades. The Lithuanian reactor will shut down as a condition of Lithuania's entry into the EU, but the Russian units are being considered for life extension and, in some cases, power upgrades.[252]

L1.6 VVER

The VVER is the Russian version of the Pressurised Water Reactor (PWR). The design, which uses light water as coolant and moderator, operates with enriched uranium dioxide fuel and at pressures of 150 bar. The Soviets have three evolutions of this reactor, being the early 6 loop VVER-440 Model V230 and VVER Model V213 designs, each of 440 MWe capacity and the later 4 loop VVER-1000 of 950 MWe capacity. More than fifty units operate in the former Soviet Union, Eastern Europe and, most recently, China. Units are under construction in Russia, China, India, and Iran.

Since the Chernobyl accident, the IAEA has made considerable efforts to enhance regulatory control and nuclear reactor safety in Eastern Europe and Russia. The first two VVER designs were not constructed with a concrete containment structure or space for regular safety inspections. The third generation VVER-1000, developed between 1975 and 1985, adopted new Soviet nuclear standards and modern international safety practices.

The next generation will be the VVER-1500, with a 60 year design lifetime and improved fuel burn-up and economics. It has been announced[253] that six VVER-1500 nuclear power stations will be constructed at a cost of US$10 billion at the Leningrad power plant to replace the existing RBMK units. Construction of the first two of these units is scheduled to begin in late 2007 or early 2008.

[103] This design is also commonly classified as a Light Water Graphite Reactor (LWGR).

[104] The Chernobyl accident is discussed in Appendix N.

L2 Current and Planned Deployment

L2.1 Existing nuclear power plants

Nuclear power technology is mature and internationally-proven. The International Energy Agency[3] records that in 2006 over 440 nuclear power plants (NPPs) are operating in 31 countries. Nuclear power plants provide over 368 GW[105] of generating capacity, compared with Australia's total installed capacity of 48 GW.

In 2005 NPPs supplied 2742 TWh[106], comprising 15 per cent of the world's total electricity production. This compares with Australia's total production of 252 TWh total electricity in 2004–5.[55]

The numbers of reactors currently operating in each country, their capacities, and electrical output in 2005 are given in Table L1 overleaf. Data from Table L1 are also plotted in Figure L6 to highlight the number of countries where nuclear power plants provide a significant part of the electricity supply.

L2.2 Planned nuclear power plants

Many countries stopped building nuclear power plants after the Three Mile Island and Chernobyl nuclear accidents (in 1979 and 1986 respectively). Several European countries (Italy, Sweden, Austria) held referendums and decided to close nuclear power plants. In other countries (US, UK, Canada) programs suffered a drop in commercial investment and no new plants were started through the 1980s and 1990s in most countries. The exception was in Asia where a steady build of new plants was maintained in Korea, Japan and China.

The situation in 2006 has changed, with renewed interest in many countries in building new nuclear power plants. The numbers of plants that are planned and under construction are given in Table L1. Currently there are 28 power plant reactors in 13 countries under construction worldwide and a further 62 reactors in 15 countries planned (that is approvals and funding have been announced). The designs for the planned build are a mixture of Generation II, III and III+, the choice often depending on in-country experience, with several countries (India, China, Russia) preferring to stay with older, familiar and proven designs. Table L2.2 indicates the status of Generation III and III+ designs which are the most likely to be offered to countries contemplating new nuclear build.

Of the 15 countries with plans for new nuclear plants, three (Iran, North Korea and Turkey) currently have no plants, although Iran has one under construction. All three countries do, however, operate research reactors.

In the US the improved performance of existing plants and concerns about energy security and greenhouse emissions has led to a resurgent interest. This has included government subsidies for the first six new power plants. Another factor is a new scheme for staged decision making that minimises financial risk to investors.[254] The sole US reactor 'under construction' in Table L1 is the mothballed Browns Ferry 1, which is scheduled for restart in 2007. Expressions of interest for construction and operating licences have been received by the US regulator for more than 25 new plants.

[105] 1 GW (gigawatt), or 1000 MW (megawatts), is the capacity of a typical modern NPP.

[106] 1 TWh (terawatt hour) = 1000 GWh (gigawatt hours) = the output from a 1 GW power plant operating at full power for 1000 hours.

Table L1 Current and planned nuclear power plants worldwide

Country	No. of reactors	Installed capacity (GW)	Gross nuclear electricity generation (TWh)	Share of nuclear in total generation (%)	Reactors building (Sep 06)*		Reactors planned (Sep 06)*	
					No.	(GW)	No.	(GW)
OECD	**351**	**308.4**	**2333**	**22.4**	**7**	**7.44**	**23**	**29.55**
Belgium	7	5.8	48	55.2				
Canada	18	12.6	92	14.6	2	1.54	2	2.0
Czech Republic	6	3.5	25	29.9				
Finland	4	2.7	23	33.0	1	1.6		
France	59	63.1	452	78.5			1	1.63
Germany	17	20.3	163	26.3				
Hungary	4	1.8	14	38.7				
Japan	56	47.8	293	27.7	2	2.285	11	14.95
South Korea	20	16.8	147	37.4	1	0.95	7	8.25
Mexico	2	1.3	11	4.6				
Netherlands	1	0.5	4	4.0				
Slovakia	6	2.4	18	57.5				
Spain	9	7.6	58	19.5				
Sweden	10	8.9	72	45.4				
Switzerland	5	3.2	23	39.1				
United Kingdom	23	11.9	82	20.4				
United States	104	98.3	809	18.9	1	1.065	2	2.72
Transition Economies	**54**	**40.5**	**274**	**17.0**	**4**	**3.30**	**12**	**13.4**
Armenia	1	0.4	3	42.7				
Bulgaria	4	2.7	17	39.2			2	1.9
Lithuania	1	1.2	10	68.2				
Romania	1	0.7	5	8.6	1	0.65		
Russia	31	21.7	149	15.7	3	2.65	8	9.6
Slovenia	1	0.7	6	39.6				
Ukraine	15	13.1	84	45.1			2	1.9
Developing Countries	**38**	**19**	**135**	**2.1**	**17**	**11.75**	**27**	**25.19**
Argentina	2	0.9	6	6.3	1	0.69		
Brazil	2	1.9	10	2.2			1	1.25
China	9	6.0	50	2.0	5	4.17	13	12.92
India	15	3.0	16	2.2	7	3.08	4	2.8
Pakistan	2	0.4	2	2.8	1	0.3	2	0.6
South Africa	2	1.8	12	5.0			1	0.17
Other	6	4.9	38	16.9	3	3.51	6	7.45
World	**443**	**367.8**	**2742**	**14.9**	**28**	**22.5**	**62**	**68.1**

Source: IEA[3]; * WNA[23]

Figure L6 Plot of data from Table L1 showing share of nuclear-generated electricity

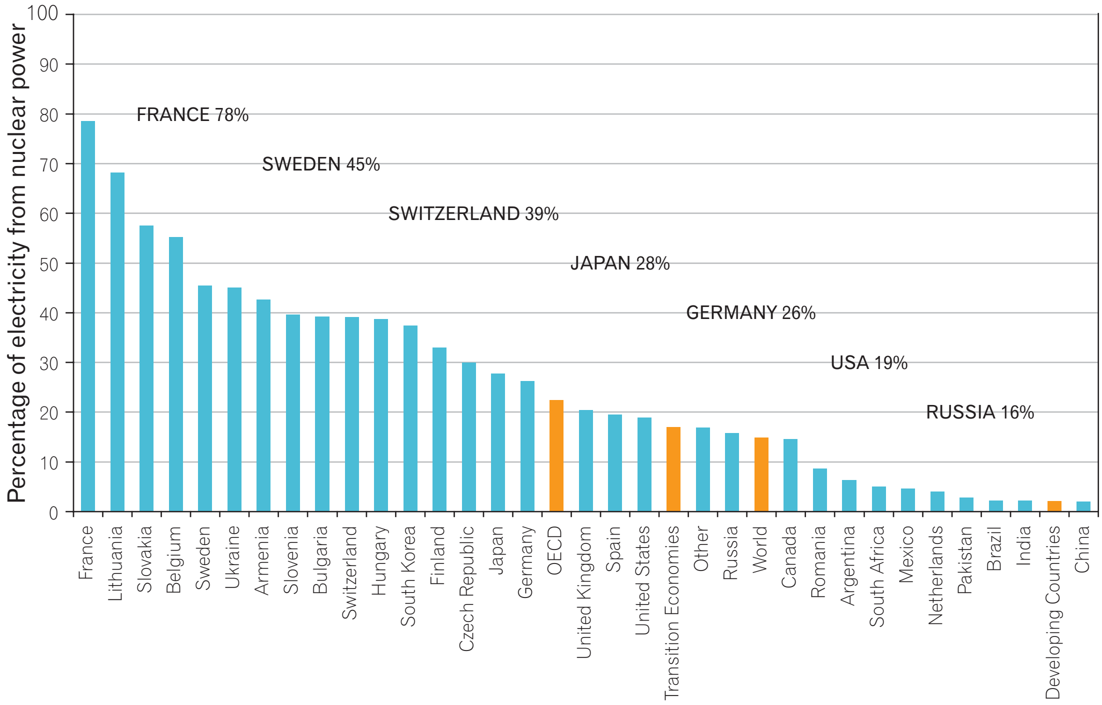


Table L2 Status of new (Generation III and III+) nuclear power reactor designs at end–2006

Reactor Design	Output MWe	Type	Country of Origin	Lead Developer	Deployment Status
ABWR	1350	BWR	US–Japan	GE, Toshiba, Hitachi	Operating in Japan. Under construction in Japan and Taiwan. Licensed in USA
CANDU-6	650	PHWR	Canada	AECL	Operating in Canada, Korea, China, Romania
VVER-1000	950	PWR	Russia	Atomstroyexport	Operating in Russia. Under construction in Russia, China, India, Iran
AHWR	490	PHWR	India	Nuclear Power Corporation of India	Two units operating at Tarapur. Further units planned
APR-1400	1400	PWR	Korea–USA	Kepco	Planned for Shin-Kori, Korea
APWR	1500	PWR	Japan	Westinghouse and Mitsubishi	Planned for Tsuruga, Japan. Pre-application for licensing submitted in USA
EPR	1650	PWR	France, Germany	Areva	Under construction in Finland. Planned in France
AP1000	1100	PWR	USA	Westinghouse	Licensed in USA
SWR	1250	BWR	France, Germany	Areva	Offered in Finland
ESBWR	1500	BWR	USA	GE	Submitted for licensing in USA
ACR	1100	PHWR	Canada	AECL	Under development
PBMR	165	VHTR	South Africa	PBMR Ltd	Under development
GT-MHR	280	VHTR	USA	General Atomics	Under development

L3 Technology Development

L3.1 Mixed Oxide Fuel

Closing of the nuclear fuel cycle through the reprocessing of spent fuel is aimed at both utilising the energy of the fissile material produced in reactors and minimising the volume of waste. Such fissile material can be produced in both thermal reactors — the current deployment of NPPs — and in fast reactors, which will be discussed later. Pu-239, for example, is produced in significant quantities in uranium-fuelled reactors through a two-stage process beginning with neutron capture on the more abundant isotope U-238. In principle, the fissile isotope U-233 can be produced in an analogous process beginning with neutron capture on Th-232, the naturally occurring isotope (100 per cent) of thorium, as will also be discussed below.

Mixed oxide fuel (MOX) is produced from a mixture of 5–9 per cent plutonium oxide (comprised predominantly of the isotope Pu-239) obtained through re-processing of spent fuel and depleted uranium obtained from enrichment tails (containing about 0.2 per cent U-235). The proportions required to produce fuel that is approximately equivalent to the LEU used in reactors varies according to the amounts of Pu-239 (the fissile component) and Pu-240 in the spent fuel. Depending on its history in a reactor, the Pu-239 content is usually in the range of 60–70 per cent.

About 20 of the reactors in France use MOX fuel, usually with about one-third of the fuel rods loaded containing MOX, the other two-thirds being standard LEU.[255] This is approximately the limit that can be accommodated because of differences in the nuclear properties of the fissile components Pu-239 and U-235. These differences are manifested in differences in the neutron energy spectrum, delayed neutron components and fission product distributions, all of which affect the reactivity and reactor operation. The higher energy neutron spectrum, for example, requires the use of higher initial levels of the 'poisons' such as soluble boron that are used to control reactivity. Specific reactor modifications are necessary for a LWR to operate with a full load of MOX fuel, some of which have been incorporated in recent designs — both the EPR and AP 1000 can run with a full MOX fuel load.

The design of the fuel rods themselves is adjusted to allow for more free internal volume to accommodate gaseous fission products. Also, the presence of contaminants in the reprocessed fuel (heavy elements such as Am-241) results in higher radioactivity. This necessitates additional procedures in the production, handling and transport of MOX fuel and fuel rods.

MOX fuel is used extensively in Europe and there are plans to use it in Japan and Russia. It currently comprises 2 per cent of new fuel used and is projected to rise to 5 per cent by 2010.[256]

L3.2 Thorium

As stated above, thorium or more precisely the isotope Th-232 is a 'fertile' material analogous to U-238. Since it does not have a fissile component, thorium cannot be used directly as a substitute for uranium, but it can be used indirectly, through breeding, as a source of the fissile isotope U-233. Initially therefore, exploitation of thorium requires its use in conjunction with a fissile material (U-235 or Pu-239), but then it could itself provide a source of U-233 to sustain the process, possibly in-situ in a reactor but more likely through reprocessing. This increases the cost and complexity of the nuclear fuel cycle compared with the current U-235-based 'once-through' fuel cycle that is favoured in most countries.

Thorium's potential as an (indirect) alternative to uranium was recognised from the earliest days of nuclear power and there has been a large amount of research into using it as a component of fuel.[257] It has a long history of experimental use in reactors, for example the German THTR and the US Fort St Vrain high temperature reactors, which combined HEU with thorium, ran as commercial electricity producing plants for many years in the 1980s. Current research is aimed at enabling use of thorium in conventional power reactors in Russia (VVER) and India (PHWR).[257]

Although yet to be exploited, one advantage of the U-233 produced from thorium that attracted early attention is that it is the only fissile isotope available for reactors that, in principle, could form the basis of a thermal breeder reactor, as opposed to a fast breeder. This is because the average number of neutrons emitted in the fission of U-233 by thermal neutrons is significantly higher than that emitted by the thermal fission of U-235 or Pu-239. With appropriate care in design, the neutron budget in a U-233 fuelled thermal reactor could allow breeding, that is to have at least two neutrons available after losses, one to continue the fission process and at least one to produce more fissionable material than is consumed.

Thorium used to produce U-233 has both advantages and disadvantages compared with uranium. The principal ones are:

- The use of U-233 together with thorium produces much less plutonium and other long-lived actinides than the U-235 based cycle
- Thorium is more abundant than uranium,[27] although it should be borne in mind that if the U-238 in depleted uranium were also used as a breeding source, then availability of fuel would not be an issue
- The proliferation sensitivity of U-233 as a weapons material is lessened to a significant extent by the higher levels of radioactivity from normal contaminants
- The presence of radioactive co-products also makes recovery and fabrication of the fissile U-233 as fuel more difficult than plutonium
- Thorium is usually irradiated as the oxide or carbide, both of which are difficult to dissolve or melt in the reprocessing stage to extract U-233. This would not be an issue however, in reactors using molten salts.

L3.3 Fast Reactors

As implied by the name, unlike thermal reactors in which moderators are used to slow down the neutrons produced in fission, fast reactors exploit the high energy neutrons directly. They are usually designed to activate 'fertile' material to create additional fissile material, as well as burning the fissile fuel through fast fission. They can also be configured to 'burn' long-lived actinides produced as waste from conventional power reactors. A reactor is called a 'breeder' when it produces more fissile material than it consumes and a 'burner' when it is a net consumer of fissile material.

Fast breeder reactors (FBRs) were developed to improve the long term viability of nuclear power, by producing fissile Pu-239 from the abundant uranium isotope U-238. As indicated above, an analogous process could be the production of U-233 from Th-232. The fast neutron reactor forms the basis of at least three of the Generation IV reactor systems and may also play an important role in exploiting depleted uranium and the management of actinide waste.

Fast breeder reactors have played varying roles in the nuclear programs of several countries including US, Russia, France, and India, with some 29 having been constructed and operated. They remain of particular strategic importance to the energy aspirations of Japan and India. India, for example, is currently constructing a 500 MWe FBR with a view to using indigenous thorium as a source of fuel.

Fast neutron reactors have not so far been commercially competitive with thermal reactors and thus have not been deployed widely for electricity generation. Nor has their breeding capability been exploited because of the continuing availability of relatively cheap uranium for commercial power reactor fuel. To date, four types of breeder reactors have been proposed or developed; the liquid metal cooled fast breeder reactor (LMFBR), the gas cooled fast breeder reactor (GCFR), the molten salt breeder reactor (MSBR) and the light-water breeder reactor (LWBR). All large-scale FBRs to date have been liquid metal (sodium) cooled.

The sodium cooled reactor design which was the subject of early development typically contains a core comprising several thousand stainless steel tubes containing 15–20 per cent plutonium-239 mixed oxide fuel. This is surrounded by a blanket of rods containing uranium oxide or thorium where sufficient new nuclear fuel is bred to supply another nuclear reactor. The period taken to breed the new fuel is known as a doubling time and can vary from 1–2 decades depending on the design. The entire assembly is cooled by molten sodium which transports heat from the system at temperatures around 550°C. A secondary sodium loop is used to produce steam for electricity generation. This reactor family includes the French Phénix, the Russian BN-600 and the Japanese Monju reactors. The first two have provided power to the grid since the early 1980s, while the latter has been shut down since a sodium leak in 1997.

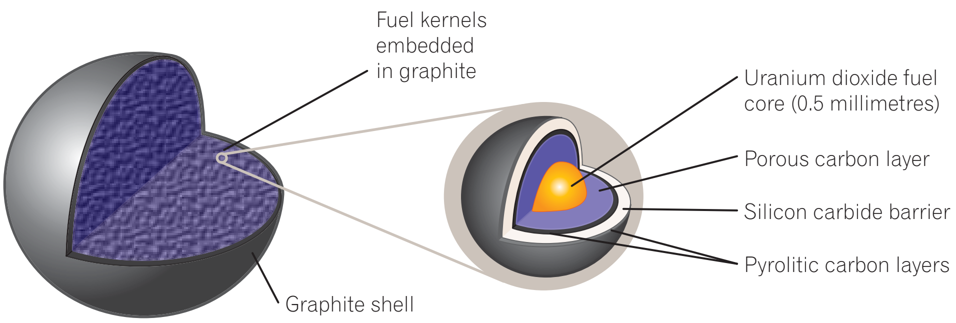
More recently, fast burner reactors have been proposed as part of the United States-proposed Global Nuclear Energy Partnership (GNEP). It envisages a leasing scheme where fuel supplier nations that hold enrichment and reprocessing capabilities would provide enriched uranium to conventional light water nuclear power plants located in user nations. Used fuel would be returned to a fuel supplier nation, reprocessed using a technology that does not result in separated plutonium (to reduce proliferation risks) and subsequently burned.

L3.4 High Temperature Gas Cooled Reactors (HTGR)

Two Generation III+ reactor systems under development are based on helium cooling and a Brayton cycle turbine using helium — the Pebble Bed Modular Reactor (PBMR) and the Gas Turbine Modular Helium Reactor (GT-MHR). These thermal designs are very similar in concept. They are helium cooled, graphite moderated, small- to mid-sized modules, with greatly improved thermal efficiencies (around 45 per cent), and higher fuel burn-up rates. Design operating temperatures and pressures are around 900°C and 75 bar respectively.

In contrast to light water reactors where the uranium oxide fuel is in the form of pellets enclosed in a metal tube, HTGR fuel is in the form of sub-millimetre diameter spheres.[107] These tiny fuel particles have a core of enriched uranium fuel (or, for example, mixtures of uranium, plutonium and thorium) coated with layers of temperature resistant ceramic. Thousands of the fuel particles are pressed together and coated with an external layer of graphite. In PBMR the pressings are in the shape of tennis-ball size spheres — the 'pebbles' in the reactor name — while GT-MHR fuel uses finger-sized cylindrical rods. The fuel is claimed to have excellent proliferation resistance and is designed to contain any fission products within the fuel particles. Its stability means that the fuel can be taken to much higher burnups than conventional LWR fuel without releasing fission products and it is easier to store and transport.

Figure L7 Diagram showing structure of fuel pebbles and constituent fuel kernels



Source: MIT[258]

[107] HTGR technology was developed in German (AVR, Oberhausen, THTR) and US (Peach Bottom and Fort St Vrain) reactor programs in the 1970s. Today, research reactors based on the pebble bed and prismatic fuel designs exist in China (HRT-10, 10MWt, INET/Tsinghua University) and Japan (HTTR, 30MWt, JAERI).

The high temperature characteristics of HTGRs have a significant effect on the nature of the nuclear fission reactions and products. They allow a deep burn of the fuel and heavy fission products, resulting in less long-lived waste. They could be used to burn the plutonium and other actinides contained in LWR spent fuel, although this would still require a reprocessing step to convert the used LWR fuel into the coated fuel particles used in HTGRs.

The PBMR is under development as a commercial reactor by PBMR Ltd. PBMR Ltd. is part-owned by the South African government, South African electric utility, Eskom, and supported by the Japanese companies Toshiba (owner of PBMR partner, Westinghouse, since May 2006) and Mitsubishi. The reactor design comprises a core containing some 450,000 tennis ball-sized pebbles and a closed-cycle recuperated helium gas turbine. It is planned to have a thermal output of around 400 MW and an electrical output of 165 MWe.

Work on the design is progressing[259] and a demonstration plant is planned to go on line at Koeberg near Cape Town by 2011. This is planned to be followed by commercial offerings of plants in 2, 4 or 8 modules which could be commissioned by 2014.

The GT-MHR concept is under development as a combined private/public sector project. It is similar to the PBMR, and has a thermal output of 600 MW, electrical output of 280 MWe and comparable efficiency. The design is advanced by an international consortium led by the United States' General Atomics Corporation and Russia's Experimental Design Bureau of Machine Building (OKBM).[260]

Two features differentiate the GT-MHR from the PBMR. Firstly, the GT-MHR fuel particles are formed into fuel rods and inserted into prismatic graphite fuel elements. A typical design includes over 100 fuel elements with channels for both the helium coolant and neutron control rods. Secondly the GT-MHR uses uranium oxycarbide-based fuel which has no history in operating reactors, in contrast to PBMR's uranium oxide based fuel. The decision to pursue this new reactor fuel, with intended higher operating and degradation resistance temperatures, is believed to be related to the strong support for the Very High Temperature Reactor (VHTR) being the Generation IV successor to the GT-MHR.[108]

Following international agreement between the United States and Russia, the first GT-MHR was scheduled to come on-line at Tomsk in Russia in approximately 2010. This reactor is planned to be fuelled by plutonium from decommissioned weapons. The schedule was set in 2002[260] but the proposed timeframe for commercial deployment of around 2015 appears unlikely.

The PBMR and the GT-MHR with their small capacity (160–300 MWe) and modular design are believed by many to be well-suited to the needs of small and/or remote electrical markets, where the capital cost or technical challenge of establishing large monolithic reactors has been prohibitive in the past. This is typical of many markets in Australia, Africa and parts of South-East Asia.

As well as their potential for power generation, PBMR, GT-MHR and other high temperature reactors such as the European Raphael project,[262] are being developed with a view to their supplying process heat. They have the potential to deliver high grade process heat (900°C) normally provided by burning fossil fuels (usually gas) to address the wider energy issues of transportation fuels and industrial heat applications for both domestic and industrial users. Possible applications include steam reforming of methane to produce syngas (feedstock for chemical production), hydrogen production for chemical production or future transport use, recovery of oil from tar sands and liquefaction of coal (via the Fischer-Tropsch process).[258,259] The United States Next Generation Nuclear Plant (NGNP) is being developed specifically with hydrogen production in mind — see Figure L8. In the Australian context, process heat from these reactors could be used to supply the steam, electricity and hydrogen for liquefaction of coal to produce transportation fuels.[263]

[108] In October 2006, the US Department of Energy awarded a $8 million USD contract to a consortium led by Westinghouse for a pre-conceptual design of the Next Generation Nuclear Plant (NGNP). PBMR, AREVA and General Atomics as part of that consortium will perform complementary engineering studies in the areas of technology, cost, design and plant configuration.[261]

Figure L8 Artists impression of the US Next Generation Nuclear Plant

Source: USDoE/GIF[239]

A strong case has been made by proponents of HTGR designs that the inherent safety of the system, including the absence of phase changes in the cooling gas, the low levels of excess reactivity and the proven resistance to damage of the fuel at very high temperatures, obviates the need for either an additional containment vessel or for significant emergency planning zones external to the reactor site. These will be issues for regulatory agencies during the design approval and licensing stages of development.

L3.5 Generation IV Reactors

The Generation IV International Forum (GIF) was created to lead the collaborative efforts of leading nuclear technology nations in developing next generation nuclear energy systems. GIF members are Argentina, Brazil, Canada, Euratom, France, Japan, South Korea, South Africa, Switzerland, the United Kingdom and the United States. China and Russia joined the GIF in November 2006. The GIF program has eight technical goals:

- Provide sustainable energy generation that meets clean air objectives and promotes long term availability of systems and effective fuel utilisation for worldwide energy production
- Minimise and manage nuclear waste, notably reducing the long term stewardship burden in the future and thereby improving protection for the public health and the environment
- Increase assurances against diversion of theft of weapons-usable material
- Ensure high safety and reliability
- Design systems with very low likelihood and degree of reactor core damage
- Create reactor designs that eliminate the need for offsite emergency response
- Ensure that systems have a clear life cycle cost advantage over other energy sources
- Create systems that have a level of financial risk that is comparable to other energy projects.

In December 2002 the six concepts were announced that represented the Forum's best judgment as to which reactor types held the greatest promise for the future and the R&D that would be necessary to advance them to commercial deployment. The six are listed in Table L3.

Table L3 Generation IV reactor concepts being studied by the GIF[239]

Reactor type	Coolant	Temp (°C)	Pressure	Waste recycling	Output	Research needs	Earliest delivery
Gas-cooled fast reactor (GFR)	Helium	850	High	Yes	Electricity and hydrogen	Irradiation-resistant materials, helium turbine, new fuels, core design, waste recycling	2025
Lead-cooled fast reactor (LFR)	Lead-bismuth	550–800	Low	Yes	Electricity and hydrogen	Heat-resistant materials, fuels, lead handling, waste recycling	2025
Molten salt reactor (MSR)	Fluoride salts	700–800	Low	Yes	Electricity and hydrogen	Molten salt chemistry and handling, heat- and corrosion-resistant materials, reprocessing cycle	2025
Sodium-cooled fast reactor (SFR)	Sodium	550	Low	Yes	Electricity	Safety, cost reduction, hot-fuel fabrication, reprocessing cycle	2015
Supercritical-water-cooled reactor (SCWR)	Water	510–550	Very high	Optional	Electricity	Corrosion and stress corrosion cracking, water chemistry, ultra strong non-brittle materials, safety	2025
Very-high-temperature reactor (VHTR)	Helium	1000	High	No – waste goes directly to repository	Electricity and hydrogen	Heat-resistant fuels and materials, temperature control in the event of an accident, high fuel burn-ups	2020

L3.6 Accelerator-driven systems

Accelerator-driven systems (ADSs) are an alternative concept to fast neutron reactors for production of electricity, burning of actinide wastes from conventional fission reactors, and breeding of fissile material from fertile thorium or depleted uranium[264,265]. Whereas a conventional fission reactor relies on having a surplus of neutrons to keep it going (a U-235 fission requires one neutron input and produces on average 2.43 neutrons, some of which are absorbed in the reactor material), an ADS uses a high energy accelerator to generate sufficient neutrons to sustain the nuclear reaction in an otherwise subcritical core. This means that when the accelerator is switched off, the chain reaction stops. This confers obvious safety benefits on ADSs, compared with the critical cores and high power densities of fast reactors.

The concept of an ADS has been around since the late 1980s but was given a higher profile by the support of the Nobel physics laureate, Carlo Rubbia, in 1993. Rubbia coined the term 'energy amplifier' for his proposal. Subsequently, it has been the subject of relatively low-level research in many countries.[266] The research has largely focused on collecting relevant physics data and defining materials requirements.

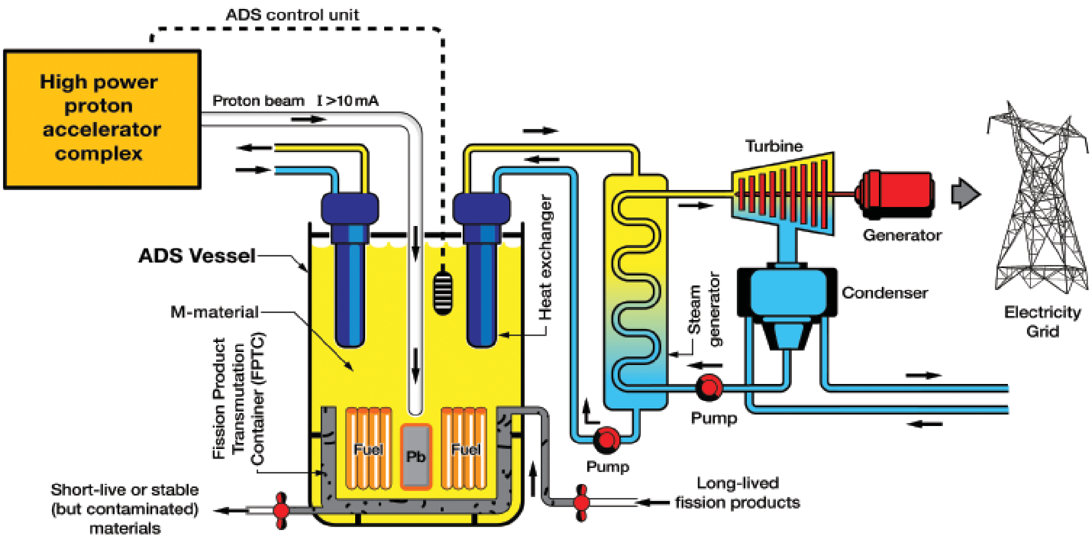
Accelerator-driven systems consist of three main units — the accelerator, target/blanket and separation units. The accelerator generates high energy (around 1 GeV) charged particles (usually protons) which strike a heavy material target. This bombardment leads to the production of a very intense shower of neutrons by a process called spallation. The neutrons enter a sub-critical core (often called a blanket) where they can be multiplied by fission of uranium or plutonium in the core. In the core and blanket, the transmutation ('burning') of actinides and fission products takes place. After a time, already transmuted nuclei have to be removed from the fuel in order to avoid their undesirable activation. In a breeder system, these could include fissile Pu-239 or U-233 bred from U-238 or thorium (Th-232) respectively. A separation unit is required to separate fissile materials, long-lived fission products and actinides so that they can be returned to the blanket. Short-lived and stable isotopes, as well as fission poisons, are removed and processed for storage. As with the fast burner reactors and reprocessing cycles proposed in recent times under the Global Nuclear Energy Partnership (GNEP), ADSs could reduce by several orders of magnitude the storage time needed for the geological disposal of nuclear wastes.

Conceptual reactor designs are similar to current reactor designs, with the great difference that the core is subcritical and there must be provision for a powerful accelerator and a feed to an associated neutron generator within the core, as shown in Figure L9. Proposals for integrated ADSs argue that such systems are feasible and could be economic by combining actinide burning with power production.[264,267]

A challenge for the ADS concept, however, is that the power of an accelerator required for a 1 GW power plant is comparable with or larger than the most powerful currently available and both the accelerator and spallation target technology would require considerable development. Possible metallurgical difficulties with the molten lead-bismuth cooling and target material and long-term corrosion also need to be addressed, as does the need for detailed studies of the nuclear cross-sections for the wide range of reactions that might occur, and which could affect the dynamic performance of the system.

A further issue is that the use of ADSs still requires separation and reprocessing facilities. It would seem unlikely that they would be deployed as stand-alone systems but rather as part of a nuclear-fuel cycle involving other reactor technologies.

Figure L9 Conceptual design[264] for an accelerator-driven system (ADS) equipped with a long-lived fission product transmutation (incineration) facility. M-material in the diagram refers to the environment that acts as neutron and heat storage medium as well as neutron moderator



L3.7 Nuclear Fusion

In contrast to the fission of heavy nuclei, fusion is a process in which light elements, such as hydrogen and its isotopes, collide and combine with each other (ie, fuse) to form heavier elements and, in the process, release large amounts of energy. Fusion is the dominant reaction that powers the sun.

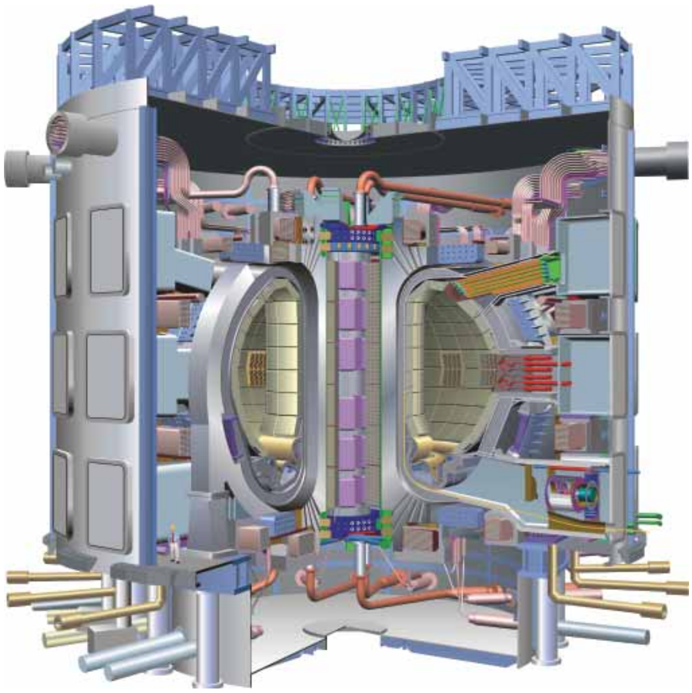
Nuclear fusion offers two major potential benefits relative to other sources of electricity. First, the reactor fuel (deuterium) can be obtained easily and economically from the ocean, providing a virtually unlimited fuel source, while another fuel component, lithium, is a common element. Secondly, fusion would produce no greenhouse gases in operation, and no long-lived radioactive waste products. In common with conventional nuclear fission, it would have a very high power density relative to renewables.

The most significant international collaborative fusion research activity currently is the International Thermonuclear Experimental Reactor (ITER). ITER partners are the European Union, Japan and the Russian Federation, the United States, China, the Republic of Korea and India. The ITER project is estimated to cost of the order of US $10 billion over 10 years.[268]

ITER's aim is to develop the technologies essential to proceed towards a functioning fusion reactor, including components capable of withstanding high neutron and heat flux environments. A sustaining fusion reaction would require temperatures of several million degrees, higher than those that prevail in the sun.

Subject to achieving these challenging objectives, the next step is construction of a demonstration fusion power plant around 2030.[269] The ITER device, shown below, is to be constructed at Cadarache in the south of France. The earliest time for the construction of a commercial fusion reactor is still widely regarded as being around 2050.

Figure L10 The ITER nuclear fusion device



Source: ITER

Appendix M. Biological consequences of radiation

M1 Summary

This Appendix summarises the core concepts of radiation and radiation protection.

The four main types of ionising radiation are alpha, beta, gamma and neutron radiations. The two main units used are the becquerel (Bq) for the amount of radioactive substance (radioactivity), and the sievert (Sv) for the dose of radiation received by a person. One sievert is a very large dose and doses in this report are generally in millisieverts (mSv): one thousandth of a sievert, and in some cases microsieverts (μSv): one millionth of a sievert.

Radiation exposure can arise from sources outside the body (external exposure) or from radioactive material inside the body (internal exposure). Radioactive material can enter the body (exposure pathway) by inhalation or ingestion.

Radiation exposure can be reduced in a number of ways. For external exposure, these include: staying further from the source, spending less time in the region of the source, or using radiation shields. For internal exposure, the main method to reduce exposure is to reduce the intake of radioactive material, for instance, the amount of radioactive dust inhaled, or accidentally ingested via food or drink. This can be done by reducing the amount of dust generated, reducing the time spent in dusty areas, or by using respiratory protection, such as dust masks and respirators. To minimise the chance of ingestion washing hands and utensils prior to eating or drinking is effective.

The health effects of radiation are well known. Very high doses from external radiation can cause radiation burns, radiation sickness or death within a short time (eg within a month). At lower doses, radiation exposure can result in an increased risk of developing cancer.

M2 Ionising radiation

Ionising radiation is defined as radiation that has enough energy to ionise matter through which it passes. Ionisation is the process of adding or removing one or more electrons from a neutral atom. The resultant ion can be positively or negatively charged, and radiation that has enough energy to cause ionisation is called 'ionising radiation'. The health effects that arise from exposure to ionising radiation are understood to derive from ionisation taking place in living cells. This Appendix describes the main types of ionising radiation, ways in which radiation exposure can occur, the effects of ionising radiation, and the ways in which people can be protected from the potentially adverse effects of exposure to ionising radiation.

M2.1 Types of ionising radiation

Ionising radiation is of two types: subatomic particles and electromagnetic radiation. The subatomic particles of interest in this report are alpha particles, beta particles and neutrons:

- Alpha particles — These consist of two protons and two neutrons (ie the nucleus of a helium atom). Alpha particles are relatively heavy and slow moving, and, because they lose their energy very quickly, they have very short ranges — around 3 cm of air. They cannot penetrate a sheet of paper, and cannot, therefore, penetrate the outer dead layers of the skin.
- Beta particles — These are high-energy electrons. They can be moderately penetrating, up to 1 m or so of air, or a few millimetres of aluminium, and a short distance into tissue.
- Neutrons — High-energy neutrons can penetrate several centimetres in concrete. Neutrons, unlike alpha and beta particles, can make objects that they irradiate radioactive. They, like gamma and X-rays, can pass right through the body.

Types of electromagnetic radiation include X-rays and gamma rays:

- X-rays and gamma rays arise from different physical phenomena. X-rays come from atomic processes while gamma-rays come from nuclear processes, but both are electromagnetic radiation and are indistinguishable in their effects. High energy X-rays and gamma-rays are strongly penetrating and may penetrate several centimetres of steel or pass right through the human body, hence their use in diagnostic and therapeutic radiology.

M2.2 Quantities and units used for radiation measurement

The major quantities used in the measurement of radiation, the measurement of radioactivity and the measurement of radiation dose and its radiation effect are:

- The radioactivity is the 'amount' or quantity of a radioactive substance, measured by the rate at which it is undergoing radioactive decay. The unit is the becquerel (Bq). One becquerel is defined as one radioactive disintegration per second.
- The gray (Gy) is the unit of 'absorbed dose'; the amount of energy deposited in the form of ionisation in matter. It is equal to one joule of energy deposited per kg of matter. The gray is a purely physical measure of radiation; it takes no account of biological effects that the radiation might produce in living matter.
- The radiation dose is the amount of radiation being absorbed by an object. The unit mostly used in this document is the sievert (Sv). It is strictly a measure of what is called the effective dose to a person. The sievert is a complex unit that allows for the energy deposited in the organs being irradiated, the radiosensitivity of the exposed organ and the radiological effectiveness of the radiation involved (alpha, beta and gamma).

M2.3 Types of radiation exposure

There are two general ways in which a person can be exposed to radiation — externally and internally.

External exposure

External exposure comes from radiation sources outside the body, such as X-ray machines or from standing on ground contaminated by radioactive material.

Figure M1 Penetration of different forms of ionising radiation

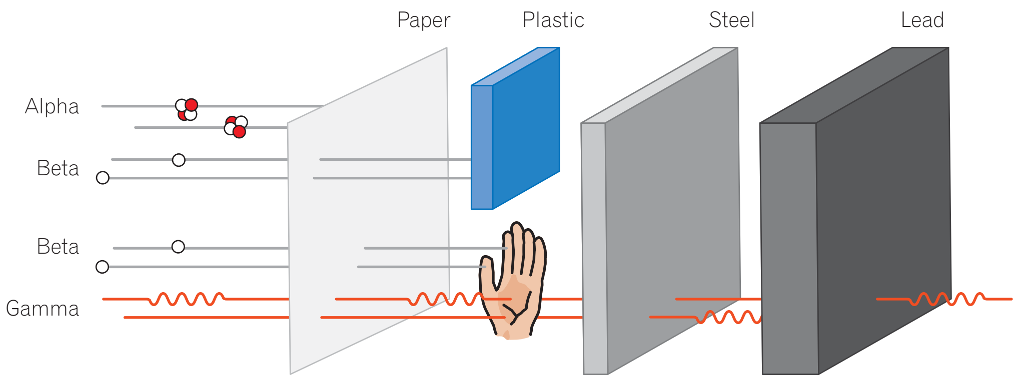


Diagram courtesy of ARPANSA

External exposure can only arise from radiation that has sufficient range and energy to penetrate any gap or shielding between the source of radiation and the person, and then pass through clothes and the outer dead layers of the skin. Hence, alpha particles cannot contribute to external dose, nor can low-energy beta particles.

External exposure to people ceases as soon as the source is removed or they move away from the source, although where clothes or equipment are contaminated a person may take radioactive material with them.

External radiation is relatively easy to assess. Instruments such as a Geiger-Müller counter can measure the radiation level (dose rate) in an area. The total radiation dose a person has received can then be calculated from the time spent in that area.

There are several dosemeters that can measure total external dose directly, the most common being the thermoluminescent dosemeter (TLD) used for personal dosimetry which replaced the traditional film badge.

Internal exposure

Internal radiation exposure is the accumulation of radiation dose from radioactive materials within the body. Most commonly, this arises from such materials that have entered the body by inhalation, ingestion (swallowing), entry through a wound or injection. Other possible internal pathways are absorption of radioactive material through the skin, or via the contamination of wounds. All forms of radiation can produce internal exposure.

It is considerably more difficult to assess internal exposure than external exposure. The intake of radioactive material — for example, by inhalation — can be estimated from the radioactive content of the air being breathed, the breathing rate and the time spent in the area. However, in order to estimate the radiation dose arising from this intake, it is necessary to have information on such matters as the particle size of the material (to determine where in the respiratory tract it will deposit), the chemical form (to determine the rate at which it will be taken up by lung fluids), circulation in the body, retention in organs, radioactive half-life and excretion rate of the relevant radionuclides (biological half-life). These values can be obtained from tables published by bodies such as the International Commission on Radiological Protection (ICRP), if sufficient is known about the materials inhaled or ingested.

Internal exposure will continue until the radioactive material in the body has either decayed away radioactively or been excreted. Thus, exposure can continue for many years after an initial intake. In the method of estimating internal dose outlined above, allowance is made for this extended exposure. The entire radiation dose that will be accumulated in the years following an intake of radioactive materials is calculated, and this dose is recorded as having occurred in the year of the intake. If doses are received in subsequent years, the same procedure is followed and the doses added.

Direct assessment of internal radiation exposure can be made by Whole Body Monitoring where the subject is placed in a specially shielded unit containing sensitive radiation detectors, in order to measure the radiation emitted by the radioactive materials inside the body. This procedure is only suitable for gamma-emitting radionuclides and is very cumbersome and restricted in its availability. Field methods for measuring the radioactive uptake are less direct and may involve sampling of an exposed person's excreta.

M2.4 Radiation exposure pathways and their control

In this section, the general principles of control for both internal and external exposures are discussed.

External exposure pathway

There are three general methods for the control of external exposures:

- Time — external exposures can be reduced by decreasing the time spent near radiation sources or in contaminated areas.

- Distance — external exposures can be reduced by increasing the distance from the source of radiation. The reduction generally follows the inverse square law — the dose is reduced by the square of the increase in distance. Thus, doubling the distance will reduce the dose to a quarter of what it would be at the original distance, increasing the distance three times reduces the dose to one ninth, and increasing distance by a factor of ten reduces the dose to one hundredth. Strictly, this law only applies to point sources, but it can be applied to large sources when the distance from a source is much greater than its lineal size. It is not applicable when close to large area sources, such as areas of contaminated soil.
- Shielding — placing some radiation-absorbing material (shielding) between the source and the potentially exposed person can reduce the resulting external radiation dose. The amount and nature of the shielding required depends on the type of radiation involved. Heavy elements, such as lead, are very effective for shielding X and gamma radiations. At high radiation energies, all materials are approximately equivalent, and the shielding depends on the density of the shield. Personal shielding, such as a lead-rubber apron, is only practical against low energy X and gamma radiation, and rapidly becomes totally impracticable at higher energies.

Millimetre thin layers of metal, or a centimetre or so of plastic, are effective for shielding beta radiation. Neutrons are quite penetrating in heavy elements. They are more effectively shielded by materials containing hydrogen such as water, wax or polythene.

Internal exposure pathway

The procedures for protection against internal exposure are not as simple as those for external exposure, given that there are numerous possible exposure pathways. Protection focuses on limiting intakes, and some general principles can be stated.

- Isolation from sources — keeping people away from potential sources of exposure, such as contaminated areas, means that the intake of radioactive materials will be reduced. Ventilation, which removes contaminated air and provides fresh air for breathing, is another way of reducing exposure.
- Reduction of sources — activities that produce potential exposure pathways should be minimised; for example, dust generation should be reduced where practicable by wetting down dusty materials.
- Personal protection — common forms of personal protection include protective clothing, footwear, gloves and respiratory protection, which removes contaminants from inhaled air. This can range from a relatively simple respirator to a complete ‘air suit’ with its own air supply. Personal protective equipment which impedes normal working arrangements is not routinely used because other means of providing a save working environment for all (for instance by ensuring buildings provide adequate shielding and have appropriate air filters) are given a higher priority in the hierarchy of occupational health and safety measures.
- Personal hygiene — this is important for reducing ingestion, particularly via hand-to mouth transfer. Removal of contaminated clothing and showering after leaving a contaminated area can reduce the spread of radioactive material to uncontaminated work or living areas. It should be noted that ‘radiation protective clothing’ does not protect against external radiation exposure, except for low-energy beta radiation, but it is an aid to decontamination after working in contaminated areas.

M2.5 Biological effects of radiation exposure

The health effects of ionising radiation are divided into two broad classes. The possible outcomes of a large dose of radiation received in a relatively short time are called deterministic or 'acute' effects. The possible longer-term effects of lower radiation doses delivered over a longer time period are traditionally called stochastic effects and include an increased likelihood of inducing cancer and potential genetic effects — that is, those that appear in the person irradiated and those that may be induced in their offspring, respectively.

Early history

Knowledge of the damaging acute effects of ionising radiation dates back to 1895 when Roentgen announced the discovery of X-rays. By 1897, over 20 cases of X-ray dermatitis had been reported and symptoms such as sickness and diarrhoea were recognised as being associated with radiation exposure. The first known death from X-rays occurred in 1914: an Italian radiologist who had worked with X-rays for 14 years.

Not long after the discovery of radium, it was realised that radiation from radioactive materials could also cause harm. Marie Curie described in her biography how her husband Pierre had:

> …voluntarily exposed his arm to the action of radium during several hours. This resulted in a lesion resembling a burn that developed progressively and required several months to heal.

Increasingly, evidence accumulated that exposure to high levels of ionising radiation is harmful. This evidence came from a range of activities, including medical and occupational exposures.

In the 1920s, steps were taken to introduce some controls on levels of exposure to ionising radiation. The second International Congress on Radiology (ICR) issued their first recommendations in 1928. They were very generalised, along the lines of:

> The dangers of over-exposure to X-rays and radium can be avoided by the provision of adequate protection and suitable working conditions.

By 1934, the measurement of ionising radiation had become formalised in a unit called the roentgen (R or r), and an exposure limit (tolerance dose) of 0.2 R per day (2 mSv/day) was proposed for work with X-rays. The ICR noted that: 'no similar tolerance dose is at present available in the case of gamma rays'.

By the early 1940s, additional health concerns were being raised about the long-term 'stochastic' effects of lower doses over a long period of time:

- some geneticists were expressing concerns that the 'tolerance dose' of 1 R per week (10 mSv/week) was too high when considering possible genetic effects
- evidence from the study of radium dial painters, who had ingested radium when painting luminous dials, was showing that ingested radioactive materials could be just as hazardous as external radiation exposures.

In 1950, the ICRP was established. The commission issued its first set of recommendations in 1951 and has continued to do so on a regular basis.

Current knowledge

There is now a large amount of information available on the effects of exposure to radiation of all types and at all dose levels. Detailed studies of the victims of the Hiroshima and Nagasaki bombs, combined with studies of people exposed medically and occupationally, particularly uranium miners, have led to a better understanding of the effects of radiation on the human body as a whole. Developments in genetics and radiobiology have added to a greater understanding of the interaction of ionising radiation with human cells.

Deterministic effects

Deterministic effects from exposure to ionising radiation arise from the killing of cells by radiation. Low doses of radiation do not produce immediate clinical effects because of the relatively small number of cells destroyed. However, at high doses, enough cells may be killed to cause breakdown in tissue structure or function. One of the most common effects, skin burn, is sometimes observed following localised high-intensity X-ray exposure. When the whole body is irradiated, high doses of radiation can break down the lining of the gastrointestinal tract, leading to radiation sickness, and the breakdown of other body functions, leading to death.

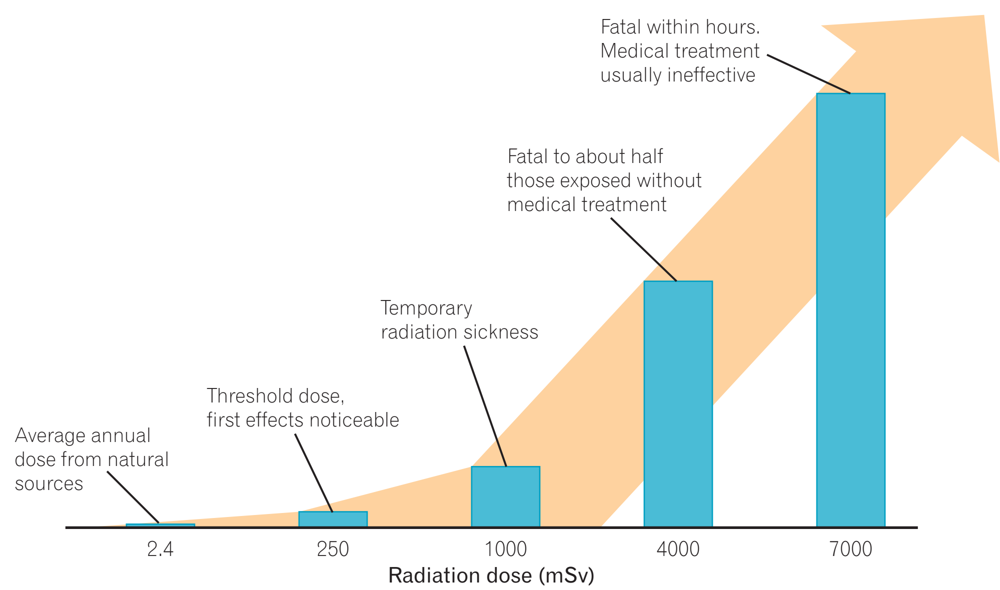
Deterministic effects are so called because the effect follows an elevated radiation exposure and it is 'determined' by the size of the exposure. There is a threshold below which deterministic effects do not occur. For the average individual, no immediate deterministic effects are observed at doses less than 1 Sv (1000 mSv, 100 rem). Above this dose, nausea, vomiting and diarrhoea from radiation sickness may occur within a few hours or so. As the dose increases, effects will be seen sooner, be more severe and persist longer.

A dose of approximately 3 to 5 Sv is likely to cause the death of approximately 50 per cent of those exposed within 60 days, known as the lethal dose (LD 50(60)). Medical attention may improve the outcomes. A dose of 15 Sv received within a short period of time will cause unconsciousness within a few minutes and death within a few days. (See Figure M2.)

For comparison, the current accepted limit for occupational exposure is 20 mSv per year, (ie 2 per cent of the dose that may induce radiation sickness), if received over a short time period, and at less than 0.5 per cent of the LD 50(60).

Deterministic effects that may result from radiation exposure include cataracts, or temporary or permanent sterility. Opacities (in the lens of the eye) have not been seen at doses below approximately 0.5 Sv and are only severe enough to affect vision at doses above approximately 5 Sv. Temporary sterility in males can occur following single doses above approximately 0.15 Sv, but fertility returns after a month or so [113].

Figure M2 Effects of varying radiation dose



Source: NEA[37]

Stochastic effects

Ionising radiation is capable of not only killing cells, but also damaging cells by initiating changes in the DNA of the cell nucleus. If the damage is not repaired and the cell remains viable and able to reproduce, this event may initiate the development of a cancer later in life. If the damaged cell is in the genetic line (egg, sperm or sperm-generating cell) then the damage may result in a genetic effect in the offspring.

The name 'stochastic' means that the effect is governed by probability. There is a certain probability that the cell damage will occur, a probability that it will not be repaired naturally, and a probability that a cancer, for example, will develop as a result. An increase in the magnitude of the dose will increase the probability of the effect, but not the severity of the effect. Stochastic effects do not generally become apparent for many years after exposure, and there is in most cases no way of distinguishing a particular cancer or genetic effect that might have been caused by radiation from one arising from other origins. There are, however, some forms of cancer that do not seem to be caused by radiation exposure.

The ICRP, based on all the available data, has estimated the probability of radiation induced fatal cancer to be 5 per cent per Sievert.[113] Stochastic effects, in particular cancer, have only been clearly demonstrated in humans following moderate or high exposures of the order of 50 mSv and above, and there is no direct evidence that these effects can arise at the significantly lower doses characteristic of present day occupational exposures. Nevertheless, the ICRP adopts the Linear No-Threshold (LNT) hypothesis as the appropriate basis for radiation protection for 'prospective' practices (for instance in the planning stages of a proposal such as comparing alternative locations for specific facilities) and this is internationally accepted. All radiation doses are assumed to carry an associated risk despite the scientific evidence that this is a conservative assumption for 'the administrative organisation of radioprotection'.[270]p2 Radiation protection standards are set at levels where the risk is small in comparison to the risks ordinarily encountered in everyday living.

A large study of exposure and health data on radiation workers has recently been completed, with results consistent with the ICRP risk values.[271] Such a large sample (407 391 individuals, with 5 192 710 person years of exposure) with good exposure data is very difficult to get, so this is a significant study that proves one of the best tests to date of radiation risk estimates at low doses. The study conclusion states: 'We have provided radiation risk estimates from the largest study of nuclear industry workers conducted so far. These estimates are higher than, but statistically compatible with, the current bases for radiation protection standards'.[271]p5 Radiation exposure has been shown to cause an increase in genetic disease in animals. No similar increase has been demonstrated in human populations, even amongst the children of Japanese atomic bomb survivors, however extrapolations from animal studies are included in the risk estimates for radiation protection purposes. The overall risk of 'severe hereditary disorders' is estimated to be approximately 1 per cent per sievert of exposure.[113]

The impact of very small doses to many people is often assessed through the use of the concept of collective dose. This tool is frequently used to estimate fatalities by summing small doses over large populations. However the International Commission for Radiological Protection advises that: '…the computation of cancer deaths based on collective doses involving trivial exposures to large populations is not reasonable and should be avoided'.[114] Nonetheless this is exactly what is done in some cases to derive very large figures for premature deaths associated with the extremely low levels of radiation emanating from the normal operation of uranium mines and other nuclear energy facilities, not withstanding the fact that the doses involved are several thousand times lower than the background radiation dose from natural sources.

M2.6 Radiation dose limits

In this section the current radiation dose limits are discussed briefly.

The radiation dose limits used in Australia promulgated by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) are derived from the recommendations of the ICRP, most directly from ICRP publication No. 60.[113] This publication recommends a 'system of dose limitation', with three elements:

- Justification — the radiation practice must produce sufficient benefit to offset the detriment arising from any radiation exposure.
- Optimisation — radiation protection measures should be implemented until the cost of additional protection is not commensurate with the resulting improved protection (ie the cost in time, effort and money outweighs any additional improvements in radiation safety). This is often expressed as the ALARA principle — radiation doses should be As Low As Reasonably Achievable, with economic and social factors taken into account.
- Limitation — individuals should not be exposed to radiation doses above specified dose limits. The currently recommended annual dose limit for workers is 20 mSv and for members of the general public is 1 mSv.

It should be recognised that this does not mean that it is acceptable to expose workers to annual doses approaching 20 mSv. This would only be acceptable if it can be demonstrated that the cost of further radiation protection measures is not commensurate with the dose reduction achieved. In practice, in Australia there are few radiation-related occupations where workers receive more than a small fraction of the legislated limits.

M2.7 Cancer incidence in the Kakadu region

In its comments on the draft report of the Review, the Australian Institute of Aboriginal and Torres Strait Islander Studies provided information from an exploratory study suggesting that the incidence of cancer in Aboriginal people in the region of Kakadu National Park is very significantly higher than that for Aboriginal people in other parts of the Northern Territory. The possible implication that such an increase in the incidence of cancer could be attributable to radiation exposure arising from the mining of uranium in the region needs to be addressed.

Estimates of the radiation dose received by members of the public from the operation of the Ranger uranium mine have been routinely assessed by the Supervising Scientist and the findings published in annual reports. These results have demonstrated that any increase in radiation levels is small compared to both the background radiation and the public dose limit of 1mSv per year. The health impact of such increases would not be measurable by any epidemiological studies.

A summary of these results, which has been the subject of independent national and international review, was published in 1999 and gave average dose rate estimates of about 0.03mSv per year and 0.01mSv per year for the atmospheric and aquatic pathways respectively.[163] Thus, noting that these dose estimates refer to people living close to the mine, the maximum radiation dose expected for Aboriginal people living in the Kakadu region over the 25 year operational life of the Ranger mine is about 1mSv. This dose is lower than that required to double the incidence of fatal cancers by a factor of about 5000.

It can be concluded that the reported increase in cancer incidence in Aboriginal people of the Kakadu region, if it were to be verified, cannot be attributed to radiation exposure arising from the mining of uranium in the region. Establishment of a social impact monitoring program agreed to by all stakeholders would be an important step in resolving past difficulties in this area.

M2.8 Radiation risk in perspective

The following is known about ionising radiation and its risks:

- Radiation and its effects on health have been studied by expert bodies for over half a century and more is known about radiation risks than about the risks associated with almost any other physical or chemical agents in the environment.
- The effects of large doses of radiation on human health are well understood.
- The conservative assumption made in protecting workers and the public is that the impact of radiation on human health is proportional to the dose of radiation received, for both large and small doses (the linear no threshold model).
- Various other models have been proposed to predict how the health effects of low-level radiation are related to the radiation dose received. The differences among these predictions are so small that they make it very difficult to validate any one model conclusively.
- Radiation does not produce a unique set of health effects. The effects that can be attributed to low-level radiation are also known to be caused by a large number of other agents. While not disregarding the risks of radiation, one must recognise that the health risks posed by some of these other agents are much greater.
- The most important late effect of radiation is cancer, which is often fatal. The fundamental process by which cancer is induced by radiation is not fully understood, but a greater incidence of various malignant diseases has been observed in groups of humans who had been exposed to relatively high doses of radiation years previously. Few persons so exposed actually contract cancer, but each person has a probability of contracting it that depends largely on the dose received.
- The major technical difficulty in establishing an increased incidence of cancers for low level exposures is caused by the fact that about 25 per cent of the population in Western society will eventually die of cancer.

  Another important possible late effect is hereditary damage, the probability of which depends on dose. The damage arises through irradiation of the gonads (ovaries, testes). However, there is no direct evidence, in human offspring, for hereditary defects attributable to exposure either from natural or artificial radiation, even among atom bomb survivors of Hiroshima and Nagasaki.

M2.9 Medical uses of radiation associated with the nuclear fuel cycle

Ionising radiation has two different uses in medicine; for diagnosis and for treatment (therapy). Most procedures involve external radiation sources. Eg X-rays, CT scans and External Beam Radiotherapy, but others require the use of radioactive materials either in the form of solid sources or materials introduced into the blood stream.

Some diagnostic procedures involve the administration of radionuclides, a process that utilises the metabolic or physiological properties of radio-labelled drugs, so that detectors outside the body can be used to observe how organs are functioning, and the chemical composition of metabolites in bodily fluids can be analysed. This is possible because some natural elements concentrate in specific parts of the body, for example iodine in the thyroid, phosphorus in the bones, potassium in the muscles, so if a radioactive isotope of the element is administered, orally or by injection, imaging instruments, eg PET or SPECT cameras, can generate images of radioactive material within the body indicating bodily function.

Some isotopes are used for treatment either by introduction into the blood stream, such as radioactive iodine to treat thyroid problems, or by using solid sources outside the body. The use of solid sources is known as brachytherapy and is used widely for the treatment of cervical, prostate and other cancers. It is also being used in cardiology in connection with angioplasty.

Production

Most radioactive materials for medical applications are produced commercially in nuclear reactors or particle accelerators such as cyclotrons. For example, when the non-radioactive target element cobalt absorbs neutrons in a reactor it is transformed into a radioisotope, cobalt-60, which is used to treat cancer and sterilise medical and consumer products such as bandages. Cyclotrons use electric and magnetic fields to accelerate particles such as protons to induce reactions that transform nuclei into radioactive isotopes. Usually only one type of radionuclide can be produced at a time in a cyclotron, while a reactor can produce many different radionuclides simultaneously.

Australian capabilities

The Australian Nuclear Science and Technology Organisation (ANSTO) is the leading manufacturer and supplier of radioisotope products for nuclear medicine in Australia producing about 70 per cent of the radiopharmaceuticals.

The radioisotope products are made from material irradiated in the National Medical Cyclotron and by the Open Pool Australian Light-water reactor research reactor (OPAL). Neutron-rich radioisotopes are produced in the reactor and neutron-deficient radioisotopes in the cyclotron. The reactor is located at the ANSTO Lucas Heights site and the cyclotron is close to the Royal Prince Alfred Hospital, Camperdown, which uses many of its products.

ANSTO also supplies radioisotope products for medical and other uses to the United Kingdom, New Zealand, India, Bangladesh, Burma, China, Hong Kong, Taiwan, the Philippines, Singapore, Thailand, Malaysia, Korea, Indonesia and Papua-New Guinea.

Australia is a regional leader in the medical applications of radiation, based on the ANSTO facilities and the cyclotrons and associated expertise at several other research laboratories, including those at universities. The expansion of nuclear energy in Australia, with an associated increase in education and research skills, would add to Australia's base of nuclear expertise.

M2.10 Note on sources

This Appendix is largely based on *Australian Participants in British Nuclear Tests in Australia, Dosimetry and Mortality and Cancer Incidence Study*, Commonwealth of Australia 2006

A general text book on radiation protection, such as Martin A and Harbison SA (1987), *An Introduction to Radiation Protection*, Chapman and Hall, London, can be consulted for more information on some of the topics covered in this Appendix.

Appendix N. The Chernobyl and Three Mile Island nuclear reactor accidents and impacts

N1 Summary

N1.1 Three Mile Island

- In 1979 a cooling malfunction caused part of the core to melt in the number 2 pressurised water reactor (TMI-2) at Three Mile Island near Harrisburg, Pennsylvania in the USA. The reactor was destroyed. The accident occurred because of a false reading indicating the status of a key valve, and operator error in diagnosing and responding to the problem, leading to a loss of coolant water and partial meltdown. The containment facility was not breached.
- Some radioactive gas was released two days after the accident, but not enough to cause any dose significantly above background levels to local residents.
- There were no injuries or adverse health effects from the accident. The radiation exposure from the release of a small amount of radioactive gas may lead to, at the very most, one potential additional cancer death in the long term.

N1.2 Chernobyl

- On 26 April 1986, a major accident occurred at Unit 4 of the nuclear power station at Chernobyl, Ukraine, in the former USSR, during an experiment.
- The operators were planning to test whether the turbine powered generators could produce sufficient electricity to keep the coolant pumps running in the event of a loss of power until emergency diesel generators came on line.
- The design of the reactor was inherently unsafe in that moderation was largely due to fixed graphite, and any excess boiling reduced the cooling and neutron absorption without inhibiting the fission reaction so that a positive feedback loop could be easily initiated. There was also no massive protective containment facility.
- To prevent any interruptions to the power of the reactor, the safety systems were deliberately bypassed or switched off. To conduct the test, the reactor output had to be reduced to 25 per cent of capacity. This procedure did not go according to plan and the reactor power level fell to less than 1 per cent. The power therefore had to be slowly increased. But 30 seconds after the start of the test there was an unexpected power surge. The emergency shutdown procedure failed.
- Fuel elements in the reactor ruptured and there was a violent steam and gas explosion. The 1000-tonne sealing cap on the reactor building was blown off. Temperatures rose to over 2000°C and the fuel rods melted. The graphite covering of the reactor then caught fire. The graphite burned for ten days, releasing large quantities of radioactive material into the environment.
- Two people were killed in the explosion, one person suffered a fatal heart attack and twenty-eight highly exposed reactor staff and emergency workers died from radiation and thermal burns within four months of the accident. Nineteen more people died by the end of 2004 (from all causes, not necessarily because of the radiation exposure).
- About 4000 individuals, most of whom were children or adolescents at the time of the accident, developed thyroid cancer as a result of the radiation exposure, and by the end of 2002 15 of them had died from the disease.
- Some 4000 people in the areas with highest radiation levels could eventually die from cancer caused by radiation exposure, and of 6.8 million others living further from the explosion who received a much lower dose, another 5000 may die as a result of that dose.

- One study suggests that of 570 million people in Europe at the time of the Chernobyl accident and exposed to low levels of radiation from the accident, 16 000 will ultimately die from induced cancers as a result of the radiation caused by the accident. This is 0.01 per cent of all predicted cancer deaths. As cancer causes about a quarter of all deaths in Europe, identifying those cases triggered by the Chernobyl-sourced radioactivity cannot be done with statistical confidence.

N2 Three Mile Island 1979

N2.1 Introduction

The Three Mile Island power station is near Harrisburg, Pennsylvania in the USA. It had two pressurized water reactors (PWR). One of 800 MWe capacity which entered service in 1974 (Unit 1) and Unit 2 (TMI-2) with a slightly larger capacity at 900 MWe was newer. It had not long been in operation at the time of the accident.

The reactor was operating at 97 per cent power when the accident to unit 2 happened. At about 4 am on 28 March 1979 a relatively minor malfunction in the secondary cooling circuit caused the temperature in the primary coolant to rise at an abnormal rate. This in turn caused the reactor to 'scram', that is to rapidly and automatically shut down within seconds. During the scram a relief valve failed to close allowing a lot of the primary coolant to drain away. This in turn meant that that the residual decay heat in the reactor core was not removed as it should have been. Heat built up to the point that the core suffered severe damage. Instrumentation malfunctioned so that the fact that the relief valve had failed to close was not conveyed to operators.

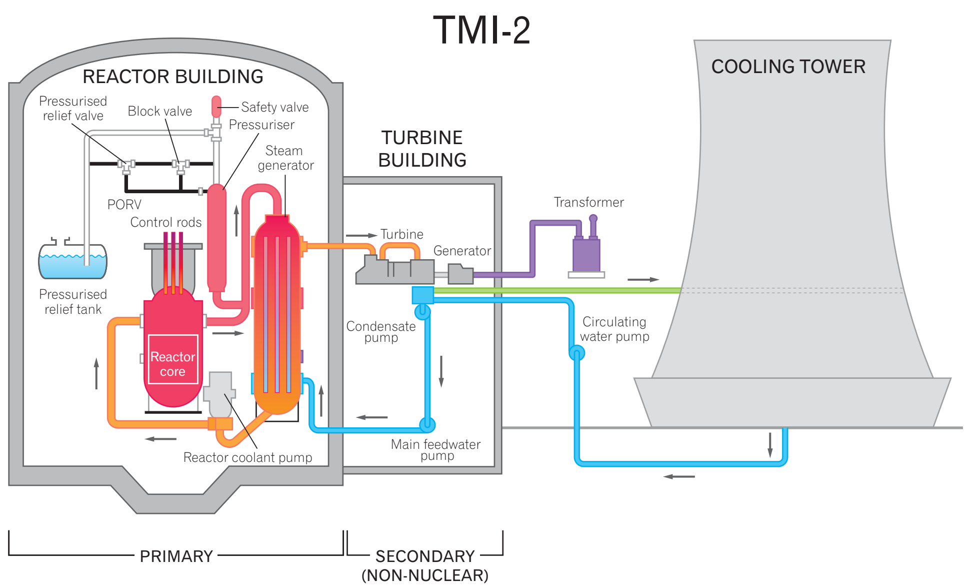
The operators were unable to diagnose or respond properly to the unplanned automatic shutdown of the reactor. The primary causes of the accident can be considered to be deficient control room instrumentation and inadequate emergency response training.

Reactor design

TMI-2 was a Babcock & Wilcox pressurized water reactor with a once-through steam generator. The steam circuit is separate from the primary heating circuit and the turbines are outside the concrete containment structure which is about two metres thick (see Figure N1).

Water in the primary loop flows around the reactor core, absorbing heat. The water in the primary loop becomes radioactive because it

Figure N1 Diagrammatic view of the Three Mile Island TMI 2 reactor



Source: US Nuclear Regulatory Commission[272] comes into contact with the core. Pumps move the water through the primary loop and heat exchanger where heat transfers from the water in the primary loop to water in the secondary loop. The water in the secondary loop turns to steam which powers a turbine connected to a generator. Pumps push the water through the secondary loop and back to where the heat is exchanged. Water in the secondary loop does not mix with the water in the primary loop and is therefore not radioactive.

N2.2 The sequence of events

Within seconds of the automatic shutdown the pilot-operated relief valve (PORV) on the reactor cooling system opened as it was designed to do. About 10 seconds later it should have closed, but it remained open, allowing vital reactor coolant water to drain away into the reactor coolant drain tank.

Instruments in the control room only indicated that a 'close' signal had been sent to the valve but there was no instrument indicating the actual position of the valve. For this reason operators assumed that the PORV was closed properly and therefore there must be some other reason for the abnormal behaviour of the reactor. In response to the loss of cooling water high-pressure injection pumps automatically forced water into the reactor system to replace the lost coolant. As water and steam escaped through the relief valve, cooling water surged into the pressuriser, raising the water level in it. (The pressuriser is a tank which is part of the reactor coolant system, maintaining proper pressure in the system. The relief valve is located on the pressuriser. In a pressurised water reactor like that used in the TMI-2 plant, water in the primary cooling system around the core is kept under very high pressure to keep it from boiling.)

The response of the operators was to reduce the flow of replacement water. Standard operator training was that the pressuriser water level was the only dependable indicator of the amount of cooling water in the system, and because the pressuriser level was increasing, the operators concluded that the reactor system must be too full of water. If it filled completely pressure in the cooling system would not be able to be controlled, and the vessel might even rupture. The highest priority was to do everything possible to keep the pressuriser from filling with water.

The now low volume of water in the reactor cooling system began to boil. Pumping a mixture of steam and water the reactor cooling pumps, designed to handle water, began to vibrate. Severe vibrations could have seriously damaged the pumps and made them unusable and so they were shut down. With no water being forced through the reactor, the water still present began to boil away to the point where the reactor fuel core was uncovered, making it even hotter. The fuel rods were damaged and released radioactive material into the cooling water. The operators still believed the system was nearly full of water because the pressuriser level remained high.

At 6:22 am operators closed a block valve between the relief valve and the pressuriser. This action stopped the loss of coolant water through the relief valve, but by this time superheated steam and gases had blocked the flow of water through the core cooling system. Operators then attempted to force more water into the reactor system to condense steam bubbles that were thought to be blocking the flow of cooling water. During the afternoon operators attempted to reduce the pressure in the reactor system to allow a lower pressure cooling system to be used and to allow emergency water supplies to be put into the system. By late afternoon operators began high-pressure injection of water into the reactor cooling system to increase pressure and eliminate steam bubbles. By 7:50 pm on 28 March they restored forced cooling of the reactor and enough steam had condensed to allow one coolant pump to run without severe vibrations.

As these events unfolded radioactive gases from the reactor cooling system built up in the makeup tank in the auxiliary building. On 29 and 30 March operators used pipes and compressors to move these gases to gas decay tanks. (Gas decay tanks are gas tight containers in which radioactive gases can be temporarily stored until the radiation level naturally drops to the level where the gas may be released with out exceeding regulatory levels). During this operation the compressors leaked and some radioactive gas was prematurely released to the environment.

On the morning of 28 March, when the core of reactor was uncovered, a high-temperature chemical reaction between water and the zircaloy metal tubes holding the nuclear fuel pellets formed hydrogen, a very light and inflammable gas. In the afternoon of the same day a sudden rise in pressure in the reactor building, as indicated by control room instruments, suggested a hydrogen burn had occurred. Hydrogen also collected at the top of the reactor vessel. From 30 March until 1 April operators removed this hydrogen 'bubble' by periodically opening the vent valve on the reactor cooling system pressuriser. For a time, regulatory (US Nuclear Regulatory Commission (NRC)) officials believed the hydrogen bubble might explode. However, such an explosion was not possible since there was not enough oxygen in the system.

By 27 April natural convection circulation of coolant was established and the reactor core was being cooled by the natural movement of water rather than by mechanical pumping. 'Cold shutdown' had been achieved.

The containment building worked as designed. Although about one-third of the fuel core melted in the intense heat, the integrity of the reactor vessel was maintained and the damaged fuel contained.

N2.3 Exposure and impacts

Radiation releases during the accident were minimal, below levels that have been associated with health effects from radiation exposure.

Nonetheless the accident generated dramatic media coverage and a mass movement of people out of the area on the basis of confused warnings and projections that an explosion leading to release of large amounts of radioactive material was possible, if not imminent. The peak of concern was on 30–31 March. The stressed and anxious atmosphere of the time is described in the official history of the role of the US Department of Energy during the accident entitled *Crisis Contained: The Department of Energy at Three Mile Island* by Philip Cantelon and Robert Williams.[273]

> 'Friday appears to have become a turning point in the history of the accident because of two events: the sudden rise in reactor pressure shown by control room instruments on Wednesday afternoon (the "hydrogen burn") which suggested a hydrogen explosion — became known to the Nuclear Regulatory Commission [that day]; and the deliberate venting of radioactive gases from the plant Friday morning which produced a reading of 1,200 millirems (12 mSv) directly above the stack of the auxiliary building.'
>
> 'What made these significant was a series of misunderstandings caused, in part, by problems of communication within various state and federal agencies. Because of confused telephone conversations between people uninformed about the plant's status, officials concluded that the 1200 millirems reading was an off-site reading. They also believed that another hydrogen explosion was possible, that the Nuclear Regulatory Commission had ordered evacuation and that a meltdown was conceivable. Garbled communications reported by the media generated a debate over evacuation. Whether or not there were evacuation plans soon became academic. What happened on Friday was not a planned evacuation but a weekend exodus based not on what was actually happening at Three Mile Island but on what government officials and the media imagined might happen. On Friday confused communications created the politics of fear.'[273]P 50

According to Cantelon and Williams hundreds of environmental samples were taken around TMI during the accident period by the Department of Energy (which had the lead sampling role) and the then-Pennsylvania Department of Environmental Resources. There were no unusually high readings, except for noble gases. Virtually no iodine was present. Readings were far below health protection limits. The TMI event nonetheless created a political storm.

N2.4 Radiological health effects

According to the operator and NRC the radiation releases during the accident were below any levels that have been associated with the health effects caused by radiation exposure. The average radiation dose to people living within 16 kilometres of the plant was 0.08 millisievert (mSv), with a calculated dose of no more than 1 mSv to any single individual. An actual individual located on a nearby island is believed to have received at most 37 millirem (0.37 mSv). The level of 0.08 mSv is equivalent the radiation received from one chest X-ray, and 1 mSv dose is about a third of the average background level of radiation received by US residents in a year.

The TMI-2 accident generated public concern about the possibility of radiation-induced health effects, principally cancer, in the area surrounding the plant. Because of those concerns and lobbying by local concerned residents the Pennsylvania Department of Health initiated and for 18 years maintained a registry of more than 30 000 people who lived within five miles of Three Mile Island at the time of the accident. The registry was discontinued in June 1997, without any evidence of unusual radiation-related health problems in the area. The Department staff and co-authors published a series of papers on various aspects of health impact that might be associated with the TMI accident (see for example [274] [275] [276]). They found no increased incidence of cancer as a result of the accident, but did find that there were some impacts that they considered to be psychological in nature.

Many studies of the accident and its potential health impacts have been undertaken since 1979 and almost all have found no evidence of an abnormal number of cancers around TMI since the accident, and no environmental impact. [277] [278] The most recent examination involved a 13-year study on 32 000 people. [279] The only detectable effect was psychological stress during and shortly after the accident.

A number of groups have challenged the official figures for radiation released as a result of the TMI accident, asserting that the levels were probably higher, at least in some places, and sufficient to cause harm to some members of the public.

In June 1996, 17 years after the TMI-2 accident, Harrisburg US District Court Judge Sylvia Rambo dismissed a class action lawsuit alleging that the accident caused health effects. In making her decision, Judge Rambo noted:

- Findings that exposure patterns projected by computer models of the releases compared so well with data from the TMI dosimeters (also called dosemeters, small portable instruments such as film badges or thermoluminescent dosimeters (TLD) for measuring and recording the total accumulated personal dose of ionising radiation) available during the accident that the dosimeters probably were adequate to measure the releases.
- That the maximum off site dose was probably 100 millirem (1 mSv), and that projected fatal cancers based on likely exposures was less than one.
- The failure of the plaintiffs to prove their assertion that one or more unreported hydrogen 'blowouts' in the reactor system caused one or more unreported radiation 'spikes', producing a narrow yet highly concentrated plume of radioactive gases.

Judge Rambo concluded: 'The parties to the instant action have had nearly two decades to muster evidence in support of their respective cases... The paucity of proof alleged in support of Plaintiffs' case is manifest. The court has searched the record for any and all evidence which construed in a light most favourable to Plaintiffs creates a genuine issue of material fact warranting submission of their claims to a jury. This effort has been in vain.'

There was an appeal against the dismissal of the case in which a re-appraisal of previous studies was presented that suggested there was a link between some cancers and the TMI accident.[280] However in December 2002 the Circuit Court declined to hear an appeal of the second ruling of Judge Rambo to dismiss the case and legal representatives for the remaining plaintiffs declared they would take no further legal action.[281]

N2.5 Three Mile Island — post accident changes to reactor design and operation

TMI-2 was closed down after a major and long clean up procedure and is in long-term monitored storage. No further use of the plant is anticipated. Ventilation and rainwater systems are monitored and equipment necessary to keep the plant in safe long-term storage is maintained.

TMI-1 was closed down at the time of the accident and was not allowed to be started until cleared by all relevant authorities in 1985. Lessons learned from the TMI-2 accident were incorporated into minor modifications of the reactor design and, more importantly — as the basic design had proved sound — changes to the operational controls, monitoring systems and operator training and emergency response procedures. It was also recognised that there was a need for improve and add transparency to community engagement, both in the United States and internationally.

Equipment changes included upgrading monitoring instrumentation so that it is capable of withstanding severe accidents (and also indicates not only what commands have been sent but also accurately monitors the status of the equipment in real time) and the addition of hydrogen recombiners. (Hydrogen recombiners are used to prevent hydrogen levels from building up to flammable or explosive concentrations. They use a catalyst containing platinum and temperatures of ~ 430 to 538 degrees C to chemically combine the hydrogen with a regulated supply of oxygen to form water.)

Training became centred on protecting the cooling capacity of a plant, whatever the triggering problem might be. At TMI-2, the operators turned to a book of procedures to pick those that seemed to fit the event. Now operators are taken through a set of 'yes-no' questions to ensure that the core of the reactor remains covered. Only then do they start to trace the specific malfunction. This is known as a 'symptom-based' approach for responding to plant events. Underlying it is a style of training that gives operators a foundation for understanding both theoretical and practical aspects of plant operations. The TMI-2 accident also led to the establishment of the Atlanta-based Institute of Nuclear Power Operations (INPO) and its National Academy for Nuclear Training. These two industry organisations have the role of promoting excellence in the operation of US nuclear plants and accrediting their training programs.

INPO was formed in 1979. The National Academy for Nuclear Training was established under INPO's auspices in 1985. TMI's operator training program has passed three INPO accreditation reviews since then. Communications and teamwork, emphasising effective interaction among crew members, are now part of the TMI training program which includes training in a full-scale electronic simulator of the TMI control room. The $18 million simulator permits operators to learn and be tested on all kinds of accident scenarios.

N3 Chernobyl 1986

N3.1 Introduction

The Chernobyl accident was the product of a flawed reactor design combined with human error. It is the only accident at a nuclear power plant in the history of commercial nuclear power generation that has caused direct and known fatalities from radiation.

There were four operating 1000-megawatt power reactors at Chernobyl on the banks of the Pripyat River, about sixty miles north of Kiev in the Ukraine, at the time of the accident part of the former Soviet Union.

The accident at Chernobyl Unit 4, on 26 April 1986, did not occur during normal operation. It happened during a test designed to assess the reactor's safety margin in a particular set of circumstances. The test had to be performed at less than full reactor power and was scheduled to coincide with a routine shut-down of the reactor.

N3.2 Reactor design

The four reactors at the Chernobyl site are all pressurised water reactors of Soviet design known as the RBMK (RBMK stands for Reactor Bolsho Moshchnosty Kanalny, meaning 'high-power channel reactor'). The design employs long (7 metre) vertical pressure tubes running through a graphite moderator. It is cooled by ordinary (light) water, which boils in the core at 290°C. The steam generated goes directly to the turbine powered generators. The fuel is low-enriched uranium oxide made up into fuel assemblies 3.5 metres long. Moderation is largely due to the fixed graphite, so any excess boiling reduces the cooling and neutron absorption without inhibiting the fission reaction, and a positive feedback loop can be initiated. The combination of graphite moderator and water coolant is found in no other modern power reactors.

The Chernobyl plant did not have the massive containment structure common to most, but not all, nuclear power plants elsewhere in the world. Without this protection, radioactive material escaped into the environment during the 1986 accident.

N3.3 The accident

Nuclear power stations produce electricity, but most conventional current designs also consume it, for example to power pumps to circulate coolant. This electricity is usually supplied from the grid. When power from the grid is unavailable, most nuclear power plants are able to obtain the required electricity from their own production. But, if a reactor is operating but not producing power, for example when in the process of shutting down, some other source of electricity is required. Back-up generators are generally used to supply the required power, but there is a delay before they can be started and begin to supply electricity.

The test undertaken at Chernobyl Unit 4 was designed to demonstrate that, in an emergency, a coasting turbine would provide sufficient electrical power to pump coolant through the reactor core while waiting for electricity from the stand-by diesel generators to come on line and power the pumps. The circulation of coolant was expected to be sufficient to give the reactor an adequate safety margin.

Figure N2 Diagram of an RBMK type reactor as installed at Chernobyl

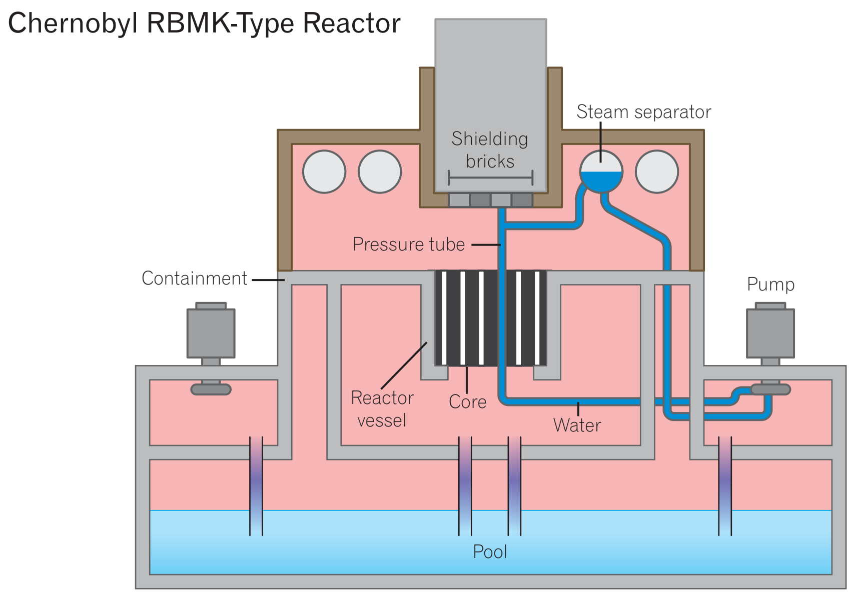


Diagram taken from: http://www.fatherryan.org/nuclearincidents/rbmk.htm

N3.4 The sequence of events

The plan was to idle the reactor at 2.5 per cent of normal power. Unexpected electrical demand on the afternoon of 25 April meant that normal power generation had to continue through to nightfall and this delayed the experiment until eleven o'clock that night. The operators then reduced the power level of the reactor too quickly. This seems to have caused a rapid build up of neutron-absorbing fission by-products in the reactor core, which 'poisoned' (slowed down) the reaction. To compensate, the operators withdrew a majority of the reactor control rods. However, even with the rods withdrawn, the power level could not be increased to more than 30 megawatts. This is an output level that the Chernobyl power plant safety rules recommended not be attempted because it is in the zone where potential reactor instability was highest.

More control rods were withdrawn and the power went up to around 200 megawatts. The reactor was still poisoned, however, and the output difficult to control. At the time the 'spinning turbine' experiment began there were only six out of 211 control rods inserted (the minimum for the RBMK reactor is supposed to be 30). The engineers had also deliberately bypassed or disconnected every important safety system, including backup diesel generators and the emergency core-cooling system.

The test began early in the morning of 26 April 1986. The turbine was shut down, reducing the electrical supply to the reactor water pumps. This in turn reduced the flow of cooling water through the reactor. In the coolant channels within the graphite-uranium fuel core the water began to boil.

Graphite facilitates the fission chain reaction in a graphite reactor by slowing neutrons. Coolant water in such a reactor absorbs neutrons, thus acting as a poison. Unfortunately when the coolant water began turning to steam, that change of phase reduced its density and made it a less effective neutron absorber. With more neutrons becoming available and few control rods inserted to absorb them, the chain reaction accelerated. The power level in the reactor began to rise.

This power surge was noticed by the operators. To reduce reactivity the emergency power-reduction system was initiated. All 205 control rods, plus emergency rods, were driven back into the reactor core. The control rods were of an unusual design in that their tips were made of graphite. The graphite tips were attached to a hollow segment one metre long, attached in turn to a five-metre absorbent segment. When the 205 control rods began driving into the surging reactor, they entered, as normal, tip first.

Graphite facilitates the fission chain reaction by slowing neutrons. Instead of slowing the reaction, the graphite tips increased it. The control rods also displaced water from the rod channels, increasing reactivity further. The reaction ran out of control, the sudden increase in heat ruptured some of the pressure tubes containing fuel. The hot fuel particles reacted with water and caused a steam explosion.

The explosion lifted the 1000 tonne cover off the top of the reactor, rupturing the rest of the 1660 pressure tubes, causing a second explosion and exposing the reactor core to the environment. About 50 tonnes of nuclear fuel evaporated and released into the atmosphere. The graphite moderator, which was radioactive, burned for 10 days, releasing a large amount of radiation. Radioactive caesium and iodine vapours were released by the explosion and during the subsequent fire. It should be emphasised that there was no nuclear explosion. No commercial nuclear reactor contains a high enough concentration of U-235 or plutonium to cause a nuclear explosion. The Chernobyl explosions were chemical ones, driven by gases and steam.

What remains of the Chernobyl 4 reactor is now enclosed in a hastily constructed concrete structure ('sarcophagus') that is growing weaker over time. Ukraine and the Group of Eight industrialised nations have agreed on a plan to stabilise the existing structure by constructing an enormous new sarcophagus around it, which is expected to last more than 100 years.

Officials shut down reactor 2 after a building fire in 1991 and closed Chernobyl 1 and 3 in 1996 and 2000, respectively.

N3.5 Exposure and impacts

The explosion and fire at Chernobyl lifted radioactive gas and dust high into the atmosphere, where winds dispersed it across Finland, Sweden, and central and southern Europe. Belarus received about 60 per cent of the contamination that fell on the former Soviet Union. A large area in the Russian Federation south of Bryansk was also contaminated, as were parts of north western Ukraine. Radioactive material from the accident did not spread evenly across the surrounding countryside but scattered patchily, in response to local and regional weather conditions.

Immediately following the accident, the main health concern was radioiodine (iodine-131) which has a half-life of eight days. If inhaled or ingested, for example in milk from cows grazing on contaminated pastures, radioiodine is taken up and concentrated in the thyroid, significantly increasing the likelihood of cancer development in that gland. In the longer term there is concern about contamination of the soil with cesium-137, which has a half-life of about 30 years.[282]

Soviet authorities started evacuating people from the area around Chernobyl 36 hours after the accident. By May 1986, about a month later, authorities had relocated all those living within a 30-kilometre(18-mile) radius of the plant — about 116 000 people.[283]

According to Soviet estimates, between 300 000 and 600 000 people participated in the clean up of the 30-kilometre evacuation zone around the reactor, but many entered the zone two years after the accident. Twenty-eight highly exposed reactor staff and emergency workers died from radiation and thermal burns within four months of the accident, and 19 more by the end of 2004 (not necessarily as a result of the accident). Two other workers were killed in the explosion from injuries unrelated to radiation, and one person suffered a fatal heart attack.

Soviet officials estimated that 211 000 workers participated in clean up activities in the first year after the accident and received an average dose of 165 mSv. Some children in contaminated areas received high thyroid doses because of an intake of radioiodine from contaminated local milk. Several studies have found that the incidence of thyroid cancer among children under the age of 15 years in Belarus, Russia and Ukraine has risen sharply. More than 4000 individuals, most of whom were children or adolescents at the time of the accident, have developed thyroid cancer as a result of the contamination, and 15 of these had died from the disease by the end of 2002.[284]

The most recent study of the impacts of the Chernobyl accident, 'Chernobyl's Legacy: Health, Environment and Socio-Economic Impacts, was published in September 2005 by the Chernobyl Forum. The Chernobyl Forum comprises the Commission of the European Communities, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), World Health Organization, Food and Agriculture Organization, International Labor Organization, and International Atomic Energy Agency (IAEA), plus the governments of Belarus, Russia and Ukraine. The objective was to examine all the available epidemiological data to settle the outstanding questions about how much death, disease and economic fallout really resulted from the Chernobyl accident.[119]

The main findings are:

- Most emergency workers and people living in contaminated areas received relatively low whole-body radiation doses, comparable to natural background levels.
- About 4000 individuals, most of whom were children or adolescents at the time of the accident, were stricken with thyroid cancer as a result of the contamination, and 15 of them have died from the disease by the end of 2002.
- The study predicts that some 4000 people in the areas with highest radiation levels eventually could die prematurely from cancer caused by radiation exposure, and of 6.8 million others living further from the explosion who received a much lower dose, the study estimates another 5000 are likely to die as a result of that dose. However, no evidence of any increases in the incidence of leukaemia and other cancers among affected residents has so far been detected. The experts found no evidence or likelihood of decreased fertility or of increases in congenital malformations that could be attributed to radiation exposure. (However critics argue that impacts may not become apparent for many years.)

- Poverty, mental health problems and 'lifestyle' diseases, such as alcoholism and tobacco dependency, pose a far greater threat to local communities than does radiation exposure. Relocation proved a 'deeply traumatic experience' for some 350 000 people moved out of the affected areas, the study noted, while persistent myths and misperceptions about the threat of radiation resulted in a 'paralysing fatalism' among residents of affected areas. Seeing themselves as 'victims' rather than 'survivors' has led to overcautious and exaggerated health concerns. (In this context it is interesting to note that other studies (reported in Walinder[285]) have estimated that fear of the potential impacts of Chernobyl radiation exposure impacting on the health of the individual or their children led to 1250 suicides among people who had been initial responders to the Chernobyl accident, and between 100 000 and 200 000 elective abortions in Western Europe in the years following the accident.)

Elizabeth Cardis of the International Agency for Research on Cancer in Lyon, is reported in a Nature Special Report as about to publish a study of the pan-European impact. [286] She concludes that, of 570 million people in Europe at the time, 16 000 will ultimately die as a result of the accident. This is 0.01 per cent of all cancer deaths. As cancer causes about a quarter of all deaths in Europe, identifying those cases triggered by the Chernobyl-sourced radioactivity cannot be done with statistical confidence. (To put this in context calculations for increases in mortality from exposure to air pollutants suggests that in the 1980s about 100 000 deaths from heart and lung disease, and 1000 cancer deaths were caused each year by air pollution in the United States.[287])

Other higher estimates of the long term impacts have been made, assuming that the official figures underestimate the true release of radioactive materials by about 30 per cent and that there was a wider spread of contamination and exposure. One predicts 30 000 to 60 000 excess cancer deaths in the longer term, 7 to 15 times greater than Chernobyl Forum estimates.[288]

This summing of very small doses over large populations to estimate fatalities over long periods of time is questionable. The International Commission for Radiological Protection (ICRP) has recently stated: '…the computation of cancer deaths based on collective doses involving trivial exposures to large populations is not reasonable and should be avoided'[114](p. 42). Similarly, a recent French Académie des Sciences and Académie Nationale de Médecine critical review of the available data regarding the effects of low doses of ionizing radiation on health concludes that 'while LNT may be useful for the administrative organization of radioprotection, its use for assessing carcinogenic risks induced by low doses, such as those delivered by diagnostic radiology or the nuclear industry, is not based on valid scientific data'.[270] (See Appendix M for discussion of the linear no threshold (LNT) hypothesis and radiation protection.)

N3.6 Post Chernobyl accident changes to the RBMK

To avoid the same sort of accident occurring again, all RBMK reactors in the former Soviet Union have been modified since the Chernobyl accident (and several have been closed down). There are still 12 RBMK reactors in operation: 11 units in Russia, and one in Lithuania.

The main objective of the changes is to reduce what is known as the 'positive void coefficient'. A reactor is said to have a positive void coefficient if excess steam voids lead to increased power generation. A negative void coefficient is the opposite situation in which excess steam voids lead to a decrease in power. As noted above, in a water cooled reactor steam may accumulate to form pockets or bubbles, known as voids. If excess steam is produced, creating more voids than normal, the operation of the reactor is disturbed, because the water is a more efficient coolant than steam and water acts as a moderator and neutron absorber while steam does not.

If a reactor has a positive void coefficient power can increase very rapidly, as any power increase that occurs leads to increased steam generation, which in turn leads to a further increase in power and more steam, a characteristic that can lead to a runaway feedback loop. On the other hand when the void coefficient is negative, excess steam generation will tend to shut down the reactor, a built in safety feature.

The majority of power reactors in operation around the world today have negative void coefficients. In those reactors where the same water circuit acts as both moderator and coolant, excess steam generation reduces the slowing of neutrons necessary to sustain the nuclear chain reaction. This leads to a reduction in power. As described above, in the RBMK design the neutron absorbing properties of the cooling water are a significant factor in the operating characteristics. In such cases, the reduction in neutron absorption as a result of steam production, and the consequent presence of extra free neutrons, enhances the chain reaction.

All operating RBMK reactors have had the following changes implemented to improve operating safety:

- The effective number of manual control rods has been increased from 30 to 45 to improve the operational reactivity margin of control.
- 80 additional absorbers have been installed in the core to inhibit operation at low power.
- Fuel enrichment has been increased from 2 per cent to 2.4 per cent to maintain fuel burn up with the increase in neutron absorption.

These factors have reduced the positive void coefficient to the extent that the possibility of a power excursion has been eliminated. In addition the time taken to shut down in an emergency has been reduced and the control rod design has been improved.

N3.7 Could a Chernobyl-type accident occur elsewhere?

With the modifications outlined above having been made to the 12 RBMK reactors still in operation the risk of an accident at one of them leading to a release of radioactivity on the scale of Chernobyl is considerably reduced. Nonetheless the RBMK reactor design is still considered to be less safe than western reactors.

It should be noted that there are other reactors in operation, in particular the UK Magnox design that, like the RBMK, lack massive containment structures. However they are considered to be inherently safer, in part because they use carbon dioxide gas as the coolant rather than water. This means there can be no explosive build up of pressure as can happen when excessively high temperature or a sudden loss of pressure allows a phase change such as when water turns explosively into steam in water cooled reactors. (Further discussion of nuclear reactor design is provided in Appendix L)

The US Nuclear Energy Institute[289] has considered the chances of a Chernobyl-like accident occurring in the US and concludes that such an accident could not occur for four main reasons:

Safer nuclear plant designs

All US power reactors have extensive safety features to prevent large-scale accidents and radioactive releases. The Chernobyl reactor had no such features and was unstable at low power levels. A large power reactor lacking safety features, with inherent instabilities, and lacking a massive containment structure, could not be licensed in the US. Post-accident analyses indicate that if there had been a US-style containment structure at Chernobyl, it is likely that none of the radioactivity would have escaped, and there would have been no injuries or deaths.

Alert and notification

The Chernobyl accident was concealed from authorities and the local population by the plant operators. As a result the government did not begin limited evacuations until about 36 hours after the accident.

In the United States, nuclear power plant operators are required to have in place evacuation and emergency management plans that have been developed in cooperation with local communities. They must also alert local authorities and make recommendations for protecting the public within 15 minutes of identifying conditions that might lead to a significant release — even if such a release has not occurred.

The US Nuclear Regulatory Commission posts resident inspectors at every nuclear power plant site to ensure the plants are following federal safety requirements.

Stringent emergency preparedness plans

Even with the design problems with the Chernobyl reactor, officials could have averted many radioactive exposures to the population with an effective emergency response. Key personnel at all US power reactors work with surrounding populations on an ongoing basis to prepare for an orderly and speedy evacuation in the unlikely event of an accident.

Protecting the food chain

Many people consumed contaminated milk and food because authorities did not promptly disclose details of the Chernobyl accident. This would be unlikely to happen in the United States. For example, following the Three Mile Island nuclear accident in 1979, the federal government monitored and tested all food and water supplies that might potentially be contaminated. Existing federal programs and regulations would ensure the government took similar action to quarantine and remove from public consumption any unsafe food or water in the case of an accident.

The majority of these requirements also apply in other IAEA member countries with commercial nuclear power plants.

N3.8 International cooperation on nuclear power plant safety

In part because of the TMI event, and with increased momentum after the much more serious Chernobyl accident six years later, an international consensus on the principles for ensuring the safety of nuclear power plants has emerged. This is supported by international cooperation mechanisms, developed through bodies such as the International Nuclear Safety Group (formerly the Nuclear Safety Advisory Group) established by the IAEA. In addition to publishing safety standard guidance documents, the IAEA provides safety services and runs seminars, workshops, conferences and conventions aimed at promoting high standards of safety. There is also an international regime of inspections and peer reviews of nuclear facilities in IAEA member countries, which has legislative backing through the international Convention on Nuclear Safety which entered into force on 24 October 1996. The Convention on Nuclear Safety aims to achieve and maintain high levels of safety worldwide. All IAEA member states with operating nuclear power reactors are parties to the convention. (see Appendix Q).

These developments mean that a Chernobyl scale accident is extremely unlikely to occur again.

N3.9 A nuclear power plant for Australia?

If Australia were to consider establishing a nuclear power industry, electricity generating companies would presumably consider the purchase of an 'off the shelf' currently available reactor design. Ideally the selected reactor would be one that had already been certified by the licensing authority in the country of manufacture or elsewhere, as meeting or exceeding the safety and operational requirements legally required. Australia would no doubt also have in place legislation requiring performance standards at least as high. In the health, safety and environmental areas our current requirements for industrial activities are considered to be on a par with world best practice.

There are a number of commercially available reactors that have been recently, or are currently, undergoing licensing certification in several countries. These reactors are discussed in more detail in Appendix L. For any of these designs the safety requirements that must be met are very high.[272] As an example the certification application to the US NRC for the new Westinghouse AP 1000 reactor estimates the risk of core damage to be one in two million (5×10^{-7}) per year of operation and the probability of a large radioactive release considerably lower at 6×10^{-8} per year.

N3.10 Note on sources

Where not otherwise referenced this Appendix is largely based on technical descriptions and summaries of the chronology of events at the Three Mile Island and Chernobyl accidents published by the US Nuclear Regulatory Commission, American Nuclear Society, Three Mile Island Alert, and Australian Uranium Association (previously the Uranium Information Centre) at the websites listed below.

US Nuclear Regulatory Commission:

http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

http://www.tmia.com/accident/NRCFactSheet.pdf

http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/chernobyl-bg.html

Three Mile Island Alert:

http://www.tmia.com/

American Nuclear Society:

http://www.ans.org/pi/matters/tmi/healtheffects.html

http://www.ans.org/pi/matters/chernobyl.html

Australian Uranium Association:

http://www.uic.com.au/nip48.htm

http://www.uic.com.au/nip22.htm

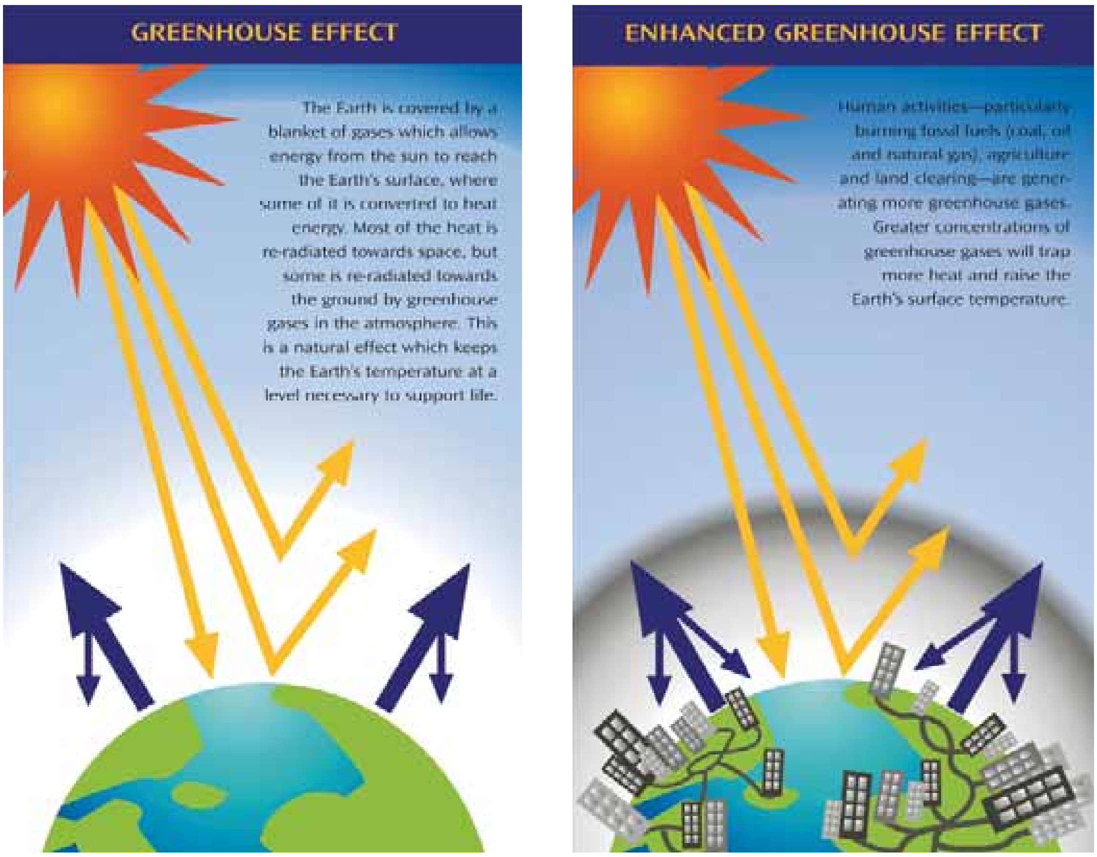
Appendix O. Climate change and greenhouse gas emissions

While the Earth's atmosphere and climate have varied with time since the planet was formed, the term 'climate change' refers to changes due to human activities that are altering the composition of the global atmosphere.[290] These changes have accompanied industrialisation and are outside the range of historically observed natural variation. Climate change enhances the natural greenhouse effect, and results on average in additional warming of the Earth's surface and atmosphere (Figure O1).

Over the past 650 000 years, greenhouse gas concentrations and global average temperatures have fluctuated within well-defined lower and upper limits across glacial and interglacial cycles. For example, atmospheric concentrations of carbon dioxide (CO_2, the chief heat-trapping greenhouse gas) have varied between around 180 and 300 parts per million (ppm),[136,291] while global average temperatures have fluctuated by about 10°C.[137]

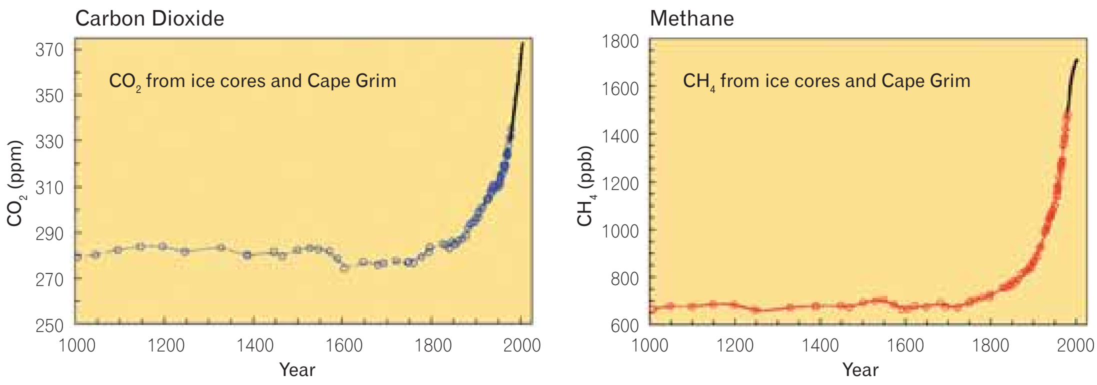
Since the beginning of the industrial revolution, atmospheric concentrations of CO_2 have risen more than one third from 280 to 380 ppm, and the growth rate appears to have accelerated in recent years.[292] The increase is primarily from the burning of fossil fuels and from deforestation. Atmospheric concentrations of methane (CH_4), the second leading greenhouse gas, have more than doubled over the past two centuries (Figure O2).[137]

Figure O1 How the greenhouse effect works



Source: Australian Greenhouse Office (AGO)[137]

Figure O2 Atmospheric concentrations of CO_2 and CH_4 over the past 1000 years



Source: AGO[137] based on Etheridge et al 1996[293] and 1998[294]

The world has, on average, warmed 0.6°C in the past century.[2] While natural factors contributed to the observed warming of the first half of the century, most of the warming over the past 50 years is probably due to the human-induced increase in greenhouse gas concentrations.[137] On current trends, it is possible that climatic changes comparable in magnitude to the difference between glacial and interglacial periods could occur in a mere 100 years, compared with several thousand years in the past.[138]

If emissions continue to grow, or even just remain at their present level, climate models indicate that global average temperatures and sea levels will rise, rainfall patterns will shift, sea ice will melt and glaciers will continue their global retreat. Impacts will vary greatly across regions. Overall however, rapid climate change presents fundamental challenges for human and biological adaptation, especially for natural ecosystems which typically evolve over millennia. It also poses fundamental questions of human security, survival and the stability of nation states.[295] Climate change is therefore an issue of major significance for all of us.

O2 Emissions and trends

O2.1 Global emissions

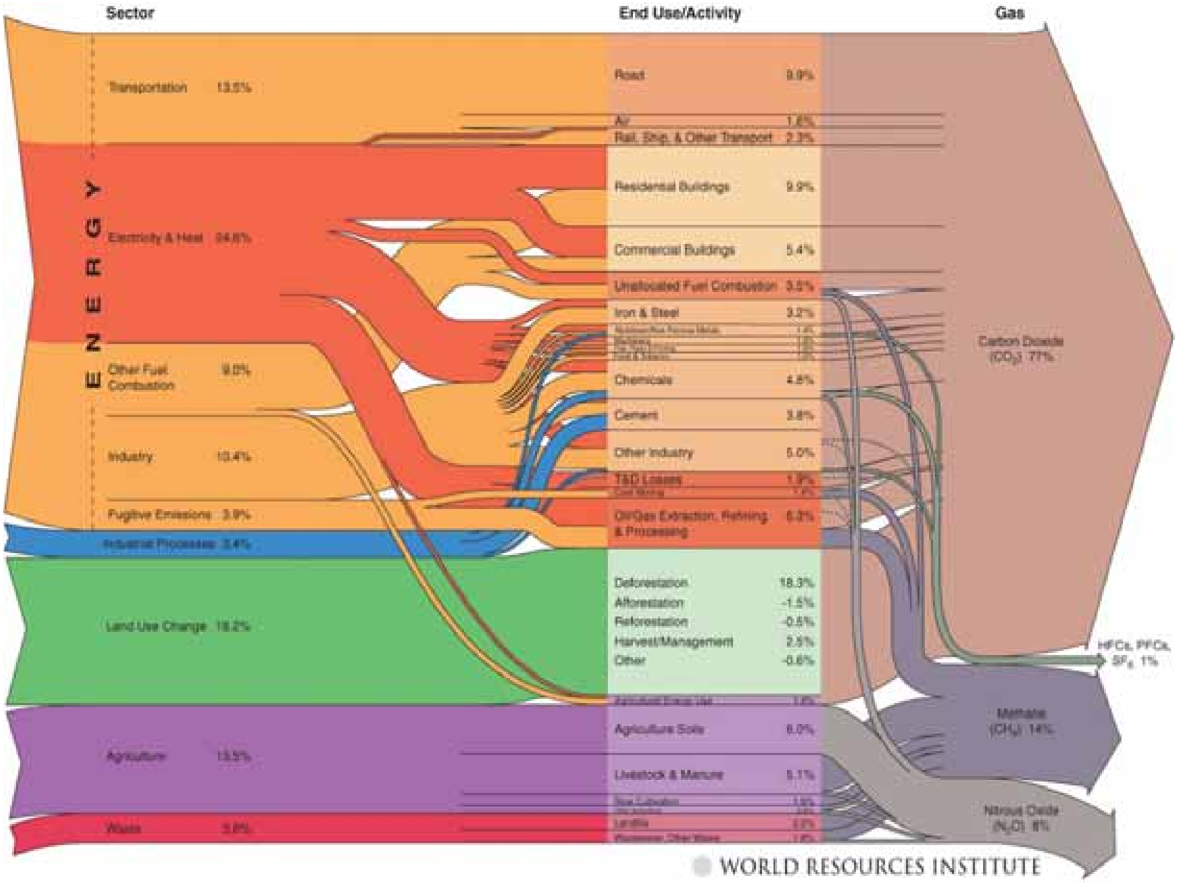
The World Resources Institute (WRI) estimates that human activity generated over 41.7 billion tonnes of CO_2-equivalent (CO_2-e)[109] in 2000.[140] Over 60 per cent of these emissions came from the production and use of energy. Land use change (particularly deforestation) and agriculture were other major sources. Figure O3 provides a breakdown of global emissions by source, by activity, and by greenhouse gas for the year 2000. This shows that energy-related emissions dominate, the electricity and heat sector is responsible for about one quarter of total emissions, and CO_2 is the most significant greenhouse gas.

A small number of nations (or a union of nations, in the case of the European Union) account for a large proportion of global greenhouse gas emissions. The United States, the European Union, China, Russia and India account for over 60 per cent of global emissions, and the United States alone accounts for more than one-fifth (see Table O1). Australia accounts for around 1.5 per cent of global emissions, and was the world's twelfth highest emitter in 2000.[110]

[109] Carbon dioxide equivalent (CO_2-e) aggregates the impact of all greenhouse gases into a single measure, adjusted to account for the different global warming potential of each gas. For example, 1 tonne of methane has the same warming effect as 21 tonnes of carbon dioxide.

[110] Note the rank of twelfth counts all EU members as one. If EU members are counted separately, Australia ranks fifteenth.

Figure O3 Flow diagram of global greenhouse gas emissions in 2000



Source: WRI.[140] All calculations are based on CO_2 equivalents. Land use change includes both emissions and absorptions. Dotted lines represent flows of less than 0.1 per cent of total greenhouse gas emissions.

Table O1 Top greenhouse gas emitters in 2000

Country	Rank	Emissions $MtCO_2$-e	Percentage of World GHGs
United States	1	6928	20.6
China	2	4938	14.7
EU-25	3	4725	14.0
Russia	4	1915	5.7
India	5	1884	5.6
Japan	6	1317	3.9
Brazil	7	851	2.5
Canada	8	680	2.0
South Korea	9	521	1.5
Mexico	10	512	1.5
Indonesia	11	503	1.5
Australia	12	491	1.5

$MtCO_2$-e = million tonnes of carbon dioxide equivalent; GHGs = greenhouse gases.

Source: WRI.[140] Gases include CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. Totals exclude emissions from international bunker fuels [ie fuels for international shipping and aircraft] and land use change and forestry.

Population and economic growth are key drivers of global emissions growth. Emissions growth rates are highest among developing countries, where CO_2 emissions increased by 47 per cent over the 1990–2002 period. CO_2 emissions in developed countries were unchanged over the 1990–2002 period, although there were considerable national differences. Emissions from Russia and Ukraine declined significantly due in part to their economic transition from centrally planned economies. Emissions in the EU declined slightly, led by significant reductions in the United Kingdom (where coal industry reforms have played an important role) and Germany (reflecting the impact of East Germany's economic transition). In contrast, the United States and Canada witnessed significant growth.[140]

O2.2 Australian emissions

While there is no official estimate of Australia's net greenhouse gas emissions prior to 1990, rapid growth in fossil fuel extraction, energy use and industrial and agricultural activity and extensive land clearing over the past century would suggest Australia's emissions history would mirror global trends.

Australia's net greenhouse gas emissions across all sectors totalled 564.7 Mt CO_2-e in 2004, an increase of 2.3 per cent from 1990 levels. This overall figure masks two opposing trends: emissions from land use, land use change and forestry fell by 93.4 Mt (72 per cent) from 1990 to 2004 (primarily due to controls and bans on broad scale land clearing) while energy sector emissions rose by almost 100 Mt (almost 35 per cent) over the same period. Trends in sectoral emissions are set out in Table O2.

The production and use of energy (including electricity production and transport) provided the single largest source, accounting for over 68 per cent of total emissions in 2004 (Figure O4). Electricity generation directly generated approximately 195 Mt of CO_2-e, of which 92.2 per cent was attributable to coal, 7 per cent to gas, and 0.8 per cent to oil and diesel.

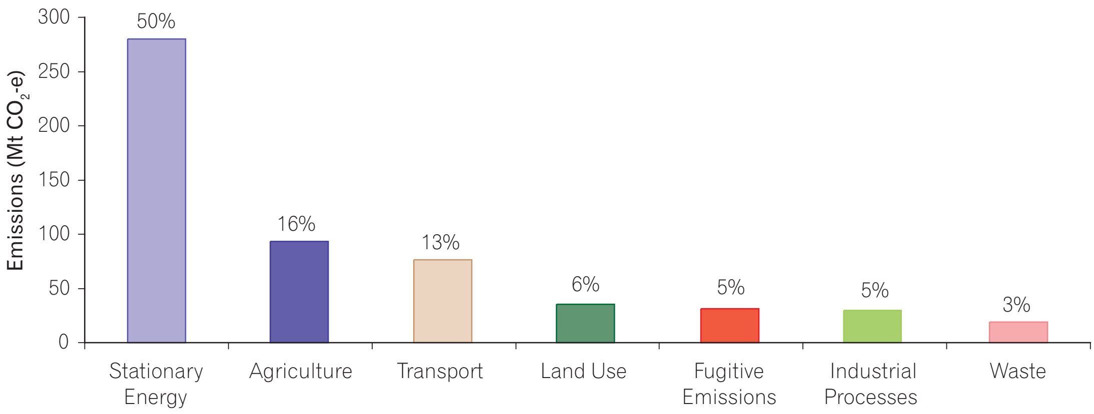
Table O2 Australia's greenhouse gas emissions by sector in 1990 and 2004

	Emissions Mt CO_2-e		Per cent change in emissions
	1990	2004	1990–2004
Australia's Net Emissions	**551.9**	**564.7**	**+2.3**
Energy	287.5	387.2	+34.7
Stationary Energy	195.7	279.9	+43.0
Transport and other	91.7	107.2	+16.9
Industrial Processes	25.3	29.8	+18.0
Agriculture	91.1	93.1	+2.2
Land Use, Land Use Change and Forestry	128.9	35.5	–72.5
Waste	19.2	19.1	–0.7

$MtCO_2$-e = million tonnes of carbon dioxide equivalent.

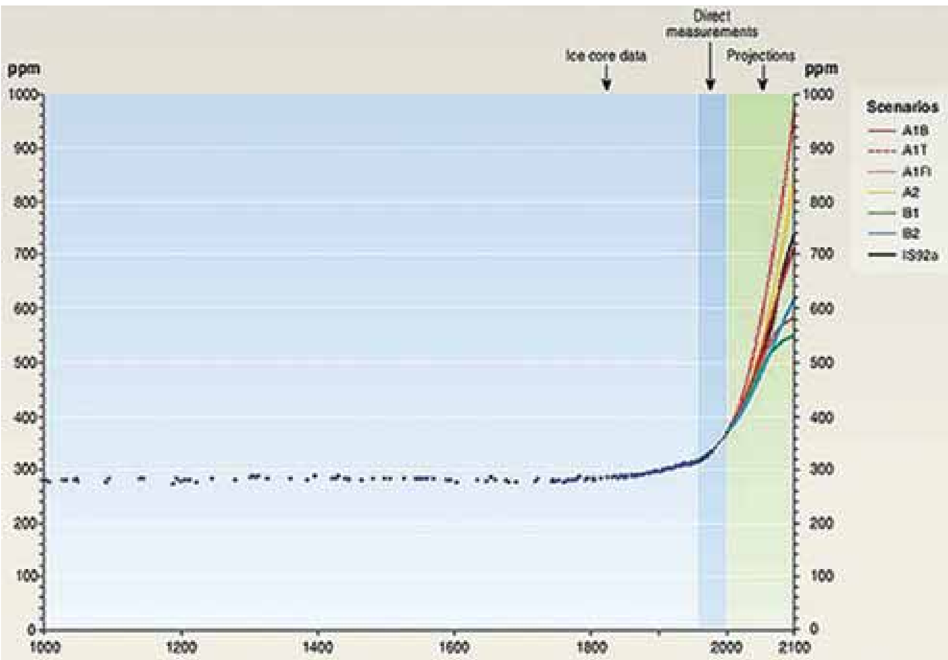
Source: AGO.[141] Figures calculated using the Kyoto Protocol accounting provisions (those applying to Australia's 108 per cent emissions target). Estimate for land use is interim only.

Figure O4 Australia's emissions by sector in 2004



$MtCO_2$-e = million tonnes of carbon dioxide equivalent
Source: AGO.[141] Land use includes land use change and forestry.

Figure O5 Atmospheric CO_2 concentration from year 1000 to year 2000 and projections to 2100



ppm = parts per million

Source: IPCC [134] Figure SPM-10a. Data from ice core and direct atmospheric measurements over the past few decades. Projections of CO_2 concentrations for the period 2000 to 2100 are based on illustrative scenarios.

O2.3 Global projections

Emissions

The evolution of future greenhouse gas emissions and their underlying driving forces is uncertain. Economic and population growth, technology development and deployment, and international and domestic policy settings all influence emission trends. Many possible future scenarios have been developed and modelled, resulting in a wide range of future emission pathways.

The Intergovernmental Panel on Climate Change (IPCC) draws on the work of thousands of experts from all regions of the world to assess the best available scientific, technical and socio-economic information on climate change. Under 'business as usual' pathways involving no climate policy intervention, the IPCC's Third Assessment Report (TAR)[111] projected total greenhouse gas emissions to rise between 63 and 235 per cent over the first half of this century. As a result, CO_2 concentrations, globally averaged surface temperature and sea levels were projected to rise over the 21st century. For the six illustrative scenarios, the projected concentration of CO_2 by the end of the century ranged from 540 to 970 ppm (Figure O5).

A number of authors have critiqued the methodology used to develop the IPCC's long term projections, proposed alternative methods, and argued for more explicit recognition of the probabilities of different future scenarios.[112] These authors do not deny the importance and reality of climate change, but they do highlight that future climate projections are very uncertain and that not all scenarios are equally likely. Their preliminary assessments suggest somewhat lower future emission levels, but the key qualitative message remains the same: under current policy settings future emissions are likely to be much higher than current levels. These issues are the subject of ongoing debate and analysis in the scientific community, and are likely to be explored further in the IPCC's Fourth Assessment Report.

Significance of the energy sector

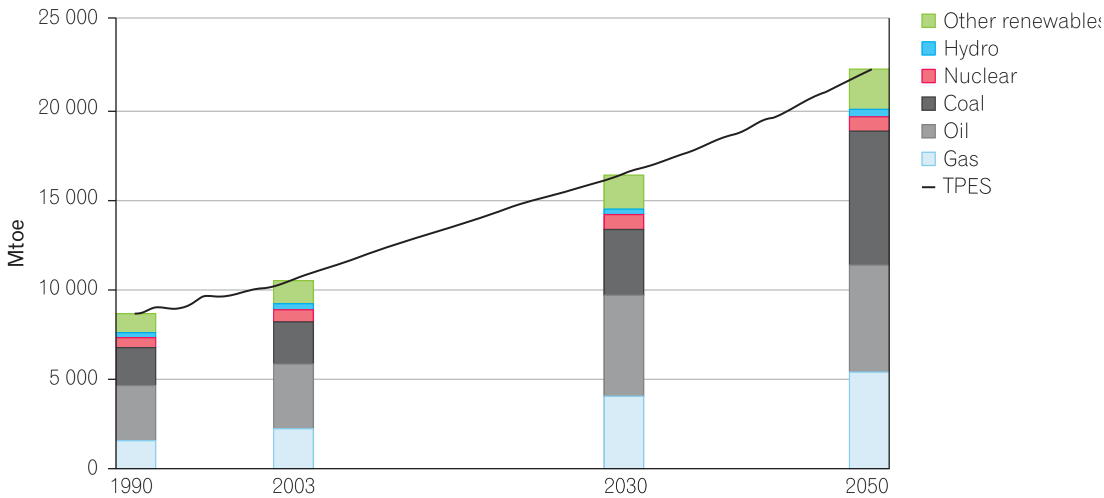
Demand for energy is projected to rise substantially, driven largely by population and economic growth and demographic change in today's developing countries: 1.6 billion people currently have no access to modern energy services; and the United Nations estimates the global population will rise from 6 billion today to 10.4 billion by 2100.

The International Energy Agency (IEA) projects that under current policy settings primary energy use will more than double between 2003 and 2050, with a very high reliance on coal (Figure O6). This is consistent with IPCC business as usual scenarios, which project global primary energy use will grow between 1.7 and 3.7-fold from 2000 to 2050. Electricity demand grows almost 8-fold in the IPCC's high economic growth scenarios, and more than doubles in the more conservation-oriented scenarios at the low end of the range. These scenarios include improvements in energy efficiency worldwide of between 1 and 2.5 per cent per year.[297] This growth in energy use would have major implications for climate change: energy-related CO_2 emissions under the IEA current policy scenario would be almost 2.5 times current levels by 2050.

[111] The IPCC TAR was published in 2001. The IPCC's Fourth Assessment Report is currently being developed and will be published in 2007.

[112] For example, see discussion of critiques by Castles, Henderson and Schneider in McKibbin 2004.[296]

Figure O6 Past and projected world total primary energy supply by fuel under current policy settings



Mtoe = million tonnes of oil equivalent.

Source: IEA[30]

Impacts

Climate models using the IPCC emissions scenarios project an increase in globally averaged surface temperature of 1.4 to 5.8°C over the period 1990 to 2100. This is two to ten times more than the observed warming over the 20th century. Nearly all land areas are very likely to warm more than these global averages, particularly those at northern high latitudes in winter.

Modelling has also projected changes to precipitation (rainfall and snow), ice cover and sea level. Under the IPCC scenarios global average precipitation increases during the 21st century, however increases and decreases are projected at regional scales. Glaciers continue their widespread retreat, while snow cover, permafrost, and sea-ice extent decrease further across the Northern Hemisphere. The Antarctic ice sheet is likely to gain mass, while the Greenland ice sheet is likely to lose mass. Global mean sea level is projected to rise between 9 and 88 cm from 1990 to 2100, but with significant regional variations. This rise is due primarily to thermal expansion of the oceans (water expands as it warms) and melting of glaciers and ice caps.[134]

A global average temperature increase of up to 1°C may be beneficial for a few regions and sectors, such as agriculture in high latitude areas.[134] However other regions and sectors would be adversely affected: even the 0.6°C average warming in the past 100 years has been associated with increasing heatwaves and floods, more intense droughts, coral bleaching and shifts in ecosystems.[137] The larger and faster the change, the greater the risk of adverse impacts. For example projections suggest:

- With additional warming of less than 1°C, 60 per cent of the Great Barrier Reef would be regularly bleached causing considerable loss of species.[135,138,139] With a 1–2°C rise, hard coral reef communities would be widely replaced by algal communities.[135]
- A sustained global temperature rise of about 2°C would bring the onset of irreversible melting of the Greenland ice sheet (and ultimately result in an average sea-level rise of about 7m).[134]
- Serious risk of large scale, irreversible system disruption such as destabilisation of the Antarctic ice sheets and the global ocean thermohaline circulation is more likely above 3°C.[133,298] Collapse of the West Antarctic ice sheets would lead to centuries of irreversible sea-level rise and coastal inundation around the world.[135]

A rise in global average temperatures of more than 5°C (equivalent to the amount of warming that occurred between the last ice age and today [137]) is likely to lead to major disruption and large-scale movement of populations. These effects are very hard to capture with current models as temperatures would be so far outside human experience.[132]

Figure O7 illustrates how the risks of adverse impacts increase with the magnitude of climate change. The left panel displays the IPCC's temperature projections under business as usual scenarios to 2100. The right panel displays the level of risk for five areas of concern, including impacts on ecosystems and extreme climate events. White indicates neutral or small positive or negative impacts or risks, yellow indicates negative impacts for some systems or low risks, and red means negative impacts or risks that are larger and/or more widespread.[299]

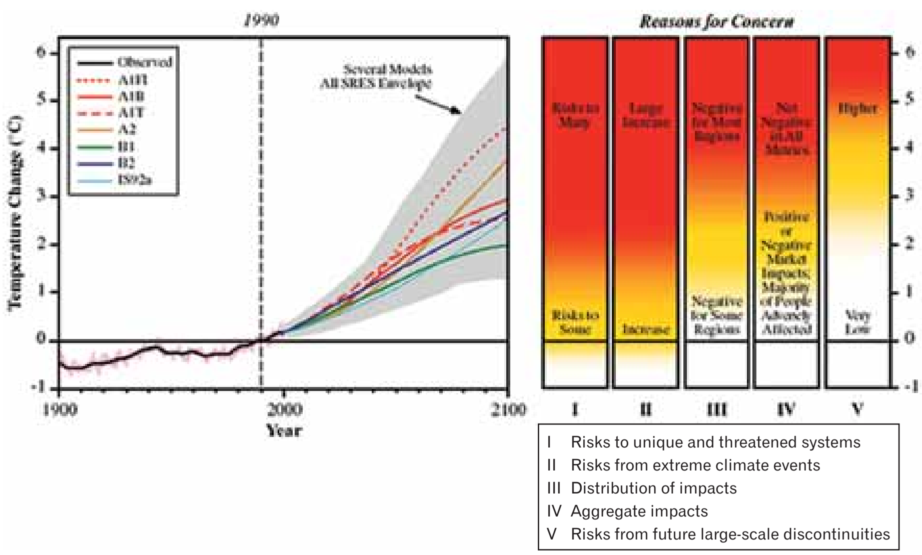
Recent science has improved our understanding of feedback loops in the global climate system, including:[136]

- the cooling effect of aerosols (small particles suspended in the atmosphere): this has dampened the effect of greenhouse gases to date, and suggests enhanced warming later this century as greenhouse gas concentrations increase and aerosols are reduced.
- a decrease in the reflectivity of the Earth's surface as snow and ice melt (the albedo effect): this exposes darker underlying land and ocean surfaces, leading to enhanced absorption of sunlight and further warming.
- changes to terrestrial carbon cycle dynamics: as temperature rises, soil organic matter, fires and carbon pools in wetlands and frozen soil are likely to release further greenhouse gases to the atmosphere, forming a positive feedback loop that intensifies the warming.

These effects increase the risk that the upper end of the IPCC TAR estimate of a 1.4 to 5.8°C temperature rise will be reached or exceeded by 2100.[136]

While uncertainties remain, the most recent scientific analysis indicates some risks are more serious than they first appeared.[132,136] The world is already experiencing an unprecedented rate of change in ice cover and climate models forecast the Arctic could be ice-free in summer by the end of the century.[2,136] Likely impacts include water shortages in Asia and South America, where hundreds of millions rely on glacial melt for their water supply; and changes to the Indian monsoon, which could trigger severe flooding or drought in India, Pakistan and Bangladesh.[132]

Figure O7 Reasons for concern about projected climate change impacts



Source: IPCC [299] Figure SPM-2. Global mean temperature change is used as a proxy for the magnitude of climate change.

O2.4 Australian projections

Emissions

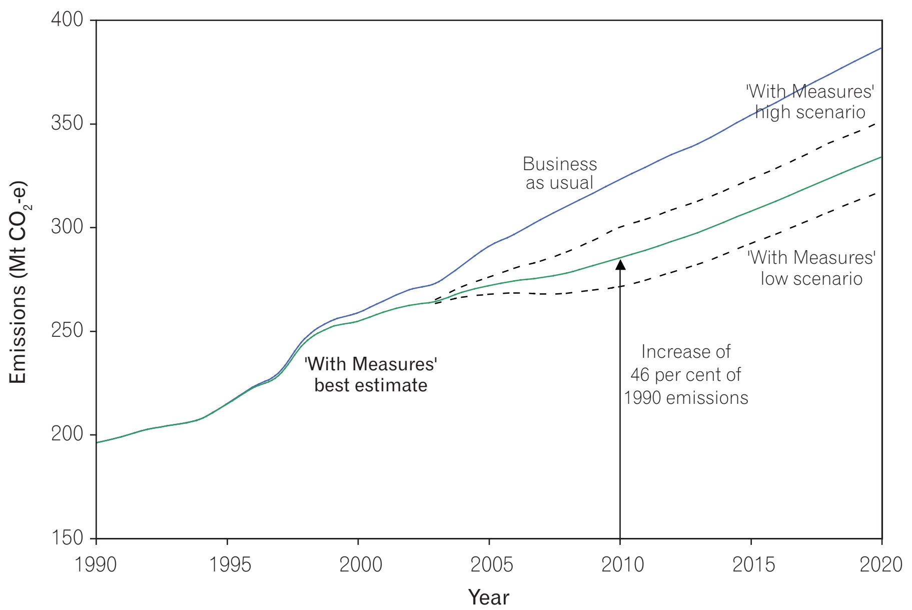
Australia's emissions are on an upward trend. Official projections published in 2005 suggest that under current policy settings emissions will grow by an average of 1.2 per cent each year from 2010, reaching 673 Mt CO_2-e by 2020 (22 per cent higher than 1990).

Annual emissions from stationary energy are projected to grow to 333 Mt CO_2-e by 2020, an increase of 70 per cent over 1990 levels (Figure O8). Electricity generation is projected to remain the largest source of these emissions, and is forecast to grow to a total of 222 Mt in 2020, 72 per cent above 1990 levels.[300]

Impacts

Australian average temperatures have risen by an estimated 0.8°C over the last century (Figure O9). The past decade has seen the highest recorded mean annual temperatures, and 2005 was Australia's warmest year on record.[301,302] Rainfall has increased over the last 50 years over northwestern Australia, but decreased in the southwest of Western Australia and in much of southeastern Australia, especially in winter. Effects on runoff are potentially serious: water supply to Perth's reservoirs has dropped 50 per cent since the 1970s, and water levels in storages in much of southeastern Australia are at near-record lows. The cause of these changes remains under discussion within the scientific community. Nevertheless, in the case of the southwest of Western Australia a combination of natural variability and a trend due to the enhanced greenhouse effect is considered to be the likely cause.[138]

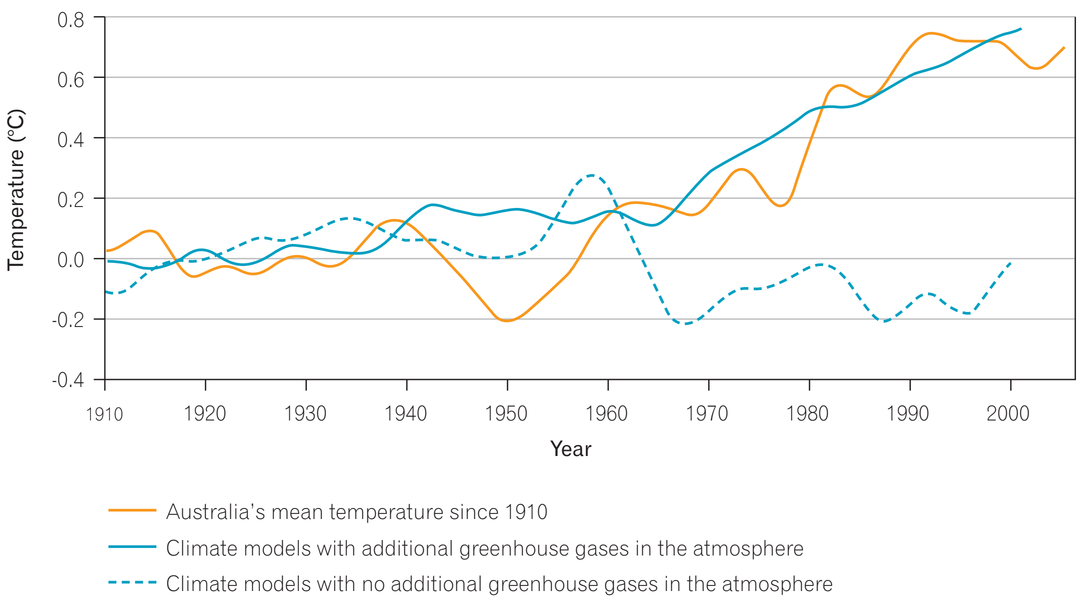
Figure O8 Australia's stationary energy emissions since 1990 and projections to 2020



$MtCO_2$-e = million tonnes of carbon dioxide equivalent. Business as usual pathway involves no climate policy intervention.

Source: AGO [300]

Figure O9 Variations of Australian mean temperatures, 1910 to 2000



Source: Based on Karoly and Braganza 2005.[303]

Australia is likely to face some degree of climate change over the next 30 to 50 years as a result of past greenhouse gas emissions, irrespective of global or local efforts to reduce future emissions. The scale of that change, and the way it will be manifested in different regions is less certain, but climate models can illustrate possible effects. Applying a range of these models to Australia for the IPCC global emissions scenarios, CSIRO has identified a number of possible outcomes:

- an increase in annual national average temperatures of between 0.4 and 2°C by 2030 and of between 1 and 6°C by 2070, with significantly larger changes in some regions
- more heatwaves and fewer frosts
- more frequent El Nino Southern Oscillation events, resulting in a more pronounced cycle of prolonged drought and heavy rains
- more severe wind speeds in cyclones, associated with storm surges being progressively amplified by rising sea levels
- an increase in severe weather events including storms and high bushfire propensity days.[304]

O2.5 Costs of impacts

Uncertainty in the scale and rate of climate change creates formidable challenges for formal modelling of its overall impact in monetary terms. Nevertheless scientific understanding of the risks is improving, allowing the potential costs to be examined through probabilistic assessment. This incorporates the full range of possible impacts — including the small risks of catastrophic change — rather than limiting analysis to averages.[132]

A major assessment of the potential global costs of climate change impacts, undertaken by Sir Nicholas Stern for the United Kingdom Government, was published in 2006. This examined potential physical impacts of climate change on the economy, on human life and on the environment.[132]

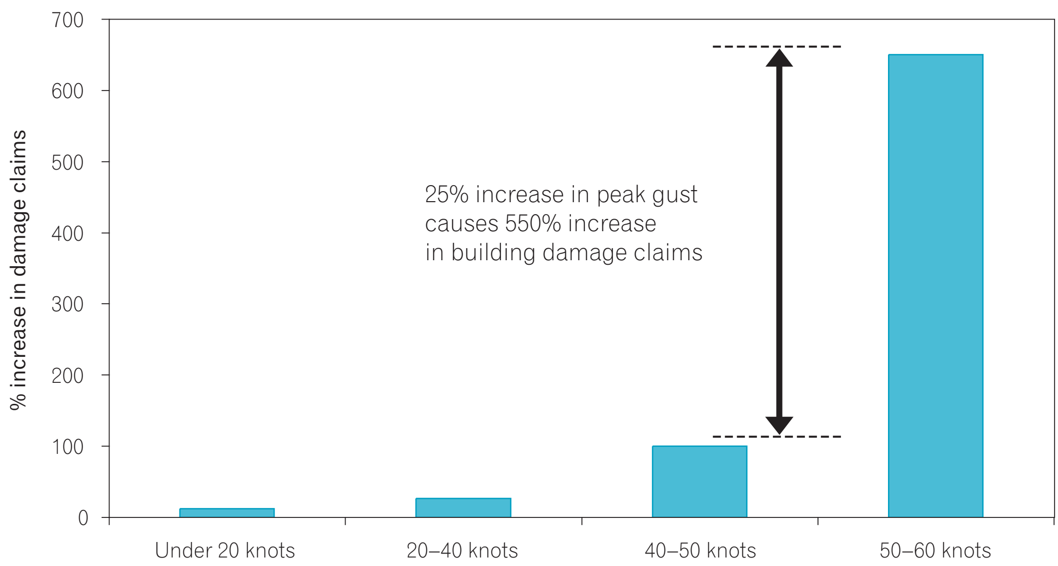
The Stern Review estimated that the total cost over the next two centuries of climate change under 'business as usual' scenarios involves impacts and risks that are equivalent to an average reduction in global per-capita consumption of at least 5 per cent, now and forever. This figure does not account for direct impacts on the environment and human health, feedback loops in the climate system and the disproportionate share of impacts which fall on poor regions of the world. If these factors are included, the total cost of business as usual climate change is estimated to be around a 20 per cent reduction in consumption per head, now and into the future.[132]

The Review noted that its results are specific to the model used and its assumptions, and that there are great uncertainties in the science and economics. Some economists have criticised the Review's assumptions (particularly the use of a very low discount rate[310]) and suggest a bias towards the most pessimistic studies.[311] However in comparison to the estimated costs of mitigation (ie reducing emissions; discussed in Section O3.3 below), these probability-weighted costs of impacts look very large. Even if the more extreme impacts are diluted as Stern's critics suggest, the costs are still significant and provide a sound argument for reducing emissions.

Australia has not yet undertaken a detailed analysis of the potential costs of climate change. However it is clear that climate change will impose direct costs, and possibly confer a smaller number of direct benefits, on the Australian economy. Examples of costs include possible lost production due to more severe and frequent droughts, the potential for higher insurance premiums due to more frequent extreme weather events,[312] and the potential for reduced runoff in much of southern Australia to affect the cost of water. Estimating these costs is very difficult given our current state of knowledge. Indirect costs such as reduced environmental amenity and poorer health outcomes can also be expected, but are even more difficult to estimate.[304]

Agriculture, which accounts for about 3 per cent of national GDP, is highly dependent on climate. The 2002–2003 drought demonstrated this dependence, and provides an indication of the potential impacts of climate change. Farm output fell by close to $3 billion, resulting in an estimated one per cent reduction in GDP.[304] Tourism is also vulnerable. For example, the Great Barrier Reef is likely to suffer from more extensive and regular coral bleaching events, adding to existing pressures from sediment and nutrient runoff and commercial fishing. Within the Great Barrier Reef catchment, tourism attracts approximately 1.8 million visitors and contributes an estimated $5.1 billion per year.[313,314] Climate model projections suggest that within 40 years water temperatures could be above the survival limit of corals, and cause transformations in coral communities that could range from cosmetic to catastrophic.[139,304]

Figure O10 Small change in hazard can lead to large change in damage



Source: Allen Consulting Group[304] based on Insurance Australia Group experience.

Similarly, our cities are highly exposed to climate patterns. The majority of Australia's population live in coastal zones — areas likely to be affected by rising ocean levels, more intense storms and more severe storm surges. Cities and infrastructure are built to accepted risk limits based on the expected frequency of severe weather events. Damage, injury and death can accelerate in a non-linear way outside these expected limits. For example, insurance industry experience indicates that a 25 per cent increase in peak wind gusts can generate a 550 per cent increase in building damage claims (Figure O10). Given that a disproportionately large share of insurance losses come from extreme weather events, an increase in the frequency and severity of storms — as is projected with climate change — could appreciably alter the price and availability of insurance.[304]

03 Response

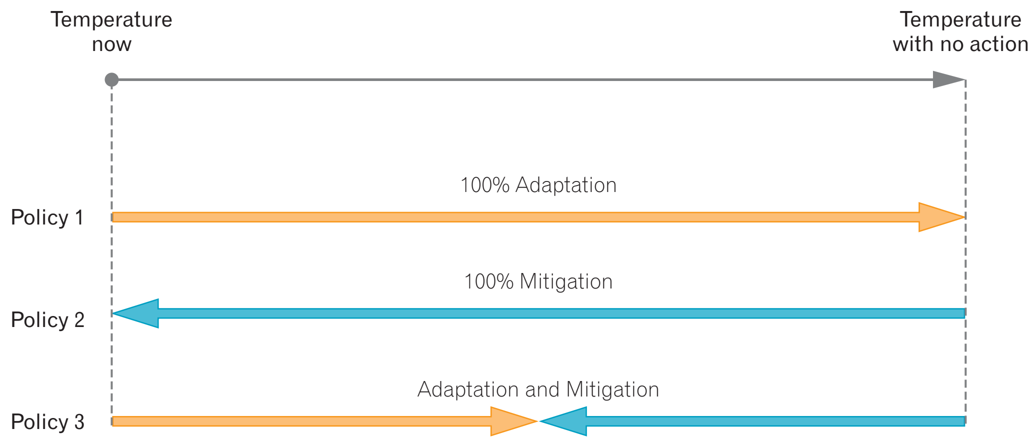
The current and projected impacts of climate change suggest the need for action on two fronts: adaptation and mitigation. Adaptation involves taking precautions against the climate changes that have and will occur (thereby reducing harm and in some cases exploiting beneficial opportunities), while mitigation addresses the root cause of climate change by reducing greenhouse gas emissions (thereby reducing the level of future climate change).

The costs and benefits of adaptation and mitigation efforts operate at different time scales. Emission cuts now will deliver future benefits by reducing the scale of climate change. Adaptation, on the other hand, will occur gradually over time as climatic patterns shift, and deliver more immediate benefits to those taking the action. Adaptation and mitigation also operate at different levels: mitigation requires concerted action by the global community, whereas adaption will occur at a local level because different places will experience different climate change impacts.

Adaptation and mitigation measures are complementary, as both can reduce the risk of harm.[134,304,315] Because of the inherently uncertain nature of climate change, it is impossible to know precisely what will happen to the climate, and to determine the costs and benefits of different mitigation and adaptation policies. Rather than pursuing one or the other in isolation, a prudent approach combines both (Figure O11), and revises actions and priorities as more and better information becomes available.

As a low emission electricity generation technology, nuclear power is most relevant to the mitigation agenda: it provides a way to reduce emissions from human activities and thereby help to reduce the scale of future climate change. The remainder of this section therefore focuses on the nature, scale, cost and feasibility of the abatement task.

Figure O11 Combining adaptation and mitigation



Source: McKibbin[315]

O3.1 Abatement task

Climate change results from the cumulative impacts of billions of individual actors around the world, and individual efforts to reduce emissions will have no appreciable impact if others continue to emit. Climate change therefore requires a global response. The international community has recognised the need for action, and agreed to the United Nations Framework Convention on Climate Change (UNFCCC) in 1992.

The objective of the UNFCCC is to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous human-driven interference with the climate system. Stabilisation should be achieved within a time-frame that allows ecosystems to adapt naturally to climate change, ensures food production is not threatened, and enables economic development to proceed in a sustainable manner.[290]

Numerous studies have attempted to define thresholds for 'dangerous interference' in terms of global temperature change, atmospheric CO_2 concentration, greenhouse gas concentration or radiative forcing. Results vary widely, and the issue is unlikely to be resolved for some time.[113] However it is clear that deep cuts in emissions will be required to stabilise emissions at any likely target.

The Kyoto Protocol builds on the UNFCCC by creating a framework for specific action, as a first step towards that objective.[316] The Protocol, which entered into force in 2005, sets binding targets and timelines for developed countries to collectively reduce their total emissions to 5 per cent below 1990 levels. The Protocol does not set binding targets for developing countries, however it reaffirms their obligation — taking account of their specific development priorities and circumstances — to take action to reduce emissions.[290,316] While Australia has not ratified the Protocol, the Australian Government has committed to meeting its target of constraining annual emissions during the Kyoto commitment period (2008–2012) to no more than 108 per cent of its 1990 emissions.[58]

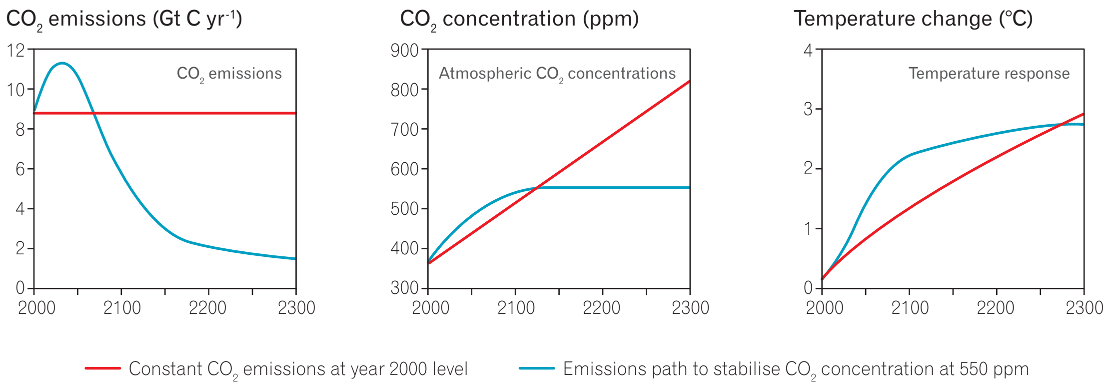
O3.2 Scale of action required

Because of the uncertainty and variability in the nature, rate and scale of potential impacts, it is not currently possible to accurately quantify the costs and benefits of particular atmospheric concentration targets. An accurate assessment is not likely to be achievable within the required timeframe, and so action will need to occur in an uncertain environment.

We do know that if global emissions are held constant at current levels, atmospheric concentrations will continue to rise. This is because greenhouse gases are being added to the atmosphere faster than they are being removed (like a bathtub being filled faster than it is draining out). The difference between stabilising emissions and atmospheric concentrations is illustrated in Figure O12. The red line shows the effect of holding emissions stable at 2000 levels: atmospheric concentrations and global average temperatures continue to rise over time. The blue line shows one pathway to limiting the change in global temperatures by stabilising atmospheric concentrations at 550 ppm (around a doubling of pre-industrial levels): emissions would need to be reduced significantly over this century, and further thereafter. However because this pathway allows further emissions growth before reductions, it involves more rapid growth in atmospheric concentrations and temperatures up to 2100.

[113] For example, see summary of fourteen sources in Preston & Jones 2006.[135] Temperature change ranged from 0.9 to 2.9°C; atmospheric CO_2 ranged from 375 to 550ppm.

Figure O12 Impact of stabilising emissions versus stabilising concentrations of CO_2



Source: IPCC[134] Figure 5.2

Inertia in the climate system means that temperatures will continue to increase long after emissions are reduced to levels that stabilise CO_2 concentrations in the atmosphere. Some changes in the climate system, plausible beyond the 21st century, would be effectively irreversible. For example, major melting of the ice sheets and fundamental changes in the ocean circulation pattern could not be reversed over a period of many human generations.[134]

The IPCC TAR analysed a range of emission and stabilisation scenarios. At the lower end, to achieve stabilisation at 450 ppm and limit global mean temperature change to between 1.2 and 2.3°C by the end of the century, emissions would need to peak within the next 10 to 20 years and then decline rapidly (to around 30 per cent of 2000 levels by the end of the century, and even lower after that).

In contrast, if emissions peak later this century and are then only gradually reduced, atmospheric levels could stabilise at 1000 ppm, bringing larger and more rapid increases in global mean temperature (Table O3).

The balance of scientific opinion is that avoiding dangerous climate change will require deep cuts in global greenhouse gas emissions. To avoid more than doubling pre-industrial levels of greenhouse gases in the atmosphere, cuts in the order of 60 per cent will be required by the end of the century.[58,134] Deeper cuts are required sooner to achieve lower stabilisation levels. Recent analysis indicates that if action to reduce emissions is delayed by 20 years, rates of emission reduction may need to be 3 to 7 times greater to meet the same stabilisation target.[298]

Table O3 Projected temperature increase for different stabilisation levels

CO_2 stabilisation level (ppm)	Year of stabilisation	Temperature increase at 2100 (°C)	Temperature increase at equilibrium (°C)
450	2090	1.2–2.3	1.5–3.9
550	2150	1.6–2.9	2.0–5.1
650	2200	1.8–3.2	2.3–6.1
750	2250	1.9–3.4	2.8–7.0
1000	2375	2.0–3.5	3.5–8.7

Source: IPCC[134]

Note: To estimate the temperature change for these scenarios, it is assumed that emissions of greenhouse gases other than CO_2 would follow the SRES A1B scenario until 2100 and be constant thereafter.

O3.3 Feasibility and cost

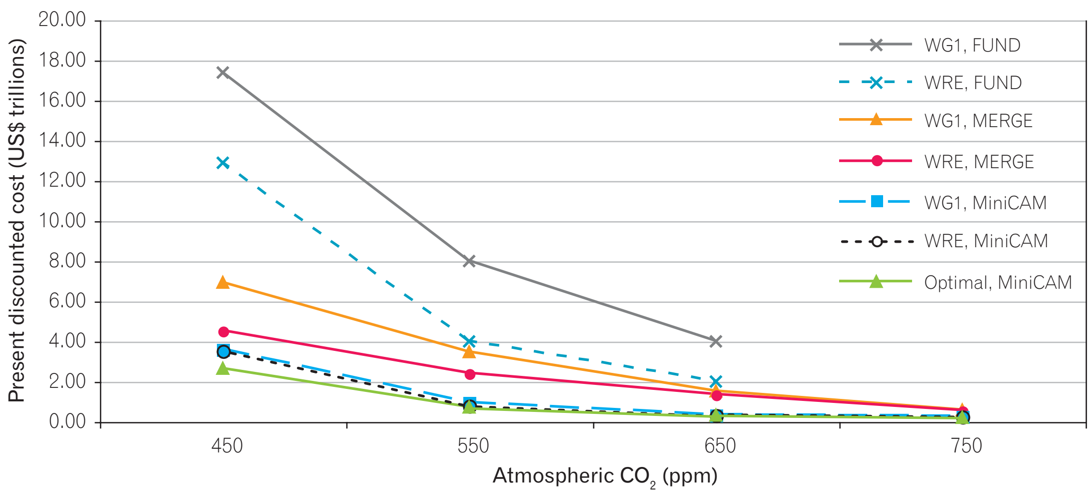
The scale of the abatement task is demanding but not insurmountable. International responses to other global environmental and resource management challenges, including the 1970s oil shock, acid rain and stratospheric ozone depletion, demonstrate collective action is possible and that society is willing and able to bear transition costs to cleaner and more sustainable practices. They also demonstrate that great challenges can stimulate innovation and ingenuity, strengthening our capacity to respond to the problem and reducing the cost of solutions. Indeed some solutions can be delivered at zero cost or with economic benefits: for example efficiency improvements reduce input costs, and lower pollution levels improve health outcomes.

Numerous studies have attempted to quantify the cost of stabilising atmospheric levels of greenhouse gases. This is a difficult task: it is hard enough to forecast the evolution of the global energy and economic system over the coming decade, let alone the coming century. Projections must therefore be treated with considerable caution. Their value lies more in the insights they provide than the specific numbers. In addition, these studies do not incorporate the costs of the impacts of climate change. They typically take the stabilisation target as a given, and seek to identify the least-cost pathway to achieve that target. A separate assessment — which compares the costs of mitigation (discussed here) with the costs of impacts (discussed in Section O2.5 above) — is required to select the ultimate target and compare the impacts of different pathways.

The IPCC TAR reviewed a range of studies, finding great diversity in the estimated costs of achieving a given stabilisation target. Cost estimates differ because of the methodology used and underlying factors and assumptions built into the analysis. As would be expected, mitigation costs increase with more stringent stabilisation targets. Incorporating multiple greenhouse gases, sinks, induced technical change, international cooperation and market-based policies such as emissions trading can lower estimated costs. Some studies suggest some abatement can be achieved at zero or negative costs through policies that correct market failures and deliver multiple benefits. On the other hand, accounting for potential short-term shocks to the economy, constraints on the use of domestic and international market mechanisms, high transaction costs and ineffective tax recycling measures can increase costs.[134,144]

Figure O13 illustrates the diversity of abatement cost estimates for given stabilisation levels (for example, the estimated cost to achieve 450 ppm ranges from around US$2.5–17.5 trillion), as well as the declining abatement cost as stabilisation levels increase (estimated cost to achieve 750 ppm is less than US$1 trillion).

Figure O13 Projected abatement costs under alternative stabilisation targets



Source: IPCC[144]

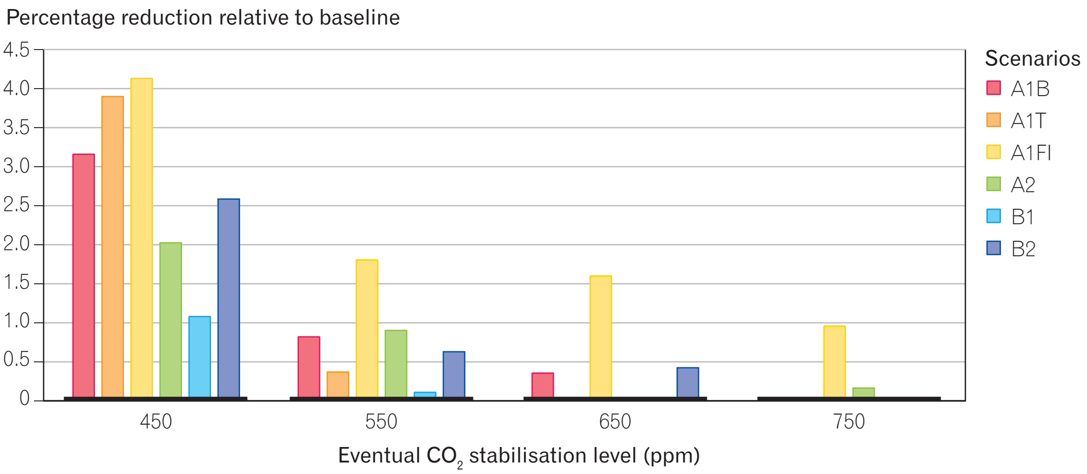
Overall, costs are lower in scenarios involving a gradual transition from the world's present energy system towards a less carbon-intensive economy. This minimises costs associated with premature retirement of existing capital stock and provides time for technology development. On the other hand, more rapid near-term action increases flexibility in moving towards stabilisation, decreases environmental and human risks and the costs associated with projected changes in climate, may stimulate more rapid deployment of existing low-emission technologies, and provides strong near-term incentives to future technological changes.

An alternative way to frame the task is to focus on society's 'willingness to pay' to avoid climate change impacts. Rather than focus on a fixed stabilisation level, this approach focuses on the acceptable cost of mitigation action. While it does not guarantee a particular level of emission cuts in the near term, it does provide a way to manage the inherent uncertainty about future climate change, and may facilitate faster and more widespread action to cut emissions.[317] In addition, as more and better information becomes available, the acceptable cost and associated level of abatement action can be varied in response.

At an economy-wide level, abatement costs are best measured through changes to consumption per capita. However most studies focus on changes to production (particularly GDP) as a rough proxy. In these studies, stabilisation scenarios are compared to a 'business as usual' baseline with continued emissions growth. The difference between the two is considered the cost of abatement. As above, the results should be treated with caution, particularly because they do not include the costs of climate change impacts, and are very sensitive to the choice of baseline scenario and underpinning assumptions. The results also require careful interpretation. GDP reductions relate to future GDP relative to a hypothetical baseline, not reductions in current GDP.

The IPCC TAR review found the average GDP reduction relative to the baseline (across all scenarios and stabilisation levels) would reach a maximum of 1.45 per cent in 2050 and then decline to 1.30 per cent in 2100. The maximum reduction across all scenarios reached 6.1 per cent in a given year, while some scenarios actually showed an increase in GDP compared to the baseline due to apparent positive economic feedbacks of technology development and transfer. The projected reductions in global average GDP for alternative stabilisation targets under different scenarios are set out in Figure O14.

Figure O14 Global average GDP reduction in the year 2050 under different scenarios



Source: IPCC[134] Figure 7.4

The reductions projected are relatively small when compared to absolute GDP levels, which continue to grow over the course of the century. In fact the annual GDP growth rate across all stabilisation scenarios was reduced on average by only 0.003 per cent per year, with the maximum reduction reaching 0.06 per cent per year.

One to two per cent of global GDP is undoubtedly a very substantial cost, and would involve significant dislocation and adjustment for some industry sectors and regions, and noticeable changes in consumer prices for emission-intensive goods and services. However, with annual GDP growth rates of two to three per cent, it means that under the stabilisation scenarios the same final level of global GDP would be attained just a few months later than in the baseline case. The small fall in future GDP needs to be set against the costs of climate change impacts, which increase for higher stabilisation levels and would be highest under the baseline case, which involves no action to reduce emissions.

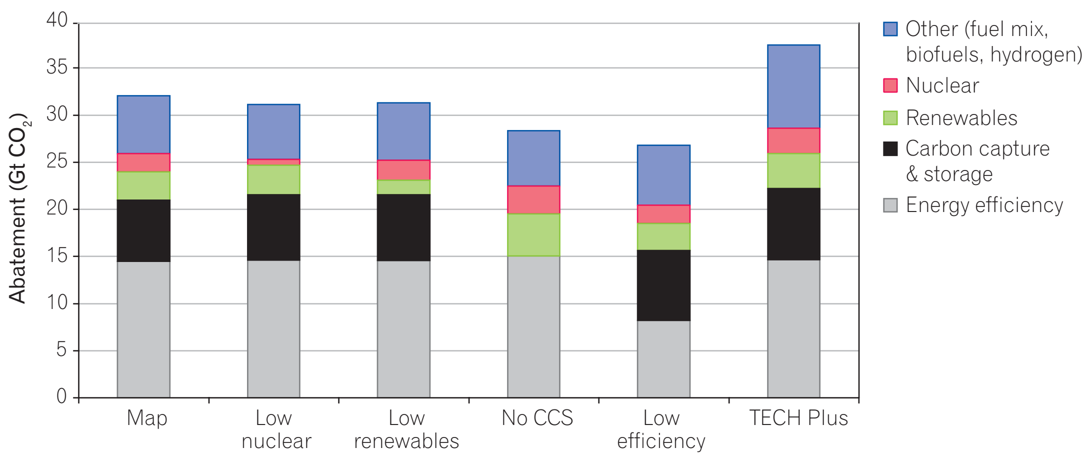
O3.4 Abatement opportunities in the stationary energy sector

Emissions from the energy sector can be reduced through demand and supply side measures: reducing the amount of energy used, and generating energy from lower-emission sources.

Demand side measures deliver dual benefits: reducing energy use (and costs) as well as reducing pressure to build new generation capacity. This can 'buy time', allowing for further technology improvements before new plant is built. Some studies suggest the global electricity industry could cut its greenhouse emissions by over 15 per cent by 2020 and reduce its costs at the same time.[318] However the overall emission benefits depend on how the cost savings are used. If these savings are allocated to other emission-intensive activities, some of the emission gains will be offset.[319] As a result, energy efficiency should not be pursued in isolation but instead accompanied by complementary policies to limit emissions.

Analysis by the IEA indicates that, by employing technologies that already exist or are under development, the world could be brought onto a much more sustainable energy path and energy-related CO_2 emissions could be returned towards their current levels by 2050. The emission reductions achieved under six illustrative scenarios are set out in Figure O15. Each scenario makes different assumptions about the cost and deployment of technologies. The 'Map' scenario makes realistic assumptions in light of current knowledge, and is relatively optimistic in the four key technology areas of energy efficiency, nuclear, renewables and carbon capture and storage (CCS). The 'TECH Plus' scenario makes more optimistic assumptions about the progress of promising new energy technologies.

Figure O15 CO_2 emission reductions from baseline by contributing factor in 2050



Gt CO_2 = billion tonnes of carbon dioxide

Source: IEA.[30] Total baseline emissions in 2050 are 58 Gt CO_2, so the TECH Plus scenario is the only one to reduce emissions below 2003 levels.

The IEA suggests energy efficiency gains are of highest priority, and identifies significant scope for more efficient technologies in transport, industry and buildings. In electricity generation, main gains are likely to come from shifting the technology mix towards nuclear power, renewables, natural gas and coal with CCS.

This work demonstrates the world has the technology and capacity to change, but a huge and coordinated international effort is required to cut emissions. The IEA suggests public and private support will be essential; as will unprecedented cooperation between developed and developing nations, and between industry and government. The IEA further notes the task is urgent, as it must be carried out before a new generation of inefficient and high-carbon energy infrastructure is built.[30]

04 Conclusion

Atmospheric concentrations of greenhouse gases are rising quickly, primarily as a result of human activities such as burning fossil fuels for energy. There is widespread acceptance in the scientific community that this is causing changes to the global climate.

The evidence for a warming Earth is strengthening and the impacts of climate change are becoming observable in some cases.[136] Global average temperatures rose 0.6°C over the past century, and on current trends are projected to rise by a further 1.4 to 5.8°C by the end of this century. Although much uncertainty still surrounds the timing, rate and magnitude of future impacts, the range of predicted outcomes from plausible scenarios include some very serious outcomes for the globe. To reduce the risk of dangerous climate change, actions to cut future emissions are clearly warranted.

A wide range of policies could create incentives to reduce future greenhouse gas emissions. Nuclear power, together with a portfolio of other low emission technologies, provides opportunities to reduce emissions from energy generation. Although low emission energy technologies cannot alone solve the problem of climate change, they are an essential component of a sensible and effective climate risk management strategy.

Appendix P. Non-proliferation

P1.1 Tracking Australian uranium

The objective of Australia's bilateral agreements is to ensure that Australian Obligated Nuclear Material (AONM) does not materially contribute to, or enhance, any military purpose. All Australian uranium exported since 1977 can be accounted for, whether it has been converted, enriched, used in power supply, is in spent fuel rods or ready for disposal. Australia does not allow its uranium (and its derivatives) to be used in the development of nuclear weapons or for other military uses. This is ensured by precisely accounting for AONM as it moves through the nuclear fuel cycle. The Australian Safeguards and Non-Proliferation Office (ASNO), along with the International Atomic Energy Agency (IAEA) administer these controls. ASNO receives notifications and reports on the disposition of AONM, which are cross-checked with other sources, including information from the IAEA. There have been no unreconciled differences in accounting for AONM.[25]

Australian uranium is currently exported as uranium oxide (U_3O_8), which is then converted, enriched and fabricated into fuel before it can be used in reactors. Due to the structure of the international nuclear fuel market, it is not unusual for each of these activities to be undertaken in a different country. Due to the impossibility of physically identifying 'Australian atoms', an equivalence principle is used: when AONM loses its separate identity because of mixing with uranium from other sources, an equivalent quantity is designated as AONM. AONM is safeguarded throughout the fuel cycle, including storage and disposal, unless safeguards are terminated because the material no longer presents a proliferation risk.

Table P1 Australia's bilateral safeguards agreements

Country	Entry into force
South Korea	2 May 1979
United Kingdom	24 July 1979
Finland	9 February 1980
United States	16 January 1981
Canada	9 March 1981
Sweden	22 May 1981
France	12 September 1981
Euratom	15 January 1982
Philippines	11 May 1982
Japan	17 August 1982
Switzerland	27 July 1988
Egypt	2 June 1989
Russia	24 December 1990
Mexico	17 July 1992
New Zealand	1 May 2000
United States (covering cooperation on Silex technology)	24 May 2000
Czech Republic	17 May 2000
United States (covering supply to Taiwan)	17 May 2000
Hungary	15 June 2002
Argentina	12 January 2005

The Euratom agreement covers all 25 member states of the European Union. In addition, two agreements with China were signed on 3 April 2006. These have not entered into force. Australia also has an agreement with Singapore concerning cooperation on physical protection of nuclear materials, which entered into force on 15 December 1989.[174]

P1.2 Reactor types and proliferation

IAEA safeguarded nuclear power plants are inspected to verify their peaceful use. Deliberate misuse of a civil power reactor would be readily identifiable to IAEA inspectors. Because all reactors (except thorium-fuelled reactors) produce plutonium, theoretically any reactor could be used as part of a nuclear weapon program. In practice, different reactor types represent different proliferation risks. There are two routes for obtaining plutonium — from spent fuel discharged from the reactor, and from uranium targets introduced into the reactor for irradiation. The proliferation potential of various reactor types is briefly outlined in table P2.

In addition to a suitable reactor, a reprocessing plant or plutonium extraction plant would be required for separating plutonium from the spent fuel or irradiation targets. This would not necessarily require a large-scale facility.

‘Weapons grade’ plutonium is defined as containing no more than 7 per cent Pu-240, ie it will be around 93 per cent Pu-239. This is also described as ‘low burnup’ plutonium. By contrast, ‘reactor grade’ plutonium from the typical operation of a power reactor is defined as containing 19 per cent or more Pu-240 — and the Pu-240 content is usually around 25 per cent. This is described as ‘high burnup’ plutonium. The higher plutonium isotopes (especially Pu-240 and Pu-242) are not suitable for nuclear weapons because they have high rates of spontaneous fission, compared with Pu-239, and this will lead to premature initiation of a nuclear chain reaction in super-critical conditions.

Table P2 Reactor types and proliferation risk

Reactor type	Proliferation risk	Comments
Research reactor	low-high, depending on power	Research reactors can be ideal plutonium producers, because they are designed for easy insertion/removal of irradiation targets. However, proliferation potential depends on power level (which determines the rate of plutonium production). The safeguards rule-of-thumb is that reactors above 25 MW thermal can produce 1 Significant Quantity (8 kg) of plutonium in a year. Reactors below 25 MW are of less concern. The ANSTO OPAL reactor in Sydney can operate at up to 20 MW.
LWR (light water reactor)	low	LWRs are shut down and refuelled every 12–18 months (when typically 1/3 of the fuel is replaced). LWRs operate at high pressure and temperature, so removal of fuel is not possible between shutdowns. A typical fuel cycle is 3–4 years, ie each fuel element remains in the reactor for 3 operating periods. At the end of this time the burnup level is high. The most attractive fuel for diversion is the initial start-up core, where 1/3 will be discharged after only 12 months. The Pu-240 level of this fuel will be relatively low, though above the weapons grade range.
OLR (on-load refuelling reactor) eg CANDU, Magnox and RBMK	high	OLRs are refuelled during operation. Obtaining low burnup (and hence plutonium) is a simple matter of refuelling at a faster rate. Hence these reactors can be a significant proliferation risk, and are given very close safeguards attention.

Reactor type	Proliferation risk	Comments
PBMR (pebble bed modular reactor)	low	These are a type of OLR — fuel spheres are continuously inserted and removed from the core. However, reprocessing to extract plutonium would be difficult because of the numbers of spheres involved (100 000s) and because the spheres are made of a graphite matrix which cannot be dissolved (the spheres would have to be crushed first).
FBR (fast breeder reactor)	high	These comprise a core and an outer blanket of uranium in which plutonium is produced. The blanket has relatively low neutron activity, hence plutonium with very high Pu-239 abundance (weapons grade) is produced.
FNR (fast neutron reactor)	low	The FNR designs being considered now do not have a blanket, all Pu production occurs in the core where the burnup levels are always high.
Thorium reactor	low	These produce U-233 rather than Pu. Theoretically nuclear weapons could be produced from U-233 but there are practical limitations (radiation levels, heat).

Source: ASNO

P1.3 Incidents involving nuclear material

There has been no significant terrorist incident involving nuclear material or weapons to date. There have been no reports of the theft of significant quantities[114] of nuclear material from the 900 known nuclear installations worldwide, nor acts of sabotage leading to the release of significant quantities of radioactive material.[174]

The IAEA maintains an international database of illicit trafficking in nuclear and radioactive materials since 1993. Of the 827 confirmed incidents, 224 incidents involved nuclear materials (see Table P3), 516 incidents involved other radioactive materials (mainly radioactive sources).[320]

The only incident that may have involved enough nuclear material to make a nuclear bomb reportedly took place in 1998 in Chelyabinsk Oblast in Russia and involved 18.5 kg of radioactive material. Although the US Central Intelligence Agency (CIA) has twice reported an incident in Chelyabinsk, the National Intelligence Council (NIC)'s 2004 Annual Report to Congress on the Safety and Security of Russian Nuclear Facilities and Military stated that the Russian security services had prevented the theft, so the material never actually left the grounds. It also remains unclear whether the material in question was weapons-grade plutonium.[321]

114 One significant quantity of nuclear material is the amount for which manufacture of a nuclear device cannot be excluded. The IAEA defines this as 8 kg of plutonium or 25 kg of U-235 in HEU.[178]

Table P3 IAEA confirmed incidents involving HEU or plutonium, 1993–2004[320]

Year	Location	Material involved	Incident
1993	Lithuania	HEU/150 g	4.4 t of beryllium including 140 kg contaminated with HEU was discovered in the storage area of a bank.
1994	Russian Federation	HEU/ 2.972 kg	An individual was arrested in possession of HEU, which he had previously stolen from a nuclear facility. The material was intended for illegal sale.
1994	Germany	Pu/ 6.2 g	Plutonium was detected in a building during a police search.
1994	Germany	HEU/ 0.795 g	A group of individuals was arrested in illegal possession of HEU.
1994	Germany	Pu/ 0.24 g	A small sample of PuO_2–UO_2 mixture was confiscated in an incident related to a larger seizure at Munich Airport
1994	Germany	Pu/ 363.4 g	PuO_2–UO_2 mixture was seized at Munich airport.
1994	Czech Republic	HEU/ 2.73 kg	HEU was seized by police in Prague. The material was intended for illegal sale.
1995	Russian Federation	HEU/ 1.7 kg	An individual was arrested in possession of HEU, which he had previously stolen from a nuclear facility. The material was intended for illegal sale.
1995	Czech Republic	HEU/ 0.415 g	An HEU sample was seized by police in Prague.
1995	Czech Republic	HEU/ 16.9 g	An HEU sample was seized by police in Ceske Budejovice.
1999	Bulgaria	HEU/ 10 g	Customs officials arrested a man trying to smuggle HEU at the Rousse customs border check point.
2000	Germany	Pu/ 0.001 g	Mixed radioactive materials including a minute quantity of plutonium were stolen from the former pilot reprocessing plant.
2001	France	HEU/ 0.5 g	Three individuals trafficking in HEU were arrested in Paris. The perpetrators were seeking buyers for the material.
2003	Georgia	HEU/ ~170 g	An individual was arrested in possession of HEU attempting to illegally transport the material across the border.
2005	USA	HEU/ 3.3 g	A package containing 3.3 g of HEU was reported lost in New Jersey.
2005	Japan	HEU/ 0.017 g	A neutron flux detector was reported lost at a nuclear power plant.

P1.4 Global Nuclear Energy Partnership

In February 2006, US President Bush proposed the Global Nuclear Energy Partnership (GNEP). GNEP aims to strengthen the global non-proliferation regime by establishing a framework for expanded use of nuclear energy while limiting the further spread of enrichment and reprocessing capabilities. GNEP envisages whole-of-life fuel leasing, where fuel supplier nations that hold enrichment and reprocessing capabilities would provide enriched uranium to conventional nuclear power plants located in user nations. Used fuel would be returned to a fuel cycle nation and recycled using a process that does not result in separated plutonium, therefore minimising the proliferation risk.

GNEP fuel supplier nations would operate fast neutron reactors and advanced spent fuel separation, in order to recycle plutonium and to transmute longer-lived radioactive materials. Reprocessing technology is proliferation sensitive because it is required to make a plutonium nuclear weapon. Current PUREX reprocessing techniques result in separated plutonium. With the advanced spent fuel separation techniques envisaged by GNEP, plutonium would not be fully separated, but remain mixed with uranium and highly radioactive materials. GNEP would reduce holdings of plutonium-bearing spent fuel and enable the use of plutonium fuels without production of separated plutonium. If the longer-lived materials are transmuted this would reduce the period most HLW has to be isolated from the environment from 10 000 years to 300–500 years. Reprocessing also reduces the volume of HLW that results from a once through cycle and potentially increases the lifetime of uranium reserves. The US hopes to develop the more proliferation-resistant pyro-processing.

Under GNEP, ‘fuel supplier nations’ would undertake to supply ‘user nations’ with reactors, and to supply nuclear fuel on a whole-of-life basis. This would include spent fuel take-back — users could return spent fuel to a fuel supplier, who would recycle the fuel and treat the eventual high level waste.

User nations would be given assurances of supply for power reactors and fuel. GNEP envisages that users will operate conventional light water reactors, obtain low enriched uranium fuel from a supplier nation, and return the spent fuel to a supplier nation (not necessarily the original supplier). This provides user nations an incentive not to develop national enrichment or reprocessing capabilities.[166,174]

GNEP is a long-term proposal, which has only recently been launched, so it can be expected to evolve considerably over time. Some of the GNEP technologies are already well established, others require major development. A timeframe for the introduction of new technologies as envisaged under GNEP may be around 20–25 years.

P1.5 A.Q. Khan

The seizure in October 2003 of the German-owned cargo vessel BBC China, which was carrying container loads of centrifuge parts (used to enrich uranium) bound for Libya, led to the exposure of the extensive nuclear black market network operated by Pakistani engineer Dr Abdul Qadeer Khan. Libya renounced its WMD program shortly after the seizure of the BBC China. Libya’s subsequent admissions concerning its procurement activities provided clear cut evidence against Khan and his network.[179,188]

Khan — a key figure in Pakistan’s nuclear program — used the access he obtained from his senior position in Pakistan’s nuclear program to build a global proliferation network which traded for profit in nuclear technologies and knowledge with states of proliferation concern. The Khan network exploited weak enforcement of export controls in several countries and revealed the increasingly devious and sophisticated methods being used by proliferators.[169]

Khan’s network is believed to have sourced nuclear components from up to 30 companies in 12 countries, including in Europe and Southeast Asia.

Table P4 Activities of A. Q. Khan

Year	Activities
1967	• Khan receives a degree in metallurgical engineering in 1967 from the Technical University in Delft, Holland.
1972	• Khan receives Ph.D. in metallurgical engineering from the Catholic University of Leuven in Belgium. • Khan begins work at FDO, a subcontractor to Ultra Centrifuge Nederland (UCN), the Dutch partner in the Urenco uranium enrichment consortium. • Khan visits the advanced UCN enrichment facility in Almelo, Netherlands to become familiar with Urenco centrifuge technology.
1974	• 18 May: India conducts its first nuclear test, a 'peaceful nuclear explosion.' • September: Khan writes to Prime Minister Zulfikar Ali Bhutto to offer his services and expertise to Pakistan. • Khan is tasked by UCN at Almelo with translations of the more advanced German-designed G-1 and G-2 centrifuges from German to Dutch, to which he has unsupervised access for 16 days.
1975	• August: Pakistan begins buying components for its domestic uranium enrichment program from Urenco suppliers, including from companies in the Netherlands that Khan is familiar with. • October: Khan is transferred away from enrichment work with FDO as Dutch authorities become concerned over his activities. • 15 December: Khan suddenly leaves FDO for Pakistan with copied blueprints for centrifuges and other components and contact information for nearly 100 companies that supply centrifuge components and materials.
1976	• Khan begins centrifuge work with the Pakistan Atomic Energy Commission (PAEC) • July: Prime Minister Bhutto gives Khan autonomous control over Pakistani uranium enrichment programs.
1978	• Khan develops working prototypes of P-1 centrifuges, adapted from the German G-1 design Khan worked with at Urenco. Pakistan enriches uranium for the first time on April 4 at Khan's enrichment facility at Kahuta.
1980s	• Khan acquires blueprints for the bomb that was tested in China's fourth nuclear explosion in 1966.
1983	• Khan is convicted, in absentia, in Dutch court for conducting nuclear espionage and sentenced to four years in prison.
1985	• Khan's conviction is overturned based on an appeal that he had not received a proper summons. The Dutch prosecution does not renew charges because of the impossibility of serving Khan a summons given the inability to obtain any of the documents that Khan had taken to Pakistan.
Mid 1980s	• Pakistan produces enough HEU for a nuclear weapon. The A.Q. Khan Research Laboratories (KRL) continue work on enrichment and is tasked with research and development of missile delivery systems. • Khan reportedly begins to develop his export network and orders twice the number of components necessary for the indigenous Pakistani program.
1986–1987	• Khan is suspected of visiting the Iranian reactor at Bushehr in February 1986 and again in January 1987.
1980s	• Khan and his network of international suppliers are reported to begin nuclear transfers to Iran.

Year	Activities
1987	• Khan is suspected of having made an offer to Iran to provide a package of nuclear technologies. • Khan is believed to make a centrifuge deal with Iran to help build a cascade of 50 000 P-1 centrifuges. • KRL begins to publish publicly available technical papers that outline some of the more advanced design features of centrifuge design and operation.
1988	• Iranian scientists are suspected of receiving nuclear training in Pakistan.
1989	• From 1989 to 1995, Khan is reported to have shipped over 2000 components and sub-assemblies for P-1, and later P-2, centrifuges to Iran.
1992	• Pakistan begins missile cooperation with North Korea. Within Pakistan, KRL is one of the laboratories responsible for missile research and will develop the Ghauri missile with North Korean assistance.
Mid 1990s	• Khan starts travel to North Korea where he receives technical assistance for the development of the Ghauri missile. Khan makes at least 13 visits before his public confession in 2004 and is suspected of arranging a barter deal to exchange nuclear and missile technologies. • Khan is suspected to have met with a top Syrian official in Beirut to offer assistance with a centrifuge enrichment facility.
1997	• Khan begins to transfer centrifuges and centrifuge components to Libya. Libya receives 20 assembled P-1 centrifuges and components for 200 additional units for a pilot enrichment facility. Khan's network will continue to supply with centrifuge components until late 2003. • Khan is suspected of beginning nuclear transfers to North Korea around this time.
1998	• India detonates a total of five devices in nuclear tests on May 11 and 13. • Pakistan responds with six nuclear tests on May 28 and 30.
2000	• Libya receives two P-2 centrifuges as demonstrator models and places an order for components for 10 000 more to build a cascade. Each centrifuge contains around 100 parts, implying approximately 1 million parts total for the entire P-2 centrifuge cascade.
2001	• Khan is forced into retirement. President Musharraf admits that Khan's suspected proliferation activity was a critical factor in his removal from KRL.
2001–2002	• Libya receives blueprints for nuclear weapons plans. The plans are reported to be of Chinese origin.
2002	• From December: Four shipments of aluminium centrifuge components are believed to have been sent from Malaysia to Dubai before August 2003, en route to Libya.
2003	• October: The German cargo ship BBC China is intercepted en route to Libya with components for 1000 centrifuges. • December: Libya renounces its nuclear weapons program and begins the process of full disclosure to the IAEA, including the declaration of all foreign procurements.
2004	• 4 February: Khan makes a public confession on Pakistani television (in English) of his illegal nuclear dealings. Khan claims that he initiated the transfers and cites an 'error of judgment.' He is pardoned soon after by President Musharraf and has been under house arrest since. The Pakistani government claims that Khan acted independently and without state knowledge.

Source: Carnegie Endowment, drawing on a range of publications.[188]

The Proliferation Security Initiative (PSI)

The PSI was announced by the United States in May 2003 as a practical measure for closing gaps in multilateral non-proliferation regimes. The initiative operates as an informal arrangement between countries sharing non-proliferation goals to cooperate to disrupt weapons of mass destruction (WMD)-related trade, including nuclear technologies and material. PSI countries operate within national and international law to combat WMD proliferation and to work together to strengthen these laws. Australia has been one of the principal drivers of the PSI since its launch in 2003. The PSI is already supported by 80 countries.[169]

The PSI specifically responds to the need to capture WMD-related transfers between states of proliferation concern, or to non-state actors, that breach international non-proliferation norms or are beyond the reach of the export control regimes. In October 2003, Italy, Germany and the United States worked together to stop the German-owned vessel BBC China from delivering a cargo of centrifuge parts for uranium enrichment destined for Libya's nuclear weapons program. Soon after, the Libyan Government renounced its WMD programs.[169]

P1.6 Security at nuclear facilities

The nuclear materials at the 'front end' of the fuel cycle — natural, depleted and low enriched uranium — present minimal risk to public health and safety when properly managed. As a direct consequence of their inherent low levels of radioactivity, these materials are of low concern as sabotage targets and are not suited to the manufacture of 'dirty bombs'. Uranium hexafluoride (UF_6) is a solid material at normal ambient temperatures, and becomes gaseous above 60°C, so is not readily dispersed to the environment. The overall risk to the public from any release of fluorine or UF_6 would be very low compared with other widely established industrial processes which typically involve much larger quantities of hazardous chemicals. Uranium mining and milling, conversion, enrichment and fuel fabrication, and the transport of these materials, do not present a significant risk to the public even if subjected to sabotage.

Spent fuel poses a greater potential risk than materials at the 'front end' of the fuel cycle, because it contains highly radioactive fission products — although these dangerously high levels of radioactivity make it self-protecting against theft. Spent fuel is present in reactor cores, reactor storage ponds, away-from-reactor storage facilities, and at reprocessing plants. Associated with these activities is the transport of spent fuel from reactors to storage or reprocessing facilities, and the transport of radioactive wastes. Consequently, reactors and reprocessing plants, and associated activities, are the subject of special attention from the physical protection perspective.[174]

Uranium enrichment

As with uranium conversion, there are no particular security concerns with regard to a uranium enrichment plant. Indeed, potential risks would be less than with conversion because smaller stocks of UF_6 are likely to be on hand at any one time. There is no significant radiation risk for facilities producing low enriched uranium because the radiation level of enriched uranium is only slightly higher than natural uranium. The principal risk comes from the presence of fluorine, a corrosive chemical, in UF_6. The risk of release of fluorine as UF_6 mainly relates to UF_6 in autoclaves at feeding and withdrawal stations — for an enrichment plant large enough to enrich all of Australia's current uranium production, the quantity of UF_6 in autoclaves at any one time could be of the order of 100–200 tonnes. The quantities of UF_6 in gaseous form undergoing enrichment at any time would be very small, only a couple of tonnes.[174]

As with conversion, the overall risk to the public from any release of UF_6 from an enrichment plant would be very low compared with other widely established industrial processes which can involve much larger quantities of hazardous chemicals.

Nuclear power plants

A typical nuclear power plant is protected by its structure and by guards and access controls. Modern plants are covered by a reinforced concrete containment building, which has the primary function of retaining any radioactive contamination released in the event of a reactor accident, but which also provides effective protection against attack.

The key for security at a nuclear reactor is robustness and defence in depth. The scenario with the greatest consequences is the possibility of an attack causing a loss of coolant and subsequent reactor core melt-down, with possible release of radiation to the outside environment. The reactor safety systems are designed to minimise the risk of melt-down and to avoid or contain any radiation release. Defence in depth requires that the safety of the plant does not rely on any one feature. The reactor vessel is robust, the reactor is contained within an inner reinforced concrete and steel biological shield, and this structure and the primary cooling circuit, as well as the emergency core cooling system, are located within a massive reinforced concrete containment structure.

Reactor cores are protected by thick concrete shields, so breaching the reactor containment and shielding would require a violent impact or explosion. Indirectly, a release might occur if enough critical safety systems were damaged, but because of defence in depth, this would require a high degree of access, co-ordination and detailed plant knowledge. The main risk of terrorist attack might be to generating units, electrical switchyards and ancillary equipment, which are outside the reactor containment area — in this respect a reactor would be no more a risk than any other large-scale power station, and would be far better protected than a non-nuclear power station, or any other large industrial activity.[174]

Aircraft attack

In 1988, the United States conducted an experiment propelling a 27-tonne twin-engine jet fighter into a reinforced concrete structure at 765 km/h. This experiment, confirmed by other studies, showed that the greatest risk of penetration is from a direct impact by a jet engine shaft — but the maximum penetration of the concrete was 60 mm. Reactor containment structures are typically more than 1 metre thick. Most of the aircraft's kinetic energy goes into the disintegration of the aircraft.[174, 199]

A study by the US based Electric Power Research Institute (EPRI)[199] using computer analyses of models representative of US nuclear power plant containment types found that robust containment structures were not breached by commercial aircraft, although there was some crushing and spalling (chipping of material at the impact point) of the concrete. The wing span of the Boeing 767–400 (170 feet) — the aircraft used in the analyses — is slightly longer than the diameter of a typical containment building (140 feet). The aircraft engines are physically separated by approximately 50 feet. This makes it impossible for both an engine and the fuselage to strike the centreline of the containment building.

Two analyses were performed. One analysis evaluated the 'local' impact of an engine on the structure. The second analysis evaluated the 'global' impact from the entire mass of the aircraft on the structure. Even under conservative assumptions with maximum potential impact force, the analyses indicated that no parts of the engine, the fuselage or the wings — nor the jet fuel — entered the containment buildings. Similar conclusions were made about an attack on spent fuel storage at power plants.[199]

Direct attack

Power plant reactor structures are similarly resistant to rocket, truck bomb or boat attack. Further, if terrorists attempted to take over a reactor, they would have to overcome the guard force. Even if they succeeded, it is unlikely that the actions they might take would result in significant radiation release to the outside environment.[174]

An EPRI study[128] into a direct attack on a nuclear power plant found that the risks to the public from terrorist-induced radioactive release are small. The probabilities of terrorist scenarios leading to core damage at a given plant were seen to be low. This was attributable to several factors:

- low likelihood of a threat to a specific plant
- high likelihood that the threat will be thwarted before an attack can be launched that could be successful in taking over the plant
- low likelihood that a successful attack could ultimately lead to core damage and release.

The study found that given an attack, the likelihood of core damage (such as the 1979 Three Mile Island Event) is unlikely because of nuclear plant capabilities to detect insider activities, physically deter the attackers, and prevent the spread of an accident with operator actions and safety systems. The likelihood of severe release is even less because of the inherent strength of containment and radioactivity removal capabilities of containment and systems design. Even if a core damage accident occurred from terrorist attack, the consequences to the public are not likely to be severe. This was attributed to the following factors:

- even for extreme types of scenarios, the containment is able to remove a significant fraction of the radioactive release before it escapes to the environment
- core damage tends to occur over several hours or a longer period, thus allowing time for emergency response measures to be taken.

Reprocessing

Reprocessing plants have inventories of highly radioactive materials — the fission products — which are conditioned for disposal, using vitrification. Countries with reprocessing plants have conducted studies of the possible vulnerabilities of these plants to terrorist attack, including by aircraft. These facilities are typically of massive concrete construction which would be resistant to attack.
For particular plants, additional protective measures have been taken, including structural upgrades, air exclusion zones, and installation of anti-aircraft missiles.[174]

Spent fuel and/or high level waste repository

Used reactor fuel is mainly stored in cooling ponds under several metres of water. Storage takes place both at reactor sites and reprocessing plants. The main mechanism by which large releases of radioactive material could occur is by loss of cooling water. This might result in overheating and damage to fuel elements, releasing radioactive material into the atmosphere.[202] The spent fuel cooling ponds at conventional Western power reactors (PWR and BWR) are sited inside the containment structure. Therefore, as with the reactor itself, spent fuel in these ponds is well protected from attack.

Transport

Over the past 35 years there have been more than 20 000 transfers of spent fuel and high level waste (HLW) worldwide, by sea, road, rail and air, with no significant security or safety incident. Principles for physical protection are well established — structurally rugged containers are used, and transfers are appropriately guarded. Experiments have demonstrated that spent fuel and HLW containers are difficult to penetrate, even using sophisticated explosives, and the risk of dispersal of radioactive contamination is limited.[174]

The EPRI study into aircraft attack found that due to the extremely small relative size of a fuel transport container compared to the Boeing 767–400, it is impossible for the entire mass of the aircraft to strike the container. Its evaluation of the worst case of a direct impact of an engine on the representative fuel transport cask showed the container body withstands the impact from the direct engine strike without breaching.[199]

Concern has been expressed that an attack on a road or rail shipment of radioactive material might be easier to accomplish than at a fixed installation, and could take place near major population centres. However, the amounts of material involved are smaller and transportation containers are robust.[202]

Appendix Q. Australia's nuclear-related international commitments

Q1 Australia's international law commitments

Australia is a party to several international legal instruments relevant to its current nuclear activities. It is implementing all current international obligations through domestic law and administrative arrangements. If Australia were to expand its nuclear fuel cycle activities it would need to continue to comply with existing international law obligations, as well as consider committing to other relevant international legal instruments.

Q1.1 Safeguards

Under Article III.1 of the NPT, Australia has undertaken to accept IAEA safeguards on all source or special fissionable material in all peaceful nuclear activities within its territory. These safeguards are set out in the Agreement between Australia and the International Atomic Energy Agency for the Application of Safeguards in connection with the NPT, ratified by Australia in 1973. Further commitments forming part of the IAEA's strengthened safeguards system are set out in the Additional Protocol to Australia's IAEA safeguards agreement. Australia ratified the Additional Protocol in 1997.

Australia has also concluded a number of bilateral agreements on peaceful nuclear cooperation with other countries to facilitate the transfer of nuclear material and technology, and to provide a framework for cooperation in relation to the peaceful use of nuclear energy.

The Commonwealth *Safeguards Act 1987* establishes the Australian Safeguards and Non-proliferation Office (ASNO) as the national authority responsible for safeguards and the physical protection of nuclear material. ASNO regulates all persons or organisations in Australia that have nuclear-related materials, items or technology. At present, this principally applies to ANSTO as Australia's only nuclear reactor operator, but also covers a diverse range of other entities including uranium mines, associated transport and storage operations, private sector laboratories, educational institutions and patent attorneys. Persons using depleted uranium for various purposes are also subject to ASNO permits.

ASNO's responsibilities covering nuclear materials (thorium, uranium and plutonium) include:

- the physical protection and security of nuclear items in Australia
- the application of nuclear safeguards in Australia (ensuring that nuclear materials and nuclear items in Australia such as facilities, equipment, technology and nuclear-related materials are appropriately regulated, protected and accounted for and do not contribute to proliferation or nuclear weapons programs)
- the operation of Australia's bilateral safeguards agreements
- contribution to the operation and development of IAEA safeguards and the strengthening of the international nuclear non-proliferation regime, as well as ensuring that Australia's international nuclear obligations are met.

Q1.2 Export controls

Under Article III.2 of the NPT, Australia has undertaken:

'…not to provide:

(a) source or special fissionable material, or

(b) equipment or material especially designed or prepared for the processing, use or production of special fissionable material, to any non-nuclear-weapon State for peaceful purposes, unless the source or special fissionable material shall be subject to the safeguards required by this Article.'

While the NPT establishes a general commitment, the Zangger Committee was established to implement Article III.2 to prevent the diversion of exported nuclear items from peaceful purposes to nuclear weapons or other nuclear explosive devices,[115] and the Nuclear Suppliers Group (NSG) has established Guidelines for nuclear exports.[116]

115 http://www.zanggercommittee.org/Zangger/Misssion/default.htm

116 http://www.nuclearsuppliersgroup.org/

Both bodies establish mechanisms to ensure harmonised national level controls over nuclear material, equipment and technology and nuclear dual-use items and technology.

Q1.3 Physical protection of nuclear material

The international community has established standards for the physical protection of nuclear material and nuclear facilities. All of Australia's bilateral safeguards agreements include a requirement that internationally agreed standards of physical security will be applied to nuclear material in the country concerned.

As well as being a party to the Convention on the Physical Protection of Nuclear Material (CPPNM), Australia is also a signatory to the International Convention for the Suppression of Acts of Nuclear Terrorism (Nuclear Terrorism Convention), and is working towards ratification. The Nuclear Terrorism Convention is aimed at strengthening the international legal framework to combat terrorism.

Q1.4 Nuclear power plant safety

Australia became a party to the Convention on Nuclear Safety (CNS) in March 1997. While Australia has no nuclear installations as defined, Australia became a party to the CNS in order to support a strengthened global nuclear safety norm and the establishment of fundamental safety principles for nuclear installations.

Q1.5 Management of spent fuel and radioactive waste

The 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management entered into force generally in June 2001. Australia became a party in 2003. The Joint Convention establishes an international legal framework for the harmonisation of national waste management practices and standards, together with a periodic peer review process similar to that under the Convention on Nuclear Safety. The Convention promotes the safe and environmentally sound management of spent fuel and radioactive waste, covering matters such as the storage, transboundary movement, treatment and disposal of these materials. The Australian National Report submitted under the Joint Convention is made on behalf of the nine jurisdictions (Commonwealth, states and territories).

ARPANSA prepares Australia's National Report under the Convention. Under section 15 of the *ARPANS Act*, the CEO of ARPANSA is responsible for promoting uniformity of radiation protection and nuclear safety policy and practices across jurisdictions.

Q1.6 Transport of radioactive material

Australia became a party to the United Nations Convention on the Law of the Sea (UNCLOS) in 1994. The Convention includes some specific rules governing the transport of radioactive material. Provided that these rules and the general UNCLOS provisions are complied with, countries are entitled to transport radioactive material under the general principles of freedom of navigation.

The 2001 Waigani Convention (Convention to Ban the Importation into Forum Island Countries of Hazardous and Radioactive Wastes and to Control the Transboundary Movement and Management of Hazardous Wastes within the South Pacific Region) prohibits the importation of all radioactive wastes into Pacific Island Developing Parties. Australia is a party to the Waigani Convention.

Australia is also a party to various transport mode-specific international instruments, which give force to the IAEA Regulations for the Safe Transport of Radioactive Material (the IAEA Transport Regulations). The IAEA Transport Regulations reflect international best practice and are incorporated into Australian domestic legislation governing the transport of radioactive material.

The International Maritime Dangerous Goods Code implements the provisions of the IAEA Transport Regulations relating to maritime safety. The Code is incorporated into the text of the International Convention for the Safety of Life at Sea (the SOLAS Convention). Australia became a party to the 1974 SOLAS Convention in 1983. The International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code) has also been made mandatory through its incorporation into the SOLAS Convention.

Australia is a party to the Convention on International Civil Aviation (Chicago Convention). A Technical Annex to the Chicago Convention gives legal force to the IAEA Transport Regulations for the air transport of radioactive material.

Q1.7 Emergency preparedness/response

The Convention on Nuclear Safety imposes certain obligations with regard to emergency planning. As a party to the Convention, Australia is obliged to take appropriate steps to ensure that it has in place on-site and off-site emergency plans that cover the actions to be taken in the event of an emergency. The plans need to be tested before any nuclear installation goes into operation and subsequently be subjected to tests on a routine basis.

The Convention on the Early Notification of a Nuclear Accident (the Early Notification Convention) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the Assistance Convention) cover situations in which an accident involving activities or facilities in one country have resulted or may result in a transboundary release that could be of radiological safety significance for other countries. These Conventions were negotiated following the 1986 Chernobyl accident. Australia is a party to both conventions.

The Early Notification Convention requires countries, in the event of an accident at a nuclear reactor, nuclear fuel cycle facility, or radioactive waste management facility, to notify those States which may be physically affected by the accident. Parties are obliged to provide exact information in order to facilitate the organisation of response measures.

The Assistance Convention is a framework agreement designed to establish a general basis for mutual assistance in the event of a nuclear accident or radiological emergency. Under the Convention, members are required to cooperate between themselves and with the IAEA to facilitate prompt assistance in the event of a nuclear accident or radiological emergency to minimise its consequences and to protect life, property, and the environment from the effects of radiological releases.

Q2 Impact of expanded domestic nuclear activity on arrangements for implementing international obligations

Any expansion of Australia's nuclear activities would need to take into account relevant international instruments regarding nuclear activities. It is possible that new obligations would come into effect under existing international commitments, if Australia were to expand its involvement in nuclear activities. For example, if Australia were to develop nuclear installations as defined by the Convention on Nuclear Safety it would be necessary to ensure any obligations are given effect in domestic law.

As well as making its own laws in relation to nuclear liability, Australia would also have to consider whether it should become a party to the international nuclear liability regime. It could do so by joining either the Vienna Convention on Civil Liability for Nuclear Damage or the Paris Convention on Third Party Liability for Nuclear Damage, and possibly also the Convention on Supplementary Compensation for Nuclear Damage, which provides a bridge between the Vienna and Paris Conventions. The international nuclear liability regime has the objective of providing protection for the victims of nuclear accidents. As mentioned in Appendix J, nuclear power utilities covered by this liability regime generally pay commercial insurance premiums.

Depending on the source country, it may also be necessary to negotiate new bilateral safeguards agreements, or amend existing agreements to enable the importation of equipment and technology for the expansion of Australia's nuclear industry.

Q3 Multilateral legal instruments

The safe and peaceful use of nuclear energy is regulated by a framework of multilateral legal instruments, including the following:

Table Q1 Nuclear-related Multilateral Legal Instruments to which Australia is a Party

Convention on Civil Aviation (Chicago Convention) 1957
International Convention for the Safety of Life at Sea (SOLAS Convention) 1960
Treaty on the Non-Proliferation of Nuclear Weapons (NPT) 1973
Agreement between Australia and the International Atomic Energy Agency for the Application of Safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons 1974
United Nations Convention on the Law of the Sea (UNCLOS) 1982
South Pacific Nuclear Free Zone Treaty 1986
Convention on the Physical Protection of Nuclear Material 1987
Convention on Early Notification of a Nuclear Accident 1987
Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency 1987
Convention for the Protection of the Natural Resources and Environment of the South Pacific Region (the SPREP Convention) 1990
Convention for the Suppression of Unlawful Acts Against the Safety of Maritime Navigation 1993
Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter (the London Convention) as amended by its 1996 Protocol
Protocol with the International Atomic Energy Agency (IAEA) Additional to the Agreement between Australia and the International Atomic Energy Agency for the Application of Safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons 1997
Convention on Nuclear Safety 1997
Convention to Ban the Importation into Forum Island Countries of Hazardous and Radioactive Wastes and to Control the Transboundary Movement and Management of Hazardous Wastes within the South Pacific Region (Waigani Convention) 2001
Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management 2003

Table Q2 Nuclear-related Multilateral Legal Instruments to which Australia is not a Party

The 1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy
The 1963 Vienna Convention on Civil Liability for Nuclear Damage
The 1988 Joint Protocol relating to the Application of the Vienna Convention and the Paris Convention
The 1997 Protocol to the Vienna Convention on Civil Liability for Nuclear Damage
The 1997 Convention on Supplementary Compensation for Nuclear Damage (signed by Australia on 1 October 1997 but not ratified)
The 2004 Protocol to the Paris Convention on Third Party Liability in the Field of Nuclear Energy
The 2005 Amendment to the Convention on the Physical Protection of Nuclear Material (signed by Australia on 8 July 2005, Australia is taking steps to ratify)
International Convention for the Suppression of Nuclear Terrorism — [2005] ATNIF 20 (signed by Australia on 14 September 2005, Australia is taking steps to ratify)
Protocol of 2005 to the Convention for the Suppression of Unlawful Acts against the Safety of Maritime Navigation — [2005] ATNIF 30 (signed by Australia on 7 March 2006, Australia will be taking steps to ratify)

Appendix R. Australian R&D, Education and Training

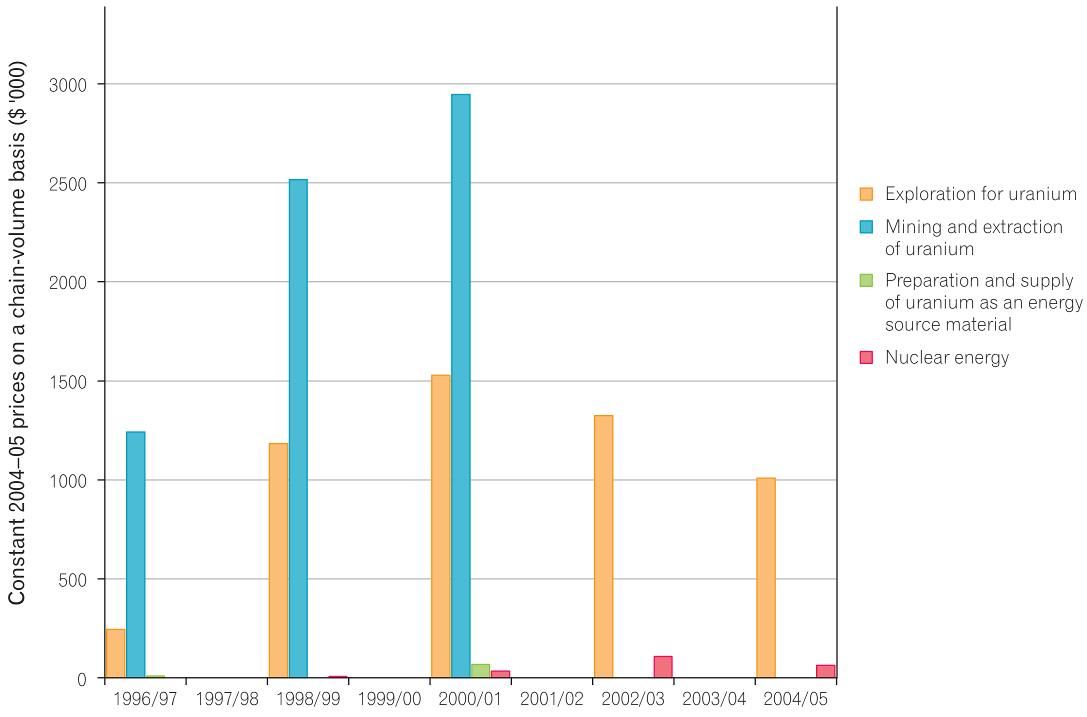
An expanded Australian nuclear energy industry would have implications for our education system and our scientific research base. A broad range of skills would be needed in policy and regulatory fields, nuclear engineering and construction, and basic research in nuclear science. Vocational training would be required in areas such as radiation protection, health and safety, and science and technology appropriate for specific industrial demands. It is important to note that highly skilled research personnel not only support future technological development, but also contribute to government policy development, and addressing regulatory issues associated with the nuclear industry.

R1 Australian nuclear R&D

The term nuclear R&D can refer to a wide range of basic and applied activities, including research related to the production of nuclear energy (in Australia such activities are largely related to uranium mining). However, nuclear R&D can also be conducted in areas that are not related to energy production, such as nuclear medicine.

Every two years the Australian Bureau of Statistics (ABS) carries out a survey of public funding for energy R&D in Australia, although the definition of what constitutes such R&D may exclude funding for some legitimate research activities in universities and government research organisations. Nevertheless, the surveys show that for the last decade over 90 per cent of publicly funded R&D was related to either exploration or mining of uranium (see Figure R1).

Figure R1 Public funding for nuclear R&D in Australia (by objective)



Source: Unpublished ABS data.

Funding for nuclear energy related R&D has been below $110 000 in all of the years examined. Public spending on R&D associated with the preparation and supply of uranium as an energy source material or nuclear energy related R&D has averaged below $20 000 a year over the period examined.

Australian private sector spending on nuclear R&D is harder to quantify, but it is likely that the recent increased uranium prices have led to higher levels of R&D. Certainly, private sector funding of R&D conducted by the ANSTO Minerals Group has increased significantly in recent years and the outlook is for this source of funding to further grow.

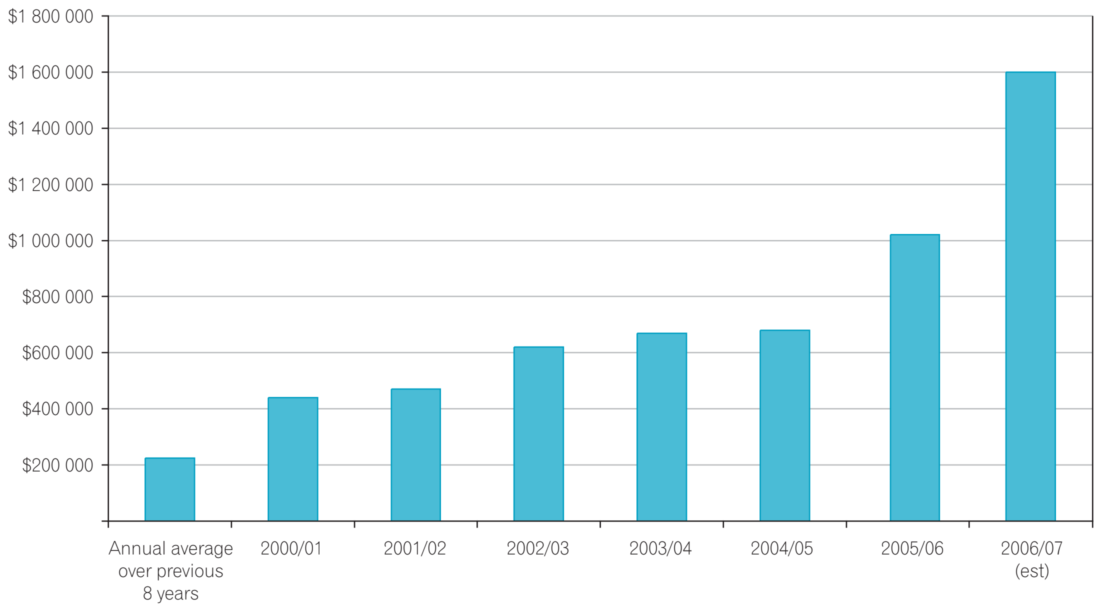
Public spending on nuclear R&D has over the decade to 2004–05 averaged around $2 million a year. The higher education sector's role in nuclear R&D is small and declining. Annual spending by this sector averaged around $150 000 in the decade to 2004–05, but as noted earlier, there may be some relevant university research that is not captured in these statistics.

In part, the low level of spending reflects the lack of higher education opportunities that are specifically related to the nuclear fuel cycle.

A comparison of FTE (full time equivalent) human resources against available R&D funding shows that each FTE person involved in nuclear R&D is on average associated with R&D funding of between $120 000 and $130 000 a year. Any significant funding increase for nuclear energy related R&D is likely to require a similar increase in researchers. Some of those researchers could come fairly quickly from a reallocation of existing resources and others may come from overseas. However, it is likely that researcher numbers will take time to respond to increased funding.

For example, the US experience suggests that it may take four to six years for postgraduate researcher numbers to respond to increased funding. This implies that a phased increase in research funding would be the most appropriate course of action should a significant increase in funding be judged to be desirable.

Figure R2 Private sector funding for ANSTO Minerals Group R&D



Source: Personal communication with ANSTO Minerals Group.

R2 Australian nuclear research facilities

Nuclear research covers a wide range of activities from nuclear physics, the nuclear fuel cycle, through to applications of nuclear techniques in a wide range of science and technology areas, including medicine, geology, and archaeology. In the sections below we limit the discussion to those areas that are likely to be fertile training areas for the kinds of skilled personnel that would be required if there was an expansion of nuclear fuel cycle activities in Australia.

R2.1 Heavy Ion Accelerator Facility, Australian National University (ANU)

The Heavy Ion Accelerator Facility at the Department of Nuclear Physics, ANU has an Electrostatic Tandem accelerator operating in the 15MV (million volts) region with the ability to inject into a modular superconducting Linear Accelerator. The accelerator produces a broad range of heavy ion beams that are delivered to ten experimental stations. These are instrumented for a range of national and international users.

The ANU facility is available for basic research in nuclear physics as well as for selected applications. The facility maintains and develops accelerator capabilities for the research community, and provides a training ground for postgraduate and postdoctoral research in nuclear physics and related areas.

The current research programme includes:

- fusion and fission dynamics with heavy ions
- nuclear spectroscopy and nuclear structure
- nuclear reaction studies
- interactions applied to materials
- accelerator mass spectrometry — development and application.

The facility operates as a de facto National Facility with over twenty per cent of the Australian users of the facility being based at institutions besides the ANU.[117] There is also a strong program of international collaboration with 48 per cent of the users coming from outside Australia.

R2.2 Australian Nuclear Science and Technology Organisation (ANSTO)

ANSTO is Australia's national centre for nuclear science and technology.[118] It is responsible for delivering specialised advice, scientific services and products to government, industry, academia and other research organisations.

ANSTO has approximately 860 personnel and an annual budget of some $160 million, which includes $40 million from commercial services. ANSTO undertakes nuclear related R&D in a wide range of areas, particularly in relation to health, the environment, engineering materials and neutron scattering. Approximately $30 million is spent annually across these areas. While ANSTO's focus is principally on activities not associated with the nuclear fuel cycle, it maintains strong R&D interest in areas such as the development of waste forms and processes for the management of nuclear and radioactive wastes. It has also sustained its research capability in areas such as uranium mining and the management of uranium mine sites.[101]

ANSTO's nuclear infrastructure, much of which is focussed on applications, includes the national research reactor, particle accelerators and radiopharmaceutical production facilities. Some are described in more detail below.

ANSTO also operates the National Medical Cyclotron at the Royal Prince Alfred Hospital in Camperdown, an accelerator facility used to produce certain short-lived radioisotopes for nuclear medicine procedures.

[117] Although operating as a de facto National Facility, at this stage, that status is not formally recognised and no direct facility funding is provided.

[118] ANSTO is located in New South Wales, just outside Sydney.

R2.3 National Research Reactor

ANSTO has operated the 10MW High Flux Australian Reactor (HIFAR) national research reactor since 1958. HIFAR produces neutrons through the fission process. These are used for a range of purposes, including:

- subatomic research, such as neutron diffraction for the study of matter
- neutron activation analysis for forensic purposes and the mining industry
- production of radioactive medicines for cancer diagnosis and therapy
- silicon irradiation doping for semiconductor use
- the production of radioisotopes for industrial uses.

HIFAR is being replaced by a new research reactor, the 20MW Open Pool Australian Light-water reactor (OPAL) which was granted an operating license in July 2006 and reached full power operation in November 2006.

The licence allows ANSTO to load nuclear fuel and carry out further testing to ensure OPAL's performance meets expectations. Subsequent shutdown of HIFAR is expected to occur early in 2007.

The neutron scattering facilities at HIFAR and OPAL are operated by the Bragg Institute.

R2.4 Australian Institute of Nuclear Science and Engineering (AINSE)

AINSE was established in 1958 to provide a mechanism for access to the special facilities at Lucas Heights (now ANSTO) by universities and other tertiary institutions and to provide a focus for cooperation in the nuclear science and engineering fields. It has a specific mandate to arrange for the training of scientific research workers and the award of scientific research studentships in matters associated with nuclear science and engineering.

In June 2006 the AINSE Council decided to facilitate the formation of an Australia-wide nuclear science and technology school. The intention is to provide education in a wide range of nuclear related matters from technical aspects of the fuel cycle and reactor operation through nuclear safety and public awareness to political matters of interest to policy makers.[119]

R2.5 Nuclear fusion research

The main areas of Australian research relevant to the possible long-term development of nuclear fusion as a source of power are in the fields of basic plasma science and modelling, carried out partly on the H-1 National Facility at the Australian National University, the development of diagnostic tools, and in a variety of materials-related research aimed at the testing and development of materials that will be able to withstand high temperatures and intense neutron fluxes.

Table R1 summarises the current range of fusion related research by members of the Australian ITER[120] Forum as at August 2006.[121]

Table R1 Current fusion energy related research in Australia

Institute	Research field
Australian National University	Plasma physics (laboratory, magnetic confinement, space physics), surface science.
University of Sydney	Plasma physics (laboratory, astrophysical and space theory), surface material.
University of Newcastle	High temperature materials.
University of Wollongong	Metallurgy, welding, surface engineering.
ANSTO	Materials, surface engineering.

Source: Australian ITER Forum[269]

[119] Stakeholders in the discussions include the Australian National University, a consortium of universities in Western Australia, the Universities of Wollongong, Newcastle, Sydney, and Melbourne, Queensland University of Technology and RMIT.

[120] International Thermonuclear Experimental Reactor.

[121] The House of Representatives Standing Committee on Industry and Resources inquiry into developing Australia's non-fossil fuel energy industry recommended that Australia secure formal involvement in the ITER project and seek to better coordinate its research for fusion energy across the various fields and disciplines in Australia.[26]

R2.6 Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)

ARPANSA conducts research in areas such as improved measurement of environmental samples for naturally occurring radioactive materials in mining and mineral sands production and for man-made radionuclides disposed of as radioactive waste. Monitoring equipment for rapid scanning of large areas following a radiological emergency has been developed and supplied to other countries. Research is also conducted into the assessment of the radiological impact of environmental contamination for both routine practices and for potential radiological emergencies.

In many mining operations the most significant exposures result from internal contamination. ARPANSA is undertaking research into in-vivo and biological monitoring techniques as well as dispersion and biological models necessary to assess doses from these pathways. ARPANSA maintains an Australia wide fallout monitoring network and continues to develop that network.

ARPANSA also undertakes research into dose calibration techniques and maintains the Australian standard for absorbed dose.

R2.7 The Environmental Research Institute of the Supervising Scientist (ERISS)

The Supervising Scientist plays an important role in the protection of the environment and people of the Alligator Rivers Region, including through research into the possible impact of uranium mining on the environment of the Region. Where potential impacts are identified, research is undertaken to develop and recommend standards and protocols to ensure that mining activities are carried out in accordance with best practice environmental management.

ERISS carries out research into topics that include biological diversity, ecological toxicity, risk assessment and ecosystem protection relating to mine site emissions via atmospheric, surface and ground water pathways. ERISS also conducts monitoring and research into improvement of environmental monitoring techniques to ensure protection of the environment in the Alligator Rivers Region from the potential effects of uranium mining. ERISS monitors and investigates radiological risk arising from present-day and historical uranium mining operations in the Alligator Rivers Region, and assists in planning for rehabilitation from physical landform, ecological and radiological perspectives.

R2.8 Additional nuclear research facilities

A number of universities conduct research involving nuclear techniques of analysis. The largest group is at the Microanalytical Research Centre of the University of Melbourne which has a 5 MV Pelletron ion accelerator and offers expertise and training in accelerator based techniques of ion beam analysis with MeV[122] ions including Rutherford Backscattering Spectrometry, Particle Induced X-ray Emission, Nuclear Reaction Analysis, Ion Beam Induced Charge, and Ion Implantation.

These techniques are applied to many materials science problems including metals, alloys, minerals, semiconductors, archaeological and art materials. Other projects involve nuclear instrumentation for pulse counting and analysis, nuclear microprobe system operation including multi-parameter event-by-event radiation detection and analysis for imaging and detector development for nuclear radiation, especially ions.

R3 Australian nuclear R&D expertise

Australia is a leader in R&D in several parts of the uranium supply chain. For example, Australia has developed research excellence in areas such as radioactive waste conditioning technology (Synroc), laser enrichment technology (SILEX), high performance materials, and the science of environmental protection during uranium mining and rehabilitation of mine sites.

[122] Million electron volts. The eV is a unit of energy. It is the amount of kinetic energy gained by a single unbound electron when it passes through an electrostatic potential difference of one volt, in vacuum.

R4 Existing Australian collaboration in international nuclear R&D

The following tables provide examples of existing international collaboration by Australian researchers. The examples of collaboration provided below are not meant to be complete or exhaustive.

R4.1 Multilateral collaboration

Australian participation in international collaboration on nuclear science and technology R&D occurs under the International Atomic Energy Agency (IAEA) Coordinated Research Projects (CRP) and the International Energy Agency Implementing Agreements, as well as under informal collaborative programs with research institutions. Table R2 provides examples of multilateral projects.

Table R2 Examples of Australian involvement in multilateral nuclear R&D collaboration

Description of Project	Overarching body	Australian participant	Start date	End date
Neutron based techniques for the detection of illicit materials and explosives in air cargo.	IAEA–CRP	CSIRO	2005	2010
Interpretation of interwell partitioning tracer data for residual oil saturation determination.	IAEA–CRP	University of Adelaide	2004	2008
Isotope studies of hydrological processes in the Murray–Darling Basin.	IAEA–CRP	ANSTO, ANU	2002	2006
Isotope methods for the study of water and carbon cycle dynamics in the atmosphere and biosphere.	IAEA–CRP	ANU	2004	2008
Atomic data for heavy element impurities in fusion reactors.	IAEA–CRP	Murdoch University	2002	2006
Nuclear Structure and Decay Data Evaluation.	IAEA–NSDD[123]	ANU	2002	cont.
Avoidance of unnecessary dose to patients while transitioning from analogue to digital radiology.	IAEA–CRP	Western Sydney Area Health Service	2002	2006
Nuclear and isotopic studies of the El Nino phenomenon in the ocean.	IAEA–CRP	ANSTO, University of Technology Sydney	2004	2009
New development and improvements in processing radioactive waste streams.	IAEA–CRP	ANSTO	2003	2007
Tracing discharges from nuclear facilities of the former Soviet Union using Plutonium and U-236.	EU-5th Framework Program	ANU	2003	2007
Plutonium speciation in marine and estuarine environments near nuclear reprocessing plants.	EU-5th Framework Program University of Dublin	ANU	2002	2006
Hydrological studies of potential nuclear waste storage sites.	EPRI–Japan CEA[124]-France	ANU	2003	2008

[123] Nuclear Structure and Decay Data

[124] Commissaria a l'Energie Atomique (French Atomic Energy Commision)

Description of Project	Overarching body	Australian participant	Start date	End date
Develop radioisotope separations technologies based on inorganic and composite organic-inorganic materials and explore their application in the wider energy and environment area.	CEA, EU 6th Framework Program	ANSTO, National Hydrogen Materials Alliance, University of SA, Melbourne University	2005	2007
International Nuclear Information System (INIS) on the peaceful applications of nuclear science and technology.	IAEA	ANSTO	Ongoing	
The Stellarator Concept Implementing Agreement.	IEA	ANU	Ongoing	

Source: IAEA, IEA and personal communications

R4.2 Bilateral collaboration

Australia also participates in various bilateral collaborative nuclear R&D agreements. Examples are listed in Table R3.

Table R3 Examples of Australian involvement in bilateral nuclear R&D collaboration

Description of Project	Collaboration partner	Australian participant	Start date	End date
Develop the design and associated safety case for the Commonwealth radioactive waste facility and provide ongoing research capability relating to environmental impact of nuclear operations.	NEA	ANSTO, DEST	2006	2009
Develop, implement and commercially exploit ANSTO's nuclear waste forms (with various collaborative and commercial partners).	Nexia Solutions, CEA/Cogema	ANSTO	Ongoing	
Atomic scale processes in nuclear materials and minerals.	Institute for Transuranium Elements and University of Muenster, Germany	ANSTO, University of Sydney	2005	2007
Irradiation growth of zircaloy and in-service inspection of pool-type research reactors.	KAERI[125]	ANSTO	2003	2009
Development of uranium molybdenum research reactor fuel.	US DOE	ANSTO	2003	2007
Adaptive response to low-dose gamma irradiation.	US DOE	Flinders University, ANSTO	2003	2005

Source: Personal communication with ANSTO

[125] Korea Atomic Energy Research Institute

Two key areas where Australian research has been prominent are in the development of Synroc for the immobilisation and management of waste and in laser enrichment technologies.

The current international program of collaboration on Synroc includes:

- continuing discussions between ANSTO and the US DOE on the use of Synroc for immobilising some types of HLW
- collaboration with Minatom for treatment of Russia's high-level wastes, including a possible a 20t/yr pilot plant
- a collaborative research program with the French Atomic Energy Commission on developing Synroc-glass waste forms using French cold-crucible melting technology
- a 2005 agreement between ANSTO and Nexia Solutions, part of British Nuclear Group, to use a composite Synroc glass-ceramic waste form for 5 tonnes of impure plutonium waste at Sellafield in the UK.

In the case of enrichment, an agreement for co-operation between the US and Australian Governments on the development of SILEX technology for the laser enrichment of uranium was signed in 2000. In May 2006 SILEX announced the signing of an exclusive Commercialisation and License Agreement for their uranium enrichment technology with the General Electric Company (GE). Subject to the receipt of relevant US government approvals,[126] the agreement provides for a phased approach to the commercialisation of the SILEX technology and the potential construction of a test loop, pilot plant, and a full-scale commercial enrichment facility. These operations would be built at GE's existing nuclear energy headquarters and technology site in Wilmington or another suitable location in the US.

R5 Australian nuclear education and training capacity

R5.1 Existing and proposed nuclear related courses

Australia does not have a dedicated school of nuclear science or engineering. However, courses are available that deal with aspects of nuclear physics. The ANU, which has the most extensive range of postgraduate teaching in nuclear physics, allied partly with the research activities of the Heavy Ion Accelerator Facility, plans to offer a Master of Nuclear Science course starting in 2007. The ANU is aiming for an intake of between five and ten students in 2007, with the numbers growing in subsequent years. Table R4 lists some existing and proposed nuclear related courses in Australia.

[126] The US Government confirmed that GE can proceed with some preliminary activities contemplated in the SILEX Technology development project. Further approvals for the project are pending.

Table R4 Existing and proposed postgraduate nuclear related courses in Australia

University	Program details	Qualification	Enrolments
University of Adelaide	Masters and PhD by research in medical physics	MSc, PhD	14 (6 Masters)
Australian National University	Master of Nuclear Science	M Nucl Sci	First enrolments in 2007
Australian National University	Masters and PhD by research in nuclear science	M Phil, PhD	10 (2 Masters)
Royal Melbourne Institute of Technology	Medical and Health Physics	M App Sc	20
Royal Melbourne Institute of Technology	Masters and PhD by research in nuclear science	M Sc, PhD	5 (all Masters)
Queensland University of Technology	Medical and Health Physics	M App Sci	15
Queensland University of Technology and WA University	Medical and Health Physics, Radiochemistry, Mining and Medical Physics	M App Sci	Under development
University of Sydney	Master of Medical Physics, Graduate Diploma in Medical Physics	M Med Phys, Grad Dip Med Phys	20
University of Sydney	Masters of Applied Nuclear Science, Graduate Diploma in Applied Nuclear Science	M App Nuc Sci, Grad Dip App Nuc Sci	First enrolments in 2008
University of Sydney	Masters and PhD by research in Medical Physics	MSc, PhD	20 PhD and MSc
University of Wollongong	Master of Medical Radiation Physics	MMRP	18
Australian Technology Network (ATN)[127]	Masters of Nuclear Engineering	M Nucl Eng	First enrolments in 2008

Source: Personal communications and AINSE submission.[231]

ANSTO plans to begin a graduate entry programme in 2007/08. This programme will recruit and train 15 graduates a year in nuclear related skills. The programme will include overseas attachments for the participating students.[128]

Studies relating to the reliability, safety, economics and environmental and societal effects of nuclear energy systems can also be undertaken. The Australian Technology Network has identified this as an area where it believes it is well placed to provide education and training for Australian students.

[127] The Australian Technology Network is an alliance of five Australian universities, Curtin University of Technology, University of South Australia, RMIT University, University of Technology Sydney, and Queensland University of Technology.

[128] The House of Representatives Standing Commitee on Industry and Resources inquiry into developing Australia's non-fossil fuel energy industry recommended that ANSTO's research and development mandate be broadened, to allow it to undertake physical laboratory studies of aspects of the nuclear fuel cycle and nuclear energy that may be of future benefit to Australia and Australian industry.[26]

R5.2 Radiation safety related courses

A wide range of radiation safety related courses are available in Australia. Table R5 lists examples of radiation safety courses provided by ANSTO or universities that have been approved by various state and territory jurisdictions. There are also a large number of radiation safety courses provided by private firms, hospitals and technical colleges.

Table R5 Examples of State and Territory approved radiation safety courses

Course provider	Course
Australian National University	Ionising Radiation Safety Workshop for XRD/ XRF Operators
Australian Nuclear Science and Technology Organisation	Advanced Radiation Safety Officer Course General Radiation Safety Officer Course Industrial Radiation Safety Officer Course Safe Use of Soil Moisture Gauges Safe Use of Nuclear Type Soil Moisture and Density Gauges Safe Use of Industrial Radiation Gauges Radiation Safety for Laboratory Workers Safe Use of X-ray Devices Safe Use of X-ray Devices in Art Conservation Work Radionuclides in Medicine Industrial Applications Radioisotopes Protection from Ionizing Radiation Ionising Radiation Protection
Central Queensland University	Industrial Radiation Safety General Radiation Safety — Level 1 General Radiation Safety — Level 2
Queensland University of Technology	Radiation Safety for X-ray Technologists School of Life Sciences, Radioisotopes Facility Induction Program General Radiation Protection
University of Newcastle	Remote Operators Course
University of New England	Safe Use of Nuclear Type Soil Moisture and Density Gauges Safe Handling of Radioactive Isotopes
University of New South Wales	Radiation Protection Training Course
University of Queensland	Safe Use of Soil Moisture and Density Gauges Introduction to Radiation Protection Radiation Protection Course Radiation Safety with Unsealed Sources — An Introductory Course Safety with Analytical X-ray Equipment
University of Sydney	Bone Mineral Densitometry
University of Western Australia	Unsealed Radioisotope Course

R6 Opportunities for increased collaboration

R6.1 Research and development

Australia has a relatively low level of effort in the area of nuclear energy related R&D. Should Australia decide to expand its level of participation in the nuclear fuel cycle beyond the uranium mining sector then it is likely that public funding for nuclear R&D will need to increase significantly, including in areas such as safety, and current and future reactor technologies. These are areas of research that already attract considerable support overseas and Australia could contribute to, and benefit from increased overseas collaboration on these and other topics.

ARPANSA's submission to the Review identified their ongoing interest in nuclear safety R&D. The NEA also argues that such research supports efficient and effective regulation across the spectrum of regulatory activities.[225]

There is little doubt that Australia has many areas of research expertise making it an attractive partner for international collaboration. It is important though that such collaboration not be seen as an alternative to increased support for Australian based research, but rather as a complementary measure that will increase the efficiency and effectiveness of the local research base.

Australia could contribute to international R&D efforts with its current skills in high performance materials and nuclear waste treatment. ANSTO's submission to the Review argues that these skills should help Australia gain entry into the Generation IV International Forum (GIF).[101] ANSTO argues that this would enable Australia not only to keep abreast of new developments, but also to influence the broader Forum to help achieve our national non-proliferation goals.

ANSTO has created a new Advanced Nuclear Technologies Group, within its Institute of Materials and Engineering Science. It plans to expand this group to supplement its capabilities in waste treatment and materials should Australia decide to be part of international nuclear research efforts such as the Generation IV International Forum. ANSTO noted that this would require agreement at the Government level. It also notes that high performance materials research is also relevant to the international R&D effort into fusion energy.[129]

R6.2 Education and training

There is a global shortfall of skilled persons in the nuclear industry. Many countries are significantly increasing their efforts in nuclear education and training to address this shortfall. New educational consortia are being formed, both within and between countries. Should Australia decide to expand its involvement in the nuclear fuel cycle then it will need to boost its level of nuclear education and training considerably.

Educational institutions can respond relatively rapidly to government policy decisions and employer demand for particular skills by introducing new courses. However, it will take time to ramp up Australia's nuclear education effort, particularly in the current environment of strong global demand for nuclear educators. Furthermore, Australian demand for particular skills may not be sufficient to support stand alone educational facilities in this country. The building of alliances with education providers or networks overseas would provide a mechanism for overcoming difficulties with expanding local education and training efforts.

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[129] Personal communication 31 August 2006.

Appendix S. Depleted Uranium

Enrichment of uranium for use as nuclear fuel produces wastes in the form of low activity depleted uranium hexafluoride gas and relatively small volumes of low activity liquid and solid waste. While depleted UF_6 presents a relatively low radiological hazard, it is a potentially hazardous chemical if not properly managed.

As depleted uranium has had only limited uses to date, depleted UF_6 stored in steel cylinders has accumulated at enrichment plants. The United States Department of Energy (DOE) is responsible for managing over 700 000 tonnes of depleted UF_6.[324] Under DOE's Advanced Fuel Cycle Initiative this material could become a significant energy resource, once transmuted into nuclear fuel for advanced reactors.[100]

Some countries are planning to convert their depleted UF_6 stocks to a more chemically stable and safer form (depleted uranium oxide and/or depleted uranium metal) pending decisions on its use. For example, the US Government plans to build de-conversion facilities at Department of Energy uranium enrichment sites. In decommissioning the former diffusion enrichment plant at Capenhurst (UK), Britain's Nuclear Decommissioning Authority plans to construct and operate a depleted uranium conversion and storage facility from 2015 to 2031.[325] In France AREVA has considerable experience in deconversion having processed over 300 000 tonnes of uranium hexafluoride over the past 20 years.

Due to uncertainty as to whether depleted uranium is a waste or a resource in a future advanced nuclear fuel cycle, no proposals have yet been developed for its disposal at a specific site. The submission to the Review by the Australian Conservation Foundation provided a paper proposing that deep geological disposal of depleted uranium waste would be appropriate.[326] The United States Nuclear Regulatory Commission considers that some form of near surface disposal would be appropriate.

The case for deep disposal of depleted uranium is based on a comparison with arrangements for disposal of plutonium contaminated waste in the Waste Isolation Pilot Project (WIPP) geological repository in New Mexico. While the depleted uranium exists in more concentrated form than the plutonium in waste disposed of at the WIPP, the radiotoxicity of plutonium is vastly greater than that of uranium — the annual limit of intake (ALI) for inhalation of plutonium is 0.6 micrograms compared with 0.2 grams for U-238, that is Pu-239 is ~300 000 times more radiotoxic than U-238 for a given mass.[327]

Several submissions to the Review argued that exposure to depleted uranium, including depleted uranium weapons, is responsible for severe health effects. The conclusions of these submissions are not supported by experts in the health physics community in Australia and overseas. These include the experts who contributed to an extensive review of the hazards presented by depleted uranium conducted in the context of an examination of the possible causes of Gulf War Illnesses.[328] The paper, 'A Review of the Scientific Literature As It Pertains to Gulf War Illnesses', notes that few previous studies had focused directly on depleted uranium. Accordingly it based its conclusions on the veterans who had the highest exposure to depleted uranium during the Gulf War as well as the extensive literature related to natural and enriched uranium. These materials have the same heavy metal toxicity as depleted uranium but are more radioactive than depleted uranium. The paper notes that 'large variations in exposure to radioactivity from natural uranium in the normal environment have not been associated with negative health effects'.

Depleted uranium sourced from Australian uranium is covered by Australia's nuclear safeguards requirements and cannot be used for any military application.

Acronyms and Abbreviations

AAEC	Australian Atomic Energy Commission (forerunner to ANSTO)
ABARE	Australian Bureau of Agricultural and Resource Economics
ABWR	Advanced boiling water reactor
AECL	Atomic Energy of Canada Limited
AGO	Australian Greenhouse Office
AGR	Advanced gas-cooled reactor
AINSE	Australian Institute of Nuclear Science and Engineering
Andra	National Radioactive Waste Management Agency (France)
ANSTO	Australian Nuclear Science and Technology Organisation
ANU	Australian National University
AONM	Australian obligated nuclear material
ARPANS Act	Australian Radiation Protection and Nuclear Safety Act 1998
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ASNO	Australian Safeguards and Non-Proliferation Office
ASO	Australian Safeguards Office (forerunner to ASNO)
BNFL	British Nuclear Fuels Limited
Bq	Becquerel
BTU	British Thermal Unit (or Therm)
BWR	Boiling water reactor
CANDU	Canadian deuterium uranium reactor
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CNS	Convention on Nuclear Safety
CNSC	Canadian Nuclear Safety Commission
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CPPNM	Convention on the Physical Protection of Nuclear Material
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTBT	Comprehensive Nuclear Test Ban Treaty
DNI	Dalton Nuclear Institute
EA	Environmental assessment
EPBC Act	Environment Protection and Biodiversity Conservation Act 1999
EPR	European pressurised water reactor
EPRI	Electric Power Research Institute
ERA	Energy Resources of Australia
FBR	Fast breeder reactor

FMCT	Fissile Material Cut-off Treaty
FOAK	First of a kind
GA	General Atomics (US privately-owned company)
GDP	Gross domestic product
GE	General Electric (US privately-owned company)
Gen IV	Generation four (the next generation of NPP designs)
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
GW	Gigawatt (10^9 watts)
GWd/tonne	Gigawatt days per tonne
GWe	Gigawatts electrical (10^9 watts)
GWh	Gigawatt hours (10^9 watt hours)
HEU	Highly enriched uranium
HIFAR	High flux Australian reactor
HLW	High-level waste
IAEA	International Atomic Energy Agency
ICRP	International Commission for Radiological Protection
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
ILW	Intermediate-level waste
I-NERI	International Nuclear Energy Research Initiative
INES	International Nuclear Event Scale
ISL	In-situ leaching
IPCC	Intergovernmental Panel on Climate Change
ITER	International Thermonuclear Experimental Reactor
JAEA	Japan Atomic Energy Agency
kWe	Kilowatts electrical (10^3 watts)
kWh	Kilowatt hours (10^3 watt hours)
LCOE	Levelised cost of electricity
LEU	Low enriched uranium
LFR	Lead-cooled fast reactor
LILW	Low and intermediate level waste
LLW	Low-level waste
LNG	Liquefied natural gas
LWR	Light water reactor

Ml	Megalitre (10^6 litres)
MOX	Mixed oxide fuel
MSR	Molten salt reactor
Mt	Megatonne (10^6 tonnes)
MWe	Megawatts electrical (10^6 watts)
MWh	Megawatt hours (10^6 watt hours)
NEA	Nuclear Energy Agency (a division of the OECD)
NEM	National Electricity Market
NOPSA	National Offshore Petroleum Safety Authority
NORM	Naturally occurring radioactive material
NPP	Nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission (USA)
NSG	Nuclear Suppliers Group
NWFZs	Nuclear Weapon-Free Zones
OCGT	Open cycle gas turbines
OECD	Organisation for Economic Co-operation and Development
OPAL	Open Pool Australian Light-water reactor
PBMR	Pebble bed modular reactor
PHWR	Pressurised heavy water reactor
ppb	parts per billion
ppm	parts per million
PWe	Petawatts electrical (10^{15} watts)
PWh	Petawatt hours (10^{15} watt hours)
PWR	Pressurised water reactor
R&D	Research and development
RAR	Reasonably assured resources
RBMK	Reaktor Bolshoi Moschnosti Kanalynyi (light water cooled, graphite-moderated reactor, Russia)
Rosatom	Russian Federal Atomic Energy Agency (or FAEA)
SCWR	Supercritical water reactor
SFR	Sodium-cooled fast reactor
SNF	Spent nuclear fuel
SPCC	Supercritical pulverised coal combustion
SWU	Separative Work Unit (kg)
Therm	British Thermal Unit (or BTU)
ThORP	Thermal Oxide Reprocessing Plant (UK)

TVO	Teollisuuden Voima Oy (Finnish company)
TWe	Terawatts electrical (10^{12} watt)
TWh	Terawatt hours (10^{12} watt hours)
UF_6	Uranium hexafluoride
U_3O_8	Uranium oxide (also known as yellow cake)
UMPNE	Uranium Mining, Processing and Nuclear Energy Review
UNFCCC	United Nations Framework Convention on Climate Change
UNSCEAR	United Nations Committee on the Effects of Atomic Radiation
UO_2	Uranium dioxide
UO_3	Uranium trioxide
USDOE	United States Department of Energy
USEC	United States Enrichment Corporation
UxC	Ux Consulting
VHTR	Very high temperature reactor
WANO	World association of nuclear operators
WNA	World Nuclear Association
WNU	World Nuclear University

Scientific numbers and their symbols

Very large and very small numbers are unwieldy to write in the usual decimal notation. Therefore, scientists recognise ways of printing or communicating them in a shorter format. Associated with these are abbreviations such as the commonly used 'kilo' for thousand.

Decimal numbers and their corresponding abbreviations

Decimal	Scientific	Commonly	Prefix	Symbol
1 000 000 000 000 000	10^{15}	–	peta	P
1 000 000 000 000	10^{12}	trillion	tera	T
1 000 000 000	10^{9}	billion	giga	G
1 000 000	10^{6}	million	mega	M
1 000	10^{3}	thousand	kilo	k
100	10^{2}	hundred	hecto	h
10	10^{1}	ten	deca	da
0.1	10^{-1}	tenth	deci	d
0.01	10^{-2}	hundredth	centi	c
0.001	10^{-3}	thousandth	milli	m
0.000 001	10^{-6}	millionth	micro	μ
0.000 000 001	10^{-9}	billionth	nano	n
0.000 000 000 001	10^{-12}	trillionth	pico	p
0.000 000 000 000 001	10^{-15}	–	femto	f

Glossary

Actinides	Elements with between 89 and 102 protons in their nucleus that behave chemically like actinium. All are radioactive and many are long-lived alpha emitters. The actinide series includes uranium (92), neptunium (93), plutonium (94) and americium (95).
Activity (of a substance)	The number of disintegrations per unit time taking place in a radioactive material. The unit of activity is the Becquerel (Bq), which is one disintegration per second.
Alpha particle	A positively charged particle emitted from the nucleus of an atom during radioactive decay. It consists of two protons and two neutrons (a helium-4 nucleus). Although alpha particles are normally highly energetic, they travel only a few centimetres in air and are stopped by a sheet of paper or the outer layer of dead skin.
Atom	A particle of matter that cannot be broken up by chemical means. Atoms have a nucleus consisting of positively charged protons and uncharged neutrons of about the same mass. In a neutral atom the positive charges of the protons in the nucleus are balanced by the same number of negatively charged electrons in motion around the nucleus.
Atomic number (Z)	The number of protons in the nucleus of an atom, which also indicates the position of that element in the periodic table.
Availability factor	Percentage of time that an electricity generating unit is able to be operated at full output.
Background radiation	The ionising radiation in the environment to which we are all exposed. It comes from many sources including outer space, the sun, the rocks and soil under our feet, the buildings we live in, the air we breathe, the food we eat, and our own bodies. The average annual background radiation dose in Australia is approximately 2 mSv (see Dose, effective).
Becquerel (Bq)	The SI unit of intrinsic radioactivity of a material, equal to one radioactive disintegration per second. In practice, GBq or TBq are the common units.
Beta particle	A particle emitted from the nucleus of an atom during radioactive decay. Beta particles are either electrons (with negative electric charge) or positrons (positive charge). High energy beta particles can travel metres in air and several millimetres into the human body. Low energy beta particles are unable to penetrate the skin. Most beta particles can be stopped by a small thickness of a light material such as aluminium or plastic.
Burn up	The percentage of heavy metal in a nuclear fuel that has been 'fissioned' or the measure of thermal energy released by nuclear fuel relative to its mass, usually expressed as MWd/tonne or GWd/tonne of uranium.
Capacity factor	Percentage of time that an electricity generating unit is producing at full load output, ie the amount of electricity that it produces over a period of time, divided by the amount of electricity it could have produced if it had run at full power over that time period.
Carbon price	The cost of emitting carbon into the atmosphere. It can be a tax imposed by government, the outcome of an emission trading market or a hybrid of taxes and permit prices. The various ways of creating a carbon price can have different effects on the economy.

Centrifuge enrichment	A method for enriching uranium that uses a rapidly rotating tube. The heavier U-238 isotope in the uranium hexafluoride gas tends to concentrate at the walls of the centrifuge as it spins and can be separated from the lighter U-235.
Chain reaction	A process in which one nuclear transformation sets up conditions for a similar nuclear transformation in another nearby atom. Thus, when fission occurs in uranium atoms, neutrons are released, which in turn may produce fission in other uranium atoms.
Class 7 Dangerous Goods	One of nine classes defined by the United Nations for the transport of dangerous goods, relating to radioactive materials including uranium oxide, uranium hexaflouride and thorium.
CO_2	Carbon dioxide.
CO_2-e (carbon dioxide equivalent)	A standard measure that takes account of the different global warming potential of different greenhouse gases and expresses the cumulative effect in a common unit.
Containment, reactor	The prevention of release, even under the conditions of a reactor accident, of unacceptable quantities of radioactive material beyond a controlled area. Also, commonly, the containing system itself.
Contamination	Uncontained radioactive material that has been dispersed into unwanted locations.
Control rods	Rods, plates or tubes containing boron, cadmium or some other strong absorber of neutrons. They are used to control the rate of the nuclear reaction in a reactor.
Coolant	The fluid circulated through a nuclear reactor to remove or transfer heat generated by the fuel elements. Common coolants are water, air and carbon dioxide.
Core, reactor	The region of a nuclear reactor in which the fuel and moderator are located and where the fission chain reaction can take place. The fuel elements in the core of a reactor contain fissile material.
Critical mass	The smallest mass of fissile material that will support a self-sustaining chain reaction under specified conditions.
Criticality	A nuclear reactor is critical when the rate of neutrons produced is equal to the rate of neutron loss, and a self-sustaining fission chain reaction can occur.
Decay, radioactive	The spontaneous radioactive disintegration of an atomic nucleus resulting in the release of energy in the form of particles (eg alpha or beta), or gamma radiation, or a combination of these.
Decommissioning	In relation to a nuclear reactor, its shutdown, dismantling and eventual removal, making the site available for unrestricted use.
Depleted uranium (DU)	Uranium having less than the naturally occurring percentage of U-235 (~0.71 per cent). As a by product of enrichment in the nuclear fuel cycle, it generally has 0.20–0.25 per cent U-235, the rest being U-238.

Deuterium	Also called 'heavy hydrogen', deuterium is a non-radioactive isotope of hydrogen having one proton and one neutron in the nucleus (ie an atomic mass of two). It occurs in nature in the proportion of one atom to 6500 atoms of normal hydrogen. (Normal hydrogen atoms contain one proton and no neutrons).
Dose limits	The maximum radiation dose, excluding doses from background radiation and medical exposures, that a person may receive over a stated period of time. International recommended limits, adopted by Australia, are that occupationally exposed workers should not exceed 20 mSv/year (averaged over five years, no single year to exceed 50 mSv), and that members of the public should not receive more than 1 mSv/year above background radiation.
Dose, absorbed	A measure of the amount of energy deposited in a material by ionising radiation. The unit is the joule per kilogram, given the name Gray (Gy).
Dose, effective	Effective dose is a measure of the biological effect of radiation on the whole body. It takes into account the equivalent dose and the differing radiosensitivities of body tissues. The unit is the sievert (Sv), but doses are usually measured in millisieverts (mSv) or microsieverts (μSv).
Dose, equivalent	Equivalent dose is a measure of the biological effect of radiation on a tissue or organ and takes into account the type of radiation. The unit is the sievert (Sv), but doses are usually measured in millisieverts (mSv) or microsieverts (μSv).
Dosimeter (or dosemeter)	A device used to measure the radiation dose a person receives over a period of time.
Electron	The negatively charged particle that is a common constituent of all atoms. Electrons surround the positively charged nucleus and determine the chemical properties of the atom.
Element	A chemical substance that cannot be divided into simpler substances by chemical means; all atoms of a given element have the same number of protons.
Enriched uranium	In order to be used as fuel for power reactors, uranium usually has to be enriched — the natural isotopic abundance of the fissile isotope U-235 (~0.71 per cent) has to be increased to approximately 3 per cent. Material with 20 per cent or greater enrichment is called high enriched uranium (HEU); below 20 per cent is low enriched uranium (LEU).
Enrichment, isotope	The elevation of the content of a specified isotope in a sample of a particular element (or compound thereof). The relative amounts of isotopes of any element can be changed from the natural occurrence by isotope enrichment.
Equivalence	Where Australian obligated nuclear material (AONM) loses its separate identity because of process characteristics, an equivalent quantity is designated as AONM, based on the fact that atoms or molecules of the same substance are indistinguishable.
Export controls	The set of laws, policies and regulations that govern the export of sensitive items for a country or company.

Export trigger list	Under Nuclear Suppliers Group guidelines, a list of nuclear-related equipment and materials that may be exported only if the recipient country accepts full-scope IAEA safeguards.
Fast breeder reactor (FBR)	A fast neutron reactor that is configured to produce more fissile material than it consumes, using fertile material such as depleted uranium or thorium in a blanket around the core.
Fast neutron reactor	A reactor with little or no moderator and hence utilising fast neutrons to sustain the nuclear chain reaction.
Fertile material	A material, not itself fissionable by thermal neutrons, that can be converted directly or indirectly into a fissile material by neutron capture. There are two basic fertile materials, U-238 and Th-232. When these fertile materials capture neutrons they are converted into fissile Pu-239 and U-233 respectively.
Fissile material	Any material capable of undergoing fission by thermal (or slow) neutrons. For example, U-233, U-235 and Pu-239 are fissile nuclides.
Fission	The splitting of a heavy nucleus into two, accompanied by the emission of neutrons, gamma radiation, and a great deal of energy. It may be spontaneous, but in a reactor is due to a uranium nucleus absorbing a neutron and thus becoming unstable.
Fission fragments	The two atoms initially formed from the fission of a heavier atom such as U-235 or Pu-239. The fission fragments resulting from each fission of U-235, for example, are not necessarily the same. Various pairs of atoms can be produced. When initially formed, most fission fragments are radioactive and emit beta particles and gamma rays and decay into other atoms.
Fission products	The collective term for the various fission fragments and their resulting decay products formed after fission of a heavy atom.
Flux, neutron	The number of neutrons passing through an area per unit time, for example, the number passing through 1 cm^2/s.
Fuel cycle, nuclear	The series of steps involved in supplying fuel for nuclear reactors and managing the waste products. It includes the mining, conversion and enrichment of uranium, fabrication of fuel elements, their use in a reactor, reprocessing to recover the fissionable material remaining in the spent fuel, possible re-enrichment of the fuel material, possible re-fabrication into more fuel, waste processing, and long-term storage.
Fuel rod	A single tube comprising fissionable material encased in cladding. Fuel rods are assembled into fuel elements.
Fusion	The formation of a heavier nucleus from two lighter ones (such as hydrogen isotopes) with an attendant release of energy (as in a fusion reactor or in the sun).
Gamma radiation	Gamma radiation is short wavelength electromagnetic radiation of the same physical nature as light, X-rays, radio waves and so on. However, gamma radiation is highly penetrating and, depending on its energy, may require a considerable thickness of lead or concrete to absorb it. Since gamma radiation causes ionisation, it constitutes a biological hazard. It is commonly used to sterilise medical products.

Gigawatt (GW)	Unit of power equal to one billion (10^9) watts. GWe denotes electricity output and GWth denotes thermal heat output from a nuclear or fossil-fired power plant.
Gray (Gy)	A measure of absorbed dose. Replaces the rad. 1 Gy = 100 rad.
Half-life	The period required for half of the atoms of a particular radioactive isotope to decay and become an isotope of another element. Half-lives vary, according to the isotope, from less than a millionth of a second to more than a billion years.
Heavy water	Water containing significantly more than the natural proportion (one in 6500) of heavy hydrogen (deuterium) atoms to normal hydrogen atoms. Heavy water is used as a moderator in some reactors because it slows down neutrons more effectively than normal (light) water.
Heavy water reactor	A reactor that uses heavy water as its moderator (eg Canadian CANDU). Also PHWR.
High enriched uranium (HEU)	Uranium enriched to at least 20 per cent U-235. Weapons grade HEU is enriched to more than 90 per cent U-235.
High-level waste (HLW)	see Radioactive waste, high level.
Intermediate-level waste (ILW)	see Radioactive waste, intermediate level.
Ion	An atom that has lost or gained one or more orbiting electrons, thus becoming electrically charged.
Ionisation	Any process by which an atom or molecule gains or loses electrons.
Ionising radiation	Radiation capable of causing ionisation of the matter through which it passes. Ionising radiation may damage living tissue.
Irradiated fuel	See Spent fuel.
Irradiation	Exposure to any kind of radiation.
Isotopes	Nuclides that have the same atomic number but different mass numbers. Different isotopes of the same element have the same chemical properties, but different physical properties.
Light water reactor (LWR)	Reactors that are cooled and usually moderated by normal water. They account for most of the world's installed nuclear power generating capacity. Included in this group are pressurised water reactors (PWR) and boiling water reactors (BWR).
Load factor	The ratio of the average load supplied during a designated period to the peak load occurring in that period, ie the actual amount of kilowatt hours delivered on a system in a period of time as opposed to the total possible kilowatt hours that could be delivered on the system over that time period.

Low-enriched uranium (LEU)	Uranium enriched above the natural level of 0.71 per cent U-235 but to less than 20 per cent U-235. LEU in modern power reactors is usually 3.5–5 per cent U-235.
Low-level waste (LLW)	see Radioactive waste, low level.
Megawatt (MW)	Unit of power equal to one million (10^6) watts. MWe denotes electricity output and MWth denotes thermal heat output from a nuclear or fossil-fired power plant.
Microsievert (μSv)	Unit of radiation dose, one millionth of a sievert.
Millisievert (mSv)	Unit of radiation dose, one thousandth of a sievert.
Mixed-oxide fuel (MOX)	Reactor fuel that consists of both uranium and plutonium oxides, usually approximately 8 per cent plutonium, which is the main fissile component.
Moderator	A material used in a reactor to slow down fast neutrons, thus increasing the likelihood of further fission. Examples of good moderators include normal water, heavy water, beryllium and graphite.
Monitoring, radiation	The collection and assessment of radiological information to determine the adequacy of radiation protection.
Neutron	An uncharged subatomic particle with a mass slightly greater than that of the proton and found in the nucleus of every atom except ordinary hydrogen. Neutrons are the links in a chain reaction in a nuclear reactor.
Neutron scattering	A technique for 'seeing' fine details of the structure of a substance. It involves firing a beam of neutrons (usually from a research reactor) at a sample and observing how it is scattered. Neutrons pass between atoms, unless they collide with the nucleus. When they do, they don't bounce off randomly, but deflect down a specific path; different structures create different pathways.
Neutrons, fast	Neutrons emitted from fission events. They travel thousands of times faster than slow neutrons and maintain chain reactions in fast reactors.
Neutrons, thermal or slow	Neutrons travelling with energy comparable to those of everyday atoms, required as links in the chain reactions in thermal reactors.
Nuclear power plant (NPP)	A nuclear reactor that converts nuclear energy into useful electrical power.
Nuclear proliferation	An increase in the number of nuclear weapons in the world. Vertical proliferation is an increase in the size of nuclear arsenals of those countries that already possess nuclear weapons. Horizontal proliferation is an increase in the number of countries that have a nuclear explosive device.
Nuclear reactor	A structure in which a fission chain reaction can be maintained and controlled. It usually contains fuel, coolant, moderator, control absorbers and safety devices and is most often surrounded by a concrete biological shield to absorb neutron and gamma ray emission.

Nuclear Suppliers Group (NSG)	A group of 45 states that agree to certain conditions on the export of nuclear materials and nuclear-related 'dual use' materials, items and technologies, as defined in annexes to IAEA document INFCIRC/254 rev 4.
Nucleus	The positively charged core of an atom. It is approximately 1/10 000 the diameter of the atom, but contains nearly all the mass of the atom. All nuclei contain protons and neutrons, except the nucleus of normal hydrogen (atomic mass of one), which consists of a single proton.
Nuclide	A nucleus of a species of atom characterised by its mass number (protons and neutrons), atomic number (protons) and the nuclear energy state.
Oxide fuels	Enriched or natural uranium in the form of the oxide UO_2, used in most power reactors.
Plutonium (Pu)	A heavy radioactive, human-made metallic element. Its most important isotope is fissionable Pu-239, produced by neutron irradiation of U-238. Pu-239 is used as a fuel for power reactors or explosive for nuclear weapons. About one-third of the energy in a light water reactor comes from the fission of Pu-239, and it is the main isotope of value recovered from reprocessing of spent fuel.
Proton	A subatomic particle with a single positive electrical charge and a mass approximately 1837 times that of the electron and slightly less than that of a neutron. Also, the nucleus of an ordinary or light hydrogen atom. Protons are constituents of all nuclei.
Radiation (nuclear)	Radiation originating from the nucleus of an atom. It includes electromagnetic waves (gamma rays) as well as streams of fast-moving charged particles (electrons, protons, mesons etc) and neutrons of all velocities.
Radioactive material	Any natural or artificial material whether in the solid or liquid form, or in the form of a gas or vapour, that exhibits radioactivity. For regulatory purposes radioactive substances may be defined as radioactive material that has an activity level of 100 Bq/g or greater.
Radioactive waste	Material that contains or is contaminated with radionuclides at concentrations or radioactivity levels greater than clearance levels established by the appropriate authority and for which no use is foreseen.
Radioactive waste, high level (HLW)	Waste which contains large concentrations of both short and long-lived radioactive nuclides, and is sufficiently radioactive to require both shielding and cooling. It generates more than 2 kW/m^3 of heat.
Radioactive waste, intermediate level (ILW)	Waste material that contains quantities of radioactive material above clearance levels, requires shielding and has a thermal power below 2 kW/m^3.
Radioactive waste, low level (LLW)	Any waste material that contains quantities of radioactive material above the clearance level (as determined in regulations) that requires minimum standards of protection for personnel when the waste is handled, transported and stored.
Radioactivity	The ability of certain nuclides to emit particles, gamma rays or x-rays during their spontaneous decay into other nuclei. The final outcome of radioactive decay is a stable nuclide.

Radioisotope	An isotope that is radioactive. Most natural isotopes lighter than bismuth are not radioactive. Three natural radioisotopes are radon-222 (Rn-222), carbon-14 (C-14) and potassium-40 (K-40).
Radionuclide	The nucleus of a radioisotope.
Radon (Rn)	A radioactive element, the heaviest known gas. Radon gives rise to a significant part of the radiation dose from natural background radiation. It emanates from the ground, bricks and concrete.
Ratification	The process by which a state expresses its consent to be bound by a treaty.
Repository	A permanent disposal place for radioactive wastes.
Reprocessing	The chemical dissolution of spent fuel to separate unused uranium and plutonium from fission products and other transuranic elements. The recovered uranium and plutonium may then be recycled into new fuel elements.
Safeguards, nuclear	Technical and inspection measures for verifying that nuclear materials are not being diverted from civil to weapons uses.
Separative work unit (SWU)	A complex unit,[322] which is a function of the amount of uranium processed and the degree to which it is enriched (ie the extent of increase in the concentration of the U-235 isotope relative to the remainder). The unit is strictly 'kg separative work unit', and it measures the quantity of separative work (indicative of energy used in enrichment) when feed and product quantities are expressed in kilograms. Approximately 100–120 000 SWU is required to enrich the annual fuel loading for a typical 1000 MWe light water reactor.
Sievert (Sv)	A measurement of equivalent dose and effective dose. Replaces the rem. 1 Sv = 100 rem.
Spent fuel	Also called spent nuclear fuel (SNF) or irradiated fuel. It is nuclear fuel elements in which fission products have built up and the fissile material depleted to a level where a chain reaction does not operate efficiently.
Stable isotope	An isotope incapable of spontaneous radioactive decay.
Synroc	A human-made rock-like ceramic material which can be used to permanently trap radioactive atoms for long-term storage. An alternative to vitrification of HLW.
Tailings	Ground rock remaining after particular ore minerals (eg uranium oxides) are extracted.
Tails	Depleted uranium remaining after the enrichment process, usually with approximately 0.2 per cent U-235.
Thermal reactor	A reactor in which the fission chain reaction is sustained primarily by thermal (slow) neutrons.
Thorium (Th)	A naturally occurring radioactive element. With the absorption of neutrons Th-232 is converted to the fissionable isotope U-233.

Transuranics	Elements with an atomic number above 92. They are produced artificially (eg when uranium is bombarded with neutrons). Some are therefore present in spent fuel (see also Actinides).
Uranium (U)	A radioactive element with two isotopes that are fissile (U-235 and U-233 and two that are fertile (U-238 and U-234). Uranium is the heaviest element normally found in nature and the basic raw material of nuclear energy.
Uranium hexafluoride (UF_6)	A compound of uranium that is a gas above 56°C and is thus a suitable form for processing uranium to enrich it in the fissile isotope U-235.
Uranium ore concentrate (UOC)	A commercial product of a uranium mill, usually containing a high proportion (greater than 90 per cent) of uranium oxide (U_3O_8).
Uranium oxide (U_3O_8)	The mixture of uranium oxides produced after milling uranium ore from a mine. Uranium is sold in this form.
Vitrification	The incorporation of intermediate and high-level radioactive waste into glass for long-term storage.
Yellowcake	Ammonium diuranate (ADU), the penultimate uranium compound in U_3O_8 production, but the form in which mine product was sold until about 1970.

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