Chapter 6
Uranium and Thorium

6.1 Summary

KEY MESSAGES

- Australia has the world's largest Reasonably Assured Resources of uranium and identified recoverable thorium resources.
- Australia is the world's third largest producer of uranium. At present, there is no thorium production.
- Currently Australia has three uranium mines operating, with two additional operations scheduled to begin production in 2010.
- World demand for uranium is projected to increase strongly over the next 20 years as new nuclear capacity is commissioned.
- Australia's uranium production is forecast to more than double by 2030.
- There are currently no plans for Australia to have a domestic nuclear power industry by 2030.
- In the longer term there is potential for thorium-fuelled reactors, but currently there are no commercial scale thorium-fuelled reactors anywhere in the world.

6.1.1 World uranium and thorium resources and market

- Uranium and thorium can be used as nuclear reactor fuel. Uranium is currently the preferred fuel; thorium may be a future fuel.
- World Reasonably Assured Resources (RAR) recoverable at less than US$80/kg of uranium are estimated to be around 3047 kilotonnes (kt U) at the end of 2008. This is equal to about 50 years of current nuclear reactor consumption levels.
- World uranium mine production has increased by an average 2.8 per cent per year since 2000, reaching 24 584 PJ (43.9 kt U) in 2008.
- Secondary supplies of uranium from blended highly enriched uranium (HEU), government stocks and mixed oxide fuels accounted for around 32 per cent of global uranium supply in 2008. This compares with 44 per cent in 2000.
- World uranium consumption has increased by 1.5 per cent per year since 2000, reaching 36 176 PJ (64.6 kt U) in 2008. Nuclear power accounted for 6.2 per cent of global primary energy consumption and 14.8 per cent of world electricity generation in 2007.
- World demand for uranium is projected to increase at 3.7 per cent per year to 2030, reflecting the commissioning of new nuclear capacity worldwide. Generation III reactors incorporate advanced safety systems and have improved fuel technologies; Generation IV reactors, currently in research and development, will utilise uranium more efficiently, minimise waste and be proliferation resistant.
- Thorium based fuels could be used in some existing uranium-fuelled reactors possibly in the medium term, but full scale commercial thorium-fuelled reactors are not likely before 2030.

6.1.2 Australia's uranium and thorium resources

- Australia has the world's largest RAR recoverable at less than US$80/kg of uranium (US$80/kg U) with 1163 kt in this category at December 2008. The estimated RAR for 2008 will last about 140 years at current Australian production levels.
- Australia has substantial potential for the discovery of new uranium resources.
- New pre-competitive data released by Geoscience Australia – notably the radiometric map of Australia and database – are providing a further stimulus to uranium exploration and discovery.
- Australia has a major share of the world's thorium resources. Estimated total recoverable Identified Resources of thorium could amount to about 490 kt.

- There is currently no exploration specifically focused on thorium. All of the information available on thorium resources has been generated by exploration and mining activities aimed principally at other mineral commodities.

6.1.3 Key factors in utilising Australia's uranium and thorium resources

- There is renewed interest worldwide in nuclear power and hence demand for uranium is expected to increase.
- Successful exploration and development of uranium deposits is dependent on several factors including state government policy, prices, production costs, ability to demonstrate best practice environmental and safety standards, and community acceptance of uranium development.
- Limited commercially viable transport options and restriction of access to two ports may limit expansion of Australian uranium exports. A reduced number of shipping firms and routes that accept uranium may result in further delays and costs.
- Global demand for thorium is dependent upon the development of widespread commercial scale thorium-fuelled reactors for electricity generation.
- There has been renewed interest in development of thorium-fuelled reactors. This is partly because of greater abundance of thorium resources in some countries, greater resistance to nuclear weapons proliferation, and a substantial reduction in radioactive waste generated.

6.1.4 Australia's uranium and thorium market

- Australia has three operating uranium mines: Ranger open pit mine in the Northern Territory, Olympic Dam underground mine and Beverley in situ recovery (ISR) mine in South Australia (figure 6.1). Two more ISR mines, Four Mile and Honeymoon in South Australia, are expected to be producing in 2010.
- Australia has been a reliable producer of uranium since the early 1950s. Australia's uranium oxide production in 2008–09 was 4872 PJ (8.7 kt U). Australia is the third largest uranium producer with 19.2 per cent of world production.

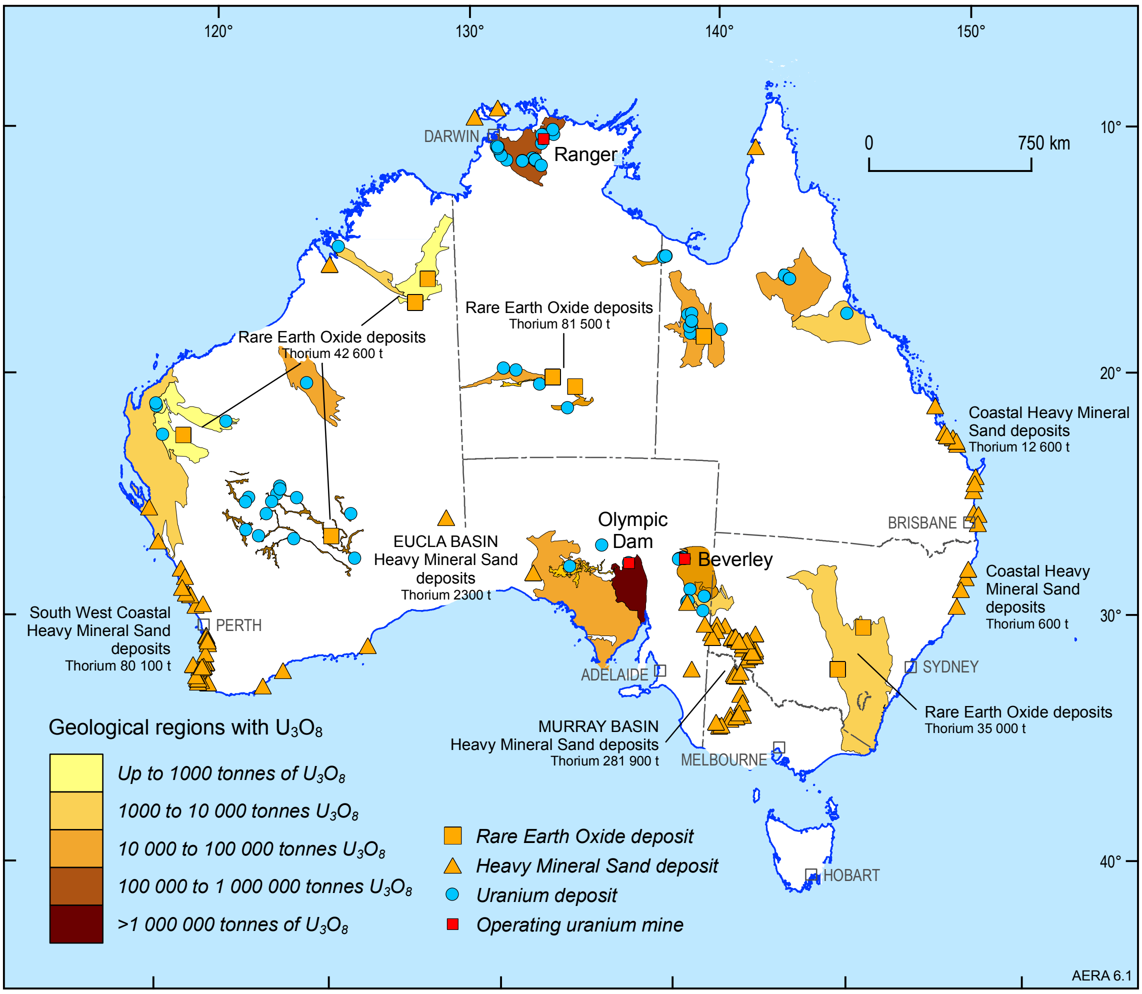

Figure 6.1 Australia's total identified uranium and thorium resources, 2008

Source: Geoscience Australia

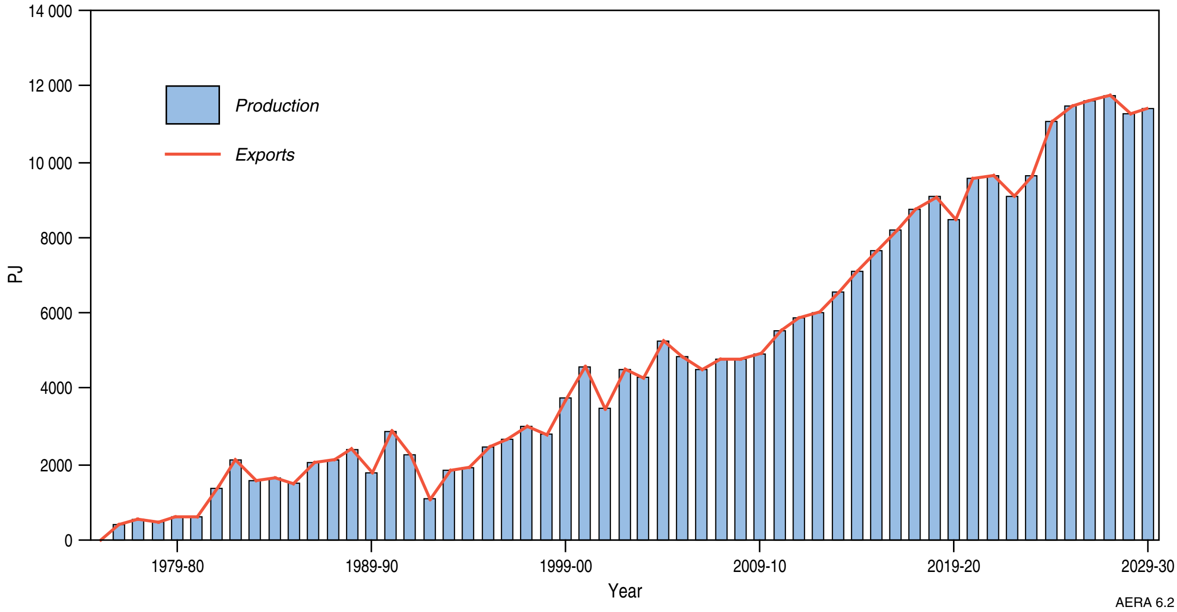

Figure 6.2 Australia's projected uranium supply-demand balance to 2029–30
Source: ABARE

- Australia does not consume any of its domestic uranium production. In 2008–09, Australia exported 4816 PJ (8.6 kt U) with an export value of A$1033 million. Australia's major export destinations are the United States, Japan and France.
- Australian production of uranium oxide is projected to increase by an average 6 per cent per year to reach 11 480 PJ (20.5 kt U) by 2029–30 (figure 6.2). All production is expected to be exported.
- Australian production and subsequent trade of thorium is not likely to occur on a large scale before 2030.
- If commercialisation of a thorium fuel cycle occurs more quickly than assumed, Australia is well positioned to supply world markets with low cost reliable sources of thorium. Currently, thorium is being diluted and disposed of at the mineral sand mine site, making these resources uneconomic to recover in the future.

6.2 Uranium

6.2.1 Background information and world market

Definitions

Uranium (U) is a mildly radioactive element that is widespread at levels of one to four parts per million (ppm) in the Earth's crust. Concentrations of uranium rich minerals, such as uraninite, carnotite and brannerite can form economically recoverable deposits. Once mined, uranium is processed into uranium oxide (U_3O_8), also referred to as uranium oxide concentrate (UOC) and is exported in this form. Natural uranium (mine production) contains about 0.7 per cent of the uranium isotope U^{235} and 99.3 per cent U^{238}.

Enriched uranium is uranium with an enhanced concentration of the U^{235} isotope, up from 0.7 per cent to between 3 and 5 per cent. Uranium is required to undergo enrichment for use in most civilian nuclear reactors. Like all thermal power plants, nuclear reactors work by generating heat, which boils water to produce steam to drive turbines that generate electricity. In nuclear reactors, the heat is produced from nuclear fission of U^{235}. Highly enriched uranium (HEU) is enriched to 20 per cent or more U^{235} and weapons-grade HEU is enriched to over 90 per cent.

Secondary sources arise from the reprocessing of spent nuclear fuel, blended down HEU from nuclear weapons, or mixed oxide fuels. Currently, secondary sources supply a significant portion of uranium demand for nuclear reactors.

Uranium supply chain

A conceptual representation of the Australian uranium supply chain is given in figure 6.3. The supply chain is divided into four distinct phases: resources exploration; development and production; processing, transport and storage; and end use markets. Australia's supply chain concludes with the exporting of uranium oxide to countries for processing, enrichment and use in nuclear power plants.

Resources exploration

There is a wide variety of geological settings that result in the formation of different types of uranium deposits. The main areas of exploration activities in Australia are:

- Gawler Craton/Stuart Shelf region (hematite breccia deposits) and Frome Embayment (sandstone deposits) in South Australia,

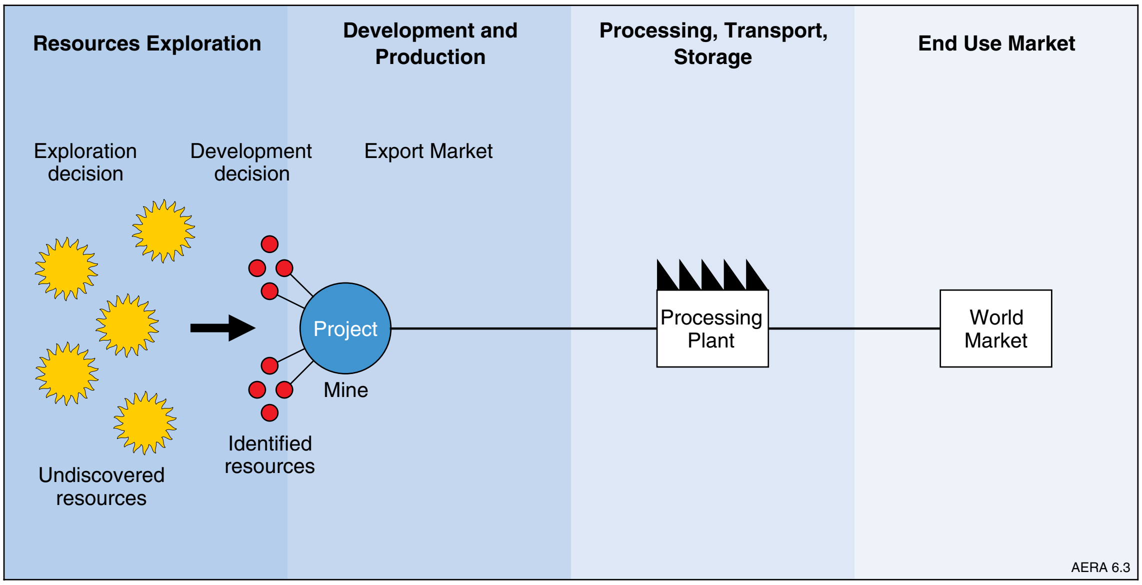

Figure 6.3 Australia's uranium supply chain

Source: ABARE and Geoscience Australia

- Paterson Province (unconformity type deposits) and Yilgarn Craton (calcrete type deposits) in Western Australia,
- Pine Creek and Arnhem Land regions (unconformity type deposits) in Northern Territory, and
- Mt Isa region in Queensland (metasomatite type deposits).

Exploration activities use geological and geophysical methods to locate and delineate potential uranium deposits. A deposit is systematically drilled and assayed to quantify the grade and tonnage of the deposit. The different types of deposits have a wide range of ore grades, tonnage and ore minerals.

South Australia and Northern Territory maintain the bulk of exploration activity. Uranium exploration and mining are prohibited in New South Wales and Victoria. Queensland has uranium resources, and previously mined uranium, but currently has a policy of no uranium mining. In late 2008, Western Australia removed its six year ban on uranium mining, which has resulted in renewed investment in uranium projects.

Development and production

Once a resource has been quantified, a company makes a decision on whether to proceed with development based on underlying market conditions, including commodity prices and the ability to finance the project. If a decision to proceed with the project is made, construction of a mine site and processing facilities begins after approval by Australian and state/territory governments.

In Australia, uranium is recovered using both conventional and ISR mining techniques. Most of Australia's uranium production is from conventional (open cut or underground) mining techniques, followed by milling and metallurgical processing. There is currently only one ISR mine, but several more are expected to begin production in the short term. ISR mining is widely used in Kazakhstan and United States and accounts for about 28 per cent of global uranium mine production. The process involves recovering uranium without removing the ore body from the ground. Uranium is extracted by means of an acid or alkaline solution which is pumped down injection wells into the permeable mineralised zone to remobilise uranium from the ore body. The uranium bearing solution is pumped to the surface and recovered in a processing plant.

Processing, transport and storage

Conventionally extracted uranium is milled, and then processed to produce U_3O_8. For ISR mining, the uranium-bearing solution is pumped to a processing plant and treated in much the same way as conventional uranium operations. The U_3O_8 is not directly usable as a fuel for a nuclear power reactor and additional processing (conversion and enrichment) and fuel fabrication are required.

The processing path and amount of uranium required annually by a 1000 megawatt electric (MWe) light water reactor is illustrated in figure 6.4. The U_3O_8 is converted into uranium hexafluoride (UF_6), which is then enriched to increase the proportion of uranium isotope U^{235} from 0.7 per cent to between 3 and 5 percent. The enriched UF_6 is converted to uranium dioxide (UO_2) and transferred to a fabrication plant. Solid ceramic pellets containing UO_2 are encased in metal tubes to form fuel rods used in the nuclear reactor. Typically, one tonne of uranium will produce 44 gigawatt hours of electricity (WNA 2009a).

Each stage of the fuel cycle produces some radioactive waste, which is disposed of using proven technologies. International conventions such as the *Joint Convention on Nuclear Safety* and the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, assert that the ultimate responsibility for ensuring the safety of spent fuel and radioactive waste management rests with the state.

In the Australian uranium supply chain, uranium mining generates tailings, the radioactivity of which is low and is managed by disposal in site-specific engineered tailings dams. The Australian regulatory regime requires mines to be approved subject to best practice environmental and safety standards.

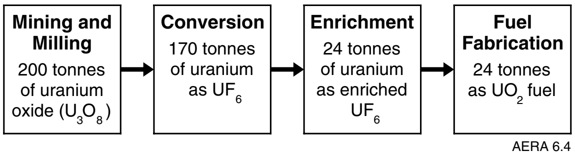

Figure 6.4 Typical annual quantity of uranium required for a 1000 MWe nuclear reactor

Source: Commonwealth of Australia 2006a

End use market

Australia does not have a domestic nuclear power industry; all of Australia's uranium production is exported. Australia has stringent requirements for the supply of uranium and nuclear material derived from it. Receiving states must be a party to and comply with the Treaty on the Non-Proliferation of Nuclear Weapons, have a bilateral safeguards agreement with Australia and, in the case of non-nuclear weapon states, have an Additional Protocol, which ensures the International Atomic Energy Agency (IAEA) has access to and inspection rights in the recipient country. These requirements apply also to third party states that may be involved in processing and transhipment of the material.

Australian uranium producers sell most of their production through long term contracts. Only a small amount of Australian uranium is sold on the world spot market.

At present U_3O_8 is exported through the Adelaide and Darwin container ports only. The U_3O_8 is shipped to international end use markets, either directly or through countries which convert and enrich the U_3O_8 and fabricate fuel. The uranium fuel is used in civilian nuclear power reactors to generate electricity, and in the manufacture of radioisotopes for medical applications.

World uranium market

Table 6.1 provides a snapshot of the Australian uranium market in a global context. Australia has the world's largest uranium resources and is the third largest producer in the world.

Resources

Uranium resources are categorised using the OECD Nuclear Energy Agency (OECD/NEA) and the IAEA classification scheme. The uranium resource estimates are for recoverable uranium, which deducts losses due to mining and milling. Uranium recoverable at less than US$80/kg U is considered to be economic at current market prices.

Table 6.1 Key uranium statistics, 2008

	unit	Australia	OECD[b]	World
Resources[a]	PJ	651 280	902 720	1 706 320
	kt U	1163	1612	3047
Share of world	%	38.2	52.9	100.0
World ranking	no.	1	-	-
Production	PJ	4760	10 696	24 584
	kt U	8.5	19.1	43.9
Share of world	%	19.2	43.6	100.0
World ranking	no.	3	-	-
Annual average growth of production 2000–08	%	1.4	-1.0	2.8
Consumption[c]	PJ	0	30 408	36 176
	kt U	0	54.3	64.6
Annual average growth of consumption 2000–08	%	-	0.1	1.5
Nuclear share of primary energy consumption	%	0	10.9	6.2[d]
Nuclear share of electricity generation	%	0	21.2	14.8[d]

a Reasonably assured resources recoverable at <US$80/kg U. Data for Australia compiled by Geoscience Australia and estimates for other countries are from OECD/NEA-IAEA. **b** ABARE estimates. **c** Amount of uranium used in nuclear power plants. **d** 2007 data

Source: OECD/NEA-IAEA 2008, Geoscience Australia 2009, WNA 2009b, IEA 2009, ABARE 2009a

World total Identified Resources (RAR and Inferred Resources) recoverable at less than US$80/kg U were estimated to be 2.7 million PJ (4.85 million tonnes U) at December 2008 (OECD/NEA-IAEA 2008, Geoscience Australia 2009). At current rates of world consumption for energy purposes this is enough to supply approximately 75 years.

At December 2008, Australia's total Identified Resources (RAR and Inferred) recoverable at less than US$80/kg U accounted for 33 per cent of global resources (table 6.2). Other countries with large resources include Kazakhstan (16 per cent), the Russian Federation (10 per cent), Canada (9 per cent) and South Africa (7 per cent).

Mine production

Uranium production is focused in a small number of countries. In 2008, world uranium production was 24 584 PJ (43.9 kt U) with Canada (20.5 per cent), Kazakhstan (19.4 per cent), Australia (19.2 per cent), and Namibia (10 per cent) accounting for nearly 70 per cent of this production (WNA 2009b; see figure 6.5). Australia was the world's second largest uranium producer from the mid-1990s through to 2007. Kazakhstan production has increased rapidly in recent years and in 2008 its production exceeded Australian production for the first time (WNA 2009b).

Table 6.2 World total Identified Resources of uranium recoverable at less than US$80/kg U, 2008

	Identified Resources (RAR & Inferred) <US$80/kg U		Reasonably Assured Resources (RAR) <US$80/kg U	
	kt U	Share of world %	kt U	Share of world %
Australia	1612.7	33.2	1163.3	38.2
Kazakhstan	751.6	15.5	344.2	11.3
Russian Federation	495.4	10.2	172.4	5.7
Canada	423.2	8.7	329.2	10.8
South Africa	343.2	7.1	205.9	6.7
Brazil	231.0	4.8	157.4	5.2
Namibia	230.3	4.7	145.1	4.8
Ukraine	184.1	3.8	126.5	4.1
Jordan	111.8	2.3	44.0	1.4
United States	99.0	2.0	99.0	3.3
Uzbekistan	86.2	1.8	55.2	1.8
Other	284.6	5.9	205.1	6.7
Total	**4853.1**	**100.0**	**3047.3**	**100**

Source: Data for Australia compiled by Geoscience Australia and estimates for other countries are from OECD/NEA-IAEA. Figures are rounded to the nearest 100 tonnes

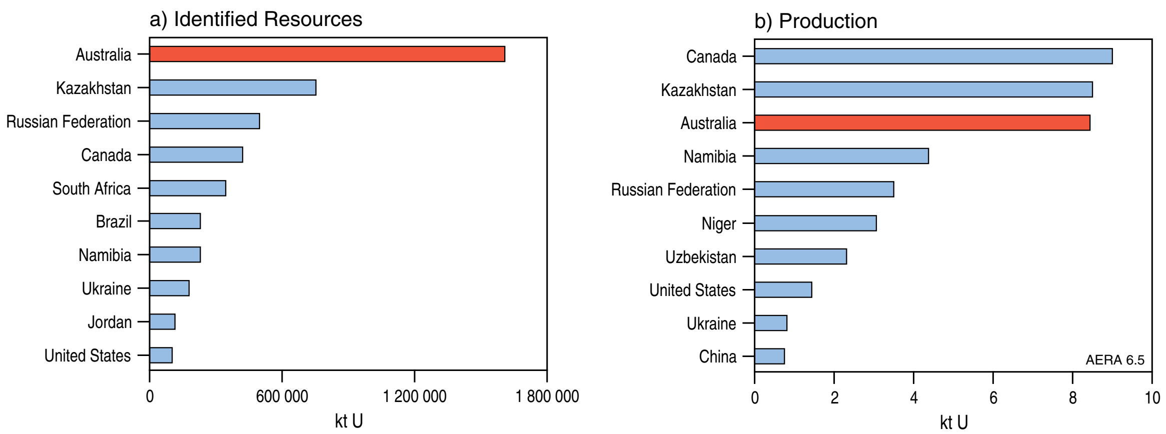

Figure 6.5 World uranium resources and production, by major country, 2008

Source: OECD/NEA-IAEA 2006, 2008; WNA 2009b

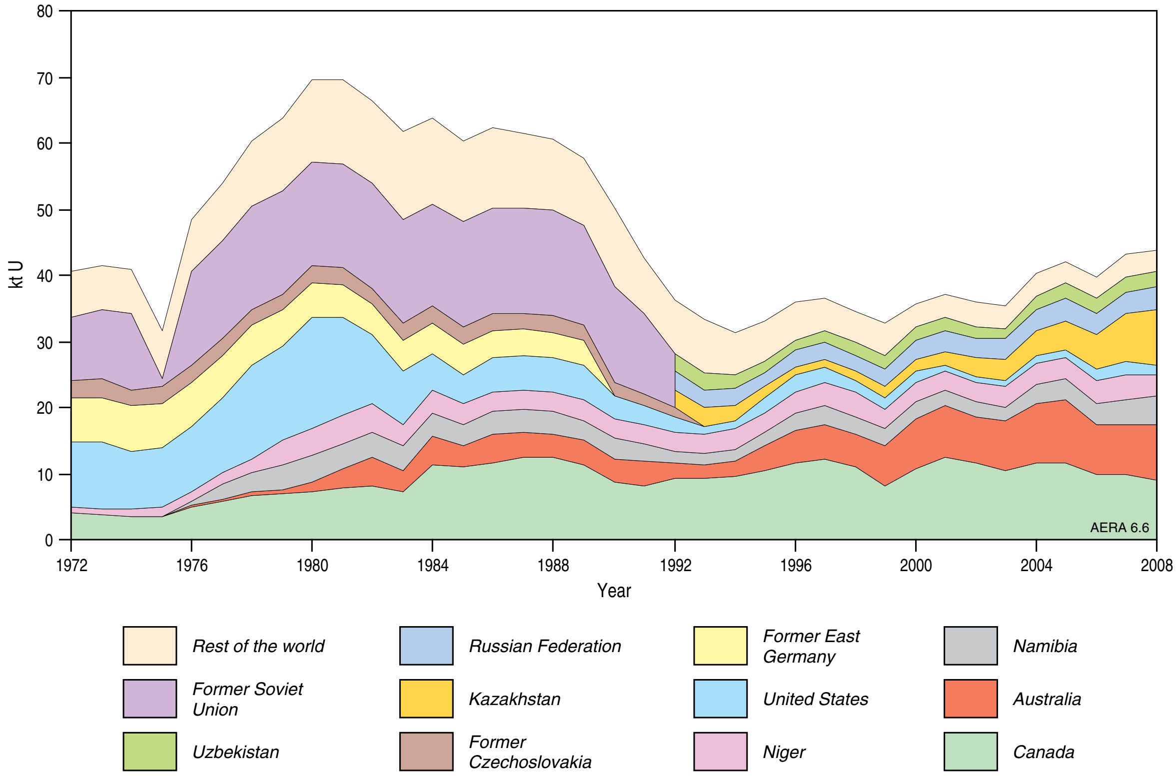

Figure 6.6 World uranium production, by major producer

Source: OECD/NEA-IAEA 2006, 2008

World uranium production peaked at 39 032 PJ (69.7 kt U) in 1980, reflecting strong demand for uranium in non-energy uses and increasing penetration of nuclear power (figure 6.6). At peak production, the largest uranium producers were the former Soviet Union, United States, Canada and East Germany. Since 1980, production in most of these countries has declined as a result of secondary sources entering the market, driving down prices and increasing competition and pressure on high cost producers. World uranium production reached a low of 17 640 PJ (31.5 kt U) in 1994. Since then, uranium production has increased steadily, reflecting higher production in countries such as Australia, Kazakhstan and Namibia.

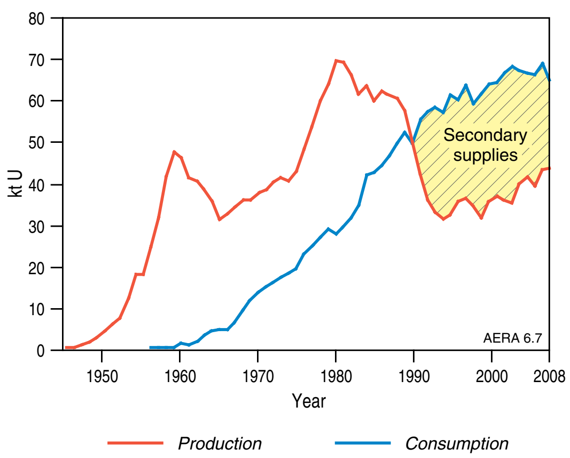

Figure 6.7 World uranium production and consumption for energy purposes

Source: OECD/NEA-IAEA 2006, 2008, WNA 2009b, 2009c

Secondary supply

Uranium production consistently exceeded requirements for energy purposes until 1989 (figure 6.7). Since 1990, global uranium demand for energy purposes has exceeded mine production, with the shortfall met from secondary supply sources.

Secondary sources include low enriched uranium (LEU) produced by blending down highly enriched uranium (HEU) from military stockpiles, mixed oxide fuels (MOX), depleted uranium tails from enrichment plants and government stocks (figure 6.8). Of these, the largest source currently is from military stockpiles of HEU, which are being progressively reduced under the terms of a number of international agreements, such as the United States-Russian Federation HEU purchase agreement and the HEU feed deal. The terms of these agreements will be complete after 2013, at which time there will be a consequent sharp reduction in uranium supply from secondary sources. The Euratom Supply Agency (2009) has forecast that secondary supplies could decline to around 10 kt U per year by 2030. Figure 6.8 illustrates a reference case which incorporates these factors, and assumes also no net changes in inventories and broadly constant supplies from government stocks over the

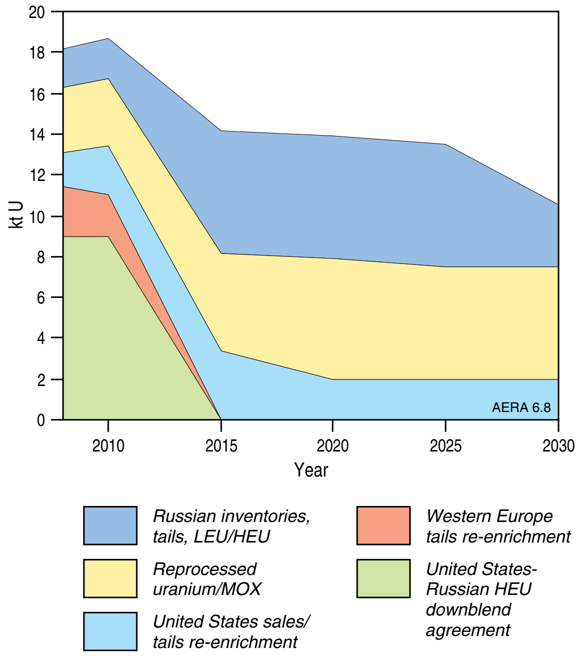

Figure 6.8 Sources of secondary supply in the world uranium market, projections to 2030

Source: Geoscience Australia, based on data provided by WNA 2009

period 2015-2025 and a decline in Russian supply after that time.

MOX is formed by mixing plutonium oxide and depleted uranium oxide. MOX is considered a viable fuel option, and is expected to be used in 15 per cent of world reactors by 2010 (Euratom Supply Agency 2009).

Consumption

Uranium is used as a fuel for nuclear power and to produce medical and industrial isotopes. The nuclear power industry requirements dominate.

Between 1971 and 2008, uranium consumption for energy purposes grew by an average 4 per cent per year to 36 176 PJ, or 6 per cent of the world's primary energy consumption (IEA 2009). In 2008, the largest consumers of uranium for power generation were the United States, France and Japan (figure 6.9). During the 1990s growth in uranium demand slowed as fewer reactors were built compared with the previous two decades. However, an increased focus on energy diversification and the need to reduce global greenhouse gas (especially carbon dioxide) emissions in recent years has stimulated renewed interest in nuclear power as a proven base load power source and low emission technology.

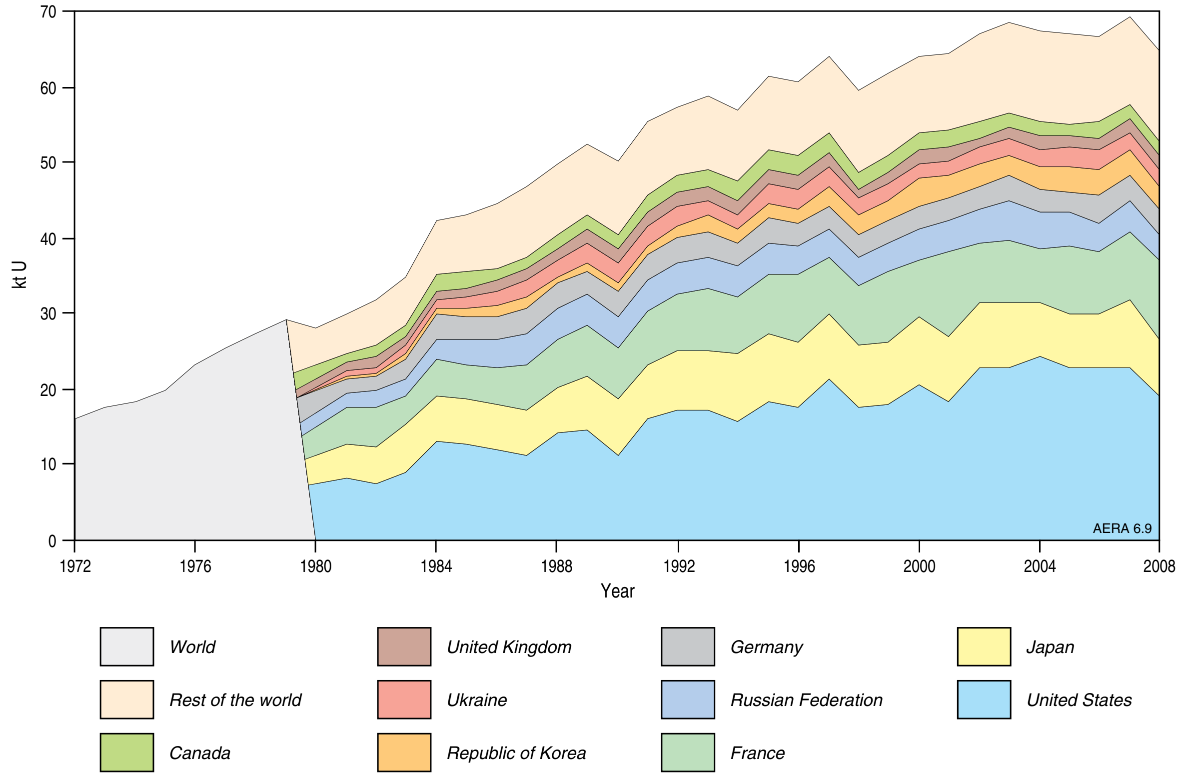

Figure 6.9 World uranium consumption for energy generation, by major country

Source: OECD/NEA-IAEA 2006, 2008, WNA 2009c

Trade

With the exception of Canada, uranium production is focused in countries without significant enrichment and conversion facilities, such as Australia, Kazakhstan, Namibia and Niger. Reflecting this, trade in U_3O_8 is common, although information on world trade is often not publicly available due to commercial sensitivities. Based on production and consumption, the largest importers of U_3O_8 in 2008 were likely to have been the United States, Japan, France, Germany and the Republic of Korea. The largest exporters of uranium were likely to have been Australia, Kazakhstan, Canada, Namibia and Niger.

World outlook for the uranium market to 2030

According to projections from the Energy Information Administration (EIA), world electricity generation from nuclear power is expected to increase by at least 45 per cent to 3844 TWh or 13 838 PJ by 2030 (table 6.3; EIA 2009a). Growth in nuclear power is driven by concerns over increasing demand for electricity, rising fossil fuel prices, energy security, and greenhouse gas emissions. Despite this growth, the share of nuclear power as a proportion of world electricity generation is projected to decrease, from 15 per cent in 2007 to 12 per cent in 2030 (EIA 2009a).

Key growth markets for nuclear power are projected to be developing economies, where electricity consumption will increase significantly over the next 20 years. Countries with the largest growth in nuclear power capacity are expected to be China and India where growing energy demand and favourable nuclear power policies are expected to drive growth. Nevertheless, growth in non-OECD Europe, Eurasia and North America are also likely to play a role in increasing nuclear power production as these economies maintain nuclear power electricity generation in their energy portfolios.

Strong projected growth in nuclear power generation implies a positive outlook for future uranium demand. Based on EIA projections of world nuclear electricity generation, ABARE has estimated future uranium consumption by region (figure 6.10). Global uranium consumption is projected to increase by an average 3.7 per cent per year to reach 104 kt U (58 240 PJ) by 2030. Non-OECD Asian economies are projected to account for most of this growth, mainly reflecting expansions to generating capacity in China and India.

There is considerable uncertainty surrounding world economic growth, energy security, adoption of greenhouse gas emission reduction targets, relative

Table 6.3 Projected nuclear electricity generation to 2030

Region/Country	Actual	Projections		
	Terawatt hours (TWh)			
	2006	2010	2020	2030
OECD				
North America	891	928	992	1053
United States	787	809	862	907
Canada	93	108	120	135
Mexico	10	11	11	11
Europe	929	922	905	902
Asia	430	441	546	624
Japan	288	299	336	381
The Republic of Korea	141	142	210	243
Australia/New Zealand	0	0	0	0
Total OECD	**2250**	**2291**	**2443**	**2579**
Non-OECD				
Europe and Eurasia	269	283	424	519
Russian Federation	144	155	251	328
Other	124	128	173	191
Asia	111	151	455	678
China	55	65	274	425
India	16	37	104	149
Other Asia	40	48	77	104
Other	31	37	62	68
Total Non-OECD	**411**	**471**	**941**	**1266**
Total World	**2660**	**2761**	**3385**	**3844**

Source: EIA 2009a

costs of generating technologies and changes in policy relating to nuclear power. All present risks to the consumption projections in figure 6.10. In particular, there is potential for nuclear power, and thus demand for uranium, to grow faster than projected if the introduction of policies such as emissions reduction targets reduce demand for coal before alternative low emission energy sources become economic.

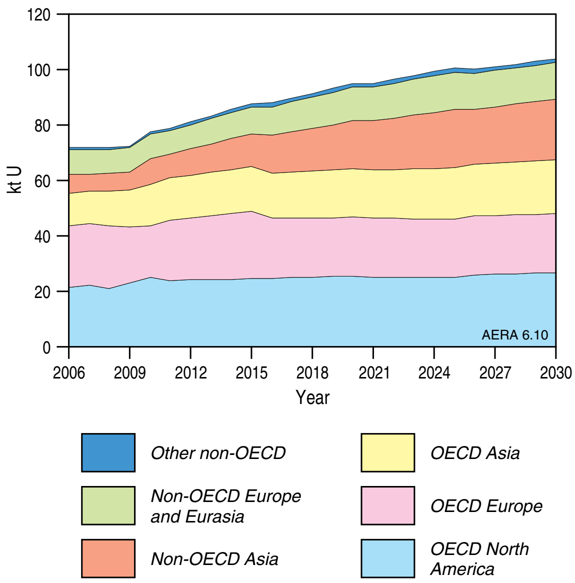

Figure 6.10 Projected world uranium consumption, to 2030

Source: ABARE

6.2.2 Australia's uranium resources and market

Uranium resources

Australia has the world's largest RAR of uranium recoverable at less than US$80/kg U, with 1163 kt of resources in this category at December 2008 (table 6.4; figure 6.11). Australia accounts for 38 per cent of world RAR recoverable at less than US$80/kg U. Based on current Australian production and RAR at 2008, the estimated resource life is about 140 years. Australia has an additional 449 kt of uranium in Inferred Resources recoverable at less than US$80/kg U, which are also the world's largest resources in this category.

Olympic Dam in South Australia is the world's largest known uranium deposit. In September 2009, BHP Billiton released its annual report stating improvements in metallurgical recovery for uranium and revising ore reserves and mineral resources. Reported ore reserves at Olympic Dam have increased by 22 per cent and total mineral resources have increased by 5 per cent. The deposit has not yet been completely drilled out. Geoscience Australia estimated that as at June 2009 Australia's RAR recoverable at less than US$80/kg U is 1210 kt U, an increase of 4 percent compared with December 2008.

The location of Australia's uranium deposits and the relative size of resources is shown in Figure 6.11.

The majority of Australia's uranium resources occur in four types of deposits which vary significantly in both tonnage and grade:

Hematite breccia complex deposits contain about 65 per cent of Australia's total uranium resources and all of these resources are at Olympic Dam (South Australia).

Unconformity-related deposits account for about 20 per cent of Australia's total resources. These deposits are mainly in the Alligator River region in the Northern Territory (Ranger, Jabiluka, Koongarra), and in one deposit in the Rudall Province, Western Australia (Kintyre). The unconformity-related deposits have the highest average grades overall but show a very wide range in size.

Sandstone deposits account for about 7 per cent of Australia's total known Identified Resources, and occur mainly in the Frome Embayment region in South Australia (Beverley, Four Mile, Honeymoon, East Kalkaroo, Goulds Dam) and the Westmoreland area in northwest Queensland (Redtree, Junnagunna, Huarabagoo). Other significant sandstone type deposits include Manyingee, Mulga Rock and Oobagooma in Western Australia, and Angela in Northern Territory.

Calcrete deposits have about 5 per cent of Australia's Identified Resources. Most calcrete deposits are low grade. The world class Yeelirrie deposit is the largest deposit of this type. Other calcrete deposits include Lake Way, Lake Maitland and Centipede (Western Australia).

Other types of uranium deposits in Australia include metasomatite deposits (Valhalla, Skal and Anderson's

Table 6.4 Australia's uranium resources, December 2008

	unit	recoverable <US$ 80/kg U	recoverable in range US$ 80 – 130/kg U
Reasonably Assured Resources (RAR)	kt	1163	13
Inferred Resources	kt	449	48
Total Identified Resources	**kt**	**1612**	**61**

Source: Geoscience Australia 2009

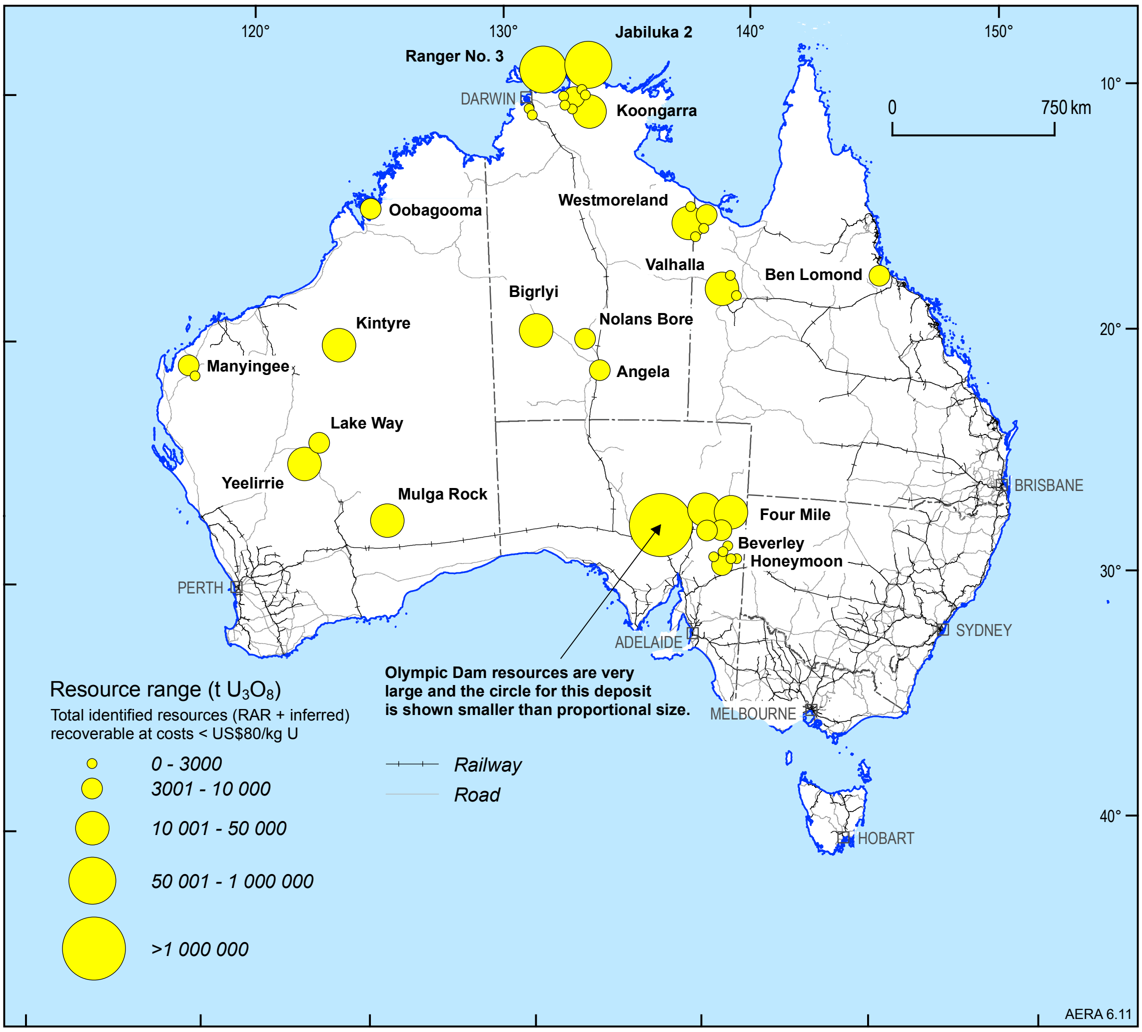

Figure 6.11 Australia's total identified uranium resources

Source: Geoscience Australia

Lode, Queensland). Australia has only small resources within metamorphic (remnant resources at Mary Kathleen, Queensland), volcanic (Ben Lomond, Maureen, Queensland) and intrusive deposits (Crocker Well, Mount Victoria, South Australia).

The major uranium ore minerals are uraninite and pitchblende, though a range of other uranium minerals are found in particular deposits. The total initial size of Australian deposits as uranium oxide grade and ore tonnage is plotted in figure 6.12. Whether a deposit has potential for development depends on several factors including the relative tonnage to grade, for example, the Nabarlek mine (Northern Territory) was high grade, but relative low tonnage. In contrast, the Olympic Dam deposit has a very large tonnage but the uranium grade is relatively low. Although the uranium grade is low, Olympic Dam is a major copper and gold producer which offsets the cost of mining uranium.

Some 9 per cent of Australia's RAR are classified as inaccessible for mining. All uranium deposits in Queensland are classified as inaccessible resources because of the state government's policy banning uranium mining. In the Northern Territory, the Jabiluka and Koongarra deposits are currently classified as inaccessible resources, as approval from Traditional Owners is required before these deposits can be developed.

There are several major undeveloped deposits that may be developed if proven economically feasible and all necessary approvals are granted. Table 6.5 summarises the total ore reserves and mineral resources of the main undeveloped deposits as reported by resources companies.

Uranium market

Production

Currently, Australia has three operating mines, Energy Resources of Australia's Ranger open pit mine in the Northern Territory, BHP Billiton's Olympic Dam underground mine and Heathgate Resources' Beverley ISR mine in South Australia. In addition, there are two ISR mines, Alliance Resources' and Quasar Resources' Four Mile and Uranium One's Honeymoon, expected to be producing in 2010.

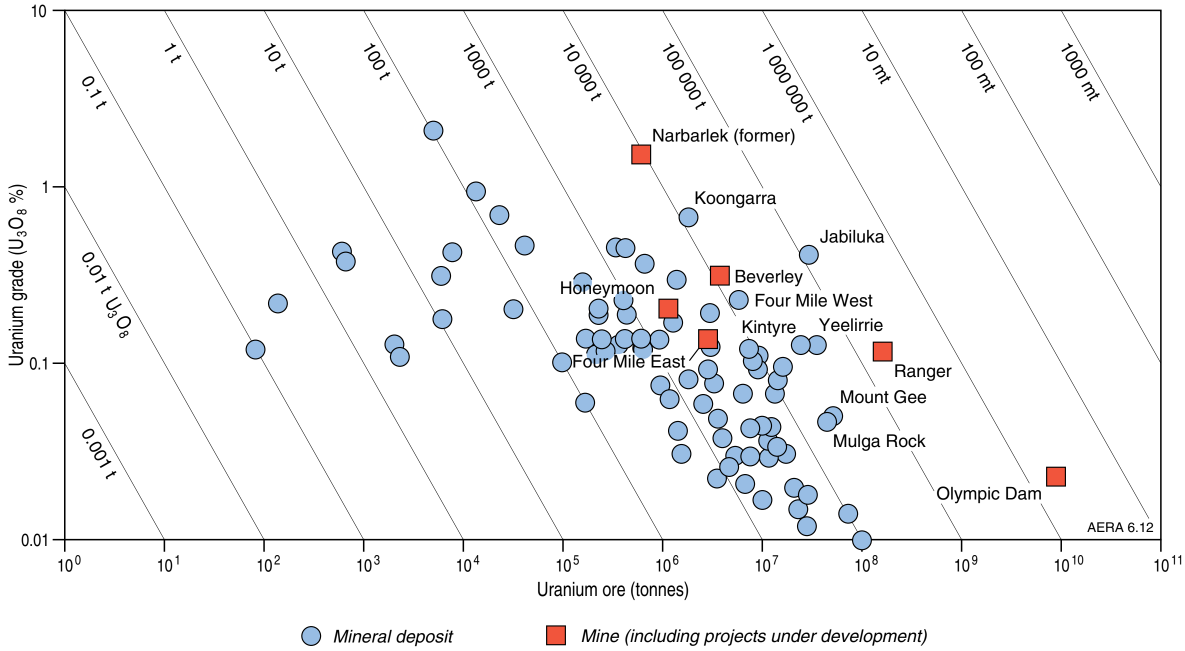

Figure 6.12 Australian mines and deposits (total resources, including past production and current remaining) by grade and tonnage

Source: Geoscience Australia

Table 6.5 Major undeveloped uranium deposits in Australia

Deposits	Ore reserves	Mineral resources
	contained U_3O_8 (kt)	
Northern Territory		
Jabiluka 2	67.70	73.94
Koongarra	14.50	
Bigrlyi	-	10.59
Angela	-	9.89
South Australia		
Mt Gee	-	31.30
4 Mile West	-	15.00
Crocker Well & Mt Victoria	-	6.74
Queensland		
Valhalla	-	25.90
Westmoreland (Redtree, Junnagunna, Huarabagoo, Sue & Outcamp)	-	23.62
Western Australia		
Yeelirrie	-	56.53
Kintyre	-	31.90
Mulga Rock	-	24.52
Manyingee	-	10.90
Oobagooma	-	9.95
Centipede-Millipede-Abercombie	-	5.04
Lake Maitland	-	8.32
Total	**82.20**	**344.14**

Note: Ore reserves and mineral resources are company estimates

Source: Geoscience Australia

In 2008, Australia was the world's third largest uranium producer, accounting for 19 per cent of world production. Australia produced around 4872 PJ (8.7 kt U) in 2008–09 from three operating mines. Ranger accounted for 54 per cent of Australian mine production while Olympic Dam produced 40 per cent and the Beverley operation accounted for around 6 per cent of Australia's uranium production.

Between 1954 and 1971, Australia produced a total of about 7.7 kt U from five mines: Radium Hill (South Australia), Mary Kathleen (Queensland), Rum Jungle (Northern Territory) and two sites in the South Alligator Valley (Northern Territory). The mines were developed to satisfy contracts with the United Kingdom Atomic Energy Authority and the Combined Development Agency, a joint United Kingdom and United States uranium purchasing agency. These mines were closed after fulfilling their contracts.

Increasing prices in the early 1970s as a result of improved demand for uranium for energy purposes led to the reopening of Mary Kathleen in 1975 and the opening of two new mines in the Northern Territory, Queensland Mines' Nabarlek mine and Energy Resources of Australia's Ranger mine, in 1979 and 1980 respectively (figure 6.13). Australian mine production increased strongly until the mid 1980s when both Nabarlek and Mary Kathleen mines were closed. The Olympic Dam operation, a major new mine in South Australia, commenced production in 1988, and offset some of the mine closures. However, reduced demand for uranium as a result of increased availability of secondary supplies resulted in Australia's uranium production declining until the mid-1990s.

Australian uranium production has expanded strongly over the past 10 years as producers have responded to growing export demand. South Australia has contributed to most of this growth, reflecting the expansion at Olympic Dam in 1999 and the development of the Beverley mine in 2001. Capital expenditure on the Beverley mine was A$30 million; it has a capacity of 1 kt U_3O_8 per year. The 1999 Olympic Dam expansion had a capital cost of nearly A$2 billion, which increased the capacity of the mine

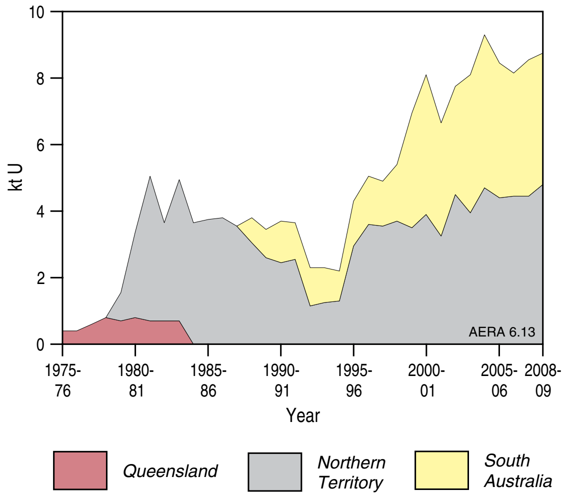

Figure 6.13 Australian uranium production, by state

Source: ABARE 2009c

to 4.3 kt U_3O_8 per year (table 6.6), together with increased copper and gold production. Production at the Ranger mine in the Northern Territory has also contributed to higher production over this period. The addition of a radiometric sorter and laterite processing plant in 2008 and 2009 respectively will support higher production at the Ranger operation in the future.

Consumption

Australia does not consume any of its locally produced uranium. A small amount of low enriched uranium is imported for use at Australia's Nuclear Science and Technology Organisation's (ANSTO) Lucas Heights OPAL research reactor. The research reactor provides medical isotopes for nuclear medicine and treatment, scientific research and irradiation of industrial materials. In 2008, Australia's consumption of uranium totalled less than 100 kg of low enriched uranium (ASNO 2009).

Trade

Australia exports all its uranium (figure 6.14) to countries within its network of bilateral safeguards agreements, which ensure that it is used only for peaceful purposes and does not enhance or contribute to any military applications.

Table 6.6 Recent developments at current Australian mines

Project	Company	State	Start up	Production capacity kt U_3O_8/ year	Capital Expenditure A$m (nominal)
Olympic Dam 1999 expansion	BHP Billiton	SA	1999	4.3	1940*
Beverley ISR mine	Heathgate Resources	SA	2001	1.0	30
Ranger radiometric sorting plant	Energy Resources of Australia	NT	2008	1.1	19
Ranger laterite plant	Energy Resources of Australia	NT	2009	0.4	44

*Capital expenditure covers total expansion of copper-gold-uranium-silver mining

Source: ABARE

Table 6.7 Australia's uranium exports to end-users, 2008

	U_3O_8 kt	Share of total %
United States	4.381	45.3
Japan	2.281	23.6
France	1.015	10.5
Republic of Korea	0.387	4.0
Sweden	0.340	3.5
China	0.313	3.2
Canada	0.256	2.7
Taiwan	0.243	2.5
United Kingdom	0.171	1.8
Spain	0.107	1.1
Finland	0.092	1.0
Germany	0.076	0.8
Total	**9.662**	**100.0**

Source: ASNO 2009

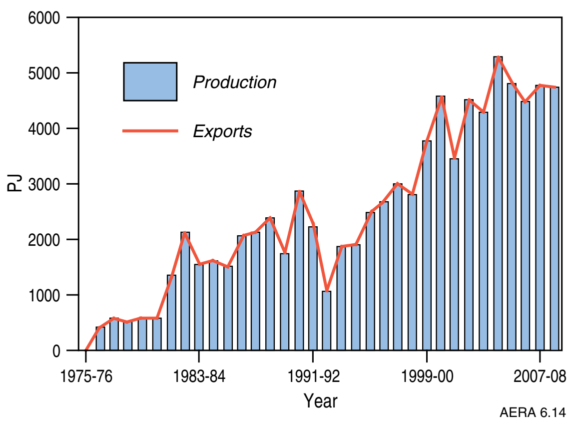

Figure 6.14 Australia's uranium supply-demand balance

Source: ABARE 20009b

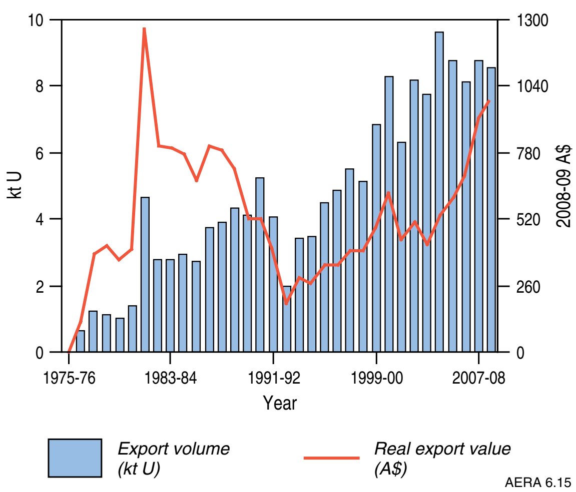

Figure 6.15 Australia's exports of uranium

Source: ABARE 2009c

Australian mining companies supply uranium under long-term contracts to electricity utilities in United States, Japan, China, the Republic of Korea, Taiwan and Canada as well as members of the European Union including the United Kingdom, France, Germany, Spain, Sweden, Belgium and Finland. In 2008, Australia's largest uranium export destination was the United States (45 per cent of total exports), followed by Japan (24 per cent) and France (10 per cent) (table 6.7). Australia's uranium exports contain sufficient energy to generate more than twice Australia's current annual electricity demand (Commonwealth of Australia 2006a).

In 2008–09, Australia exported 4805 PJ (8.58 kt U) valued at $1033 million (ASNO 2009). This was 13 per cent higher than in 2007–08 ($914 million in 2008–09 dollars) despite a modest decline in export volumes. The value of Australia's uranium export earnings has increased significantly over the past 15 years, reflecting growth in both export volumes and prices (figure 6.15; ABARE 2009a, b).

Uranium is commonly traded through long term contracts which are negotiated in both price (spot and long term) and quantity terms. In Australia, uranium producers sell most of their production through these long term contracts. Only a small amount of Australian uranium is sold on the world spot market. Historically, secure contract prices have been negotiated for long time periods. More recently an industry trend of indexing contract prices to spot prices has emerged, although most of Australia's current long term contracts do not have these provisions.

As most trade is conducted through long term contracts, the uranium spot market is illiquid (small number of buyers and sellers) which can lead to volatility in prices. Reflecting this, the average export price for Australian uranium producers has been considerably less volatile than the spot price in recent years (figure 6.16). In late 2008, the spot price was also influenced by the development of a futures market resulting in speculative purchases of uranium by investment companies.

In the future, it is likely that an increasing number of Australian producers will sell their production on the spot market, reflecting the small size of many of the planned uranium operations. If this occurs, Australian uranium producers may be exposed to increased volatility in export earnings. It is also possible that future long term contracts may be linked to spot prices, further contributing to income volatility.

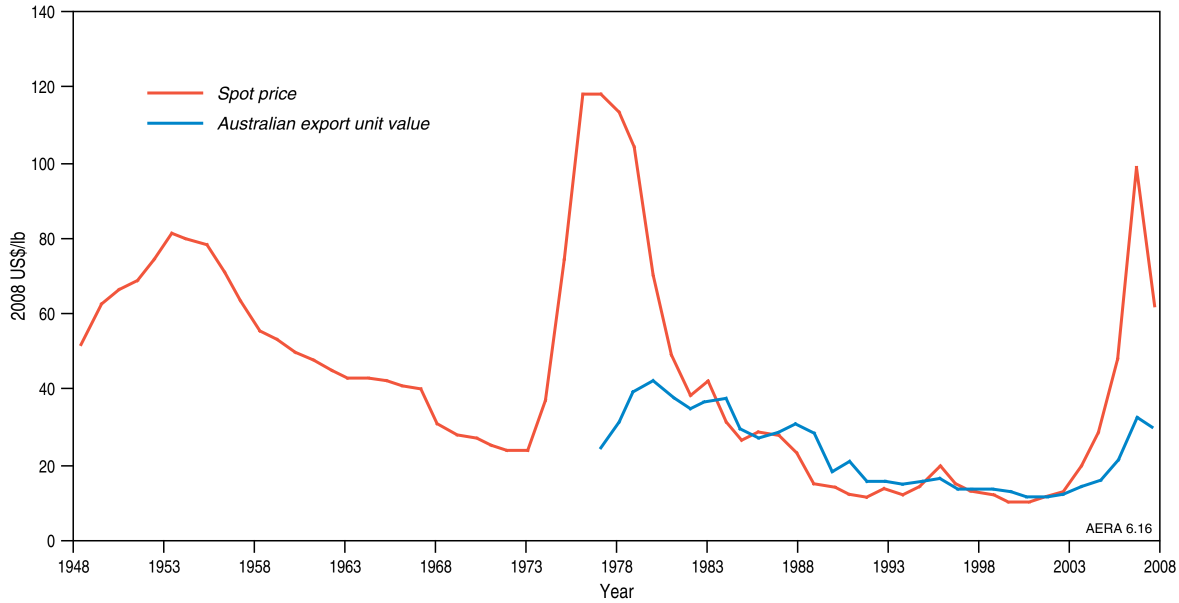

Figure 6.16 Uranium spot prices and average Australian export unit prices

Source: ABARE 2009c; Ux Consulting 2009

6.2.3 Outlook to 2030 for Australia's resources and market

The outlook to 2030 is based on Australia continuing to be a major producer and exporter of uranium as nuclear fuel to world markets. There are no plans for Australia to have a commercial nuclear power industry or enrichment facilities; all of Australia's uranium production will continue to be exported. There is renewed interest worldwide in nuclear power. Demand for reliable supplies of uranium will therefore grow to meet the continued expansion of electricity generation from nuclear power.

Australia has the largest uranium resources in the world. There are several significant known but undeveloped deposits, and there is a strong likelihood of new resource discoveries from the exploration of prospective areas currently under way.

In the medium to long term, Australia's production of uranium is expected to increase significantly, reflecting Australia's large low cost uranium resources, proposed new mines and increasing export demand.

Australia's uranium production is projected to more than double from 4872 PJ (8.7 kt U) in 2008–09 to 11 760 PJ (21 kt U) by 2029–30.

Key factors influencing the outlook

A report to government on uranium mining, processing and nuclear energy in Australia (Commonwealth of Australia 2006a) noted that Australia was 'well positioned to increase production and export of uranium to meet market demand' and that 'downstream steps of uranium conversion, enrichment and fuel fabrication could add a further A$1.8 billion of value annually if Australian uranium was processed domestically'. The report noted however that there were commercial, technology and regulatory impediments to downstream processing.

The report also considered issues associated with the potential development of nuclear power in Australia and concluded that even if the current legislative impediments were removed it would be at least 10 years and most likely 15 years before nuclear electricity could be delivered. By then, Generation IV reactors, which use uranium more efficiently, result in less waste and are less conducive to nuclear weapon proliferation, are likely to be the industry standard.

World demand for uranium as a nuclear fuel is expected to continue to grow with the expansion of nuclear power worldwide. The factors that will influence demand include:

- Commitment to greenhouse gas emissions reduction targets,
- Increased demand for low emission electricity generation provided by nuclear power,
- Increased demand for new reactors that provide greater security and safety, generate less radioactive waste and are more resistant to nuclear weapon proliferation, and
- Conversely, increased efficiency of these reactors, which may constrain the expected growth in uranium demand through more efficient use of uranium and the ability to use reprocessed nuclear fuel.

As a reliable and secure supplier of uranium to the world market, Australia is well placed to meet a significant proportion of any increased demand for uranium for use as an energy resource. Any expansion of Australian uranium production and exports to meet this demand will be influenced by several factors, including;

- significant potential for new uranium discoveries,
- undeveloped deposits that are capable of being developed at low cost,
- limited port and shipping company options for export uranium, and
- uranium mining prohibitions in Queensland, New South Wales and Victoria.

Cost competitiveness – increased global competition

Australia is well placed to make a greater contribution to meeting the projected increase in global demand for uranium because of its large low cost uranium resources and the potential to develop projects at the lower portion of the cost curve. Australia is a reliable supplier of uranium, which is of strategic importance to utilities.

The capital costs vary with mining method. In general, ISR operations are lowest cost, with underground and open pit mines being more expensive per tonne of uranium produced. For an operation of comparable size, open cut mining may be less capital intensive than underground mining. However, large scale bulk underground operations that achieve economies of scale can be comparable to open cut operations.

Conventional open cut and underground mining is the most common extraction technique in the uranium industry, accounting for around 72 per cent of world uranium production, with ISR accounting for the remaining 28 per cent (WNA 2009b).

The differences in cost are dependent in part on ore grade and type, infrastructure requirements, and economies of scale. Operating costs are dependent on the metallurgical process required to produce U_3O_8. Uranium deposits comprising uraninite typically have a relatively simple acid leach metallurgy process with estimated production costs of US$15–30 per pound U_3O_8. Calcrete deposits commonly require alkali leach and can have higher production costs of US$35–50 per pound U_3O_8 (TORO Energy Limited 2008).

Cost pressures have influenced the development of uranium mines. In 2007 and 2008, input costs increased dramatically, reflecting rising costs for fuel, labour, power and acid for processing. Recently there has been some indication that cost pressures have eased in the mining sector following the global economic downturn, with the price of major inputs declining. However, this fall may be only short-lived, with cost pressures likely to return once demand for energy and mineral commodities returns.

A further factor which may increase the cost of developing a mine is the site itself – the more remote and difficult the location, the higher the infrastructure costs (Schodde and Trench 2009).

In general, the next generation of uranium development projects worldwide will be lower average grade and of smaller deposit size than the currently operating mines. Many existing mining operations are planning expansions, which may result in new development projects being deferred until mines close or demand grows significantly. Expansions of existing mines are generally less capital intensive than greenfield projects.

Over the past decade, growth in new uranium mines has been slow and concentrated in a small number of countries, mainly Kazakhstan, Namibia and Niger. Of the seven major mines developed since 2006, five were ISR developments (table 6.8).

ISR mines tend to be smaller with a limited surface disturbance, hence capital costs are lower than conventional mines reflecting reduced infrastructure requirements. However, ISR is only suitable for deposits in sandstones which are water saturated and in which the mining solutions can be contained. It is estimated sandstone hosted uranium deposits account for approximately 20 per cent of world uranium resources and 7 per cent of Australia's total uranium resources (OECD/NEA and IAEA 2008).

Table 6.8 Uranium projects completed recently worldwide

Project	Location	Mining method	Commenced production	Capacity kt U_3O_8/year	Capital cost US$m (nominal)	Unit cost US$/t U_3O_8 (nominal)
Kayelekera	Malawi	Open cut	2009	1.65	167	101 212
Irkol	Kazakhstan	ISR	2009	0.88	-	-
Kharasan (1 & 2)	Kazakhstan	ISR	2009	5.9	430	72 931
West Mynkuduk	Kazakhstan	ISR	2008	1.18	-	-
Moinkum (Muyunkum)	Kazakhstan	ISR	2006	0.59	90	152 542
Langer Heinrich	Namibia	Open cut	2006	1.18	120	101 781
Zarechnoye	Kazakhstan	ISR	2006	1.18	60	50 891

Note: ISR = in situ recovery. Capacity is the nominal target production capacity
Source: WNA Country briefs

Table 6.9 Costs of Australian ISR uranium projects

Project	State	Production commencement	Capacity kt U_3O_8/year (nominal)	Capital cost A$m	Unit cost A$/t (nominal)
Beverley	SA	2000	1.00	58	58 000
Four Mile*	SA	2010	1.36	112	82 400
Honeymoon	SA	2010	0.40	118	295 000

* Four Mile operation is using the processing facilities at Beverley
Source: ABARE

In Australia, there is one operating ISR mine (Beverley) and two ISR projects approved for development (table 6.9). Capital costs per unit of production vary considerably between these three projects reflecting the time of construction. The Four Mile ISR project has an expected capital cost per tonne of capacity of A$82 400. The low unit cost of the Four Mile operation is because the mined material will be processed at the nearby Beverley operation. In contrast, the Honeymoon operation has an expected capital cost of A$295 000 per tonne of capacity, reflecting the additional cost of constructing a processing facility.

The time and cost of the approval process is an additional factor in development costs. In Australia, new and expanding uranium mines require environmental and development approvals prior to any development occurring. The approval process period for the development of a uranium mine can be lengthy and costly if it is not well managed. Companies are required to provide a detailed environmental assessment for a uranium development proposal, which is assessed by both Australian and state/territory governments before approval to develop is granted. As demonstration of the detail involved in this process, BHP Billiton recently released an Environmental Impact Statement (EIS) for the proposed Olympic Dam expansion, which is a three stage project from a current production of 4.3 kt to 19 kt per year of U_3O_8. Reflecting the complexity of the expansion and changes to project configuration, the EIS took the company nearly five years to complete. The approval process is expected to take at least another year. In contrast, the small Four Mile ISR project (South Australia) producing 1.36 kt U_3O_8 per year will take less than five years from discovery to production, which reflects, in part, the type of mine and the fact that the operation will use pre-existing processing facilities at the adjacent Beverley mine.

Secondary supply – continues to fill demand

The uranium requirement for nuclear reactors is currently met from both mined uranium and secondary supply. Secondary supply from blending down highly enriched uranium (HEU) is expected to decline from 2013 (figure 6.8), but uranium from reprocessed nuclear fuel may play an important role in supplying uranium to met demand.

According to Euratom, reprocessing is an attractive option, both environmentally and economically (Euratom Supply Agency 2009). Euratom considers that the process not only provides secondary supply (referred to as reprocessed uranium, or RepU) but also reduces the volume, and level of radioactivity of high-level waste material. It also reduces the possibility of plutonium being diverted from civilian use. Technically, at least, recovered uranium and plutonium can be recycled as fresh fuel, with a potential saving of up to 30 per cent of the natural uranium that would otherwise be used.

Almost 90 kt (of the 290 kt discharged) of used fuel from commercial power reactors has been reprocessed. There are reprocessing plants in France, Japan, the Russian Federation and the United Kingdom. Annual reprocessing capacity is now some 4 kt per year for normal oxide fuels. Between 2009 and 2030 around 400 kt of used fuel is expected to be generated worldwide, which is a potential secondary source (WNA 2009e).

Technology developments – new generation of nuclear reactors

At at October 2009, there were 436 nuclear power reactors in operation in 30 countries requiring around 65 kt U per year. There are 53 reactors under construction in several countries including China, India, the Republic of Korea and the Russian Federation. Over 135 reactors are planned with approvals, funding or firm commitments in place; they are expected to be in advanced stages of construction, if not operating, within eight years. There are 295 further reactors proposed in over 30 countries. These proposals are expected to result in reactors in operation within 15 years (WNA 2009f). Altogether, there are about 483 reactors under construction, planned or proposed.

The nuclear power industry has been developing and improving reactor technology for more than five decades (box 6.1). Generation I prototype reactors were developed in the 1950s. Generation II reactors were developed as commercial reactors in the late 1960s, and are currently operating for electricity generation in most countries with nuclear power. Over the last 20 years many of these reactors have received extensions of operating licences from 40 to 60 years. In addition there have been increased operating efficiencies and improved maintenance which have resulted in increased capacity and electricity output. In the United States, the average capacity factor increased from 56 per cent in 1980 to over 90 per cent in 2002 (EIA 2009b). Worldwide, the average unit capacity factor from 2006 to 2008 was 82.4 per cent (IAEA 2009). Consequently, electricity generation has increased markedly over the two decades despite little increase in installed capacity.

Generation III (and III+) reactors incorporate improved fuel technology, thermal efficiency and passive safety systems. The first Generation III reactors have been operating in Japan since 1996. Generation III reactors are currently being built (and planned to be built) in many countries.

Generation IV reactors are still being designed and none have been built to date. The Generation IV International Forum, representing 13 countries, has selected six reactor technologies which will form the future of the nuclear power industry (box 6.1). Generation IV reactors will operate at higher temperatures (in the range 500°C to 1000°C) than current commercial light water reactors (less than 300°C). The technology and design of these new reactors are aimed at:

- using passive safety features which require no active controls or operational intervention to avoid accidents in the event of malfunction;
- being more resistant to diversion of materials for weapons proliferation, and secure from terrorist attack;
- using the uranium fuel efficiently by using U^{238} and plutonium, as well as all the U^{235}; and using spent fuel from current commercial reactors;
- utilising uranium up to 60 times more efficiently; and
- greatly reducing amounts of high level radioactive waste compared with current reactors.

Generation IV reactors will have a lower demand for uranium due to the more efficient fuel burn and will minimise high level waste sent to repositories. These nuclear reactors will alter the nature and scale of high level radioactive waste (HLW) disposal by substantially reducing the volume of these wastes (Commonwealth of Australia 2006a). Less HLW and less heat generated from radioactive waste (compared with current spent fuel) will enable more effective use of geological HLW repositories. Current planning for HLW repositories in many countries is based on assessment of the amount of waste from current commercial reactors. This will be modified when Generation IV reactors become commercially viable and advanced fuel processing is successful. It is too early to determine which of the Generation IV technologies will be commercially adopted.

Best practice sustainable uranium projects

The Australian Government supports the development of uranium deposits in line with world's best practice environmental and safety standards. New uranium mines are subject to approval by the Australian and state/territory governments. Development of uranium mines is permitted in South Australia, Northern Territory, Western Australia and Tasmania. New South Wales and Victoria have legislated against uranium exploration and mining. Queensland government policy bans the development of uranium mines.

Uranium mining proposals involve integrated consideration under both the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) and state/territory legislation. Regulation of all mines in Australia focuses on the outcomes to be achieved and is largely the responsibility of state/territory authorities. The principles and approaches for all mining

BOX 6.1 GENERATION I TO IV REACTOR TECHNOLOGIES

Nuclear reactors have been in commercial operation since the 1950s with reactors evolving from early designs (Generation I) to five Generation II reactor designs which today account for most nuclear reactors operating in the world. Reactors currently under construction are Generation II and III (III+) reactors.

Generation III reactors have standardised more robust design with inherent safety features and higher 'burn-up' to maximise use of fuel and reduce the amount of waste created. The standardised design is reducing capital cost and construction time.

Generation IV reactors are currently in research and development and are not expected to be available for commercial construction before 2030. The goals of the Generation IV reactors are improved nuclear safety, proliferation resistance, increased fuel utilisation, minimised waste and decreased cost to build and operate. The six Generation IV systems selected for R&D are:

Gas-Cooled Fast Reactor (GFR) – a fast-neutron-spectrum, helium cooled reactor and closed fuel cycle;

Very-High-Temperature Reactor (VHTR) – a graphite-moderated, helium cooled reactor with a once-through uranium fuel cycle;

Supercritical-Water-Cooled Reactor (SCWR) – a high-temperature, high pressure water cooled reactor;

Sodium-Cooled Fast Reactor (SFR) – features a fast-spectrum, sodium-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides;

Lead-Cooled Fast Reactor (LFR) – features a fast spectrum lead of lead/bismuth eutectic liquid-metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides; and

Molten Salt Reactor (MSR) – uses a circulating molten salt fuel mixture with an epithermal-spectrum reactor and a full actinide recycle fuel cycle.

Nuclear reactors in operation

Table 6.10 provides an overview of the types of nuclear reactors currently in operation and under construction, followed by a summary of the features of the five common nuclear reactors types.

Pressurised Water Reactors (PWR) and Boiling Water Reactors (BWR) are collectively referred to as Light Water Reactors (LWR). These reactors are cooled and moderated using ordinary water (fresh or seawater). The designs are simpler and cheaper to build than other types of nuclear reactor, and they are likely to remain the dominant technology for the present.

Table 6.10 Nuclear reactors in operation or under construction, by reactor type, in 2009

	no.	GW(e)
Operational		
Pressurised Water Reactors	264	243.1
Boiling Water Reactors	92	83.7
Pressurised Heavy Water Reactors	44	22.4
Gas Cooled Reactors	18	8.9
Light Water Graphite-moderated Reactors	16	11.4
Fast Breeder Reactors	2	0.7
Total	**436**	**370.2**
Under Construction		
Pressurised Water Reactors	43	39.9
Pressurised Heavy Water Reactors	4	1.3
Boiling Water Reactors	3	3.9
Fast Breeder Reactors	2	1.2
Light Water Graphite-moderated Reactors	1	0.9
Total	**53**	**47.2**

Source: IAEA

Pressurised Water Reactors (PWR)

The PWR consists of a primary and a secondary circuit of water; both circuits are closed systems. The primary circuit contains pressurised water (to prevent it from boiling) which is heated to over 300°C as it moves through the reactor core. Once heated, water in the primary circuit circulates through heat exchangers which boil water in a secondary circuit. Steam produced in the secondary circuit drives a turbine to produce electricity – the water is then condensed and returned to the heat exchangers to be transformed back into steam. PWR are the most common nuclear reactors. There are 264 generating units currently in operation with a total capacity of 243.1 gigawatts electric (GWe).

Boiling Water Reactors (BWR)

BWR utilise a similar method to the PWR except that a single circuit is used to heat water and produce steam to generate electricity. Water in the circuit is maintained at a low pressure allowing it to boil at around 285°C. The water is condensed and returned to the core to be transformed back to steam. BWR have a less complicated design and are often cheaper to build; however this cost advantage is often offset by the increased costs incurred as a result of residual radiation on turbines. They are the second most common reactor design, accounting for around 21 per cent of the world's 436 nuclear reactors.

Pressurised Heavy Water Reactors (PHWR)/CANDU reactors

The PHWR or CANDU reactors are designed to use low enriched uranium directly as a fuel. The PHWR use a similar design to the PWR with a reaction in the core heating a coolant in a primary circuit which is then used to boil water in a secondary circuit. The PHWR differ from the PWR in that heavy water (water containing deuterium) is used as a coolant. The fuel rods are cooled by a flow of heavy water under high pressure in the primary cooling circuit. The pressure tube design means that the reactor can be refuelled progressively without shutting down. Forty four PHWR are currently in operation (around 40 per cent in Canada) with a combined capacity of 22.4 GWe.

Gas Cooled Reactors (GCR) and Advanced Gas-cooled Reactors (AGR)

GCR are considered safer than traditional water cooled reactors as the cooling properties of gas do not change with temperatures. The GCR use natural uranium fuel and the AGR use an enriched uranium dioxide fuel. Carbon dioxide is used as coolant which circulates through the core, reaching 650°C before passing through a steam generator creating steam in a secondary circuit. In the 1980s, following the success of LWR, the United Kingdom made the decision to adopt LWR technology. As a result no gas cooled reactors have been built since.

Light water graphite-moderated reactors (LWGR)

The LWGR are Russian-designed, based heavily on the BWR. The design operates with enriched uranium dioxide fuel at high pressure and uses water as a coolant which is allowed to boil at around 300°C. This design can have a positive feedback problem that results in excessive heat being released from the core. For this reason there are no plans to build new LWGRs beyond the one currently under construction. Currently, 16 of these reactors are in operation in the Russia Federation and Lithuania.

Source: WNA 2009g, h

have helped achieve increased trust by stakeholders through a clear up-front agreement on the environmental outcomes to be achieved and a demonstration by the mining operator that environmental, social and economic elements of the project are being managed appropriately.

The Australian Government and the jurisdictions that currently permit uranium mining (South Australia, Northern Territory and Western Australia) are developing a national ISR uranium mining best practice guide, to ensure that ISR proposals represent best practice environmental and safety standards. The guide outlines and discusses the general principles and approaches that should apply to all mining in Australia, before considering ISR uranium mining more specifically.

With regard to radiation protection in mining, state and territory governments adopt the regulatory approach outlined in the Code of Practice and Safety Guide on Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005) produced by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

Sustainable growth of the uranium industry requires community engagement to communicate the environmental and safety practices built into the project and to demonstrate that there are effective regulatory controls. Engagement, consent and land use agreements with Indigenous communities are essential in areas where Indigenous groups hold rights over or interests in the land.

The Australia Government's Uranium Industry Framework (UIF) Steering Group was established in 2005 to identify opportunities for, and impediments to, the further development of the Australian uranium mining industry over the short, medium and longer term while ensuring world's best environmental, health and safety standards. An Implementation Group was established to progress the recommendations from the UIF Steering Group report (Commonwealth of Australia 2006b). The priorities to date include: development of a national radiation dose register for uranium workers; facilitating discussion of uranium exploration and mining issues with Indigenous communities; addressing concerns about the transport of uranium and instances of international shipping denials and delays; establishing nationally accredited radiation safety training programs; and reviewing regulation applying to the uranium industry.

Transportation issues

All Australian exports of radioactive material, such as U_3O_8, require an export permit. These are assessed by the Australian Government to ensure that Australia's uranium is exported to countries for peaceful purposes under Australia's network of bilateral safeguards agreements. Each shipment of uranium leaving Australia must be reported to the Australian Government and is tracked and accounted for in the international nuclear fuel cycle.

Any significant expansion of uranium exports will require improved access to transport options. Currently, uranium is exported from two ports, Darwin in the Northern Territory and Adelaide in South Australia.

In South Australia, uranium exports through the Adelaide port will continue to grow as planned projects such as Honeymoon and Four Mile commence shipping uranium through this port. In addition, the Olympic Dam Expansion plans to export uranium through both Adelaide and Darwin container ports with the uranium transported by train to both of these destinations.

Western Australian uranium production is likely to commence in the medium term with projects such as Yeelirrie and Kintyre potentially entering production. Current plans for uranium transport is by road to rail heads, loaded onto trains and transported to the Darwin or Adelaide ports for export.

Uranium oxide is classified as a Class 7 Dangerous Good which has specific handling and transport requirements. It is transported by rail, road and sea in 200 litre drums packed in secure shipping containers.

There are increased international transport constraints affecting Class 7 goods, such as the consolidation of the international shipping industry and associated reduction in scheduled routes, and reduction in ports where vessels carrying uranium can call or transit, even where this cargo remains on board. The consolidation of shipping firms and denial of routes result in increased delays and costs to the uranium industry. International transport issues, such as denial of shipping, are being progressed through the IAEA's International Steering Committee on Denial of Shipping.

Outlook for uranium resources

Uranium deposits are known in all states (except Victoria and Tasmania, which only have uranium occurrences) and Northern Territory. Favourable geological settings and limited exploration since 1980 mean that there is significant potential for discovering new deposits. New discoveries are likely to significantly increase Australia's resource base and encourage further exploration in surrounding areas.

Uranium exploration expenditure in Australia has increased since 2003 mainly because of the significant increases in spot market uranium prices, which reached a peak in July 2007 (US$136/lb U_3O_8) and subsequently declined during 2008 (figure 6.17).

In 2008, uranium exploration expenditure reached a record of A$220.5 million (ABS 2009a). The majority of expenditure was in South Australia (42 per cent), followed by the Northern Territory (26 per cent), Queensland (19 per cent) and Western Australia.

A large number of new companies have been floated in recent years specifically to explore for uranium.

World uranium exploration budgets in 2009 totalled US$664 million, down from US$1151 million in 2008. Australia received 26 per cent (US$175 million) making it the second largest after Canada which received 29 per cent (Metals Economics Group 2009). According to the Metal Economics Group there were 319 companies engaged in uranium exploration worldwide of whom 124 had active exploration in Australia.

Historically uranium exploration in Australia has been highly successful (figure 6.18). Of the 85 currently known uranium deposits in Australia, approximately 50 were discovered from 1969 to 1975 with another four discovered between 1975 and 2003. Annual expenditure on uranium exploration in Australia fell progressively for 20 years from the peak in 1980 until 2003 due to low uranium prices. The most recent significant discovery was the Four Mile deposit in South Australia in 2005, which is the first new uranium mine proposal to be approved by the Australian Government since 2001.

More recently, discoveries of new uranium deposits have not significantly increased Australia's resources. Growth in Australia's uranium resources in recent years has been largely due to ongoing delineation of resources at known deposits. The Olympic Dam deposit in South Australia has been the major contributor to increases in Australia's uranium resources since 1983.

The recent strong exploration activity saw the reporting of a number of intersections of economic interest, including in the Pine Creek area, Northern Territory and Frome Embayment, South Australia. Whether intersections of uranium result in a new deposit will depend on further exploration. The discovery of a deposit may not be acknowledged until some years later, after subsequent exploration work. For example the discovery year for the Olympic Dam deposit was 1975, but it was a few years later before the full significance of the discovery was appreciated; moreover, the published resources are still growing.

Discovery of new deposits takes time and requires considerable exploration expenditure. Exploration is an uncertain activity with only a small percentage of exploration expenditure leading directly to the discovery of an economic resource. However, exploration is important to developing new deposits and sustaining existing operations by replacing resources as deposits are mined. The price of uranium and future export demand are typically the most important factors affecting the level of expenditure in exploration as these factors influence the return on a deposit and the capital available to operations.

Not all discoveries result in mines. Recent studies found that less than half of the uranium discoveries made in the world since the 1970s have been developed into mines (R Schodde, personal communication 2009). A major factor for the high level of failed projects is the low grade and/or small size of these discoveries. Only the best projects are developed; the rest are placed in inventory waiting better prices or improved business conditions.

Australia has a rich uranium endowment that is related to the widespread occurrence of uranium enriched felsic igneous rocks (Lambert et al. 2005). Major

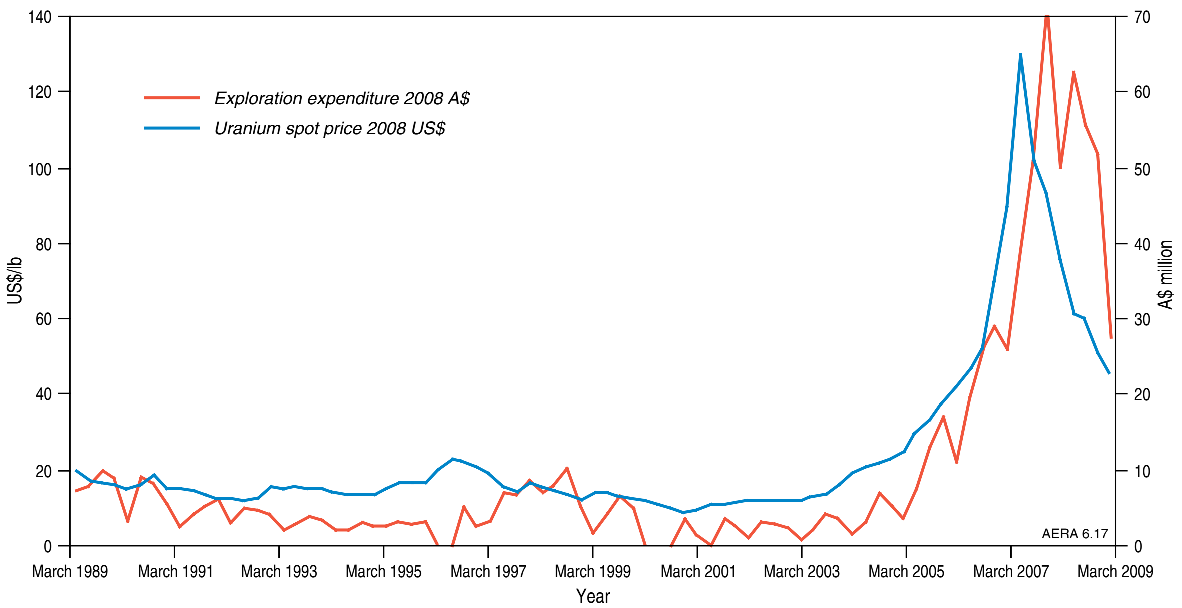

Figure 6.17 Australian exploration expenditure and uranium spot prices in real dollars

Source: ABS 2009a, Ux Consulting 2009. Note: Expenditure and spot prices are quarterly figures magmatic events during the Precambrian era (especially the Proterozoic) produced the greatest volumes of uraniferous igneous rocks, which are widespread in South Australia, Northern Territory and parts of Western Australia and Queensland. There is a clear spatial relationship between known uranium deposits and uranium-enriched bedrocks. While some uranium deposits, such as Olympic Dam, appear to have formed during these thermal events, most uranium deposits have formed from subsequent lower temperature processes that redistributed and concentrated the primary uranium to form new ore minerals.

In general, uranium mineralisation is younger than the spatially related igneous rocks. This is the case for sandstone, calcrete and unconformity related deposits that appear to have formed as a result of remobilisation of uranium from older-uranium enriched rocks. In particular, the Cainozoic calcrete deposits in the western part of the continent, including the large Yeelirrie deposit, are spatially related to the Archaean felsic rocks; and the unconformity related deposits are spatially associated with the Palaeoproterozoic to late Archaean felsic igneous rocks. Sandstone deposits are widely distributed in Australia. Those in the Frome Embayment, South Australia are believed to be derived from the adjacent exceptionally uranium-rich Proterozoic felsic rocks.

World uranium resources are dominated by sandstone, breccia complex and unconformity style deposits. Unconformity deposits are dominant in Australia and Canada. Australia has the world's largest resources of uranium recoverable at low cost, principally in the Olympic Dam hematite breccia deposit and the unconformity-related deposits of Ranger and Jabiluka. Major sandstone hosted uranium resources are known in Kazakhstan and the United States. Australia has only a small proportion of the world's resources in sandstone type deposits. In addition, uranium deposits related to magmatic processes appear under-represented in Australia given the abundance of uranium-rich igneous rocks (Skirrow et al. 2009).

There are no published estimates for Australia's undiscovered uranium resources. Geoscience Australia has undertaken a preliminary assessment of specific undiscovered uranium deposits related to sedimentary basins, such as unconformity and sandstone hosted deposits. This quantitative assessment for undiscovered uranium deposits was based on uranium ore density distribution in sedimentary basins that have the necessary geological features to form unconformity and sandstone type deposits. The assessment does not include the hematite breccia complex or calcrete deposits, which currently account for about 65 per cent and 5 per cent of Australia's uranium resources respectively.

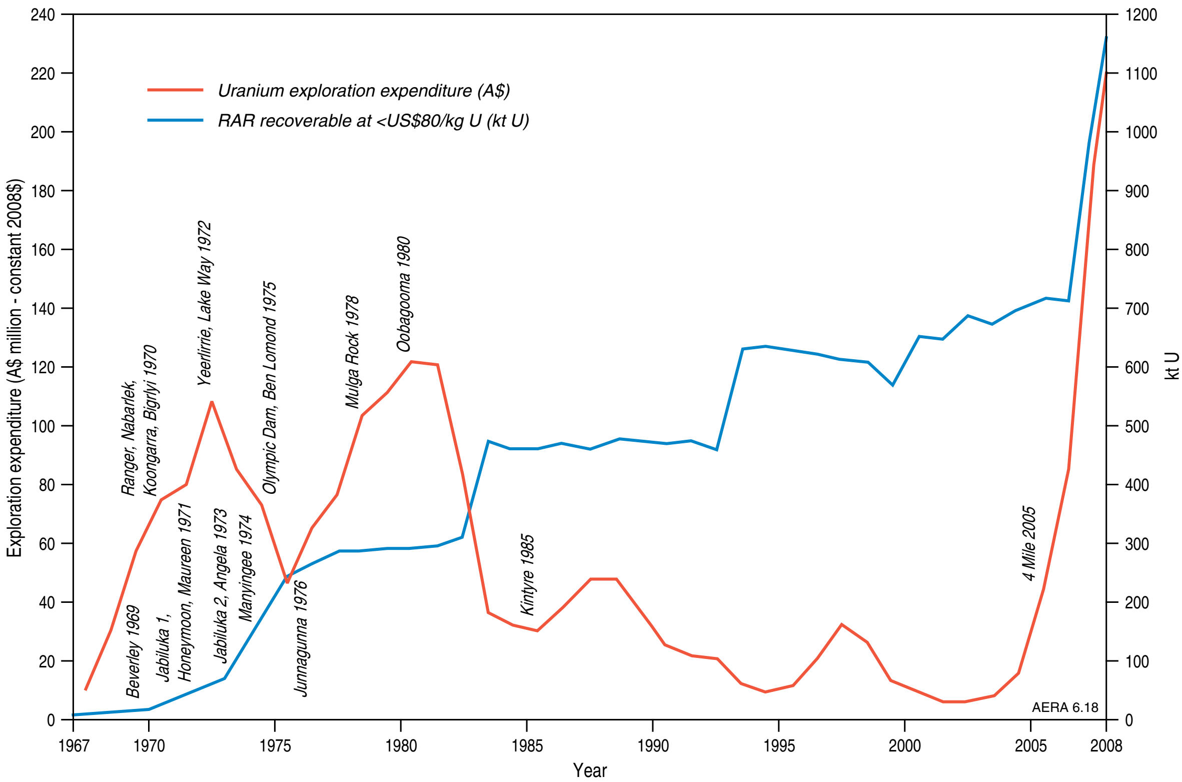

Figure 6.18 Australia's annual uranium exploration expenditure, discovery of deposits and growth of uranium resources

Source: Geoscience Australia

Geological settings considered favourable to host unconformity-related deposits, such as the Ranger deposit, exist in other areas in the Northern Territory and Western Australia. A quantitative assessment for those basins with all of the necessary geological features suggest that there is a 50 per cent probability that these basins contain up to 400 kt of undiscovered U_3O_8 in unconformity-related deposits.

Australia has many large sedimentary basins, many of which have had only limited or no exploration for sandstone hosted uranium deposits. The known paleochannel sandstone hosted deposits are located in about 3 to 5 per cent of known paleochannels which means some 95 percent of paleochannels are unexplored and considered favourable for uranium mineralisation. It is reasonable to conclude that there is high potential for discovery of significant further sandstone hosted uranium resources in Australia. Recent intensive exploration has resulted in new discoveries such as Four Mile and Pepegoona (Beverley North) deposits in the Frome Embayment area, South Australia.

A quantitative assessment of suitable basins to host sandstone type deposits suggest that even if 10 per cent of the suitable basins were prospective there is a 50 per cent chance that these basins contain up to 370 kt U_3O_8 in sandstone type deposits.

Regional and national assessments being undertaken as part of the Australian Government's Onshore Energy Security Program (OESP) are scheduled to finish in mid 2011 (Geoscience Australia 2007). The OESP is aimed at boosting investment in exploration, especially in greenfield areas, by delivering reliable, pre-competitive geoscience data. There are several outputs being delivered, some of which include:

- the radiometric map of Australia, which facilitates rapid assessment of uranium prospectivity from the national scale through to the local scale;
- geochemical survey of Australia, which provides a nation-wide dataset on the geochemical composition of surface and near-surface materials;
- airborne electromagnetic (AEM) surveys, seismic acquisition and processing in under-explored areas that are considered to have potential for uranium and thorium mineralisation; and
- developing a new understanding of uranium mineralisation processes.

Outlook for uranium market

Uranium supply-demand balance

In the medium to long term, Australia's production of uranium is expected to increase significantly, reflecting Australia's large low-cost uranium resources, proposed new mines and increasing world demand for uranium. World demand is projected to grow strongly over the outlook period given the projected strong growth in world nuclear electricity generation. Given that there are no plans for Australia to have a commercial nuclear power industry or enrichment facilities prior to 2030, all of Australia's uranium production will continue to be exported (figure 6.19).

In the medium term, Australia's mine production is forecast to increase by around 8 per cent per year to reach 6170 PJ (11 kt U) by 2014–15 (ABARE 2010). Potential growth in uranium production is expected to come from Four Mile, Honeymoon, Oban and Crocker Well projects in South Australia and Yeelirrie, Kintyre, Lake Maitland and Wiluna uranium projects in Western Australia. In addition, plans are underway to expand underground operation at the existing Olympic Dam mine.

Based on planned projects and the likelihood of additional currently less advanced projects (discussed further below) entering production before 2030, ABARE projects Australian uranium

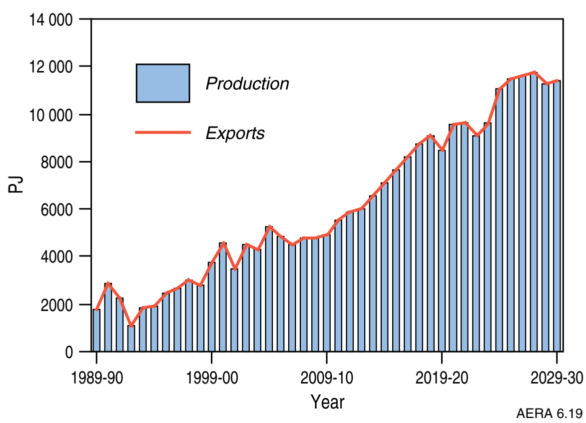

Figure 6.19 Projection of Australia's uranium supply-demand balance to 2029–30

Source: ABARE

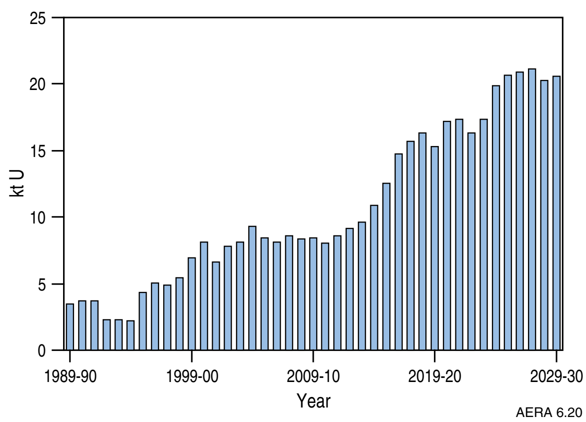

Figure 6.20 Projection of Australia's uranium production to 2029–30

Source: ABARE

193

mine production will increase at an average annual rate of 12 per cent to around 11 760 PJ (21 kt U) by 2029–30 (figure 6.20). It should be noted that only uranium projects that have progressed to, or beyond, a pre-feasibility stage of development are included in this figure. Although other projects are likely to enter production over this period, they have not been included given the limited nature of information available on these projects. Projects that are likely to contribute most notably to this growth include the phased expansion of Olympic Dam and the development of Yeelirrie in Western Australia which collectively could add as much as 20 kt U to Australia's existing uranium mine capacity.

Australia's uranium exports are projected to increase in line with higher production, reaching 11 760 PJ by 2029–30.

Uranium project developments in Australia

Australia has a large number of uranium mining projects planned to enter production over the next decade (table 6.11, box 6.2). If all of these projects are realised, Australian uranium mine production capacity has the potential to increase from around 8.5 kt U per year up to 21.5 kt U by 2020–21. The supply forecasts are based on current reported resources. In practice, it is highly likely that additional ore reserves will be found and mine lives extended and possibly expanded. Figure 6.21 illustrates this potential growth in mine capacity, assuming all projects begin production at times announced by project developers. It should be noted that some of these projects will not be realised in the time frame announced; this is taken into account in ABARE's uranium production projections presented in figures 6.19 and 6.20.

Table 6.11 Uranium development projects

Project	Company	Location	Status	Scheduled production start	Capacity kt U_3O_8/ year (nominal)	Capital A$m (nominal)
Honeymoon ISR	UraniumOne/ Mitsui	NE of Adelaide, SA	Under construction	2010	0.4	118
Four Mile ISR	Alliance Resources/ Quasar Resources	N of Adelaide, SA	Mine development approved	2010	1.36	112
Ranger pit extension	Energy Resources of Australia	E of Darwin, NT	Put on hold while alternative options are considered	2011	na	57
Olympic Dam expansion stage 1 - optimisation	BHP Billiton	Roxby Downs, SA	EIS under way	2016	4.5	na
Olympic Dam expansion stage 2	BHP Billiton	Roxby Downs, SA	EIS under way	2018	14.5	na
Olympic Dam expansion stage 3	BHP Billiton	Roxby Downs, SA	EIS under way	2021	19	na
Oban ISR	Curnamon Energy	N of Cockburn, SA	EIS under way	2010	0.2	na
Yeelirrie	BHP Billiton	N of Kalgoorlie, WA	EIS under way	2014	5	na
Crocker Well and Mount Victoria	Pepinnini Minerals/ Sino Steel	W of Broken Hill, SA	Feasibility study under way	2011	0.4	160
Bigrlyi	Energy Metals/ Paladin Energy	NW of Alice Springs, NT	Pre-feasibility study under way	2012	0.6	70
Wiluna (Centipede-Lake Way)	Toro Energy	SE of Wiluna, WA	Pre-feasibility study completed	2013	0.73	162
Valhalla	Summit Resources/ Paladin Resources	N of Mt Isa, Qld	On hold	na	Initially 2.7 Increasing 4.1	400
Lake Maitland	Mega Uranium / JAURD / Itochu	SE of Wiluna, WA	Scoping study completed	2012	0.75	102
Mt Gee	Marathon Resources	NE of Leigh Creek, SA	Scoping study completed	2013	1	400
Westmoreland	Laramide Resources	NW of Burketown, Qld	On hold	na	1.36	317

Source: ABARE 2009d

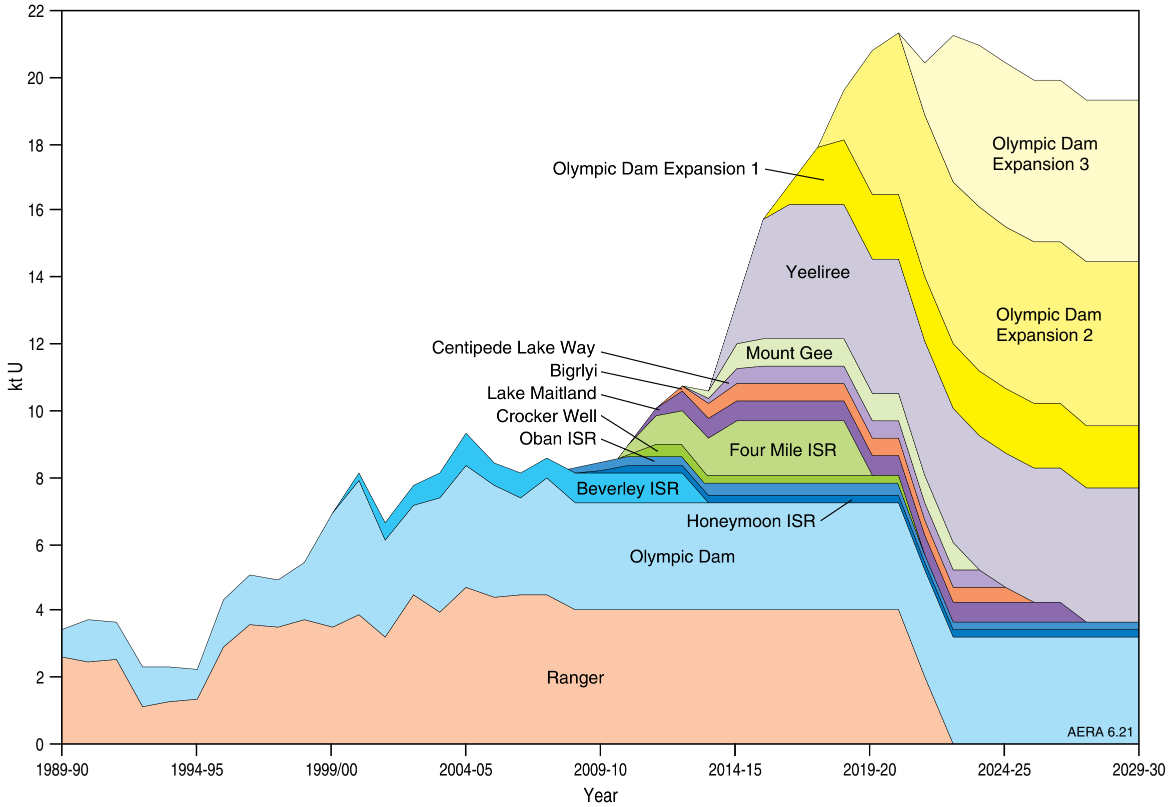

Figure 6.21 Potential Australian uranium mine capacity

Source: ABARE

BOX 6.2 URANIUM PROJECT DEVELOPMENTS IN AUSTRALIA

Projects that are expected to enter production during 2010 include Four Mile and Honeymoon operations in South Australia. Alliance Resources and Quasar Resources, a wholly owned subsidiary of Heathgate Resources, plan to develop the Four Mile ISR mining operation with the resin trucked 8 km to Heathgate Resources' Beverley plant for recovery of uranium (table 6.11). Production is scheduled to commence in 2010 with a projected production rate of 1.36 kt U_3O_8 per year. Uranium One's Honeymoon ISR operation is planned to commence production in mid 2010. The operation is expected to produce 0.4 kt U_3O_8 per year with a six year mine life. In addition, Curnamona Energy is undertaking ISR field leach trials at the small Oban deposit (65 km north of Honeymoon mine) and plans to be in commercial production in late 2010.

Of the major uranium projects planned, BHP Billiton's proposed Olympic Dam expansion is the largest. The proposed expansion will increase uranium production from the current capacity of 4 kt U_3O_8 per year to approximately 19 kt U_3O_8 per year. This expansion is based on a very large open pit to mine the south-east portion of the deposit. Mining of ore from the open pit is currently scheduled to commence in 2016.

Energy Resources of Australia Ltd (ERA) is planning to construct a heap leach facility to process existing low-grade ore at its Ranger operations in the Northern Territory. A 10 million tonnes per year dynamic heap leach facility will be constructed to recover about 15–20 kt U_3O_8 contained in low grade mineralised material. The leach solutions will be treated in a process similar to that used in the existing Ranger plant. In January 2009, ERA announced the discovery of a very significant ore body at depth adjacent to the current Ranger 3 operating pit. The company is planning an underground exploration drilling program to evaluate the extent and continuity of the ore body. A planned pit expansion has been put on hold while the underground option is explored.

6.3 Thorium

6.3.1 Background information and world market

Definitions

Thorium (Th) is a naturally occurring slightly radioactive metal, three to five times more abundant than uranium. The most common source of thorium is a rare earth phosphate mineral, monazite (WNA 2009i).

Thorium is a potential future nuclear fuel through breeding to U^{233}. Thorium has the potential to generate significantly more energy per unit mass of thorium than uranium (WNA 2009h).

Historically there has been only one commercial scale thorium-fuelled nuclear plant – the Fort St Vrain reactor in the United States that operated between 1976 and 1989. It was a high-temperature (700°C), graphite-moderated, helium-cooled reactor with a thorium/HEU fuel designed to operate at 330 megawatt electric (MWe) capacity. Almost 25 tonnes of thorium was used in fuel for the reactor (WNA 2009i).

Currently, there are no commercial scale thorium-fuelled reactors in the world and therefore no demand for thorium as a fuel. Any future large-scale commercial demand for thorium resources will depend on development of economically viable thorium-fuelled reactors.

Thorium supply chain

Figure 6.22 provides a representation of the potential thorium supply chain in Australia. As with uranium, the supply chain is divided into four distinct processes: resources exploration; development and production; processing transport and storage; and end use markets.

As most of the thorium resources in Australia are in known heavy mineral sand deposits, thorium production could be initiated with the recovery of thorium and rare earth elements from the monazite in operating heavy mineral sand mines without the need for an exploration phase.

World thorium market

Currently, there are no commercial scale thorium-fuelled reactors. However research continues in countries with abundant thorium but little uranium resources.

Resources

Thorium resources are categorised according to the OECD/NEA-IEA classification scheme. OECD/NEA-IAEA published in 2008 estimates of thorium resources on a country-by-country basis. The estimates are subjective because of variability in the quality of the data, much of which is old and incomplete. Table 6.12 has been derived by Geoscience Australia from information presented in the OECD/NEA-IAEA analysis. The total Identified Resources refer to RAR plus Inferred Resources recoverable at less than US$80/kg thorium (US$80/kg Th).

World RAR of thorium recoverable at less than US$80/kg Th are estimated at 1.2 million tonnes, with total Identified Resources estimated at 2.6 million tonnes (OECD/NEA-IAEA 2008). However, in the absence of large scale demand for thorium, there is little incentive to undertake further work to convert Inferred Resources to RAR.

Australia's total recoverable Identified Resources of thorium amount to 490 kt (Geoscience Australia 2009), nearly one-fifth of total world identified thorium resources.

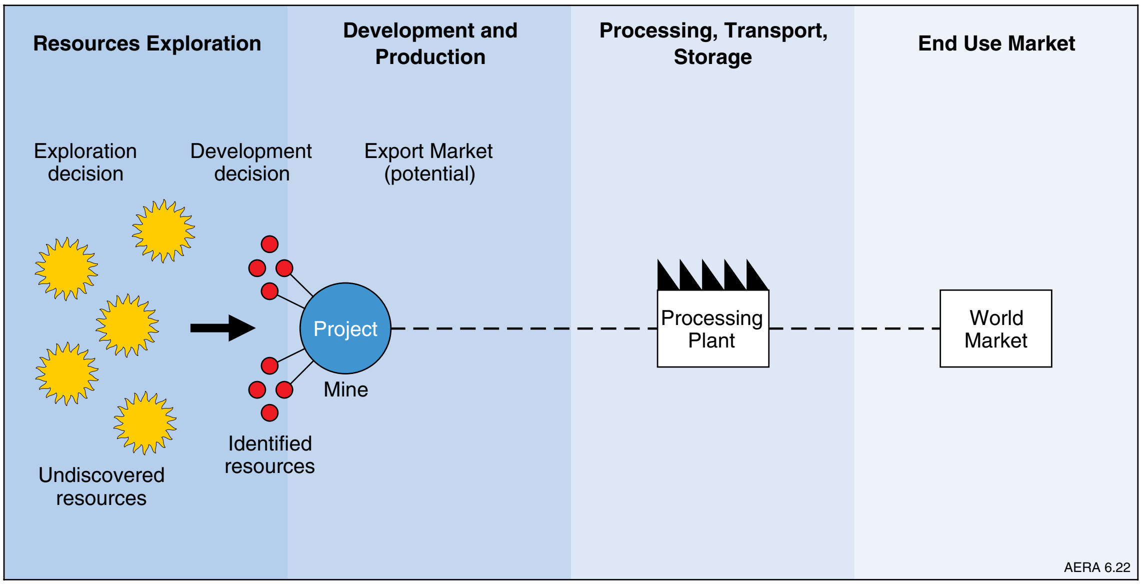

Figure 6.22 Potential Australian thorium supply chain

Source: ABARE and Geoscience Australia

Table 6.12 World total Identified Resources of thorium, 2007

Country	Reasonably Assured Resources <US$ 80/kg Th		Inferred Resources <US$ 80/kg Th		Total Identified Thorium Resources <US$ 80/kg Th	
	kt	%	kt	%	kt	%
Australia	76	6.3	414	29.4	490	18.7
United States	122	10.1	278	19.7	400	15.3
Turkey	344	28.6	NA	NA	344	13.2
India	319	26.5	NA	NA	319	12.2
Brazil	172	14.3	130	9.2	302	11.6
Venezuela	NA	NA	300	21.3	300	11.5
Norway	NA	NA	132	9.4	132	5.1
Egypt	NA	NA	100	7.1	100	3.8
Russian Federation	75	6.2	NA	NA	75	2.9
Greenland	54	4.5	NA	NA	54	2.1
Canada	NA	NA	44	3.1	44	1.7
South Africa	18	1.5	NA	NA	18	0.7
Others	23	1.9	10	0.7	33	1.3
Total	**1203**	**100.0**	**1408**	**100.0**	**2610**	**100.0**

Source: Data for Australia compiled by Geoscience Australia; estimates for all other countries are from OECD/NEA-IAEA 2008

Table 6.13 World and Australian thorium resources according to deposit type

	World		Australia	
Major deposit type	Resources (kt Th)	%	Recoverable Resources (kt Th)	%
Carbonatite	1900	31.3	24	4.9
Placer	1524	24.6	340	69.3
Vein-type	1353	21.4	73	14.9
Alkaline	1155	18.4	53	10.8
Other	258	4.2	-	-
Total	**6190**	**100.0**	**490**	**100.0**

Modified after OECD/NEA-IAEA (2008). Note: Australia's thorium resources expressed as 'recoverable' resources after an overall reduction of 10 per cent for mining
Source: Geoscience Australia

OECD/NEA-IAEA (2008) have grouped thorium resources according to four main types of deposits as shown in table 6.13. Thorium resources worldwide appear to be moderately concentrated in carbonatite type deposits (carbonate mineral rich intrusives), which account for about 30 per cent of the world total. The remaining thorium resources are more evenly spread across the other three deposit types in decreasing order of abundance, in placers (sand deposits), vein type deposits, and alkaline rocks. In Australia, a larger proportion of resources is located in placers, with heavy mineral sand deposits accounting for about 70 per cent of known thorium resources.

World production, consumption and trade

World production and consumption data are unavailable, but current production and consumption are thought to be negligible. There are at present no commercial scale thorium-fuelled reactors for electricity generation in the world. Reasons for the lack of a thorium based nuclear fuel cycle in the past have included the high cost of thorium fuel fabrication and the abundance of cheap uranium fuel for the established uranium based reactors.

However, research into the thorium fuel cycle has continued, because it is considered to be less conducive to the proliferation of nuclear weapons, results in reduced nuclear waste, and represents increased energy security for countries with abundant thorium but little in the way of uranium resources. The construction of a 500 MWe prototype fast breeder reactor has commenced at Kalpakkam, India. This reactor will have a plutonium based core and a thorium-uranium (Th^{232} – U^{238}) blanket and will breed both U^{233} from thorium and plutonium^{239} (Pu^{239}) from the uranium in the blanket. The reactor is expected to be operating in 2011. India is also planning to complete a 300 MWe technology demonstration thorium-fuelled Advanced Heavy Water Reactor (AHWR) after 2017. However, full commercialisation of the AHWR is not expected before 2030.

6.3.2 Australia's thorium resources and market

Australia has the world's largest Identified Resources of thorium. Almost three quarters of Australia's thorium resources are in the mineral monazite within heavy mineral sand deposits.

Thorium resources

Geoscience Australia estimates Australia's monazite resources in the heavy mineral deposits to be around 6.2 million tonnes and inferred thorium resources in the heavy mineral sands are estimated to be around 377.7 kt Th. Australia's total indicated and inferred in situ resources, including those in predominantly rare earth element deposits, amount to about 544 kt Th (table 6.14).

As there are no publicly available data on mining and processing losses for extraction of thorium from these resources, the 'recoverable' resource of thorium is not known. However, assuming an arbitrary figure of 10 per cent for mining and processing losses in the extraction of thorium, then the 'recoverable' thorium resources could amount to about 489.6 kt Th. About 75.7 kt of this is RAR of recoverable thorium at less than US$80/kg Th.

Table 6.14 Australia's thorium resources, 2008

	unit	In situ	recoverable <US$ 80/kg Th
Reasonably Assured Resources (RAR)	kt	84	75.6
Inferred Resources	kt	460	413.9
Total Identified Resources	**kt**	**544**	**489.6**

Source: Geoscience Australia 2009

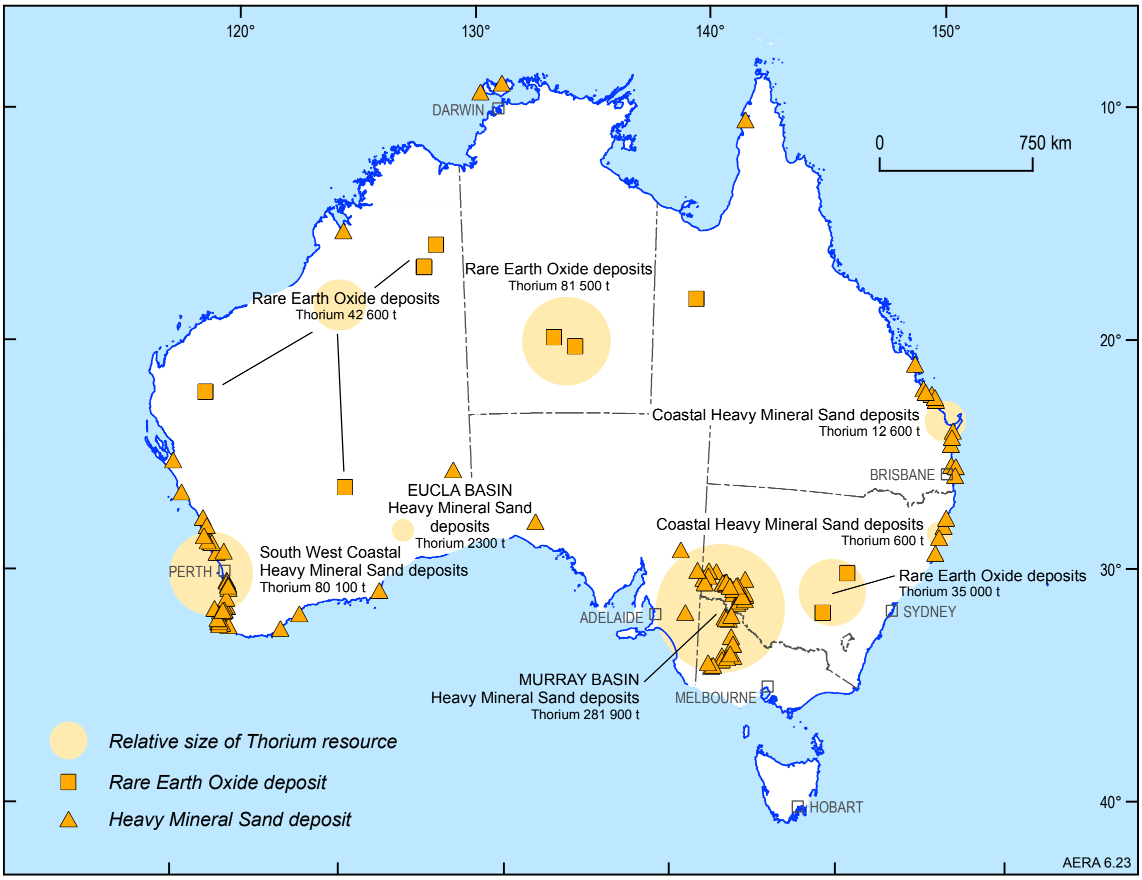

Figure 6.23 Australia's total in situ identified thorium resources

Source: Geoscience Australia

About three quarters of Australia's thorium resources are in the rare earth-thorium phosphate mineral monazite within heavy mineral sand deposits, which are mined for their ilmenite, rutile, leucoxene and zircon content (figure 6.23). Most of the known resources of monazite in mineral sands are in Victoria and Western Australia. The monazite in Australian heavy mineral sand deposits averages about 6 per cent thorium and 60 per cent rare earths. Prior to 1996, monazite was being produced from heavy mineral sand operations and exported for extraction of rare earths. Other thorium deposits are discussed in Box 6.3.

In current heavy mineral sand operations, the monazite is generally dispersed back through the original host sand (to avoid the concentration of radioactivity) when returning the mine site to an agreed land use. In doing so, the rare earths and thorium present in the monazite are negated as a resource because it would not be economic to recover the dispersed monazite for its rare earth and thorium content. The monazite content of heavy mineral resources is seldom recorded by mining companies in published reports.

Thorium market

Historically, Australia has exported large quantities of monazite from heavy mineral sands mined in Western Australia, New South Wales and Queensland, for the extraction of both rare earths and thorium. Between 1952 and 1995, Australia exported 265 kt of monazite with a real export value (2008 dollars) of A$284 million (ABS 2009b). However, since production ceased in 1995 it is believed no significant quantities of thorium, or materials containing thorium, have been imported or exported by Australia.

Production of monazite no longer occurs in Australia as the high disposal cost of thorium is considered to make the extraction of rare earths from monazite uneconomic.

6.3.3 Outlook to 2030 for Australia's resources and market

There is currently no large scale demand for thorium resources and therefore no comprehensive, reliable body of data either on resources or projected demand. Australia has a major share of the world's thorium resources, based on limited information available.

The full commercialisation of a thorium fuel cycle is unlikely to take place prior to 2030. As a result, large scale Australian production and subsequent trade of thorium are not likely within this time period. If commercialisation of a thorium fuel cycle occurs more quickly than assumed, Australia is well positioned to supply world markets with cheap reliable supplies of thorium. Large resources of thorium at deposits currently exploited for other minerals and the possible development of multi mineral deposits containing thorium are likely to support this production.

Key factors influencing the outlook

There has been a significant renewal of interest in development of a thorium-fuelled nuclear cycle for electricity generation, partly because of the relative abundance of thorium, its greater resistance to nuclear weapons proliferation and the substantial reduction in radioactive waste generated from a thorium-fuelled nuclear cycle. However, much work remains to be done before a commercial scale thorium-fuelled reactor for electricity generation can become a reality.

BOX 6.3 THORIUM DEPOSITS IN AUSTRALIA

Apart from heavy mineral sand deposits (placer deposits), thorium is present in other geological settings such as alkaline intrusions and in veins and dykes.

A significant example is the Nolans Bore rare earth, phosphate uranium deposit which occurs in veins and dykes north of Alice Springs in the Northern Territory. This deposit contains about 81.8 kt of thorium.

The Yangibana dykes (termed 'ironstones'), northeast of Carnarvon in Western Australia, crop out over an area of 500 km^2. Whole rock chemical analyses of a number of ironstone samples record more than 1000 parts per million of thorium.

In New South Wales, the Toongi intrusive, south of Dubbo, hosts a 35.7 million tonnes of measured resources and 37.5 million tonnes of Inferred Resources at a grade of 0.0478 per cent thorium, giving a total of about 35 kt contained thorium.

Other alkaline complexes with known rare earth and thorium mineralisation include Brockman in Western Australia. Exploration reports indicate thorium occurrences, but no estimates of thorium resources have been reported.

Data on the thorium content of carbonate mineral rich intrusions in Australia are sparse. Mount Weld and Cummins Range deposits in Western Australia are both known to contain some thorium.

Source: Geoscience Australia 2009.

Technology developments – future development of thorium reactors

Demand for thorium resources depends upon the development and widespread adoption of thorium-fuelled reactors for electricity generation. The main drivers for interest in thorium-fuelled reactors are:

- Some countries, such as India, have much larger thorium resources than uranium and see thorium-fuelled reactors as a more secure source of energy.
- The thorium fuel cycle is considered to be less conducive to nuclear weapon proliferation than the uranium fuel cycle.
- The thorium fuel cycle generates much less radioactive waste than the uranium fuel cycle.

Current research and development for use of thorium in reactors for electricity generation are directed primarily towards:

- Research into thorium fuel designed to be used in currently operating uranium-fuelled reactors.
- Development and construction of a purpose-built thorium-fuelled reactor for electricity generation.
- Development of some other advanced nuclear reactors which could use thorium fuels.

Further details of the research and developments are presented in Box 6.4.

Cost competitiveness

As there is no established large scale demand and associated price information for thorium, there is insufficient information to determine how much of Australia's thorium resources are economically viable for electricity generation in thorium reactors.

However, as all of Australia's thorium resources occur either in the heavy mineral sand deposits or in rare earth mineral deposits, mining and processing cost for the extraction of thorium would be shared with other commodities.

Infrastructure, environment and other issues

Most thorium resources are contained in heavy mineral sand deposits and rare earth deposits that already have essential infrastructure. Some of these deposits are currently being mined or in advanced stages of development with infrastructure costs being borne by commodities being extracted.

Apart from improved resistance to proliferation of nuclear weapons, a thorium fuel cycle is generally considered to generate less radioactive waste and has fewer long-lived transuranic elements. The extent of these potential advantages over the current uranium fuel cycle varies according to different designs of the thorium fuel cycle.

There are little readily available nuclear industry data on the issues of nuclear proliferation and volumes and storage of nuclear waste because there are no currently operating commercial scale thorium-fuelled reactors.

BOX 6.4 R&D THORIUM PROJECTS

Thorium fuel design

At this stage it appears that thorium fuel could be used in existing uranium-fuelled reactors such as the latest Canadian CANDU reactors or possibly the Russian VVER-1000 reactors. This would involve using thorium fuels designed by Lightbridge Corporation (formerly Thorium Power Ltd), possibly by 2020 (Thorium Power Ltd 2009).

Atomic Energy of Canada Ltd (AECL) is moving towards certification of an Advanced CANDU Reactor (ACR) 1000 (Generation III+ 1200 MWe) in Canada. The earliest in-service date for an ACR 1000 is 2016. It is anticipated that use of thorium fuel will be introduced at a later stage. In mid 2009, AECL signed agreements with three Chinese entities to develop and demonstrate the use of thorium fuel in its CANDU reactors at Qinshan in China. Another agreement in mid 2009 between Areva and Thorium Power Ltd will assess the use of thorium fuel in Areva's European Pressurised Reactor (EPR), drawing upon earlier research.

Thorium Power Ltd is preparing preliminary licensing documentation for its thorium fuel assembly design for use in the current Russian VVER-1000 reactors (Thorium Power Ltd 2009). The timeframe for this work is unknown. Two VVER-1000 reactors are currently being built in India, which has extensive thorium resources but very limited uranium resources.

Thorium-fuelled reactors

A purpose built thorium-fuelled reactor – the Indian 300 MWe Advanced Heavy Water Reactor (AHWR) – has been proposed for construction as a technical demonstration. The AHWR will have fuel assemblies of 30 $Th\text{-}U^{233}$ oxide pins and 24 plutonium-Th oxide pins around a central rod with burnable absorber. It is designed to be self-sustaining in relation to U^{233} bred from Th^{232} and have a low plutonium inventory and consumption. It is designed for a 100 year plant life and is expected to utilise 65 per cent of the energy of the fuel, with two thirds of the energy coming from thorium. The technical demonstration version is expected to be completed some time after 2017, but full scale commercial AHWR reactors are not anticipated before 2030.

In 2009 India announced an export version of the AHWR – the AHWR-LEU. This design will use low-enriched uranium plus thorium as a fuel, dispensing with the plutonium input. About 39 per cent of the power will come from thorium (via in situ conversion to U^{233}). The uranium enrichment level will be 19.75 per cent, giving 4.21 per cent average fissile content of the U-Th fuel. Plutonium production will be less than in light water reactors, and the fissile proportion will be less, providing inherent proliferation resistance benefits (WNA 2009g; Kakodkar 2009).

India is the only country that has been involved in development of a full scale thorium reactor, the AHWR in stage 3. This program had a high priority while India was under an international trade ban for nuclear technology and on imports of uranium. The Nuclear Suppliers' Group agreement in September 2008 and the United States-India nuclear agreement in October 2008 now allow India to trade in nuclear technology and import uranium fuel. In addition, India has also signed a nuclear cooperation agreement with France. It is unclear if India will maintain a high priority on the development of its thorium fuel cycle.

Advanced reactors

Generation IV reactors will also be capable of using thorium fuel in the high-temperature gas-cooled reactors (HTGRs) or the molten salt reactors (MSR).

There are two types of high temperature gas-cooled reactors (HTGRs): prismatic fuel and pebble bed. General Atomics is developing a Gas Turbine-Modular Helium Reactor (GT-MHR) that uses a prismatic fuel. The GT-MHR core can accommodate a wide range of fuel options, including HEU/Th, U^{233}/Th and Plutonium/Th. Pebble bed reactor development builds on previous work in Germany and is under development in China and South Africa. A pebble bed reactor can potentially use thorium in the fuel pebbles.

The molten salt reactor (MSR) is an advanced breeder concept, in which the coolant is a molten salt, usually a fluoride salt mixture. The fuel can be dissolved enriched uranium, thorium or U^{233} fluorides. The fission products dissolve in the salt and are removed continuously in an online reprocessing loop and replaced with Th^{232} or U^{238}. Actinides remain in the reactor until they fission or are converted to higher actinides which do so. The MSR was originally studied in depth in the 1960s, but is now being revived because of the availability of advanced technology for the materials and components. There is renewed interest in the MSR concept in Japan, the Russian Federation, France and the United States and the MSR is one of the six Generation IV designs selected by the international forum of 13 countries for further development.

As with a purpose built thorium-fuelled reactor, these advanced HTGR and MSR reactors are not likely to come on stream much before 2030, and the extent to which they will use thorium rather than uranium is also uncertain.

6.4 References

ABARE (Australian Bureau of Agricultural and Resource Economics), 2006, Uranium, Global Market Developments and Prospects for Australian Exports, Canberra

ABARE, 2009a, 'Uranium', Australian Commodities, vol 16 no 1, March quarter, pp. 158-166, Canberra, March

ABARE, 2009b, Australian Energy Statistics, Canberra, August

ABARE, 2009c, Australian Mineral Statistics, Canberra, September

ABARE, 2009d, Minerals and energy, major development projects – October 2009 listing, Canberra, November

ABARE, 2009e, Australian Commodity Statistics 2009, Canberra, December

ABARE, 2010, Australian Commodities, vol 17, no 1, March quarter, Canberra, March

ABS (Australian Bureau of Statistics), 2009a, Mineral and Petroleum Exploration, June quarter 2009, Cat. No 8412.0, Canberra, <http://www.abs.gov.au>

ABS, 2009b, International trade, Cat. No. 5465.0, Canberra

ANSTO (Australian Nuclear Science and Technology Organisation), 2006, Introducing Nuclear Power to Australia: an economic comparison, Canberra, <http://www.ansto.gov.au>

ASNO (Australian Safeguards and Non-proliferation Office), 2009, Annual report 2008–09, Canberra, <http://www.asno.dfat.gov.au/annual_reports.html>

Australian Uranium Association, 2008, Outlook for the Uranium Industry — Evaluating the economic impact of the Australian uranium industry to 2030, Sydney, <http://www.aua.org.au>

Commonwealth of Australia, 2006a, Uranium Mining, Processing and Nuclear Energy — Opportunities for Australia?, Report to the Prime Minister by the Uranium Mining, Processing and Nuclear Energy Review Taskforce, December 2006

Commonwealth of Australia, 2006b, Uranium Industry Framework, Canberra, <http://www.ret.gov.au/resources/mining/australian_mineral_commodities/uranium/Pages/Uranium.aspx>

Commonwealth of Australia, 2006c, Australia's uranium – Greenhouse friendly fuel for an energy hungry world, Canberra

EIA (Energy Information Administration), 2009a, International Energy Outlook 2009, <http://www.eia.doe.gov/oiaf/ieo/index.html>

EIA, 2009b, Nuclear Power: 12 percent of America's Generating Capacity, 20 percent of the Electricity, <http://www.eia.doe.gov/cneaf/nuclear/page/analysis/nuclearpower.html>

Euratom Supply Agency, 2009, Annual Report 2008, Eurpoean Commission, Luxembourg, <http://ec.europa.eu/euratom>

Geoscience Australia, 2009, Australia's Identified Mineral Resources, 2009, Geoscience Australia, Canberra, <http://www.australianminesatlas.gov.au/aimr/index.jsp>

Geoscience Australia, 2007, Onshore Energy Security Program 5 Year Plan, <http://www.ga.gov.au/image_cache/GA10075.pdf>

IAEA (International Atomic Energy Agency), 2009, Power Reactor Information System (PRIS), <http://www.iaea.org/programmes/a2/>

IEA (International Energy Agency) 2009, World Energy Balances, OECD, Paris, <http://www.iea.org>

Kakodkar A, 2009, Statement by Dr Anil Kakodkar, Chairman of the Atomic Energy Commission and leader of the Indian delegation, IAEA 53rd General Conference, Vienna, 16 September 2009

Lambert I, Jaireth S, McKay A, and Miezitis Y, 2005, Why Australia has so much uranium, AusGeo News, Issue 80, December 2005

Metals Economics Group, 2009, Corporate Exploration Strategies study, <http://www.metalseconomics.com/default.htm>

OECD/NEA (Nuclear Energy Agency) and IAEA (International Atomic Energy Agency), 2006, Forty Years of Uranium Resources, Production and Demand in Perspective, The Red Book Retrospective, OECD/NEA-IAEA, Paris

OECD/NEA and IAEA, 2008, Uranium 2007: Resources, Production and Demand, OECD/NEA-IAEA, Paris, <http://www.nea.fr/index.html>

Schodde R, and Trench A, 2009, Benchmarking uranium projects; How do the next generation of mines compare to current operations?, AusIMM International Uranium Conference, June 2009, Darwin, Northern Territory

Skirrow RG, Jaireth S, Huston DL, Bastrakov EN, Schofield A, van der Wielen SE, Barnicoat AC, 2009, Uranium mineral systems: Processes, exploration criteria and a new deposit framework, Geoscience Australia, Record 2009/20

Thorium Power Limited, 2009, Annual shareholders meeting, 29 June 2009, <http://ir.thoriumpower.com/phoenix.zhtml?c=121550&p=irol-irhome>

TORO Energy Limited, 2008, Presentation to investors and shareholders, 16 October 2008, <http://www.toroenergy.com.au/presentations.html>

Ux Consulting 2009, Historical Ux Price Data, <http://www.uxc.com/c/prices/uxc_prices-mth-historic.xls>

Ux Consulting, Uranium Market Outlook, Quarterly report, UxC, Roswell, Ga, <http://www.uxc.com>

WNA (World Nuclear Association), 2005, The New Economics of Nuclear Power, WNA, London, <http://www.world-nuclear.org/reference/pdf/economics.pdf>

WNA, 2008, WNA Market Report, London, <http://www.world-nuclear.org/reference/publications.html>

WNA, 2009a, The Nuclear Fuel Cycle, January 2009, <http://www.world-nuclear.org/info/inf03.html>

WNA, 2009b, World uranium mining, July 2009, <http://www.world-nuclear.org/info/default.aspx?id=430&terms=uranium+production>

WNA, 2009c, World Nuclear Power Reactors 2007–09 & Uranium Requirements, December 2008, <http://www.world-nuclear.org/info/reactors-dec2008.html>

WNA, 2009d, The Global Nuclear End Market – Supply and Demand 2009–2030

WNA, 2009e, Processing of used nuclear fuel, September 2009, <http://www.world-nuclear.org/info/inf69.html>

WNA, 2009f, World nuclear power reactors and uranium requirements, October 2009, <http://www.world-nuclear.org/info/reactors.html>

WNA, 2009g, Generation IV nuclear reactors, August 2009, <http://www.world-nuclear.org/info/default.aspx?id=530&terms=Generation+IV>

WNA, 2009h, Advanced Nuclear Power Reactors, September 2009, <http://www.world-nuclear.org/info/default.aspx?id=528&terms=advanced+nuclear+reactors>

WNA, 2009i, Thorium, November 2009, <http://www.world-nuclear.org/info/inf62.html>