7

Nuclear Fuel Resources

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CONTENTS

7.1 Introduction

Uranium is the basic raw material for nuclear power. Section 7.2 considers its main characteristics and overall abundance, whereas Section 7.3 looks at uranium resources in rather more detail, showing that uranium is actually a relatively abundant element in the earth's crust. Section 7.4 outlines some basic uranium geology, making the point that it is available in a wide variety of geological settings. Section 7.5 moves onto consider mining techniques that may be employed to exploit known uranium deposits, highlighting the rise of in-situ leaching (ISL) techniques in recent years. Section 7.6 briefly highlights the milling of extracted uranium ore, while Section 7.7 considers the important environmental aspects of uranium mining. Section 7.8 examines uranium production in some detail, by country, company and major mines. Section 7.9 then looks at the world uranium market and considers price determination. Section 7.10 examines uranium conversion, the next necessary step in the nuclear fuel cycle. Finally, Section 7.11 considers thorium as an alternative nuclear fuel.

7.2 Uranium and Depleted Uranium

Uranium (chemical symbol, U) is a slightly radioactive metal that occurs throughout the earth's crust. It is about 500-times more abundant than gold, 40-times as silver and about as common as tin, tungsten, and molybdenum. It occurs in most rocks in concentrations of

2–4 ppm, for example, at about 4 ppm in granite, which makes up 60% of the earth's crust. In fertilizers, uranium concentration can be as high as 400 ppm (0.04%), and some coal deposits contain uranium at concentrations >100 ppm (0.01%). It is also found in the oceans, at an average concentration of 1.3 parts per billion (ppb).

On a scale arranged according to the increasing mass of their nuclei, uranium is the heaviest of all the naturally occurring elements (hydrogen is the lightest). Uranium has a specific gravity of 18.7.

There are several areas around the world where the concentration of uranium in the ground is sufficiently high that extraction of it for use as nuclear fuel is economically feasible. Such "economic concentrations" are called "ore." When mined, it yields a mixed uranium oxide product, (U_3O_8). Uraninite or pitchblende is the commonest uranium mineral.

Uranium was discovered in pitchblende by the German chemist Martin Klaproth in 1789, and was named after the planet Uranus. It was apparently formed in super novae about 6.6 billion years ago. While it is not common in the solar system, today its radioactive decay provides the main source of heat inside the earth, causing convection and continental drift.

For many years from the 1940s, virtually all of the uranium that was mined was used in the production of nuclear weapons, but this ceased to be the case in the 1970s. Today the only substantial use for uranium is as fuel in nuclear reactors, mostly for electricity generation. Uranium-235 is the only naturally occurring material that can sustain a fission chain reaction, releasing large amounts of energy.

In the past, uranium was also used to color glass (from as early as 79 AD) and deposits were once mined to obtain its decay product, radium. This element was used in luminous paint, particularly on the dials of watches and aircraft instruments, and in medicine for the treatment of disease.

While nuclear power is the predominant use of uranium, heat from nuclear fission can also be used for industrial processes. It is also used for marine propulsion (mostly naval), whereas research reactors are important for making radioisotopes.

Like other elements, uranium occurs in slightly differing forms known as "isotopes." These isotopes differ from each other in the number of neutron particles in the nucleus. "Natural" uranium as found in the earth's crust is a mixture of three isotopes: uranium-238 (U-238), accounting for 99.275%; U-235 (0.720%); and traces of U-234 (0.005%). U-235 is important because under certain conditions it can be readily, yielding a lot of energy. It is therefore said to be "fissile," and we use the expression "nuclear fission."

Like all radioactive isotopes, it decays. U-238 decays very slowly, its half-life being the same as the age of the earth. This means that it is barely radioactive, less so than many other isotopes in rocks and sand. U-238 has a specific radioactivity of 12.4 kBq/g, and U-235 80 kBq/g, so natural uranium is 13 kBq/g. In decay it generates 0.1 watts/tonne and this is enough to warm the earth's mantle.

For most of the world's reactors, enriched uranium is required as fuel. Enrichment increases the proportion of the U-235 isotope from its natural level of 0.7% to 3–5%. This enables greater technical efficiency in reactor design and operation, particularly in larger reactors, and allows the use of ordinary water as a moderator. A by-product (or waste product) of enrichment is depleted uranium (about 89% of the original feed). Every tonne of natural uranium produced and enriched for use in a nuclear reactor gives about 130 kg of enriched fuel (≥3.5% U-235). The balance is depleted uranium (U-238, with 0.25–0.30% U-235). This major portion has been depleted in its fissile U-235 isotope by the enrichment process. It is commonly known as "DU."

DU is stored as UF_6 or it is de-converted back to U_3O_8, which is more benign chemically and thus more suited for long-term storage. It is also less toxic. Every year, >50,000 tonnes of depleted uranium joins already substantial stockpiles in the United States, Europe and Russia. World stock is about 1.3 million tonnes.

Some DU is drawn from these stockpiles to dilute high-enriched (>90%) uranium released from weapons programs, particularly in Russia, and destined for use in civil reactors. This weapons-grade material is diluted about 25:1 with depleted uranium, or 29:1 with depleted uranium that has been enriched slightly (to 1.5% U-235) to minimize levels of (natural) U-234 in the product.

Other uses are more mundane, and depend on the very high density (1.7-times that of lead) of the metal. Hence, where maximum mass must fit in minimum space (e.g., aircraft control surface and helicopter counterweights, yacht keels), it is often well suited. Until the mid-1970s it was used in dental porcelains. In addition it is used for radiation shielding, being some five-times more effective than lead in this role. Also because of its density, it is used as solid slugs or penetrators in armour-piercing projectiles, alloyed with abut 0.75% titanium.

7.3 Uranium Resources

Measured resources of uranium, the amount known to be economically recoverable from orebodies, are naturally relative to costs and prices. They are also dependent on the intensity of past exploration effort, and are basically a statement about what is known rather than what is present in the earth's crust.

Changes in costs or prices, or further exploration, may alter measured resource figures markedly. At 10-times the current price, seawater may become a potential source of vast amounts of uranium. Thus, predictions of the future availability of any mineral (including uranium) which are based on current cost and price data and current geological knowledge are likely to be extremely conservative.

From time to time concerns are raised that the known resources may be insufficient when judged as a multiple of present rate of use. This is the "Limits to Growth" fallacy, a major intellectual blunder recycled from the 1970s which does not take into account the very limited nature of the knowledge we have at any time of what is actually in the earth's crust. Our knowledge of geology is such that we can be confident that identified resources of metal minerals are a small fraction of what is present. With those major qualifications, Table 7.1 gives some idea of our present knowledge of uranium resources. It can be seen that Australia has a substantial part of the world's uranium, followed by Kazakhstan and Canada.

Current usage is about 65,000 tU/yr, so the world's present measured resources of uranium (4.7 Mt) and used only in conventional reactors, are enough to last for about 70 years. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are consumed. There was very little uranium exploration between 1985 and 2005, so the significant increase in exploration effort that is now currently underway will probably substantially increase the known economic resources.

This is suggested in the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA)

TABLE 7.1

Known Recoverable Resources of Uranium, 2005

	Reasonably Assured Resources		
	<US$40/kgU	<US$80/kgU	<US$130/kgU
Australia	701	714	747
Brazil	140	158	158
Canada	287	345	345
Kazakhstan	279	378	514
Mongolia	8	46	46
Namibia	62	151	183
Niger	173	181	181
Russia	57	132	132
South Africa	89	177	256
United States	0	102	342
Uzbekistan	60	60	77
Others	91	199	316
Total	1,947	2,643	3,297

Source: *OECD NEA & IAEA,* Uranium 2005: Resources, Production and Demand, (*"Red Book"*).

figures in Table 7.1 if those covering estimates of all conventional resources are considered—10 million tonnes (beyond the 3.3-Mt known economic resources), which takes us to over 200 years' supply at today's rate of consumption. It omits unconventional resources such as phosphate/phosphorite deposits (22-Mt uranium recoverable as by-product) and seawater (up to 4000 Mt), which are likely to be uneconomic to extract in the foreseeable future.

Widespread use of the fast breeder reactor could increase the utilization of uranium to ≥50-fold. This type of reactor can be started up on plutonium derived from conventional reactors and operated in closed circuit with its reprocessing plant. Such a reactor, supplied with natural or depleted uranium for its "fertile blanket," can be operated so that each tonne of ore yields 60-times more energy than in a conventional reactor.

7.4 Geology of Uranium Deposits

The major primary ore mineral is uraninite (basically UO_2) or pitchblende ($U_2O_5.UO_3$, better known as U_3O_8), though a range of other uranium minerals are found in particular deposits. These include carnotite (uranium potassium vanadate), the davidite-brannerite-absite type uranium titanates, and the euxenite-fergusonite-samarskite group (niobates of uranium and rare earths).

A large variety of secondary uranium minerals are known, many are brilliantly colored and fluorescent. The commonest are gummite (a general term like "limonite" for mixtures of various secondary hydrated uranium oxides with impurities); hydrated uranium phosphates of the phosphuranylite type, including autunite (with calcium), saleeite (magnesium) and torbernite (with copper); and hydrated uranium silicates such as coffinite, uranophane (with calcium), and sklodowskite (magnesium).

Uranium occurs in several different igneous, hydrothermal and sedimentary geological environments. Uranium deposits worldwide have been grouped into 14 major categories of deposit types based on the geological setting of the deposits. The most significant are discussed below.

Unconformity related deposits arise from geological changes occurring close to major unconformities. These constitute approximately one-third of world uranium resources and include some of the largest and richest deposits. Minerals are uraninite and pitchblende. The main deposits are in Canada (Athabasca Basin, Saskatchewan and Thelon Basin, Northwest Territories); and Australia (Alligator Rivers region in the Pine Creek Geosyncline, NT and Rudall River area, Washington). Today, all of Canada's uranium production is from unconformity related deposits—Rabbit Lake (heavily depleted), and McClean Lake and McArthur River deposits. Another large, exceptionally high-grade unconformity related deposit currently being developed in Saskatchewan is Cigar Lake (averaging almost 20% U_3O_8, with some zones >50% U_3O_8).

The Olympic Dam deposit is one of the world's largest deposits of uranium, accounting for about 66% of Australia's reserves plus resources and is categorized as a breccia complex deposit. It is overlain by approximately 300 m of flat-lying sedimentary rocks, and the deposit contains iron, copper, uranium, gold, silver, and rare earth elements. Only copper, uranium, gold, and silver have been recovered. Uranium grades average from 0.08% to 0.04% U_3O_8, the higher-grade mineralisation being pitchblende. Copper grades average 2.7% for proved reserves, 2.0% for probable reserves, and 1.1% for indicated resources. Gold grades are 0.3–1.0 g/t.

Sandstone deposits constitute about 18% of world uranium resources. Orebodies of this type are commonly low to medium grade (0.05–0.4% U_3O_8) and individual orebodies are small to medium in size (ranging up to a maximum of 50,000 t U_3O_8). The main primary uranium minerals are uraninite and coffinite. Conventional mining/milling operations of sandstone deposits have been progressively undercut by cheaper in-situ leach mining methods. The United States has large resources in sandstone deposits in the Western Cordillera region, and most of its uranium production has been from these deposits, recently by ISL mining. The Powder River Basin in Wyoming, the Colorado Plateau and the Gulf Coast Plain in south Texas are major sandstone uranium provinces. Other large sandstone deposits occur in Niger, Kazakhstan, Uzbekistan, Gabon (Franceville Basin), and South Africa (Karoo Basin). Kazakhstan has reported substantial reserves in sandstone deposits with average grades ranging from 0.02% to 0.07% U.

Surficial deposits comprise about 4% of world uranium resources, and such deposits represent 5% of Australia's total reserves and resources of uranium. They formed where uranium-rich granites were deeply weathered in a semi-arid to arid climate. The Yeelirrie deposit in Washington is by far the world's largest surficial deposit.

Volcanic deposits occur in acid volcanic rocks and are related to faults and shear zones within the volcanics. Uranium is commonly associated with molybdenum and fluorine. These deposits make-up only a small proportion of the world's uranium resources. Significant resources of this type occur in China, Kazakhstan, Russian Federation, and Mexico.

Intrusive deposits are associated with intrusive rocks, including alaskite, granite, pegmatite, and monzonites. Major world deposits include Rossing (Namibia) and Palabora (South Africa).

Quartz-pebble conglomerate deposits make-up approximately 13% of the world's uranium resources. Where uranium is recovered as a by-product of gold mining, the grade may be as low as 0.01% U_3O_8. In deposits mined exclusively for uranium, average grades range as high as 0.15% U_3O_8. Individual deposits range in size from 6000 t to 170 000 t contained U_3O_8. Major examples are the Elliot Lake deposits in Canada (where mining operations have ceased) and the Witwatersrand gold-uranium deposits in South Africa.

Vein deposits constitute about 9% of world uranium resources. Major deposits include Jachymov (Czech Republic) and Shinkolobwe (Zaire).

7.5 Mining Techniques

The decision as to which mining method to use for a particular deposit is governed by the nature of the orebody, safety and economic considerations. In the case of underground uranium mines, special precautions, consisting primarily of increased ventilation, are required to protect against airborne radiation exposure. Excavation and in situ techniques are used to recover uranium ore. Excavation may be underground and open pit mining.

In general, open pit mining is used if deposits are close to the surface and underground mining is used for deep deposits, typically >120-m deep. Open pit mines require large holes on the surface, larger than the size of the ore deposit, because the pit walls must be sloped to prevent collapse. As a result, the quantity of material that must be removed to access the ore may be large. Underground mines have relatively small surface disturbance and the quantity of material that must be removed to access the ore is considerably less than in the case of an open pit mine.

An increasing proportion of the world's uranium now comes from ISL. This technique, also known as "solution mining," involves leaving the ore where it is in the ground, and using liquids that are pumped through it to recover the minerals out of the ore by leaching. Consequently there is little surface disturbance and no tailings or waste rock generated. However, the orebody must be permeable to the liquids used, and located so that they do not contaminate ground water away from the orebody.

ISL mining was first tried on an experimental basis in Wyoming during the early 1960s. The first commercial mine began operating in 1974. Today, a few projects are licensed to operate in the United States (Wyoming, Nebraska and Texas) and most of the operating mines date from the 1990s. They are small (under 1000 t/yr) but they supply most of the U.S. uranium production. About a quarter of world uranium production is now by ISL (including all Kazakhstan and Uzbekistan output). ISL can also be applied to other minerals such as copper and gold.

Uranium deposits suitable for ISL occur in permeable sand or sandstones, confined above and below by impermeable strata, and which are below the water table. There are two operating regimes for ISL, determined by the geology and groundwater. If there is significant calcium in the orebody (as limestone or gypsum), alkaline (carbonate) leaching must be used. Otherwise, acid (sulfate) leaching is generally better. Techniques for ISL have evolved to the point where it is a controllable, safe, and environmentally benign method of mining which can operate under strict environmental controls and which often has cost advantages.

Mining methods have been changing. In 1990, 55% of world production came from underground mines, but this shrunk dramatically to only 33% by 2000. Since then, new Canadian mines have increased it again. By-production of uranium (where uranium is produced in combination with other metals such as copper and gold) has been fairly constant over time at around 10% of output, and today mainly reflects the production levels at the Olympic Dam mine in South Australia (copper and gold) rather than South Africa (gold) . The share of ISL production has been rising, reaching 26% in 2006, owing mainly to improving production levels in Kazakhstan, a recovery in Uzbekistan and the commissioning of the Beverley mine in Australia.

7.6 Milling

Milling, which is generally carried out close to a uranium mine, extracts the uranium from the ore. Most mining facilities include a mill, although if mines are close together, one mill may process the ore from several mines. Milling produces a uranium oxide concentrate which is shipped from the mill. It is sometimes referred to as "yellowcake" and generally contains >80% uranium. The original ore may contain as little as 0.1% uranium.

In a mill, uranium is extracted from the crushed and ground-up ore by leaching, in which a strong acid or a strong alkaline solution is used to dissolve the uranium. The uranium is then removed from this solution and precipitated. After drying and usually heating, it is packed in 200-L drums as a concentrate.

The remainder of the ore, containing most of the radioactivity and nearly all the rock material, becomes tailings, which are emplaced in engineered facilities near the mine (often in the mined-out pit). Tailings contain long-lived radioactive materials in low concentrations and toxic materials such as heavy metals; however, the total quantity of radioactive elements is less than in the original ore, and their collective radioactivity will be much shorter-lived. These materials need to be isolated from the environment.

7.7 Environmental Aspects of Uranium Mining

In many respects, uranium mining is much the same as any other mining. Projects must have environmental approvals prior to commencing, and must comply with all environmental, safety and occupational health conditions applicable. Increasingly, these are governed by international standards, with external audits.

Once approved, open pits or shafts and drives are dug, and waste rock and overburden is placed in engineered dumps. Tailings from the ore processing must be placed in engineered dams or underground. Finally the whole site must be rehabilitated at the end of the project. Meanwhile air and water pollution must be avoided. In the case of ISL mining, there is much less disturbance, simply multiple boreholes, and rehabilitation is simpler.

Uranium is radioactive, though with the major isotope U-238, having a half-life equal to the age of the earth, is certainly not strongly radioactive. U-235 has a half-life one-sixth of this and emits gamma rays as well as alpha particles. Hence a lump of pure uranium would give off some gamma rays, but less than those from a lump of granite. Its alpha radioactivity in practical terms depends on whether it is as a lump (or in rock as ore), or as a dry powder. In the latter case the alpha radioactivity is a potential, though not major, hazard. It is also toxic chemically, being comparable with lead. Uranium metal is commonly handled with gloves as a sufficient precaution. Uranium concentrate is handled and contained so as to ensure that people do not inhale or ingest it.

At an early stage of a mine feasibility study, environmental studies of the site begin. These escalate in detail and progressively focus on issues of concern in relation to the proposal, in consultation with the governmental authorities. Depending on the government jurisdiction, an environmental effects or impact statement is published and may be made available for public comment. After consideration of comments and in the light of judgements by a wide range of authorities, approval may then be given for the project to proceed.

In most respects, conventional mining of uranium is the same as mining any other metalliferous ore, and well-established environmental constraints apply to avoid off-site pollution. From open cut mining, there are substantial volumes of barren rock and overburden waste. These are placed near the pit and used in rehabilitation or shaped and revegetated where they are.

However, uranium minerals are always associated with more radioactive elements such as radium and radon in the ore. Therefore, although uranium itself is not very radioactive, the ore which is mined, especially if it is very high-grade such as in some Canadian mines, is handled with some care for occupational health and safety reasons. Mining methods, tailings and run-off management and land rehabilitation are subject to government regulation and inspection. Mining operations are undertaken under relevant national health and radiation protection codes of practice. These set strict health standards for exposure to gamma radiation and radon gas. Standards apply to workers and members of the public.

Solid waste products from the milling operation are tailings. They comprise most of the original ore and they contain most of the radioactivity in it. In particular they contain all the radium present in the original ore. At an underground mine they may be first cycloned to separate the coarse fraction which is used for underground fill. The balance is pumped as a slurry to a tailings dam, which may be a worked-out pit.

When radium undergoes natural radioactive decay, one of the products is radon gas. Radon occurs in most rocks and traces of it are in the air we all breathe. However, at high concentrations it is a health hazard. Because radon and its decay products ("daughters") are radioactive and because the tailings are now on the surface, measures are taken to minimize the emission of radon gas. During the operational life of a mine the material in the tailings dam is usually covered by water to reduce surface radioactivity and radon emission (though with lower-grade ores neither pose a hazard at these levels).

On completion of the mining operation, it is normal for the tailings dam to be covered with some 2 m of clay and topsoil to reduce radiation levels to near those normally experienced in the region of the orebody, and for a vegetation cover to be established.

Run-off from the mine stockpiles and waste liquors from the milling operation are collected in secure retention ponds for isolation and recovery of heavy metals or other contaminants. The liquid portion is disposed of by natural evaporation or recirculation to the milling operation. Process water discharged from the mill contains traces of radium and some other metals which would be undesirable in biological systems downstream. This water is evaporated and the contained metals are retained in secure storage. During the operational phase, such water may be used to cover the tailings while they are accumulating.

With ISL operations, the orebody stays in the ground and uranium is recovered by circulating oxygenated and acidified groundwater through it, using injection and recovery wells. The main environmental consideration with ISL is avoiding pollution of groundwater away from the orebody, and leaving the immediate groundwater no less useful than it was initially.

Apart from tailings, other solid wastes at a mine include equipment which is not able to be sold at the end of the operation. This is usually buried with the tailings.

At the conclusion of mining, tailings are covered permanently with enough clay and soil to reduce gamma radiation levels and radon emanation rates to levels near those naturally occurring in the region, and enough rock to resist erosion. A vegetation cover is then established. Apart from groundwater considerations discussed above, rehabilitation of ISL mines is very straightforward, making this a technique with remarkably low environmental impact. Upon decommissioning, wells are sealed or capped, process facilities removed, any evaporation pond revegetated, and the land can readily be returned to its previous uses.

At the concentrations associated with uranium (and some mineral sands) mining, radon is a potential health hazard, as is dust. Precautions taken during the mining and milling of uranium ores to protect the health of the workers are listed below:

- Good forced ventilation systems in underground mines to ensure that exposure to radon gas and its radioactive daughter products is as low as possible and does not exceed established safety levels.
- Efficient dust control because the dust may contain radioactive constituents and emit radon gas.
- Limiting the radiation exposure of workers in mine, mill and tailings areas so that it is as low as possible, and in any event does not exceed the allowable dose limits set by the authorities. In Canada, this means that mining in very high-grade ore is undertaken solely by remote control techniques and by fully containing the high-grade ore where practicable.
- The use of radiation detection equipment in all mines and plants.
- Imposition of strict personal hygiene standards for workers handling uranium oxide concentrate.

At any mine, designated employees (those likely to be exposed to radiation or radioactive materials) are monitored for alpha radiation contamination and personal dosimeters are worn to measure exposure to gamma radiation. Routine monitoring of air, dust and surface contamination is undertaken. If uranium oxide is ingested it has a chemical toxicity similar to that of lead oxide. Similar hygiene precautions to those in a lead smelter are therefore taken when handling it in the drying and packing areas of the mill. The usual radiation safeguards are applied at an ISL mining operation, despite the fact that most of the radioactivity remains well underground and there is hence minimal increase in radon release and no ore dust.

7.8 Uranium Production

Although there are some uncertainties remain about the amounts of uranium mined in the former Soviet Union in the period between 1945 and 1990, it is nevertheless now possible to produce a rough picture of cumulative world production since the end of the Second World War. Table 7.2 summarises historical production, with estimates of production in countries where data are unavailable.

Cumulative world uranium production is estimated to be 2.25 million tU since 1945, split into approximately 1.4 million tU from Western producers and 850,000 tU from the East. The uncertainties in the latter figure relate mainly to the former Soviet Union prior to 1991, and to China and Ukraine to the present day. The patterns of production have been markedly different in each area.

Within the West, the period can be divided into four "ages of uranium," as detailed below.

TABLE 7.2

Cumulative Uranium Production, 1945–2006, tU

Country/Area	Cumulative Production
Australia	140,000
Canada	409,000
France	77,000
Gabon	26,000
Namibia	88,000
Niger	100,000
South Africa	159,000
USA	358,000
Others	52,000
Total West	**1,409,000**
Bulgaria	24,000
China[a]	36,000
Former Czechoslovakia[b]	110,000
Former East Germany	217,000
Hungary	18,000
Romania	18,000
Russia[a]	134,000
Central Asian Republics[a]	237,000
Ukraine[a]	56,000
Total East[a]	**850,000**
World total[a]	**2,259,000**

Source: World Nuclear Association.
[a] WNA estimate;
[b] Czech Republic from 1993.

- A military era, from 1945 to the late 1960s. The generation of electricity from nuclear fuel was incidental to the arms race as production rose rapidly during the 1950s to satisfy the military requirement for highly enriched uranium (HEU) and plutonium. Uranium demand from this source fell sharply from 1960 onwards and, in response, production halved by the mid-1960s.
- A period of rapidly expanding civil nuclear power, lasting from the late 1960s to the mid-1980s. Uranium production picked up again as reactor orders expanded. Many new mines were quickly brought into production, frequently underwritten by long-term contracts agreed with electricity utilities in North America, Japan and Western Europe. Production peaked in 1980 and stayed above annual reactor requirements until 1985.
- An age dominated by an inventory over-hang, extended by supply from the former Soviet Union (NIS), lasting from the mid-1980s up to about 2002. By 1985, nuclear construction programmes had been cut back severely. However, many utilities had signed uranium contracts in anticipation of building additional nuclear plants. Honouring these resulted in a build-up of utilities' uranium inventories. As these were being run down, mines closed or cut production. Utilities satisfied much of their requirements without recourse to new production. This period was extended by the arrival on Western markets of uranium from the NIS in the early 1990s.

Markets formerly almost completely segregated reached the first stage of integration, although the material flow was effectively one-way only.

- A strong market reaction to the perception that secondary supplies are beginning to run out and that primary production needed to rise sharply to fill more of the gap still evident with reactor requirements. This started in 2003 with a strong upward movement in world uranium prices and continued into 2007 (the spot market price rose by a factor of 13 between 2003 and mid-2007). This is likely to remain the dominant theme for at least the next few years.

Figure 7.1 summarises the position in the West since 1945. Production was substantially ahead of reactor requirements until 1985, but has since fallen. Since 1985, requirements have exceeded production by approximately 400,000 tU.

Within the former Soviet Union and Eastern Europe, significant reductions in uranium production occurred much later than in the West. Fissile material production was considered vital in the Soviet Union with central plans seeking to maximise production irrespective of civil reactor demand. This resulted in the accumulation of large quantities of materials in various forms. Uranium production began to fall sharply only from the late 1980s onwards, largely as a consequence of the end of the arms race, but also of the exhaustion of some resources and the economic disruptions during the collapse of the Soviet Union.

The opening-up of Western markets for nuclear fuel to producers in the former Soviet Union also occurred at this time. The additional outlet for material was certainly welcome by producers there, but application of market financial criteria indicated that much production from these countries was uneconomic. Even though uranium exports from the former Soviet Union to the West have been subject to trade restrictions, it is believed that approximately 170,000 tU has so far reached Western markets from there.

Table 7.3 shows that Canada produces the largest share of uranium from mines (25% of world supply from mines in 2006), followed by Australia (19%).

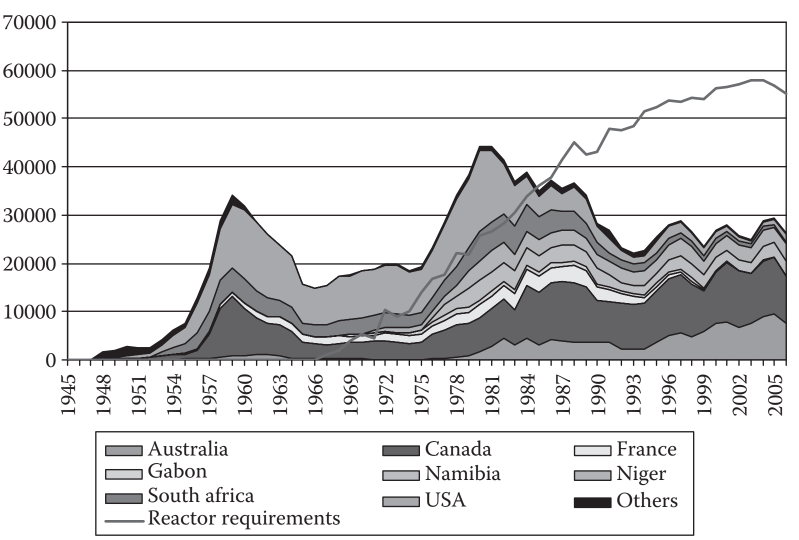

FIGURE 7.1
Western world uranium production and demand 1945–2006.

TABLE 7.3

Uranium Production by Country (Tonnes U), 2004–2006

	2004	2005	2006	% Change 2005–2006
Australia	8,982	9,516	7,593	–20
Brazil	300	110	190	73
Canada	11,597	11,628	9,862	–15
China[a]	750	750	750	0
Czech Republic	412	408	359	–12
France	7	7	5	–29
Germany	150	77	50	–35
India[a]	230	230	177	–23
Kazakhstan	3,719	4,357	5,279	21
Namibia	3,038	3,147	3,067	–3
Niger	3,282	3,093	3,434	11
Pakistan[a]	45	45	45	0
Romania[a]	90	90	90	0
Russia	3,200	3,431	3,262	–5
South Africa	755	674	534	–21
Ukraine[a]	800	800	800	0
United States	878	1,039	1,672	61
Uzbekistan	2,016	2,300	2,260	–2
Total	**40,251**	**41,702**	**39,429**	**–5**

Source: World Nuclear Association.

[a] WNA estimate.

Following a slight increase in 2005, total Australian production decreased to 2003 levels due to a series of weather-related and technical problems. Total production of 7,593 tU represented about 19% of world production in 2006. ERA's production at Ranger was lower in 2006 at 4,026 tU, somewhat below rated capacity. Ranger production was impacted by unusually high levels of rainfall that prevented access to higher-grade ore and difficulty in restarting ore processing facilities after a maintenance shutdown. Plans to develop the Jabiluka orebody, 20 km from the existing Ranger mill, remain on hold and depend on agreement being achieved with local communities. Higher uranium prices have resulted in the reclassification of reserves at the existing Ranger orebody and mill production is expected to continue until 2020.

Uranium output at BHP's Olympic Dam copper/uranium mine decreased in 2006 to 2,868 tU, well below 2004/2005 production levels in the 3,700 tU range. BHP continues to investigate the feasibility of substantial increases in uranium and copper production capacity at Olympic Dam. If a decision is made to proceed, uranium production capacity could triple to a rate of about 12,700 tU per year with production starting in the 2014 time frame. Production at the Beverley ISL mine in Southern Australia, owned by Heathgate Resources (a General Atomics subsidiary), decreased to 699 tU in 2006, below rated capacity. Development of the Honeymoon ISL uranium project in South Australia has been approved with plans to commission the mine in 2008. Honeymoon is expected to have an annual production capacity of 340 tU with a mine life of 6–7 years.

Canada's uranium output decreased to 9,862 tU in 2006, a decrease of 15% compared with 2005 production. It easily retained its place as the leading world producer, accounting for 25% of the total. Output at McArthur River remained steady at its licensed capacity of 7,200 tU. An application to increase licensed capacity to 8,460 tU is pending regulatory approval. Rabbit Lake production was a little lower at 1,972 tU. Mine life has been extended to 2011 with the addition of about 7,300 tU of reserves. McClean Lake production decreased significantly to 690 tU during 2006 as a result of low ore grades and operational issues with the milling circuit. The level of production expected over the next several years will mainly depend on the development schedule for the Cigar Lake and Midwest projects. Development of the Cigar Lake mine has been delayed by several years due to a water inflow in 2006. The start-up date is expected to be in the 2010/2011 timeframe, with a ramp up of production scheduled over 3 years. Production at Midwest is expected to begin in late 2010 or 2011, with a maximum production rate of about 3,000 tU per annum.

In Europe, French uranium production continues with a small amount of residual production associated with decommissioning activities. German production was also solely associated with the decommissioning and environmental clean-up of mining operations belonging to Wismut in the former East Germany, which ceased production in the early 1990s after being a major world producer in the 1950s to 1980s. DIAMO in the Czech Republic is now the only significant European producer, and has recently decided to extend production beyond 2008. Production in 2006 was 359 tU. Romanian production is believed to have remained constant at 90 tU.

Within Africa, overall production remained relatively steady in 2006 at 7,032 tU, about 2% lower than in 2005. Niger's production from Akouta and Arlit remained above the 3,000-tU level at 3,434 tU. Production in South Africa was lower at 534 tU from 674 tU in 2005. South African uranium is a by-product from AngloGold Ashanti's Vaal River property. Production at the Rossing mine in Namibia remained steady in 2006 at 3,067 tU. In late 2005, Rio Tinto decided to extend the life of the operation until 2016 with a goal of restoring annual production capacity of 3,400 tU. The increased uranium price has encouraged several companies to advance several projects in Africa. Paladin's Langer Heinrich mine began production in late 2006 and is expected to reach an annual rate of 1,000 tU. A development decision has also been made on the Kayelekera project in Malawi with first production possible in 2008. Uranium One has started production at its Dominion Reefs property in South Africa with a planned ramp-up to 1,460 tU per year.

Production in the United States increased by >60% in 2006 to 1,672 tU from 1,039 tU in 2005 as rising uranium prices provided the necessary incentive to restart several mining properties and expand production at existing operations. Cameco's ISL operations produced 1,066 tU with plans to expand production to more than 1,700 tU by 2011. Production from URI's Kingsville Dome and Vasquez properties, Mestena's Alta Mesa mine, and alternate feed processing by Denison's White Mesa mill contributed an additional 606 tU. Given current market conditions, further production increases can be expected as production at these facilities is increased and additional properties are brought on line.

In Kazakhstan, production rose by about 21% from 4,357 tU in 2005 to 5,279 tU in 2006. Kazakhstan has followed a strategy of establishing joint ventures with other industry participants to expand existing mines and develop new projects. Approximately one-half of the recent production increases have resulted from these joint initiatives. Given current market conditions, several other projects—including Inkai (Cameco JV), Zarechnoye (Tenex JV), Tortkuduk (Areva JV), Kharassan, and South Inkai (both Uranium One/UrAsia JVs)—will likely advance to commercial production within the next few years.

Russian production remains steady at about 3,262 tU, with most of the output coming from the Priargunsky mining area at 2,900 tU. Russia has announced plans to expand its nuclear capacity and, accordingly, announced its intention to increase production significantly by 2020 to meet domestic uranium requirements.

Production is believed to remain virtually constant in the Ukraine and Pakistan. Production in India reportedly decreased 23% in 2006 to 177 tU from 230 tU in 2005. Chinese production appears to be remaining steady with production of 750 tU in 2006. Each of these countries can be termed "captive producers" in that they produce largely for domestic reactor requirements only. Their reserves tend to be low grade, making widespread commercial exploitation unlikely. Brazil recommenced production in 2000 and achieved output of 190 tU in 2006. Production is expected to rise in the future to fully utilize mine capacity. Uzbekistan production declined slightly in 2006 to 2,260 tU from 2,300 tU in 2005, a 2% decrease.

Looking ahead, the production outlook has now improved, owing to the substantial uranium price escalation. The prospect is for a steady rise in world production towards 60 000 tU per annum over the next 3–5 years, led by the major producers such as Canada, Australia, and Kazakhstan, but with increases also expected in Southern Africa (Namibia and South Africa) and the United States. The trend for supply to become concentrated in a few large low-cost mines in a few countries may abate as new producers start up. Some of the smaller projects mentioned over the last few years will now find it easier to compete now uranium prices have risen. Delays to approval for the major projects may provide a further opportunity for these, as would any interruption in the expected supply of blended-down HEU. Kazakhstan has announced that it intends to expand production very sharply, partly via joint ventures with foreign companies. The increasing demand to feed Russian-designed reactors, for example in India and China, suggests that production will also increase in Russia.

During the 1990s, the uranium production industry was consolidated by takeovers, mergers and closures. In 2006, the eight mining companies with >1000 t output (equity interest) accounted for 85% of world mine production (Table 7.4).

Production has also become increasingly concentrated in a few major mines throughout the world. Table 7.5 shows that 69% of production came from the ten largest mines.

TABLE 7.4

Uranium Production by Company, Tonnes U, 2006

	Production tU	World Share %
Cameco	8,249	21
Rio Tinto	7,094	18
Areva	5,272	13
Kazatomprom	3,699	9
TVEL	3,262	8
BHP Billiton	2,868	7
Navoi	2,260	6
Uranium One	1,000	3
Subtotal	33,703	85
World Total	39,429	100

Source: World Nuclear Association.

TABLE 7.5

Uranium Production from the Top Ten Mines, Tonnes U, 2006

Mine	Country	Main Owner	Mine Type	Production (tU)	% of World Production
McArthur River	Canada	Cameco	Underground	7200	18%
Ranger	Australia	Rio Tinto	Open Pit	4026	10%
Rossing	Namibia	Rio Tinto	Open Pit	3067	8%
Priargunsky	Russia	TVEL	Underground	2900	7%
Olympic Dam	Australia	BHP Billiton	By-product/ underground	2868	7%
Rabbit Lake	Canada	Cameco	Underground	1972	5%
Akouta	Niger	Areva/Onarem	Underground	1866	5%
Arlit	Niger	Areva/Onarem	Open Pit	1565	4%
Akdala	Kazakhstan	UrAsia/Uranium One	ISL	1000	3%
Highland-Smith	Ranch USA	Cameco	ISL	786	2%
Total from Top Ten Mines				**27251**	**69%**
World Total				39427	

Source: World Nuclear Association.

7.9 Uranium Market and Prices

All mineral commodity markets tend to be cyclical, i.e., prices rise and fall substantially over the years, but with these fluctuations superimposed on long-term decline in real prices. In the uranium market, very high prices in the late 1970s gave way to very low prices in the early 1990s, the spot prices being below the cost of production for most mines. In 1996 spot prices recovered to the point where most mines could produce profitably, though they then declined again and only started to recover strongly late in 2003.

The reasons for fluctuation in mineral prices relate to demand and perceptions of scarcity. The price cannot indefinitely stay below the cost of production, nor will it remain at very high levels for longer than it takes for new producers to enter the market and anxiety about supply to subside.

About 439 reactors with combined capacity of some 370 GWe require 64,000 tonnes of uranium from mines (or the equivalent from stockpiles or secondary sources) each year. The capacity is growing slowly, and at the same time the reactors are being run more productively, with higher capacity factors, and reactor power levels. However, these factors increasing fuel demand are offset by a trend for increased efficiencies, so demand is dampened; over the 20 years from 1970 there was a 25% reduction in uranium demand per kWh output in Europe due to such improvements, which continue today. Each GWe of increased capacity will require about 200 tU/yr of extra mine production routinely, and about 2.5-times this for the first fuel load.

Because of the cost structure of nuclear power generation, with high capital and low fuel costs, the demand for uranium fuel is much more predictable than with probably any other mineral commodity. Once reactors are built, it is very cost-effective to keep them running at high capacity and for utilities to make adjustments to load trends by cutting back on fossil fuel use. Demand forecasts for uranium thus depend largely on installed and operable capacity, regardless of economic fluctuations.

Looking 10 years' ahead, the market is expected to grow slightly. Demand thereafter will depend on new plants being built and the rate at which older plants are retired. Licensing of plant lifetime extensions and the economic attractiveness of continued operation of older reactors are critical factors in the medium-term uranium market. However, with electricity demand by 2030 expected (by the OECD's International Energy Agency) to double from that of 2006, there is plenty of scope for growth in nuclear capacity in a greenhouse-conscious world.

Mines in 2006 supplied some 39,400 tU or about 60% of utilities' annual requirements (see above). The balance is made-up from secondary sources or stockpiled uranium held by utilities, but those stockpiles are now largely depleted. As well as existing and likely new mines, nuclear fuel supply may be from secondary sources, including:

- Recycled uranium and plutonium from spent fuel as mixed oxide (MOX) fuel
- Re-enriched depleted uranium tails
- Ex-military weapon-grade uranium
- Civil stockpiles
- Ex-military weapon-grade plutonium

Major commercial reprocessing plants are operating in France and UK, with capacity of >4000 tonnes of used fuel per year. The product from these re-enters the fuel cycle and is fabricated into fresh MOX fuel elements. About 200 tonnes of MOX is used each year, equivalent to less than 2000 tonnes of uranium from mines.

Military uranium for weapons is enriched to much higher levels than that for the civil fuel cycle. Weapons-grade is about 97% U-235, and this can be diluted about 25:1 with depleted uranium (or 30:1 with enriched depleted uranium) to reduce it to about 4%, suitable for use in a reactor. From 1999, the dilution of 30 tonnes of such material is displacing about 10,600 tonnes per year of mine production as a result of the 1994 "Megatons to Megawatts" agreement between USA and Russia. The United States and Russia agreed to dispose of 34 tones each of military plutonium by 2014. Most of it is likely to be used as feed for MOX plants, to make about 1500 tonnes of MOX fuel which will progressively be burned in civil reactors.

The perception of imminent scarcity drove up the spot price of uranium for uncontracted sales to US$ 138 per pound U_3O_8 by mid-2007, but prices subsequently fell back significantly to US$75 per pound by the autumn. Most uranium however is supplied under long-term contracts and the prices in new contracts have, in the past, reflected a premium above the spot market. Note that at the prices which utilities are likely to be paying for current delivery, only one-quarter of the cost of the fuel loaded into a nuclear reactor is the actual ex-mine (or other) supply. The balance is mostly the cost of enrichment and fuel fabrication.

The spot prices shown in Figure 7.2 apply to marginal trading from day to day and usually represent <20% of supply. Most trade is 3–10-year term contracts with producers selling direct to utilities, but with the price often related to the spot price.

7.10 Conversion

The product of a uranium mill is not directly usable as a fuel for a nuclear reactor. Additional processing, generally referred to as "enrichment," is required for most types of reactors.

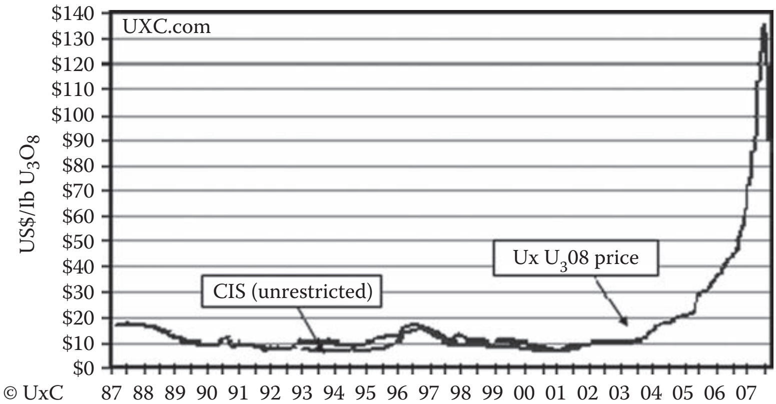

FIGURE 7.2
Uranium spot prices 1987 to date.

This process requires uranium to be in gaseous form and the way this is achieved is to convert it to uranium hexafluoride, which is a gas at relatively low temperatures.

At a conversion facility, uranium is first refined to uranium dioxide, which can be used as the fuel for those types of reactors that do not require enriched uranium. Most is then converted into uranium hexafluoride, ready for the enrichment plant. It is shipped in strong metal containers. The main hazard of this stage of the fuel cycle is the use of hydrogen fluoride.

Light water reactors (LWRs) require a process that involves transforming natural uranium concentrates into UF_6. The UK's gas-cooled reactors (AGRs) also require UF_6 conversion. Heavy water reactors (HWRs), which are mainly of the CANDU design, require conversion from natural uranium concentrates directly to UO_2. For the UK's Magnox gas-cooled reactors, conversion from natural uranium concentrates to uranium metal and fuel fabrication is handled domestically in dedicated facilities.

Russia has produced two main reactor designs, known as VVERs and RBMKs. The former is a type of LWR, whereas the latter are light water-cooled graphite reactors. These reactors predominately exist in Russia, other countries that were part of the former Soviet Union, and Eastern Europe. Both designs use enriched uranium and therefore require UF_6 conversion.

Worldwide requirements for conversion services, averaged over an extended period, will be equal to aggregate demand for uranium requirements, as outlined above, after allowing for the few reactors which do not require conversion. Accordingly, those factors, which affect annual worldwide uranium demand, must be considered when examining conversion demand, as well as any factors that are indigenous to the conversion market.

Countries operating CANDUs or other HWRs with requirements for UO_2 conversion are Argentina, Canada, China, India, Korea, Pakistan and Romania. The key to future growth in demand is the magnitude of the Indian nuclear programme, which relies heavily on HWRs.

Worldwide, five major suppliers meet the majority of the demand for UF_6 conversion services. Together, they have a combined capacity of 62,500 tU per annum. However, it should be noted that it is unfeasible for production plants to continually sustain 100% of nameplate capacity, and therefore production figures of <62,500 tU per annum should be expected.

With regard to UO_2 conversion supply, Cameco's plant is by far the largest supplier, with a licensed annual capacity of 2,800 tU. In addition, smaller plants exist to meet the local needs in India, Argentina and Romania. Cameco Corporation owns and operates uranium refinery and conversion facilities located respectively at Blind River and Port Hope. The Blind River plant refines natural uranium concentrates (U_3O_8) into uranium trioxide (UO_3), and was commissioned in 1983. The intermediate product is shipped to the Port Hope plant (commissioned 1984) where further processing produces natural UF_6.

Many of the secondary sources of uranium described above also displace demand for UF_6 conversion. These include inventories of UF_6 and low enriched uranium (LEU), Russian and U.S. ex-military HEU and plutonium, uranium and plutonium recovered by civil spent fuel reprocessing and UF_6 supply from the re-enrichment of tails. In addition, "underfeeding" of enrichment facilities can also affect the UF_6 market.

7.11 Thorium

Thorium is a naturally occurring, slightly radioactive metal discovered in 1828 by the Swedish chemist Jons Jakob Berzelius, who named it after Thor, the Norse god of thunder. It is found in small amounts in most rocks and soils, where it is about three-times more abundant than uranium. Soil commonly contains an average of around 6 ppm of thorium.

Thorium occurs in several minerals, commonest being the rare earth-thorium-phosphate mineral, monazite, which contains up to about 12% thorium oxide (but average 6–7%). There are substantial deposits in several countries (Table 7.6).

The 2005 IAEA-NEA "Red Book" gives a figure of 4.5 million tonnes of reserves and additional resources, but points-out that this excludes data from much of the world. Geoscience Australia confirms the above 300,000 tonne figure for Australia, but stresses that this is based on assumptions, not direct geological data in the same way as for most mineral resources.

Thorium-232 decays very slowly (its half-life is about three-times the age of the earth) but other thorium isotopes occur in the decay chain of it and uranium. Most of these are short-lived and hence much more radioactive than Th-232, though on a mass basis they are negligible.

TABLE 7.6

Worldwide Thorium Resources

(Economically Extractable)	
Country	**Reserves (Tonnes)**
Australia	300,000
India	290,000
Norway	170,000
USA	160,000
Canada	100,000
South Africa	35,000
Brazil	16,000
Other countries	95,000
World total	1,200,000

Source: U.S. Geological Survey, *Mineral Commodity Summaries*, January 1999.

When pure, thorium is a silvery white metal that retains its luster for several months. However, when it is contaminated with the oxide, thorium slowly tarnishes in air, becoming gray and eventually black. Thorium oxide (ThO_2), also called thoria, has one of the highest melting points of all oxides (3300°C). When heated in air, thorium metal turnings ignite and burn brilliantly with a white light. Because of these properties, thorium has found applications in light bulb elements, lantern mantles, arc-light lamps, welding electrodes and heat-resistant ceramics. Glass containing thorium oxide has a high refractive index and dispersion, and is used in high-quality lenses for cameras and scientific instruments.

Thorium, as well as uranium, can be used as a nuclear fuel. Although not fissile itself, thorium-232 (Th-232) will absorb slow neutrons to produce uranium-233 (U-233), which is fissile. Hence, like uranium-238 (U-238), it is fertile.

In one significant respect U-233 is better than uranium-235 and plutonium-239: its higher neutron yield per neutron absorbed. Given a start with some other fissile material (U-235 or Pu-239), a breeding cycle similar to but more efficient than that with U-238 and plutonium (in slow-neutron reactors) can be set up. The Th-232 absorbs a neutron to become Th-233, which normally decays to protactinium-233 and then U-233. The irradiated fuel can then be unloaded from the reactor, the U-233 separated from the thorium, and fed back into another reactor as part of a closed fuel cycle.

Over the last 30 years, there has been interest in utilizing thorium as a nuclear fuel because it is more abundant in the earth's crust than uranium. Also, all of the mined thorium is potentially useable in a reactor, compared with the 0.7% of natural uranium, so about 40-times the amount of energy per unit mass may theoretically be available (without recourse to fast breeder reactors).