

# Uranium

March 2010

## Definition, mineralogy and deposits

### Definition and characteristics

Uranium is a naturally occurring, very dense, metallic element with an average abundance in the Earth's crust of about 3 ppm (parts per million). It forms large, highly charged ions and does not easily fit into the crystal structure of common silicate minerals such as feldspar or mica. Accordingly, as an incompatible element, it is amongst the last elements to crystallise from cooling magmas and one of the first to enter the liquid on melting.

Under oxidizing conditions uranium exists in a highly soluble form,  $U^{6+}$  (an ion with a positive charge of 6), and is therefore very mobile. However, under reducing conditions it converts to an insoluble form,  $U^{4+}$ , and is precipitated. It is these characteristics that often result in concentrations of uranium that are sufficient for economic extraction.

Uranium is naturally radioactive. It spontaneously decays through a long series of alpha and beta particle emissions, ultimately forming the stable element lead.

If an atom of uranium is struck by, and manages to absorb, an extra neutron it will undergo nuclear fission. In this process the atom breaks apart forming 'daughter products' (typically strontium and xenon) and releasing a large quantity of energy, plus more neutrons. If these neutrons collide with further atoms of uranium a chain reaction can occur. The energy released in nuclear fission is used in nuclear power stations to convert water into steam, which is then used to turn a turbine and generate electricity.

Uranium occurs as several isotopes, of which the most abundant are uranium-238 (U-238; about 99.3 per cent) and uranium-235 (U-235; about 0.7 per cent). U-235 is required for the operation of nuclear power stations. Most early designs of power station used uranium in its natural state, but all modern plants require enrichment to increase the proportion of U-235 to between 3 and 5 per cent.

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Symbol	U	
Atomic number	92	
Atomic weight	238.03	
Density at 298 K	19 050	kg/m <sup>3</sup>
Melting point	1132	°C
Boiling point	3927	°C
Mineral Hardness	6	Moh's scale
Electrical resistivity	28 x 10 <sup>-8</sup>	Ohm m

Table 1 Selected properties of uranium.

Other physical properties are summarised in Table 1.

### Mineralogy

Uranium is known to occur in over 200 different minerals, but most of these do not occur in deposits of sufficient grade to warrant economic extraction. The most common uranium-bearing minerals found in workable deposits are shown in Table 2.



Figure 1 Uranium ore. Courtesy: Mineral Information Institute ([www.mii.org](http://www.mii.org))

Name	Group of minerals	Formula	Most common depositional environment
Uraninite	Uranium oxide	UO <sub>2</sub>	Magmatic <sup>1</sup> , hydrothermal <sup>2</sup> or sedimentary-hosted <sup>3</sup> deposits
Pitchblende	Uranium oxide (a massive variety of uraninite)	UO <sub>2</sub>	Magmatic, hydrothermal or sedimentary-hosted deposits
Coffinite	Uranium silicate	U(SiO <sub>4</sub> ) <sub>0.9</sub> (OH) <sub>0.4</sub>	Hydrothermal or sedimentary-hosted deposits
Brannerite	Uranium titanate	(UCaCe)(TiFe <sup>2+</sup> )O <sub>6</sub>	Hydrothermal or sedimentary-hosted deposits
Carnotite	Uranyl vanadate	K <sub>2</sub> (UO <sub>2</sub> ) <sub>2</sub> (VO <sub>4</sub> ) <sub>2</sub> ·3(H <sub>2</sub> O)	Sandstone-hosted deposits
Tyuyamunite	Uranyl vanadate	Ca(UO <sub>2</sub> ) <sub>2</sub> (VO <sub>4</sub> ) <sub>2</sub> ·6(H <sub>2</sub> O)	Sandstone-hosted deposits
Uranophane	Uranyl silicate	CaH <sub>2</sub> (SiO <sub>4</sub> ) <sub>2</sub> (UO <sub>2</sub> )·5(H <sub>2</sub> O)	Sandstone-hosted deposits

Table 2 The most common uranium minerals found in economic deposits.

Deposit type	Brief description	Typical grade (ppm U)	Examples
Unconformity-related	Associated with unconformities in ancient sedimentary basins	5000 to 200 000	McArthur River, Canada; Ranger, Australia
Sandstone-hosted	Oxidising-reducing conditions in sandstones	400 to 4000	Beverley, Australia; Inkai, Kazakhstan
Hematite breccia complex	Funnel or pipe-shaped deposits of broken rock	300 to 500	Olympic Dam, Australia
Vein	Cavities such as cracks, fissures, pore spaces or stockworks	250 to 10 000	Lianshanguan, China
Quartz-pebble conglomerates	Ancient sedimentary deposits buried before oxidisation took place	130 to 1000	Hartebeestfontein, South Africa
Intrusive	Associated with the crystallisation or remobilisation of a magma	60 to 500	Rössing, Namibia
Phosphorite	Associated with sedimentary phosphates	60 to 500	Melovoe, Kazakhstan (closed)
Collapse breccia	Concentrated in the matrix and fractures surrounding breccia pipes	2500 to 10 000	Arizona 1, USA (closed)
Volcanic & caldera related	Associated with felsic lava, ash fields and related sediments (e.g. rhyolite or trachyte)	200 to 5000	Xiangshan (Zoujiashan), China
Surficial	Unconsolidated near-surface sediments. Sometimes cemented with calcium carbonate	500 to 1000	Langer Heinrich, Namibia; Yeelirre deposit Australia
Metasomatite	Alteration of minerals within a rock, often caused by the nearby emplacement of magma	500 to 2000	Ingulkii, Ukraine
Metamorphic	Concentration by processes such as partial melting. Often remobilised by fluids	500 to 2000	Mary Kathleen, Australia (closed)
Lignite	Associated with coalified plant detritus or adjacent clay and sandstone	Less than 1000	Koldjat, Kazakhstan (closed)
Black shale	Rocks of marine origin with high organic content	Less than 1000	Schaenzel, France (closed)

Table 3 Summary of uranium deposit types.

<sup>1</sup>Magmatic – related to magma, molten rock and fluid originating deep within or below the Earth's crust.

<sup>2</sup>Hydrothermal – hot fluids

<sup>3</sup>Sedimentary-hosted – mineralisation contained within a sedimentary rock.

## Deposits

Uranium deposits are found throughout the world in a variety of geological environments. They can be grouped into 14 major categories based on geological setting (IAEA, 2009a), but not all of these are actively worked. Key features of these are shown in Table 3.

## Major deposit classes

### **Unconformity-related deposits**

These are formed as a result of geological changes close to major unconformities<sup>4</sup>. Below the unconformity the rocks are usually reduced, deformed, faulted or brecciated, whereas the overlying younger rocks may not be. Mineralisation is believed to occur where hot, oxidising, metal-bearing fluids migrate through overlying porous rocks and encounter reducing conditions below the unconformity. Deposits can be found immediately below, across, or immediately above the unconformity, depending on the specific sub-type (WNA, 2009; NEA/OECD, 2006).

This category of deposit tends to be found in ancient sedimentary basins where rocks are typically 1600 Ma or older. Deposit grades tend to be relatively high, commonly 5000 ppm U, although they can locally reach 200 000 ppm U. Typically, the mineralisation consists of pitchblende or uraninite, together with coffinite and other minor uranium oxides. Some deposits, such as Cigar Lake, Canada, also contain significant quantities of nickel-cobalt arsenides.

Canada is the world's largest producer of uranium, and both of its currently operating mines are working this type of deposit in the Athabasca Basin, Saskatchewan. Another major unconformity-related deposit currently being mined is at Ranger in Northern Territory, Australia.

### **Sandstone-hosted deposits**

The most significant deposits in this category are contained in permeable, medium- to coarse-grained, sandstones that are poorly sorted and usually of fluvial<sup>5</sup> or marginal marine origin. Lacustrine<sup>6</sup> or aeolian<sup>7</sup> sandstones may also host mineralisation.

The source of uranium is usually igneous rocks (volcanic ash or granite plutons) either close by, interbedded with, or

overlying the host sandstones. Mineralisation occurs when oxidising fluids transport the uranium into the sandstone, where it is deposited under reducing conditions (caused by organic matter, sulphides, hydrocarbons or ferromagnesium minerals such as chlorite).

There are four main types of sandstone deposits (NEA/OECD, 2006):

Rollfront — crescent-shaped bodies that crosscut sandstone bedding;

Tabular — irregular, elongated lenses within reduced sediments;

Basal channel — elongated or ribbon-like bodies that occur along former watercourses;

Tectonic/lithologic — adjacent to permeable fault zones.

The host sandstones can be of almost any age and deposit grades are generally in the range 400–4000 ppm U. The oxidised part of the deposit usually contains uraninite or coffinite, but close to the rollfront other minerals occur such as carnotite, tyuyamunite and uranophane.

These are probably the most common type of deposit but, due to their lower grade, production tends to be less than unconformity-related deposits. Currently there are mines operating in rollfront type deposits in Uzbekistan, Kazakhstan, the USA and China. Tabular deposits are worked in Niger, Romania, Czech Republic and the USA, and basal channel deposits are worked in Australia and Russia.

### **Hematite breccia<sup>8</sup> complex deposits**

The Olympic Dam deposit in South Australia is one of the world's largest uranium deposits and is of this type. Breccias generally occur within relatively stable continental areas where extensional tectonics have caused rifting and the formation of grabens<sup>9</sup>. Mineralisation occurs due to the presence of nearby granitic or volcanoclastic<sup>10</sup> sediments and possibly also shallow hydrothermal processes.

Mineralisation in these deposits varies widely, from the monometallic 'Kiruna' type (mostly iron with some phosphorus) to the polymetallic 'iron-oxide-copper-gold' (IOCG) type. The Olympic Dam deposit is towards the latter end

<sup>4</sup>An unconformity is where one rock formation is overlain by another that is not the next in geological succession.

<sup>5</sup>Fluvial — associated with rivers

<sup>6</sup>Lacustrine — associated with lakes

<sup>7</sup>Aeolian — deposited by wind

<sup>8</sup>A breccia is a fragmented, rock deposit consisting of angular pieces, i.e. pieces which are not rounded by water.

<sup>9</sup>A graben is formed where tectonic extension causes blocks of crust to subside between near parallel fault lines.

<sup>10</sup>Volcanoclastic sediments are particles of a volcanic origin, transported and deposited by a fluid.

of this continuum where iron, copper, gold, uranium, silver and rare earth elements are present.

Although it is believed there are deposits of this type in several countries, currently only Olympic Dam in Australia is being mined. The grade of this deposit is 300–500 ppm U, but it is made economic by the co-production of copper, gold and silver. The chief uranium mineral is uraninite, but coffinite and brannerite are also present.

### **Vein deposits**

This is a collective term for any deposit of uranium that is formed in cracks, bedding planes, fissures, pore spaces (spaces between rock particles) or stockworks (multiple intersecting cracks). These deposits can be located within igneous, metamorphic or sedimentary rocks. Mineralisation occurs chiefly through hydrothermal or geothermal activity.

The ages of the host rock, and the grades of uranium, are highly variable. Most deposits have grades in the range < 1000 ppm U, although higher grades have also been reported. Ore minerals are mostly uraninite, but also brannerite and, locally, coffinite in shear zones. Vein deposits are exploited in Russia, Romania, India, China, Czech Republic and Kazakhstan. Many other countries have also worked these deposits in the past.

### **Quartz-pebble conglomerates**

These deposits are believed to have formed before 2200 Ma, when the atmosphere was less oxidizing than today. Eroded particles from the source rock were deposited in a fluvial environment and buried while the uranium remained in its insoluble form. Alternatively, it has been suggested that rapid basin filling by rivers could have isolated the uranium before oxidation could take place. However, no deposits of this type have been identified in rocks younger than about 2200 Ma.

All currently worked deposits of this type are located in South Africa. There was a significant deposit at Elliot Lake in Canada, but this has now been depleted. These deposits tend to be large in volume but of low grade, typically 130 – 1000 ppm U. The mineralisation comprises mostly uraninite.

### **Deposits related to intrusive rocks**

This is a collective term for deposits associated with granites or anatectic<sup>11</sup> rocks. It includes alkaline intrusions, carbonatites (high carbonate rock derived from magmatic fluids) and pegmatites (formed from the very last part of a magma to crystallise) (NEA/OECD, 2006). The only mine currently working this type of deposit is Rössing in Namibia. Grades are typically between 60 and 500 ppm U, with the mineralisation comprising mostly uraninite. In some of these deposits the uranium is bound in refractory minerals such as zircon or pyrochlore, making extraction more difficult.

### **Volcanic/caldera related**

Deposits of this type are located within, or near to, a volcanic caldera<sup>12</sup> which is filled by mafic<sup>13</sup> to felsic<sup>14</sup> volcanic complexes and interleaved sediments (NEA/OECD, 2006). Mineralisation is typically related to faults or shear zones (WNA, 2009) and may be either magmatic- or hydrothermal-related. Ore minerals are principally pitchblende and often associated with molybdenum, other sulphides, fluorine or quartz (NEA/OECD, 2006). Deposit grades are typically in the range 200 to 5000 ppm U but the deposits tend to be small in size. The most significant deposits are located within the Streltsovsk caldera in Russia but this type of deposit is also worked in China.

### **Surficial**

This group of deposits are Tertiary to Recent in age (up to 65 Ma old), near-surface concentrations in sediments or soils. Mineralisation is associated with deeply weathered uranium-rich granites and occurs with secondary cementing minerals, most commonly calcrete<sup>15</sup> but also gypsum, ferric oxide or halite<sup>16</sup> (WNA, 2009). These deposits can occur in valley-fill sediments along Tertiary drainage channels and in playa lake sediments (NEA/OECD, 2006).

The only mine working this type of deposit is Langer Heinrich, which opened in Namibia in early 2007. Here deposit grades range from 500 ppm to 1000 ppm and the main mineral is calcrete-hosted carnotite. The Yeelirrie deposit in Western Australia is another example of this type of deposit.

### **Metasomatite**

Deposits of this type are confined to areas of tectono-magmatic activity in Precambrian shields (older than 542

<sup>11</sup> Anatectic rocks are high temperature metamorphic rocks where magma is regenerated.

<sup>12</sup> A caldera is a large crater formed by a volcanic explosion or the collapse of a volcano cone

<sup>13</sup> Mafic – dark coloured rocks containing iron- and magnesium-bearing minerals, with virtually no felsic minerals such as quartz or feldspar.

<sup>14</sup> Felsic – rocks containing light coloured silicate minerals such as quartz and feldspar

<sup>15</sup> Calcrete – calcium and magnesium carbonates

<sup>16</sup> Halite – native salt



Ma) and are related to alkali metasomatism<sup>17</sup> (NEA/OECD, 2006). Ore minerals are typically uraninite or brannerite and deposit grades are usually in the range 500 to 2000 ppm. All three currently worked deposits of this type are in Ukraine (IAEA, 2009a).

## EXTRACTION METHODS AND PROCESSING

### Extraction

There are four main methods by which uranium ore is extracted: the method chosen in each case will largely depend on the type of deposit.

#### **Open-pit**

Approximately 20% of all uranium ore mined in 2008 was from open pits (less than 200 m depth and open to the surface). This extraction method is similar to any other surface mine or quarry and involves drilling and blasting in benches. Hydraulic excavators load the broken ore into large trucks for transport to the crushing and milling plant. Some of the world's largest uranium deposits (Ranger, Australia; Rössing, Namibia; McClean Lake, Canada) are mined by open-pit methods.

#### **Underground**

In 2008, 42% of uranium ore was mined from underground. This method is used if the ore body is too deep to be extracted by open-pit. There are several ways in which underground mining is carried out, but the hazards involved with high-grade ores in enclosed spaces, as a result of radon gas and radioactivity, mean that unique, remote-controlled methods have been developed to minimise the risk of exposure to operators. For example, at the world's largest uranium mine at McArthur River in Canada the following method is used:

1. A shaft is sunk to the required depth, with horizontal levels above and below the ore body.
2. A pilot hole is drilled through the ore deposit by a raisebore machine located on the upper level.
3. A rotating reaming head is attached on the lower level and raised upward through the ore body towards the raisebore machine.
4. The ore falls down to a remote-controlled loading system that removes it to the processing circuit.
5. The first stages of processing the ore, which reducing it to a fine slurry, are also carried out underground.

Other underground uranium mines are located at Rabbit Lake in Canada and Akouta in Niger.

#### **In-situ leaching**

In 2008, 28% of uranium mining was carried out by in-situ leaching. This technology is only suitable for permeable ore bodies such as sandstone-hosted deposits. The host rock is relatively undisturbed and no large cavities are created. Consequently there is less surface disturbance and no waste tailings are produced.

In this method either an alkaline (if there is significant calcium in the ore body) or acid solution is injected into the ore body from a grid of wells (known as the wellfield) along with an oxidant. The uranium is dissolved into the solution and the uranium-bearing fluid is pumped to the surface. After the uranium has been removed from the solution, the fluid is re-injected into a closed circuit. A small amount of the fluid is removed to ensure that any movement of groundwater is into the mined area to avoid any contamination of surrounding aquifers.

The largest mining operation using this method is at Beverley in South Australia, although several smaller mines also use this technology.

#### **Co-product or by-product**

In 2008, 10% of uranium mined was recovered as a by-product or co-product of copper or gold mining operations. Most of this was at the Olympic Dam mine in South Australia.

The ore at Olympic Dam is extracted and crushed underground before being transported to the surface for milling. It is then treated in a copper sulphide flotation plant to remove copper. Approximately 80% of the uranium remains in the tailings from the flotation cells and is recovered by acid leaching. The copper concentrate is also processed through an acid leach to remove any remaining uranium.

#### **Processing**

The ore extracted by open pit or underground mining is first crushed and ground to a fine powder and then mixed with water into a slurry. The slurry is pumped into leaching tanks where acid is used to dissolve the uranium minerals from the ore. The uranium in solution is then separated from the depleted solids (known as tailings) and, after filtering, is pumped to a solvent extraction process.

<sup>17</sup> Alkali metasomatism involves the introduction of sodium, calcium or potassium into the rocks

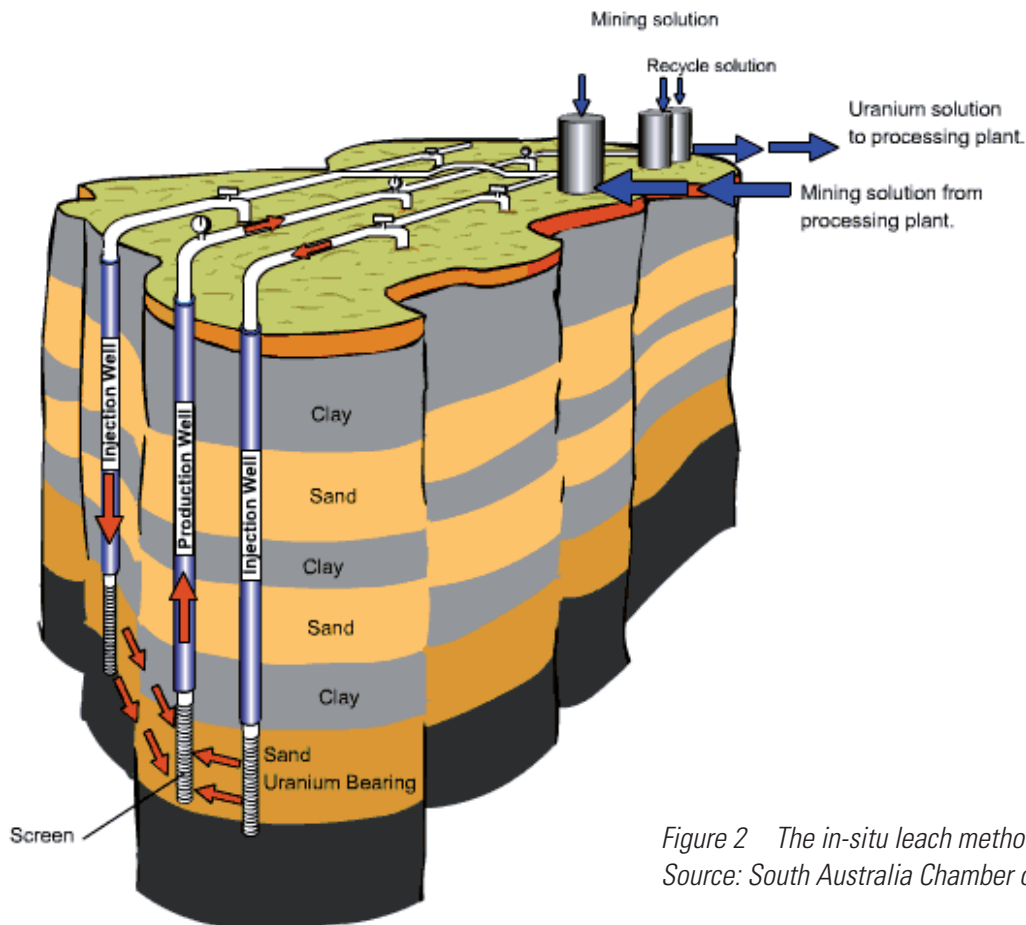


Figure 2 The in-situ leach method of uranium extraction. Source: South Australia Chamber of Mines & Energy.

In the solvent extraction circuit various chemicals are used to selectively remove uranium from the acid and any other elements contained in the ore. The further addition of ammonia in a precipitation tank results in the precipitation of a uranium compound (ammonium diuranate), which is also known as 'yellowcake' because of its bright yellow colour.

The yellowcake is put through a centrifuge and finally roasted in a calciner (furnace) to produce uranium oxide ( $U_3O_8$ ), (Figure 3).

With the in-situ leaching method the process is different because there is no crushing and grinding. The uranium-bearing fluid is pumped to the surface and the uranium is removed, using either an ion exchange system or solvent extraction depending on the salinity of the fluid. With the ion exchange system the uranium slurry is dewatered and dried to give hydrated uranium peroxide instead of uranium oxide. If the solvent extraction method is used the process continues from stage (6) of Figure 3.

If uranium is extracted as a by-product the acid leach fluid mentioned above (containing the dissolved uranium) continues through the process from stage (4) of Figure 3. Copper (or other metal) concentrates are treated in a separate system.

### The fuel cycle

For use in power stations,  $U_3O_8$  has to be further refined before being made into fuel rods. Most reactors also need fuel that is enriched in uranium-235 relative to natural uranium. Reactor fuel rods usually contain between 3% and 5% of uranium-235.

### Conversion

The enrichment process requires the uranium to be first refined to uranium dioxide and then converted to a gas, uranium hexafluoride. At atmospheric pressure uranium hexafluoride is a gas above  $57^\circ C$ , but converts directly to a solid below this temperature. Currently there are 8 plants operating this conversion process commercially. These are located in Russia (x 2), Canada, China, France, UK, USA, and Argentina (IAEA, 2009b).

### Enrichment

Several methods of enrichment have been demonstrated in a laboratory, but only two are operated on a commercial scale.

Gaseous diffusion forces pressurised uranium hexafluoride gas through a series of porous membranes or diaphragms. It relies on U-235 molecules having a smaller mass and faster movement rates than U-238 molecules, enabling them to pass more easily through the pores in the

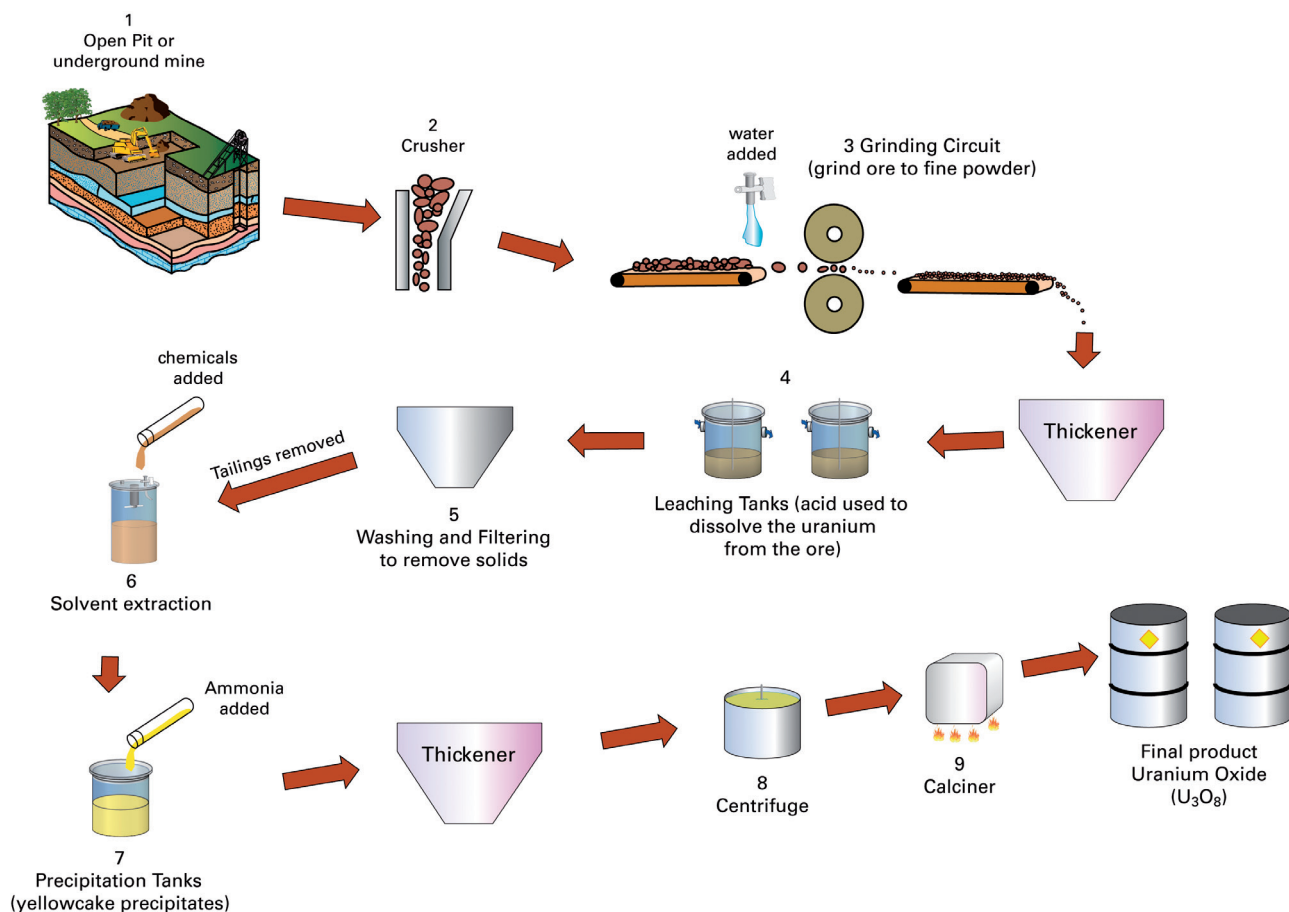


Figure 3 Simplified uranium extraction process.

membrane. The gas that passes through the membrane is therefore slightly enriched in U-235. The process is repeated many times through a cascade until a gas with 3–4% U-235 is obtained (WNA, 2009). Although several countries have operated these plants in the past, currently only the USA and France have commercial plants using this process (IAEA, 2009b).

The other method uses a series of centrifuges. Uranium hexafluoride gas is fed into a series of vacuum tubes, each containing a rotor that is spun at 50,000 to 70,000 rpm. Because U-238 has a greater mass than U-235, its concentration is increased towards the cylinder's outer edge while that of U-235 increases towards the centre (WNA, 2009). The process is repeated 10 to 20 times. This technology is more economic on a smaller scale than diffusion and is gradually replacing the generally older gaseous diffusion plants. There are 11 commercial centrifuge plants operating, located in Russia (x 4), China (x 2), Germany, Japan, Netherlands, Pakistan, and the UK (IAEA, 2009b)

The uranium from which U-235 is extracted during enrichment becomes depleted in this isotope and is known as 'depleted uranium' or 'uranium tails' (which is not to be

confused with 'tailings', the waste rock slurry generated by mining). This depleted uranium contains a higher relative proportion of U-238. Enrichment services are sold in SWUs (Separative Work Units), which are a measure of the quantity of effort required to meet a specified level of enrichment. The more SWUs used, the lower the proportion of U-235 remaining in the depleted tails (known as the tails assay) (van Eeden, 2005).

### Fuel fabrication

In the next stage enriched uranium hexafluoride gas is reconverted to produce solid enriched uranium oxide. This is then pressed and baked at high temperatures (over 1400°C) to form ceramic pellets. These are encased in zirconium metal tubes to form fuel rods. Several fuel rods are arranged in a fuel assembly ready for introduction into a reactor. There are currently 40 commercial fuel fabrication plants in 18 countries around the world (IAEA, 2009b).

### Spent fuel

When spent fuel assemblies are removed from reactors they are still very radioactive and continue to generate heat. They are placed under at least 3 metres of water to shield the radiation, where they are cooled for several

years. The spent fuel still contains some U-235, together with plutonium and U-238, and as such represents a potential resource. Although many countries treat spent fuel rods as 'waste', increasingly this material is being re-processed to recover the uranium and plutonium for future use as fuel. Where this process happens the fuel cycle is described as 'closed'.

### **Reprocessing**

The principal reasons for reprocessing spent nuclear fuel are to recover unused uranium and plutonium, which can be converted into new fuel for power plants and generate an additional 25 per cent of energy from the original uranium, and secondly to reduce the volume of material treated as 'waste'. In addition the waste after reprocessing is much less radioactive than the spent fuel (WNA, 2009).

All commercial reprocessing plants use a hydrometallurgical method known as the 'PUREX' process. This involves dissolving the fuel elements in concentrated nitric acid and chemically separating the uranium and plutonium by solvent extraction (WNA, 2009). The uranium is then returned to the fuel cycle at a conversion plant prior to re-enrichment, while the plutonium can be returned direct to a fuel fabrication plant where it is incorporated into a mixed-oxide (or MOX) fuel. The remaining material, approximately 3% of the total, is then treated as High Level Waste. Currently there are 9 reprocessing plants in the world, located in the UK (x 2), France (x 2), Russia (x 2), India, Japan and the USA, although only the plants in the UK, France and one in Russia are operating on a commercial scale. (IAEA, 2009b).

Several variations of the PUREX process, or other methods of recycling nuclear waste, are being developed, with the intention of reducing the proliferation risk from reprocessing spent fuel by not isolating plutonium from the uranium and/or other fission products. As a consequence, the plutonium can only be used as a fuel for nuclear power and not other purposes. Further details of these processes are given in the World Nuclear Association's Information Paper 'Processing of Used Nuclear Fuel' (WNA, 2009).

### **Waste**

One of the reasons nuclear power is such a politically sensitive issue is the question of what to do with the potentially dangerous waste that is generated during the enrichment and fission process. However, it should be noted that 90 per cent of the waste generated from nuclear power stations is classified as 'Low Level Waste' and, as such, contains only small quantities of radioactivity. Low Level Waste comprises paper, clothing, filters,

etc and can be safely compressed and buried in specially constructed repositories.

Intermediate Level Waste comprises 7 per cent of the total volume of nuclear waste and is made up of metal fuel cladding, resins and chemical sludge. Some of this material requires shielding and is often encased in concrete for long-term storage or burial in repositories.

Of greatest concern is the 3 per cent of nuclear waste that is categorised as High Level Waste, which contains 95 per cent of the total radioactivity produced in the process of electricity generation. This is either the spent fuel itself, or the waste remaining after reprocessing spent fuel. High level waste is highly radioactive and hot, requiring both shielding and cooling. The heat and radioactivity of this waste reduces significantly during storage, such that after 40–50 years the levels are only one thousandth of those occurring when the spent fuel was removed from the power plant (WNA, 2009).

Currently High Level Waste is stored pending final disposal. The favoured option involves 'multiple barrier' disposal whereby the waste will be immobilised in an insoluble material such as borosilicate glass, encased in non-corrosive stainless steel, and buried deep underground in a geologically stable location. However, the major issue is the identification of a suitable location that is acceptable to local public opinion. Sweden and Finland are the furthest advanced with the development of repositories, with both countries selecting sites (Osthammar, Sweden; Olkiluoto, Finland). The USA had selected a site at Yucca Mountain, Nevada but the process has now stalled for political reasons. Many other countries are carrying out research into potential locations for repositories. In the case of spent fuel, consideration is also being given to the possibility of future generations wishing to retrieve the material for reprocessing and reuse (WNA, 2009).

## **Specification and Uses**

The production of electricity represents the main use for uranium in the modern world. A much smaller amount is used for the propulsion of ships, research, desalination and military ordnance.

### **Electricity**

Most nuclear power stations use the fission of uranium-235 as a heat source for converting water into steam. The steam is then used to turn turbines, which generate electricity, in the same way fossil fuels are used in conventional power stations.



The main contrast with fossil fuels, such as coal, lies in the concentration of energy generated by nuclear fission. One kilogram of uranium-235 produces approximately  $8.2 \times 10^{13}$  joules of energy during nuclear fission, compared with only  $2.8 \times 10^7$  joules derived from burning 1 kilogram of coal. In other words, as an energy source, weight for weight, uranium-235 is 3 million times more concentrated than coal. One significant advantage of nuclear power is that it does not release carbon dioxide during the generation of electricity and as a consequence many nations are including this option into their 'low carbon' energy mix.

As over 95 per cent of uranium is used in nuclear power stations to generate electricity, future demand will depend on the number of operating nuclear power stations. The quantity of world electricity produced from nuclear sources increased sharply from less than 200 TWh<sup>18</sup> in 1971 to over 2000 TWh by 1990. Over the same period the proportion of electricity produced by nuclear-fission methods increased from two per cent to 16 per cent. The proportion of electricity-generation share remained similar until 2004 but then dropped slightly to 13.8 per cent in 2007, while the quantity of electricity produced from nuclear power had increased to 2719 TWh in 2007.

Individual countries vary widely in their dependence on nuclear power to generate electricity, as shown in Figure 4. As of February 2010 there were 436 nuclear reactors operating to generate electricity around the world, with a further 53 under construction (20 of these are in China). A further 142 reactors are listed as 'on order or planned' (including 37 in China, 23 in India and 13 in Japan) and as many as 327 are 'proposed' (including 120 in China, 37 in Russia, 24 in South Africa and 20 in Ukraine), according to the World Nuclear Association (WNA, 2009). However, a number of currently operating reactors are nearing the end of their operating life and are expected to be shut down in the near future.

### **Thermal reactors**

Most nuclear power stations currently operating are classed as thermal reactors, or 'burner' reactors (because they 'burn' uranium).

As mentioned in section 1.1, natural uranium contains approximately 0.7 per cent of uranium-235 with 99.3 per cent being uranium-238. Only a few nuclear power stations make use of uranium in its natural state. These include the older 'Magnox' type in the UK and the pressurised water reactors, known as 'Candu', which were developed in Canada.

The newer designs, such as the Pressurised Water Reactors and Advanced Gas Cooled Reactors, use uranium that has been enriched to contain between 3 per cent and 5 per cent of uranium-235. This fuel is sometimes known as LEU, or low enriched uranium, to distinguish it from the more highly enriched material needed for weapons.

All thermal reactors use water or graphite as a 'moderator' to slow down the speed of neutrons to enable uranium-235 atoms to absorb them and thus continue the fission chain reaction. These reactors also need a coolant, usually water or carbon dioxide gas, and control rods made of a neutron-absorbing material, such as boron, to keep the chain reaction at the required level. The uranium is typically contained in zirconium alloy tubes to form a fuel rod because zirconium is a corrosion-resistant material that is permeable to neutrons.

### **Fast breeder reactors**

These reactors are designed to cause fission in uranium-238 rather than uranium-235. Because uranium-238 is a larger molecule it has to collide with fast moving neutrons before fission occurs, hence the term 'fast neutron reactor' is sometimes used. These reactors are built without a moderator (which slows the neutrons in thermal reactors), but the high levels of heat produced means that water or carbon dioxide are insufficient to act as coolants. Instead, liquid sodium is used because it has a high thermal conductivity. However this causes additional technical problems in the design of such reactors.

The main technical advantage of fast breeder reactors, other than the fact they use the much more abundant uranium-238, is that the process creates plutonium. Part of this plutonium undergoes spontaneous fission, adding to the heat produced in the reactor. Furthermore, much more plutonium is produced than the quantity of uranium and plutonium 'burned'. Thus the reactor 'breeds' more fuel.

However these reactors are more expensive to build than thermal reactors and currently only a few plants remain in operation, many of which are 'experimental' or small in size. However, one power station at Beloyarsk in Russia has been supplying electricity since 1980 and is said to have the best production record of all Russia's nuclear power plants.

### **Advanced designs**

The first of the 'generation III' designs is now operational in Japan, with several others under construction or on

<sup>18</sup>TWh = Terra Watt hour, 1 TWh =  $1 \times 10^{12}$  Watt hours

order. The advantages of these third generation reactor designs, over the previous plants are:

- Better safety features. Many incorporate ‘passive’ or inherent safety features, which require no operational intervention to avoid accidents in the event of a malfunction;
- Standardised design, which reduces capital cost and construction time;
- A simpler and more rugged design, that makes them easier to operate and less vulnerable to operational upsets;
- Operating lives are longer, typically 60 years;
- Higher fuel burn-up and therefore less waste.

The Generation IV International Forum (consisting of the USA, Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland and the UK), announced in 2003 the selection of six new reactor designs which they believe represent the future shape of nuclear energy. The aims of these new designs are to meet increased energy demands in a safe, clean and more cost-effective way with improved security against both terrorist attack and weapons proliferation.

Of these designs, three are ‘fast reactors’ and one other can be built as a fast reactor. Coolants in these designs vary considerably from light water or helium to lead-bismuth, sodium or fluoride salt. Operating temperatures are in the range of 510°C to 850°C, compared to 330°C for current light water reactors, with power outputs between 150 to 1500 MWe<sup>19</sup>. Non-proliferation concerns are addressed in the fast reactor designs by having plutonium production within the core of the reactor where burn-up is high and from where reprocessing without separating this plutonium is possible. These generation IV designs are not likely to be operational until 2020.

### Other uses

#### Nuclear-powered ships

The first nuclear-powered submarine was launched by the USA in 1955. This marked the transition of submarines from slow underwater vessels to warships capable of maintaining 20–25 knots and remaining submerged for weeks at a time. By the end of the Cold War more than 400 nuclear-powered submarines had been either built or were under construction (WNA, 2009); more than half of these have since been scrapped.

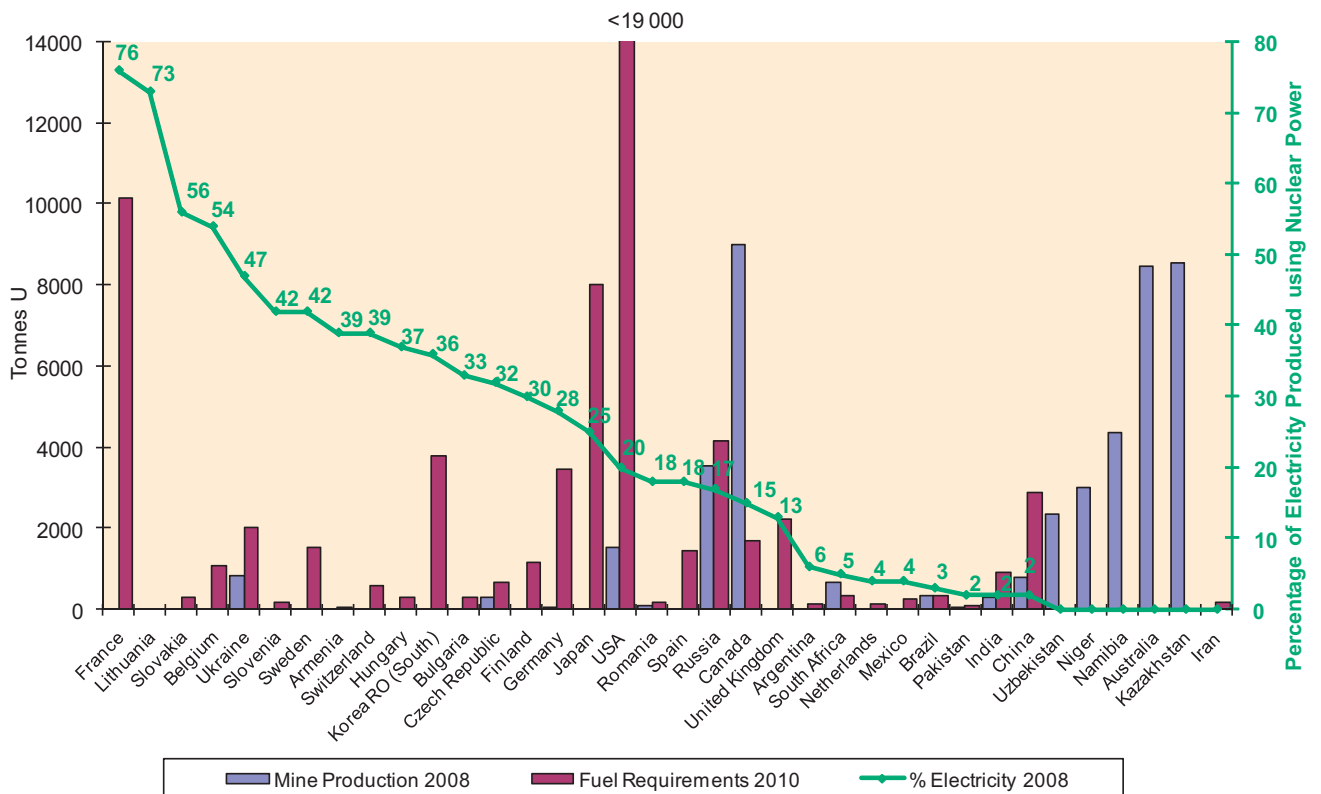


Figure 4 Mine production and uranium requirements by country with percentage of electricity produced from nuclear power. Source: BGS (2010), IAEA (2009c) & WNA (2010).

<sup>19</sup>MWe = Mega watts of electricity

Surface vessels may also be powered by nuclear reactors — 11 of the USA's aircraft carriers are propelled this way. Nuclear propulsion has proven to be particularly useful in the Russian Arctic where operating conditions are so difficult that they are beyond the capabilities of conventional icebreakers.

The reactors used for marine propulsion are mostly pressurised water reactors, which run on highly enriched uranium (generally around 20–40% uranium-235, although some may be as much as 90%) to give a large amount of power from a small volume of fuel. In addition, they are fitted with a 'burnable poison', such as gadolinium, which is progressively depleted as fission products build up. The reduced efficiency caused by the build up of fission products is effectively cancelled out by the increased efficiency from a reduction in gadolinium. As a result nuclear reactors on ships have a long core life, and many do not need refuelling for 10 years or more (WNA, 2009).

### **Research**

There are currently around 250 research reactors in 56 countries around the world. They comprise a wide range of civil and commercial reactors not used for power generation, and are generally of simple design and small size. Traditionally they have used highly enriched uranium (often about 20% uranium-235, although some use fuel up to 90% enriched) but gradually this is being replaced with low-enriched uranium fuels.

Research reactors are used to create neutron beams suitable for studying the structure and dynamics of materials at atomic level. They are also used to produce radioisotopes for medical applications (e.g. for the treatment of cancer) and in some industrial processing.

### **Desalination**

Desalination, whether by the 'multi stage flash' process or 'reverse osmosis', is a very energy intensive process. In a few countries, such as Kazakhstan, India and Japan, desalination takes place alongside electricity generation in some pressurised water reactor plants. An estimated one fifth of the world's population does not have access to safe drinking water and, with increasing pressure on water resources, several nuclear powered desalination plant projects have been proposed or are being developed around the world.

### **Weapons**

Uranium has long been a sensitive political topic because highly enriched uranium (HEU - over 90% uranium-235) can be used in nuclear warheads. No uranium used in power

stations is capable of use in a weapon because it contains either natural or low enriched uranium (LEU - at a maximum of 5% uranium-235). However, LEU can be converted to HEU with further enrichment.

Reductions in weapons in recent years by the USA and Russia have seen some quantities of military HEU diluted with depleted uranium and then converted into fresh fuel rods for use in civil power stations. This is being managed in a highly controlled manner, within the safeguards operated by the International Atomic Energy Authority (IAEA).

To prevent the spread of nuclear weapons, the IAEA has operated a system of safeguards since 1970 under the Nuclear Non-Proliferation Treaty (NPT). A large number of states have signed the NPT, including the 5 nations who obtained nuclear weapons before 1967: the USA, Russia, China, UK and France. Many other nations have the technical capability, but have made the decision not to pursue such weapons. There are three states that are outside the NPT: India, Pakistan and Israel, because they have developed nuclear weapons since 1970 and would have to dismantle them before they would be allowed to sign the NPT. Special arrangements were agreed with India in 2008 (WNA, 2009).

In April 2003, North Korea became the first nation to withdraw from the NPT and, despite subsequent negotiations, is believed to have tested nuclear weapons underground in October 2006 and May 2009. Negotiations have proved to be difficult and, although their nuclear facilities were closed in 2007, they subsequently expelled IAEA inspectors and have recommenced reprocessing of spent nuclear fuel. Another country causing concern is Iran. It is a signatory of the Treaty and insists that its construction of facilities is for peaceful purposes; however, Iran has not been entirely transparent regarding its activities, in contravention of obligations under the NPT.

The work of the IAEA in attempting to enforce safeguards under the NPT is often difficult and politically sensitive.

## **World resources**

Measured resources of uranium are the amount known to exist within certain limits of confidence and also the amount that is economically recoverable under prevailing market conditions. Therefore, these figures depend on the costs of extraction and market prices, as well as the degree of geological evaluation. Increases in price may cause sub-economic deposits to become recoverable. Table 4 shows the currently known resources by country that are economically recoverable.

	Resources (tonnes U)	% of World Total
Australia	1 243 000	23
Kazakhstan	817 000	15
Russian Fed.	546 000	10
South Africa	435 000	8
Canada	423 000	8
USA	342 000	6
Brazil	278 000	5
Namibia	275 000	5
Niger	274 000	5
Ukraine	200 000	4
Jordan	112 000	2
Uzbekistan	111 000	2
India	73 000	1
China	68 000	1
Mongolia	62 000	1
Others	210 000	4
<b>World total</b>	<b>5 469 000</b>	<b>100</b>

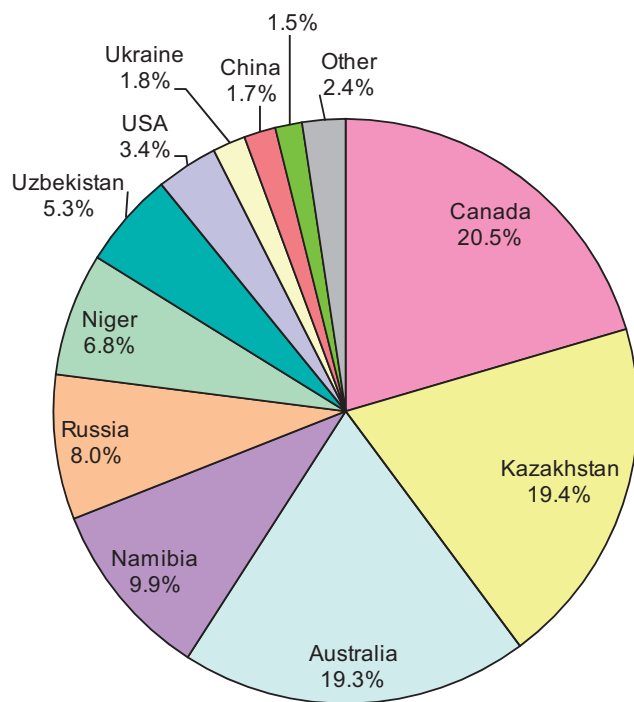


Figure 5 Uranium mine production by country 2008.  
Source: BGS World Mineral Statistics Database.

Table 4 Known recoverable resources of uranium 2007.  
(Reasonably Assured Resources plus Inferred Resources,  
to US\$130/Kg U). Source: NEA & IAEA (2007).

Country	2004	2005	2006	2007	2008	% of World Total 2008	% change 2004 to 2008
Canada	11599	11627	9862	9475	9001	20.5%	-22.4%
Kazakhstan	3719	4357	5279	6637	8521	19.4%	129.1%
Australia	9010	9516	7606	8603	8471	19.3%	-6.0%
Namibia	3159	2855	2782	2879	4366	9.9%	38.2%
Russia	3280	3431	3262	3413	3521	8.0%	7.3%
Niger	3273	3093	3431	3153	2993	6.8%	-8.6%
Uzbekistan	2035	2629	2270	2320	2338	5.3%	14.9%
USA	878	1034	1579	1744	1501	3.4%	71.0%
Ukraine (est)	800	800	800	846	800	1.8%	0.0%
China (est)	750	750	750	712	769	1.7%	2.5%
South Africa	752	674	542	525	654	1.5%	-13.0%
Brazil	300	110	190	299	330	0.8%	10.0%
Czech Re-public	435	420	383	322	290	0.7%	-33.3%
India (est)	230	230	177	270	271	0.6%	17.8%
Romania	90	90	90	77	77	0.2%	-14.4%
Pakistan (est)	45	45	45	45	45	0.1%	0.0%
Germany	77	80	65	41	40	0.1%	-48.1%
World total	40432	41741	39113	41361	43988		8.8%

Table 5 Mine production of uranium by country (tonnes, metal content).  
Source: BGS World Mineral Statistics Database.

Mine	Country	Main Owner	Type	Production (tU)	% of World
McArthur River	Canada	Cameco	Underground	6383	14.5
Ranger	Australia	ERA (Rio Tinto)	Open-pit	4527	10.3
Rössing	Namibia	Rössing (Rio Tinto)	Open-pit	3449	7.8
Olympic Dam	Australia	BHP Billiton	By-product	3344	7.6
Krazbokamensk	Russia	ARMZ	Underground	3050	6.9
Arlit	Niger	Areva/Onarem	Open-pit	1743	4.0
Rabbit Lake	Canada	Cameco	Underground	1368	3.1
Akouta	Niger	Areva/Onarem	Underground	1289	2.9
McClellan Lake	Canada	Areva	Open-pit	1249	2.8
Akdala	Kazakhstan	Uranium One	In-situ leach	1034	2.4
		<b>Total</b>		<b>27436</b>	<b>62.4</b>

Table 6 Top 10 producing uranium mines, based on 2008 output  
Source: World Nuclear Association and BGS

Company	Main Operations	Total attributable production (tU)	% of World
Rio Tinto	Ranger (Australia), Rössing (Namibia)	7989	18.2
Cameco	McArthur River and Rabbit Lake (Canada), Smith Ranch-Highland (USA)	6655	15.1
Areva	Arlit and Akouta (Niger), McClellan Lake (Canada)	6307	14.3
Kazatomprom	Inkai and Kharassan (Kazakhstan)	5225	11.9
ARMZ	Krazbokamensk and Dalamatovskoe (Russia), Karatau (Kazakhstan)	3687	8.4
BHP Billiton	Olympic Dam (Australia)	3344	7.6
Navoi	Various in Uzbekistan	2338	5.3
Uranium One	Akdala (Kazakhstan)	1115	2.5
Paladin Energy	Langer Heinrich (Namibia)	948	2.2
	<b>Total</b>	<b>37608</b>	<b>85.5</b>

Table 7 Top producing uranium companies, based on 2008 output.  
Sources: Boytsov, et al (2010), BGS and individual company websites.

## World production

Mine production of primary uranium was nearly 44,000 tonnes in 2008, with 20 per cent coming from Canada and just over 19 per cent each from Kazakhstan and Australia (Figure 5, Table 5).

The annual uranium output in 2008 was the highest recorded since 1989 and this was largely due to significant increases in the production in Namibia and Kazakhstan compared to 2007. These increases resulted in Kazakhstan overtaking Australia to become the second largest producing country in the world and Namibia moving into the fourth spot. Both these countries have seen new uranium mines open in recent years, and have more prospect

sites which may commence production in the near to medium-term. In particular, Kazakhstan is believed to have increased output further in 2009 and become the largest producing country in the world.

In contrast, mine production in both Canada and Australia declined in 2008 compared with 2007, and are expected to have declined further in 2009. In Canada, the McClellan Lake mine has now closed and in Australia output was reduced at the Olympic Dam mine as a result of an accident which caused serious damage to the main hoisting shaft. The opening of the Cigar Lake mine in Canada has been delayed due to remediation work following a flooding incident. However, in South Australia there are two possible new mines which are expected to open in the near future



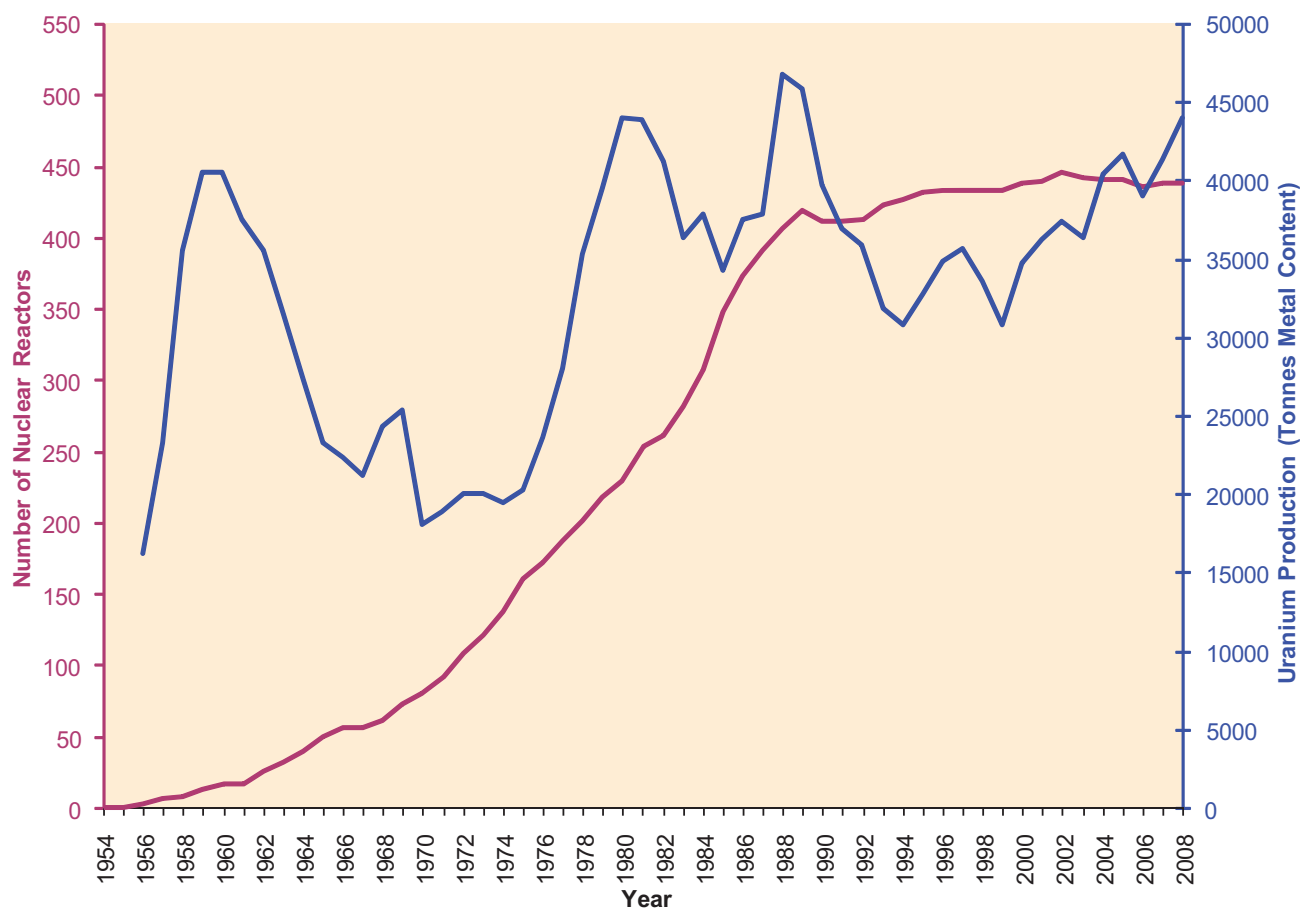


Figure 6 Number of operational nuclear reactors in the world compared to mine production of uranium (in tonnes metal content). Source: BGS World Mineral Statistics and World Nuclear Association.

and a change in State government for Western Australia may now lead to prospects there being developed.

Despite recent increases, primary production of uranium is currently not sufficient to meet world reactor requirements, which are expected to be more than 68 000 tonnes in 2010. The shortfall of supply in recent years has been met by reprocessing nuclear fuel, drawing down from existing stockpiles, and converting ex-military materials into fuel. However, with many new mines opening, or planning to open in the near future, this shortfall is reducing.

The top 10 producing mines in 2008 are shown in Table 6, and the top producing companies in 2008 are shown in Table 7. Many mines are operated as 'joint ventures' and therefore the figures in Table 7 reflect these shareholdings in the attributed production.

Figure 6 compares the level of mine production of uranium (tonnes metal content) with the growth of nuclear reactors operating in the world. Whilst this graph does not show the size of the reactors, and therefore does not indicate their actual fuel requirements, it does reveal the significant

production of uranium in the late 1950s and early 1960s, which was most likely for military use.

## World Trade

The marketing of uranium is quite unlike that of any other mineral commodity due to political sensitivities and associated safeguards aimed at restricting the development of nuclear weapons. Exporting countries closely monitor their exports, and the purposes for which the uranium will be used. The International Atomic Energy Agency (IAEA) also carries out audits of the trade in uranium, along with inspections of nuclear facilities, in order to ensure compliance with the conditions of the Nuclear Non-Proliferation Treaty (NPT). The purpose of these measures is to ensure that uranium is used for civilian energy purposes and not diverted into weapons.

Uranium is traded chiefly as U<sub>3</sub>O<sub>8</sub> (yellowcake), but other traded forms include uranium hexafluoride, low enriched uranium dioxide and fuel rods ready for use in nuclear reactors. There is also a substantial trade in spent fuel rods for reprocessing. However, due to the political sensitivi-

ties, it is believed that international trade is incompletely reported and therefore it is not possible to give accurate figures for all countries.

Of the 17 countries that produced uranium in 2005 (Table 5), five countries do not have any nuclear power stations and therefore export virtually all production — these are Australia, Kazakhstan, Niger, Namibia and Uzbekistan. Many industrialised nations, including the three countries with the largest requirements (the USA, France and Japan), are strongly dependent on imports of uranium to fuel their nuclear power stations. This is only partly alleviated by reprocessing spent fuel or other alternatives.

Even where mine production is used domestically, uranium is still moved around the world as a consequence of the NPT. For example, Brazil has historically produced sufficient uranium to supply its own needs, but has agreed with the IAEA not to build its own conversion or enrichment plants, thus preventing Brazil from diverting any material

into weapons. Brazilian uranium is therefore exported as yellowcake for conversion and enrichment, and is then re-imported as fuel rods for their two nuclear power stations. In some instances, many different countries are involved in the supply chain. For example, uranium as yellowcake could be purchased from Canada or Australia, converted in Canada or France, enriched in Russia, fabricated into fuel rods in Germany and then used in nuclear power reactors in Finland.

## Prices

More than 80 per cent of uranium is sold under long-term contracts, however, a spot market has been in existence for several years and this is frequently referred to when negotiating prices for long-term contracts. From 1988 to 2004 spot market prices were very low, rising to a mere US\$20 per pound by the end of 2004. However, demand for uranium for electricity generation is much higher than mine production levels and concerns over continuity of supply resulted in a significant increase in prices through-

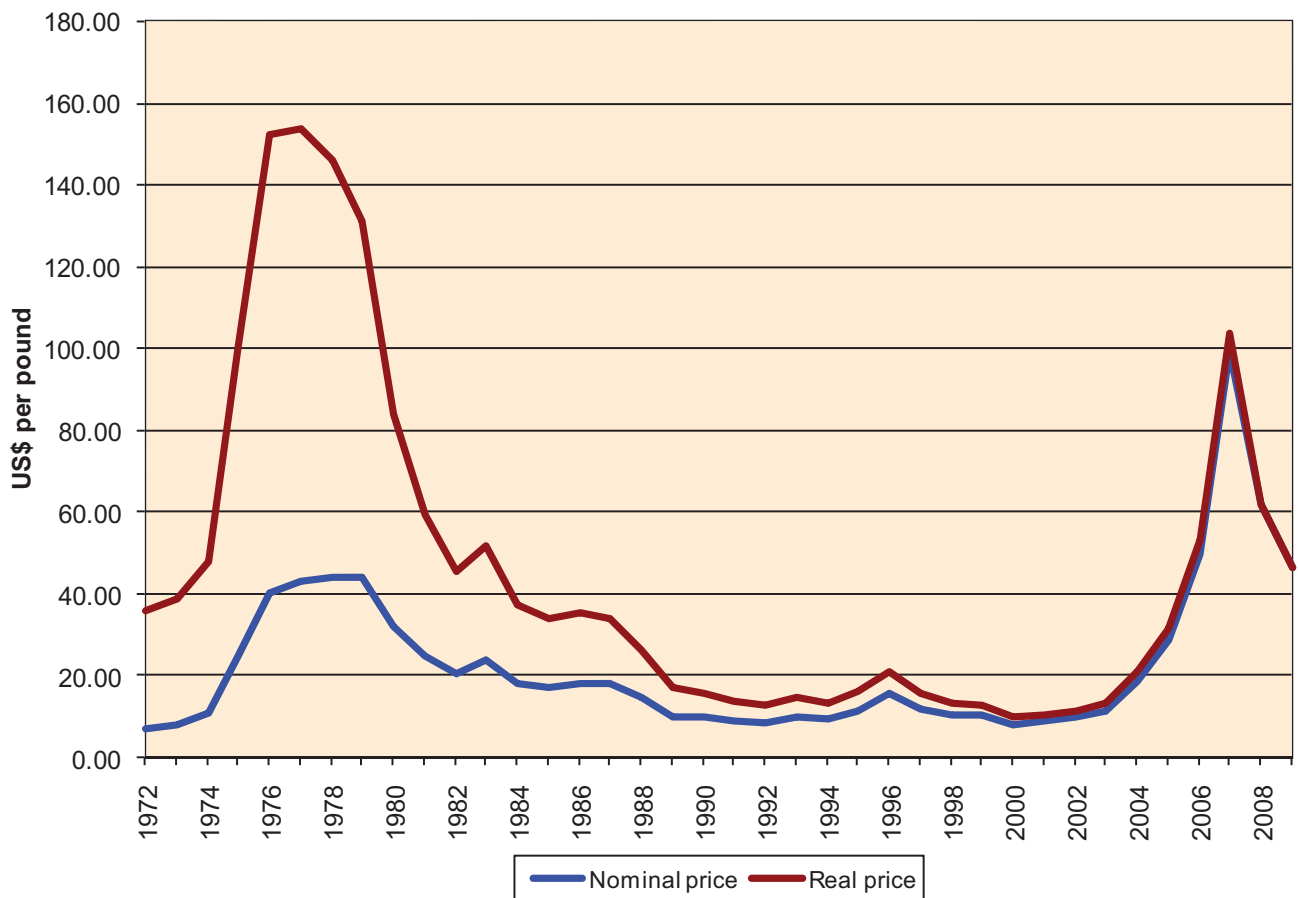


Figure 7 Historical spot price for uranium yellowcake (Real price is adjusted for changes in the value of money, compared to 2010).

Source: Industry Averages.

out 2005 to 2007, spurred on by speculative activity. The price reached a high of US\$138 per pound in June 2007; but this peak was followed by a sharp drop during the second part of 2007 and throughout 2008. In 2009 the price reached a three-year low of around US\$42 per pound although it then recovered slightly to end the year at approximately US\$45 per pound.

Ongoing international efforts to reduce carbon dioxide emissions, which are implicated in climate change, have caused many countries to re-examine the nuclear power option with a consequent increase in demand for uranium fuel. Most large producers are now raising output from primary uranium mines, but, with plans to build new power stations, particularly in China and India, demand remains strong.

## Alternative technologies

There are no alternatives to uranium as a fuel in nuclear power stations. Different designs of nuclear reactors require different degrees of enrichment, and thus use different amounts of uranium. Some plants can be designed to use a mixed oxide fuel (known as MOX) but this also contains a proportion of uranium along with plutonium.

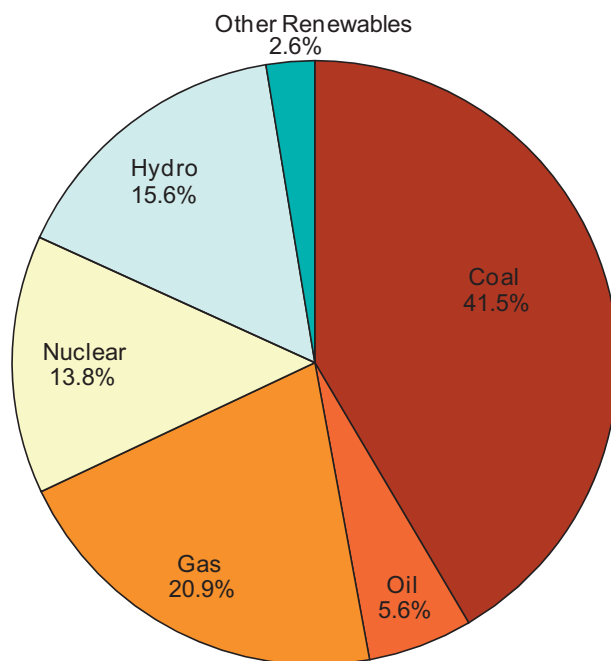


Figure 8 World electricity generation, 2007.  
Source: IEA, 2009.

However, there are alternatives to using nuclear power stations to generate electricity. These include well-established technologies involving fossil fuels (coal, oil and natural gas) and also the renewable sources of

power: hydro, wind, solar, geothermal, biomass, waves and tides.

## Fossil fuels

Nearly 70 per cent of world electricity generation uses coal, oil or natural gas for fuel. Resources of these are finite, although many years of reserves, particularly of coal, are known to exist. When they are burned, whether for electricity or other forms of power, they all emit large quantities of carbon dioxide.

## Renewable energy sources

Currently less than 20 per cent of the world's electricity comes from some form of 'renewable' source. This term is used because these sources are not finite in quantity. They are regarded as the environmentally friendly option because they do not directly release carbon dioxide into the atmosphere. However, as with any other source of electricity, some carbon dioxide will be released during the construction of the plant and equipment required to capture the energy and therefore their lifecycle emissions may not be entirely negligible.

The most commonly used renewable energy source is hydroelectricity, which is the harnessing of the energy of falling water and using it to turn turbines to generate electricity. In many countries there is potential to generate more electricity this way, but there are environmental consequences, in particular relating to the areas that are flooded behind large dams and the disruption to natural flows of rivers.

Tidal electricity generation uses the rise and fall of oceanic tides to generate power. Clearly the higher the tidal range the greater the potential for generating electricity. Wave power technology, using the motion of waves, is also available but is not widely used at present due to practical problems such as storm damage and risks to shipping.

There has been significant growth in both the number and size of wind turbines in recent years. The installed capacity around the world is nearly 160 000 MW (mega watts), with more than 38 000 MW added in 2009 alone (World Wind Energy Association, 2010). There is considerable potential for expansion but alternatives still need to be available to provide additional power on less windy days.

Solar energy technology is improving and the quantity of electricity generated this way is growing, although still much smaller than hydro or wind energy. It is also intermittent (like wind) and alternative sources of power are required during the night.

Biomass is the growing of crops to burn as fuel in power stations (in the same way as fossil fuels are burned). It results in the recirculation of current carbon dioxide to/from the atmosphere and does not add extra. In contrast, fossil fuels represent carbon that has been locked away for millions of years and is released during combustion.

Geothermal power systems harness the natural heat of the Earth by bringing hot underground steam to the surface to turn electricity generating turbines. This has the greatest potential where there has been recent volcanic activity, for example in countries such as Iceland or New Zealand.

## Focus on Britain

### Known occurrences

Although uranium is not currently mined in the United Kingdom, minor occurrences of uranium mineralisation are widespread in south-west England and in northern Scotland. Exploration for uranium was conducted between 1945 and 1951, between 1957 and 1960 and again from 1968 to 1982. These investigations identified sub-economic mineralisation at several localities in the UK (Figure 9).

In south-west England, pitchblende-hydrocarbon-sulphide mineralisation occurs within the main tin-copper veins and in association with lead-zinc-cobalt-nickel mineralisation. There was some uranium extraction at the end of the 19<sup>th</sup> century at the South Terras mine, near St Austell in Cornwall, and also as a by-product of tin and copper mining at Wheal Trenwith, near St Ives. Very small quantities, at most a few tonnes, were produced at Wheal Owles mine at St Just, East Pool mine near Camborne and at St Austell Consols.

Total production from the region only amounted to a few hundred tonnes of uranium, which was mostly used for colouring stained glass. Subsequent exploration in south-west England, carried out in the 1960s and 1970s, identified up to 440 ppm U at St Columb Major and up to 1330 ppm at Luton, on the margin of the Dartmoor granite.

The source rock for these occurrences is the south-west England batholith, which is a high heat production (HHP) granite, with an average content of 30 ppm U.

In Scotland the most important uranium mineralisation occurs in three locations:-

1. in low-grade, phosphatic and carbonaceous horizons in the Middle Devonian lacustrine basin of the Orkneys and Caithness;

2. in Devonian arkosic breccias marginal to the Caledonian Helmsdale granite at Ousdale on the east coast of Caithness;
3. in veins marginal to the Caledonian Criffel granodiorite at Dalbeattie.

The Ousdale area was drilled in the early 1970s on a 130 m square grid with 41 percussion holes to depths of 80 m. The maximum value found was 850 ppm U within a 15 m intersection.

Uranium-lead mineralisation occurs in a fault breccia in Devonian sediments at Mill of Cairston, near Stromness on Orkney. The fault was drilled by the BGS and a mining company consortium in 1971–1972 when maximum values of 1000 ppm U were found, together with 5.5% lead.

Elsewhere, low-grade occurrences have been identified in a black shale member of the upper Cambrian Dolgelly series around the Harlech Dome in Wales and the White Leaved Oak Shales in the Malvern Area. The lower horizons of the Carboniferous Limestone exhibit patchy enhanced radioactivity in the Castleton area of Derbyshire and at Grassington, Yorkshire. Black shales of the basal horizons of the Namurian Millstone Grit in the vicinity of the Derbyshire Dome were widely found to contain concentrations up to 120 ppm U. Boreholes into Namurian black shales in South Wales, Gloucestershire and at Brampton in Devon have also indicated the presence of uranium. However, none of these occurrences are likely to be economic to mine.

### Uranium consumption

The structure of the nuclear industry has been complicated by various privatisations in recent years. The current situation is outlined in Table 8 and the locations are shown on Figure 10.

Britain has a long history of nuclear installations. Research into atomic energy began in 1946 and the first civilian power station was commissioned at Calder Hall in 1956. In total there have been 62 reactors constructed at 19 different locations around the country, but many of these are now in the process of being decommissioned. Electricity continues to be generated by nuclear power by 19 reactors at 10 locations. These sites generated 13 per cent of UK electricity demand in 2008.

The early nuclear power stations were of the Magnox design, which were constructed between 1956 and 1976, but more recent power stations are of the Advanced Gas Cooled design (AGR), built between 1976 and 1988. Only



Figure 9 Locations of principal known uranium occurrences in Britain.  
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Location	Company	No of Reactors	Type of Reactors	Current Status	Date Started	Date Ceased	Scheduled to Cease
Windscale	NDA / Sellafield Ltd	3	Magnox & AGR	C&M Preparations	1947	1957/1981	-
Berkeley	NDA / Magnox South	2	Magnox	C&M Preparations	1962	1989	-
Hunsterston A	NDA / Magnox North	2	Magnox	C&M Preparations	1964	1989	-
Harwell	NDA / RSR Ltd	5	Various	Decommissioning	1946	1990	-
Trawsfynydd	NDA / Magnox North	2	Magnox	C&M Preparations	1965	1991	-
Dounreay	NDA / DSR Ltd	3	FBR	Decommissioning	1950's	1994	-
Winfrith	NDA / RSR Ltd	8	Various	Decommissioning	1958	1995	-
Hinckley Point A	NDA / Magnox South	2	Magnox	C&M Preparations	1965	2000	-
Bradwell	NDA / Magnox South	2	Magnox	C&M Preparations	1962	2002	-
Calder Hall	NDA / Sellafield Ltd	4	Magnox	C&M Preparations	1956	2003	-
Chapelcross	NDA / Magnox North	4	Magnox	Defuelling	1959	2004	-
Dungeness A	NDA / Magnox South	2	Magnox	Defuelling	1965	2006	-
Sizewell A	NDA / Magnox South	2	Magnox	Defuelling	1966	2006	-
Oldbury	NDA / Magnox North	2	Magnox	Operating	1967	-	2010
Wylfa	NDA / Magnox North	2	Magnox	Operating	1971	-	2010
Culham	NDA / JET	2	Fusion Research	Operating	1983	-	Not known
Heysham 1	BE	2	AGR	Operating	1983	-	2014
Hartlepool	BE	2	AGR	Operating	1983	-	2014
Hunterston B	BE	2	AGR	Operating	1976	-	2016
Hinckley Point B	BE	2	AGR	Operating	1976	-	2016
Dungeness B	BE	2	AGR	Operating	1983	-	2018
Heysham 2	BE	2	AGR	Operating	1988	-	2023
Torness	BE	2	AGR	Operating	1988	-	2023
Sizewell B	BE	1	PWR	Operating	1995	-	2035

Companies - NDA = Nuclear Decommissioning Authority, RSR Ltd = Research Sites Restoration Ltd (subsidiary of UKAEA), DSR Ltd = Dounreay Site Restoration Ltd (subsidiary of UKAEA), BE = British Energy (now part of EDF Energy), JET = Joint European Torus (operated by UKAEA under a contract from EURATOM), UKAEA = UK Atomic Energy Authority  
Types - FBR = Fast Breeder Reactor, AGR = Advanced Gas Cooled Reactor, PWR = Pressurised Water Reactor

Current Status - C&M Preparations = Care and Maintenance preparations, i.e. removal of waste, demolition of auxiliary buildings, securing of reactor buildings.

Table 8 Nuclear reactors in Britain  
Source: Nuclear Decommissioning Authority and British Energy

## Key

+ Potential New Nuclear Plants

### Operating Nuclear Facilities

■ MAGNOX

◆ AGR

● PWR

▲ Research/other

### Decommissioning Nuclear Facilities

■ MAGNOX

◆ AGR

● Fast breeder

▲ Research/other

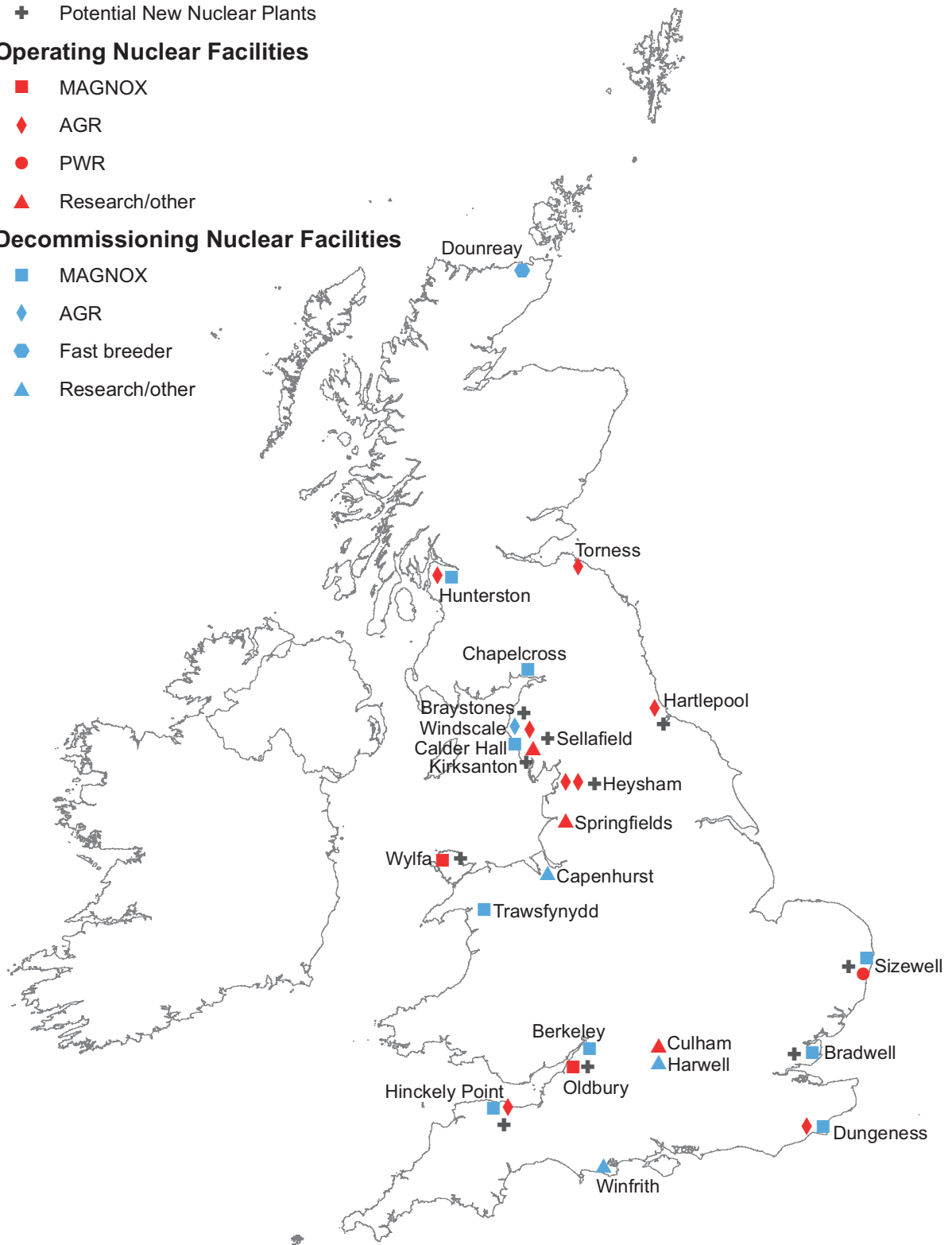


Figure 10 Locations and status of nuclear reactors and related facilities in Britain. OS topography © Crown Copyright. All rights reserved. 100017897/2010.

one Pressurised Water Reactor (PWR) was built in Britain, at Sizewell in 1995. Further PWRs were planned but never built. An experimental Fast Breeder Reactor was built at Dounreay in Scotland but this closed in 1994.

Uranium is imported to Britain (mostly from Australia) but the country is self-sufficient in all other nuclear facilities including conversion, enrichment, fuel fabrication, reprocessing and waste treatment. A large number, but not all, of these other facilities are concentrated at Sellafield in Cumbria.

In January 2008, following a consultation exercise, the UK Government issued a white paper 'Meeting the Energy Challenge – a White Paper on Nuclear Power' (BERR, 2008) in which they set out the conclusion that nuclear power should be part of a low-carbon energy mix in the UK and that this includes the building of new nuclear power stations. Following this, the Office for Nuclear Development and the Nuclear Development Forum were established to focus efforts on the actions required to facilitate the development of these new power stations (DECC, 2010a).

A total of 11 sites were nominated in 2009 as part of the 'Strategic Siting Assessment', but one of these (Dungeness) was subsequently removed from consideration due to concerns over coastal erosion and flooding risks. The remaining ten sites are shown on Figure 10 and these are considered as 'potentially suitable for the deployment of new nuclear power stations by the end of 2025' (DECC, 2009a). Most, but not all, of these sites are adjacent to existing nuclear facilities. Three additional sites were identified during an 'Alternative Site Study' carried out by Atkins Ltd on behalf of the Government, but were subsequently considered to be 'not suitable' for new nuclear power stations (DECC, 2009a).

The Office for Nuclear Development has also put in place legislation which will ensure that money is put aside throughout the operation of any new nuclear power stations to cover the cost of the eventual decommissioning. Several companies have expressed interest in building new nuclear power stations (DECC, 2010b) and the first formal planning applications are expected during 2010 or 2011 (DECC, 2009b).

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Cameco	<a href="http://www.cameco.com">www.cameco.com</a>
ERA (Energy Resources Australia)	<a href="http://www.energyres.com.au">www.energyres.com.au</a>
International Energy Agency	<a href="http://www.iea.org">www.iea.org</a>
World Energy Council	<a href="http://www.worldenergy.org">www.worldenergy.org</a>

This commodity profile was produced by the  
British Geological Survey (2010).

It was compiled by Teresa Brown and Gus Gunn with  
the assistance of Debbie Rayner.

This report is one of a series of Commodity Profiles  
available to download free-of-charge from  
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