Uranium Mining Overview

Updated May 2012

* **In the last sixty years uranium has become one of the world’s most important energy minerals.**
* **It is mined and concentrated similarly to many other metals.**

While uranium is used almost entirely for making electricity, a small proportion is used for the important task of producing medical isotopes. Some is also used in marine propulsion, especially naval.

Uranium is a naturally occurring element with an average concentration of 2.8 parts per million in the Earth's crust. Traces of it occur almost everywhere. It is more abundant than gold, silver or mercury, about the same as tin and slightly less abundant than cobalt, lead or molybdenum. Vast amounts of uranium also occur in the world's oceans, but in very low concentrations.

Table 1. The largest-producing uranium mines in 2011

| **Mine** | **Country** | **Main owner** | **Type** | **Production (tU)** | **% of world** |
| --- | --- | --- | --- | --- | --- |
| **McArthur River** | Canada | Cameco | underground | 7686 | 14 |
| **Olympic Dam** | Australia | BHP Billiton | by-product/ underground | 3353 | 6 |
| **Arlit** | Niger | Somair/ Areva | open pit | 2726 | 5 |
| **Tortkuduk** | Kazakhstan | Katco JV/ Areva | ISL | 2608 | 5 |
| **Ranger** | Australia | ERA (Rio Tinto 68%) | open pit | 2240 | 4 |
| **Kraznokamensk** | Russia | ARMZ | underground | 2191 | 4 |
| **Budenovskoye 2** | Kazakhstan | Karatau JV/Kazatomprom-Uranium One | ISL | 2175 | 4 |
| **Rossing** | Namibia | Rio Tinto (69%) | open pit | 1822 | 3 |
| **Inkai** | Kazakhstan | Inkai JV/Cameco | ISL | 1602 | 3 |
| **South Inkai** | Kazakhstan | Betpak Dala JV/ Uranium One | ISL | 1548 | 3 |
| **Top 10 total** |  | | | **27,951** | **52%** |

Uranium mines operate in some twenty countries, though in 2011 some 52% of world production comes from just ten mines in six countries (Table 1), these six providing 85% of the world's mined uranium. Most of the uranium ore deposits at present supporting these mines have average grades in excess of 0.10% of uranium – that is, greater than 1000 parts per million. In the first phase of uranium mining to the 1960s, this would have been seen as a respectable grade, but today some Canadian mines have huge amounts of ore up to 20% U average grade. Other mines however can operate successfully with very low grade ores, down to about 0.02% U.

Some uranium is also recovered as a by-product with copper, as at Olympic Dam mine in Australia, or as by-product from the treatment of other ores, such as the gold-bearing ores of South Africa, or from phosphate deposits such as Morocco and Florida. In these cases the concentration of uranium may be as low as a tenth of that in orebodies mined primarily for their uranium content. An orebody is defined as a mineral deposit from which the mineral may be recovered at a cost that is economically viable given the current market conditions. Where a deposit holds a significant concentration of two or more valuable minerals then the cost of recovering each individual mineral is reduced as certain mining and treatment requirements can be shared. In this case, lower concentrations of uranium than usual can be recovered at a competitive cost.

Generally speaking, uranium mining is no different from other kinds of mining unless the ore is very high grade. In this case special mining techniques such as dust suppression, and in extreme cases remote handling techniques, are employed to limit worker radiation exposure and to ensure the safety of the environment and general public.

Searching for uranium is in some ways easier than for other mineral resources because the radiation signature of uranium's decay products allows deposits to be identified and mapped from the air.

Thorium is a possible alternative source of nuclear fuel, but the technology for using this is not established. Thorium requires conversion to a fissile isotope of uranium actually in a nuclear reactor. However, supplies of thorium are abundant, and the element currently has no commercial value. Accordingly, the amount of resource is estimated rather than directly measured as with uranium.

Different Kinds of Mines

Open Pit and Underground Mining

Where orebodies lie close to the surface, they are usually accessed by open cut mining, involving a large pit and the removal of much overburden (overlying rock) as well as a lot of waste rock. Where orebodies are deeper, underground mining is usually employed, involving construction of access shafts and tunnels but with less waste rock removed and less environmental impact. In either case, grade control is usually achieved by measuring radioactivity as a surrogate for uranium concentration. (The radiometric device detects associated radioactive minerals which are decay products of the uranium, rather than the uranium itself.)

At Ranger in north Australia, Rossing in Namibia, and most of Canada's Northern Saskatchewan mines through to McClean Lake, the orebodies have been accessed by open cut mining. Other mines such as Olympic Dam in Australia, McArthur River, Rabbit Lake and Cigar Lake in Northern Saskatchewan, and Akouta in Niger are underground, up to 600 meters deep. At McClean Lake and Ranger, mining will be completed underground.

In Situ Leach (ISL) mining

Some orebodies lie in groundwater in porous unconsolidated material (such as gravel or sand) and may be accessed simply by dissolving the uranium and pumping it out – this is in situ leach (ISL) mining (also known in North America as in situ recovery - ISR). It can be applied where the orebody's aquifer is confined vertically and ideally horizontally. Certainly it is not licensed where potable water supplies may be threatened. Where appropriate it is certainly the mining method with least environmental impact.

ISL mining means that removal of the uranium minerals is accomplished without any major ground disturbance. Weakly acidified groundwater (or alkaline groundwater where the ground contains a lot of limestone such as in the USA) with a lot of oxygen in it is circulated through an enclosed underground aquifer which holds the uranium ore in loose sands. The leaching solution dissolves the uranium before being pumped to the surface treatment plant where the uranium is recovered as a precipitate. Most US and Kazakh uranium production is by this method.

In Australian ISL mines the oxidant used is hydrogen peroxide and the complexing agent sulfuric acid to give a uranyl sulphate. Kazakh ISL mines generally do not employ an oxidant but use much higher acid concentrations in the circulating solutions. ISL mines in the USA use an alkali leach to give a uranyl carbonate due to the presence of significant quantities of acid-consuming minerals such as gypsum and limestone in the host aquifers. Any more than a few percent carbonate minerals means that alkali leach must be used in preference to the more efficient acid leach.   
  
In either the acid or alkali leaching method the fortified groundwater is pumped into the aquifer via a series of injection wells where it slowly migrates through the aquifer leaching the uranium bearing host sand on its way to strategically placed extraction wells where submersible pumps pump the liquid to the surface for processing.  
  
For very small orebodies which are amenable to ISL mining, a central process plant may be distant from them so a satellite plant will be set up. This does no more than provide a facility to load the ion exchange (IX) resin/polymer so that it can be trucked to the central plant in a bulk trailer for stripping. Hence very small deposits can become viable, since apart from the wellfield, little capital expenditure is required at the mine and remote IX site.

**Heap leaching**

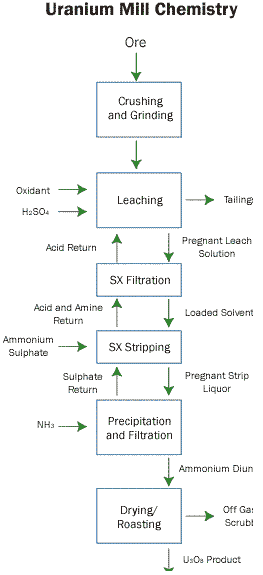
Some ore, usually very low-grade (below 0.1%U), is treated by heap leaching. Here the broken ore is stacked about 5 to 30 meters high on an impermeable pad and irrigated with acid (or sometimes alkaline) solution over many weeks. The pregnant liquor from this is collected and treated to recover the uranium, as with ISL, usually using ion exchange. After the material ceases to yield significant further uranium, it is removed and replaced with fresh ore. Recoveries are typically 50-80%. The depleted material has the potential to cause pollution so must be emplaced securely so as not to affect surface water or groundwater. Usually this will be in mined-out pits.

Milling and Processing

Conventional mines have a mill where the ore is crushed and ground to liberate the mineral particles, then leached with sulfuric acid to dissolve the uranium oxides. The solution is then processed to recover the uranium.

Most of the ore is barren rock or other minerals which remain undissolved in the leaching process. These solids or 'tailings' are separated from the uranium-rich solution, usually by allowing them to settle out. The remaining solution is filtered and the uranium is recovered in some form of ion exchange (IX) or solvent extraction (SX) system. The pregnant liquor from ISL or heap leaching is treated similarly. The uranium is then stripped from this and precipitated – see box. The final chemical precipitate is filtered and dried.

Mill chemistry



The crushed and ground ore, or the underground ore in the case of ISL mining, is leached with sulfuric acid:

UO3 + 2H+ ====> UO22+ + H2O  
UO22+ + 3SO42- ====> UO2(SO4)34-

The UO2 is oxidized to UO3.

With some ores, carbonate leaching is used to form a soluble uranyl tricarbonate ion: UO2(CO3)34-. This can then be precipitated with an alkali, e.g. as sodium or magnesium diuranate.

The uranium in solution is recovered in a resin/polymer ion exchange (IX) or liquid ion exchange (solvent extraction - SX) system. The pregnant liquor from acid ISL or heap leaching is treated similarly.   
  
Further treatment for IX involves stripping the uranium from the resin/polymer either with a strong acid or chloride solution or with a nitrate solution in a semi-continuous cycle. The pregnant solution produced by the stripping cycle is then precipitated by the addition of ammonia, hydrogen peroxide, caustic soda or caustic magnesia. Solvent extraction is a continuous loading/stripping cycle involving the use of an organic liquid to carry the extractant which removes the uranium from solution.

Typically, in solvent extraction, tertiary amines\* are used in a kerosene diluent, and the phases move counter currently.

2R3N + H2SO4 ====> (R3NH)2SO4  
2 (R3NH)2SO4 + UO2(SO4)34- ====> (R3NH)4UO2(SO4)3 + 2SO42-

\* "R" is an alkyl (hydrocarbon) grouping, with single covalent bond.

The loaded solvents may then be treated to remove impurities. First, cations are removed at pH 1.5 using sulfuric acid and then anions are dealt with using gaseous ammonia.

The solvents are then stripped in a countercurrent process using ammonium sulfate solution.

(R3NH)4UO2(SO4)3 + 2(NH4)2SO4 ====> 4R3N + (NH4)4UO2(SO4)3 + 2H2SO4

Precipitation of ammonium diuranate is achieved by adding gaseous ammonia to neutralize the solution (though in earlier operations caustic soda and magnesia were used).

2NH3 + 2UO2(SO4)34- ====> (NH4)2U2O7 + 4SO42-

The diuranate is then dewatered and roasted to yield U3O8 product, which is the form in which uranium is marketed and exported.

Peroxide products can be dried at ambient temperatures to produce a product containing about 80% U3O8. Ammonium or sodium diuranate products are dried at high temperatures to convert the product to uranium oxide concentrate - U3O8 - about 85% uranium by mass. This is sometimes referred to as yellowcake, though it is usually khaki.  
  
In the case of carbonate leaching the uranyl carbonate can be precipitated with an alkali, e.g. as sodium or magnesium diuranate.   
  
The product is then packed into 200 liter steel drums which are sealed for shipment. The U3O8 is only mildly radioactive (the radiation level one meter from a drum of freshly-processed U3O8 is about half that – from cosmic rays - on a commercial jet flight). In ISL mills the process of uranium recovery is very similar, without the need for crushing and grinding.

**Tailings management and mine rehabilitation**

From open cut mining, there are substantial volumes of barren rock and overburden waste. These are placed near the pit and either used in rehabilitation or shaped and revegetated where they are.

Uranium minerals are always associated with more radioactive elements such as radium and radon in the ore which arise from the radioactive decay of uranium over a few million of years. Therefore, although uranium itself is barely 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. For instance in Australia the Code of Practice and Safety Guide: Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing was published in 2005, updating previous versions.  
  
Solid waste products from the milling operation are tailings, ranging in character from slimes to coarse sands. 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 cyclone to separate the coarse fraction which is returned underground and used for underground fill. The balance is pumped as a slurry to a tailings dam, which may be a worked-out pit as at Ranger and McClean Lake, or an engineered structure.  
  
When radium undergoes natural radioactive decay one of the products is radon gas. Because radon and its decay products (daughters) are radioactive and because the ground rock comprising the tailings is 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 often kept covered by water to reduce surface radioactivity and radon emission (though with lower-grade ores neither pose a hazard at these levels). This water needs to be recycled or evaporated since it contains radium, which is relatively soluble. Most Australian mines and many others adopt a “zero discharge” policy for any pollutants.  
  
On completion of the mining operation, it is normal for the tailings dam to be covered by some two meters of clay and topsoil with enough rock to resist erosion. This is to reduce both gamma radiation levels and radon emanation rates to levels near those normally experienced in the region of the orebody, and for a vegetation cover to be established. At Ranger and Jabiluka in North Australia, tailings will finally be returned to the mine pit or underground, as was done at the now-rehabilitated Nabarlek mine. In Canada, ore treatment is often remote from the mine that the new ore comes from, and tailings are emplaced in mined-out pits wherever possible, and engineered dams otherwise.  
  
At established ISL operations, after mining is completed the quality of the remaining groundwater must be restored to a baseline standard determined before the start of the operation so that any prior uses may be resumed. Usually this is potable water or stock water (usually les than 500 ppm total dissolved solids). Contaminated water drawn from the aquifer is either evaporated or treated before reinjection.  
  
In contrast to the main US operations, the water quality at the Australian sites is very poor to start with, and it is quite unusable. At Beverley the original groundwater in the orebody is fairly saline and orders of magnitude too high in radionuclides for any permitted use. At Honeymoon the original water is even more saline, and high in sulfates and radium. When oxygen input and leaching are discontinued, the water quality reverts to its original condition over time.  
Upon decommissioning, ISL wells are sealed or capped, process facilities removed, any evaporation pond revegetated, and the land can readily revert to its previous uses.  
  
Mining is generally considered a temporary land use, and upon completion the area with any waste rock, overburden, and covered tailings needs to be left fit for other uses, or its original use. In many parts of the world governments hold bonds to ensure proper rehabilitation in the event of corporate insolvency.

The Health of Workers

In Australia all uranium mining and milling operations are undertaken under the Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing. This was drawn up by the national government in line with recommendations of the International Commission on Radiological Protection (ICRP), but it is administered by state health and mines departments. The Code, which was updated in 1995 and again in 2005, sets strict health standards for radiation and radon gas exposure, for both workers and members of the public.

In Canada the Canadian Nuclear Safety Commission is responsible for regulating uranium mining as well as other aspects of the nuclear fuel cycle. In Saskatchewan, provincial regulations also apply concurrently, and set strict health standards for both miners and local people.

Uranium itself is only slightly radioactive. However, radon, a radioactive inert gas, is released to the atmosphere in very small quantities when the ore is mined and crushed. Radon occurs naturally in most rocks - minute traces of it are present in the air which we all breathe and it is a significant contributor to the natural radiation dose that we all receive. Because it is airborne, special care must be taken to ensure that mine worker exposure, especially in poorly ventilated mines, is limited.

Open cut mines are naturally well ventilated. The Olympic Dam and Canadian (as well as other) underground mines are ventilated with powerful fans. Radon levels are kept at a very low and certainly safe level in uranium mines. (Radon even in non-uranium mines also may need control by ventilation.)

Gamma radiation may also be a hazard to those working close to high-grade ores. It comes principally from uranium decay products in the ore, so exposure to this is regulated as required. In particular, dust is suppressed, since this represents the main potential exposure to alpha radiation as well as a gamma radiation hazard.

At the concentrations associated with uranium (and some mineral sands) mining, radioactivity is a potential health hazard. Precautions taken during the mining and milling of uranium ores to protect the health of the workers include:

* 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, often including personal dose badges.
* 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.

Canadian mine and mill facilities are designed to handle safely ore grades of up to 26% U.

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 protection procedures are applied at an ISL mine, despite the fact that most of the orebody’s radioactivity remains well underground, and there is hence minimal increase in radon release and no ore dust.

**Sustainable development reporting and audit**

As well as international quality control standards such as ISO 14001 applying to environmental management at many mines, there is now emerging an industry audit framework in collaboration with consumers of uranium, especially utilities which are sensitive to sustainable development principles, including those of their suppliers. Historically some electric utilities such as Vattenfall and EdF have applied Life Cycle Analysis to include audits of the mines and other fuel cycle facilities supplying them so that they are confident of and can vouch for the standards applying to those activities, both environmentally and socially (especially in relation to indigenous peoples).

The World Nuclear Association (WNA) has developed a framework for internationally standardized reporting on the sustainable development performance of uranium mining and processing sites. This has been agreed to by the main mining companies and developed in close collaboration with utilities so that they are in a position to report to their stakeholders. WNA is working towards implementation of a common audit program to be used worldwide by utilities and mines. There are moves to involve government regulators in this, since it complements their role, and national mining associations. The data supplied by mines will be subject to a verification process.

Uranium Resources and Supply

Table 2 shows the current known recoverable resources of uranium by country. Uranium is not a rare element and occurs in potentially recoverable concentrations in many types of geological settings. As with other minerals, investment in geological exploration generally results in increased known resources. Over 2005 and 2006 exploration effort resulted in the world’s known uranium resources increasing by 15% in that two years.

There is therefore no reason to anticipate any shortage of uranium that will prevent conventional nuclear power from playing an expanding role in providing the world’s energy needs for decades or even centuries to come. This does not even take into account improvements in nuclear power technology which could effectively increase the available resource dramatically.

The most common uranium product from mines is U3O8 which contains about 85% uranium. Table 2 refers to pure uranium, but the production figures may be expressed in terms of U308 by multiplying by 1.1793.

|  |  |  |
| --- | --- | --- |
|  | **tons U** | **percentage of world** |
| **Australia** | 1,673,000 | 31% |
| **Kazakhstan** | 651,000 | 12% |
| **Canada** | 485,000 | 9% |
| **Russia** | 480,000 | 9% |
| **South Africa** | 295,000 | 5.5% |
| **Namibia** | 284,000 | 5% |
| **Brazil** | 279,000 | 5% |
| **Niger** | 272,000 | 5% |
| **USA** | 207,000 | 5% |
| **China** | 171,000 | 3% |
| **Jordan** | 112,000 | 2% |
| **Uzbekistan** | 111,000 | 2% |
| **Ukraine** | 105,000 | 2% |
| **India** | 80,000 | 1.5% |
| **Mongolia** | 49,000 | 1% |
| **other** | 150,000 | 3% |
| **World total** | **5,404,000** |  |

Table 2. Known Recoverable Resources of Uranium

Reasonably Assured Resources plus Inferred Resources, to US$ 130/kg U, 1/1/09, from OECD NEA & IAEA, Uranium 2009: Resources, Production and Demand ("Red Book")

The current global demand for uranium is about 68,500 tU/yr. (tons uranium per year). The vast majority is consumed by the power sector with a small amount also being used for medical and research purposes, and some for naval propulsion. At present, about 53% of uranium comes from conventional mines (open pit and underground) about 41% from in situ leach, and 5% is recovered as a by-product from other mineral extraction.

In total this mined uranium accounts for 78% of annual nuclear power station requirements. The remainder is made up from secondary supplies as outlined below. Kazakhstan is now the world's leading uranium producer, followed by Canada (which long held the lead) and then Australia.

Thus the world's present measured resources of uranium (5.4 Mt) in the cost category a bit above present spot prices and used only in conventional reactors, are enough to last about 80 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 used up.  
  
In the third uranium exploration cycle from 2003 to the end of 2009 about US$ 5.75 billion was spent on uranium exploration and deposit delineation in over 600 projects. In this period over 400 new junior companies were formed or changed their orientation to raise over US$ 2 billion for uranium exploration. About 60% of this was spent on better defining and quantifying previously-known deposits. All this was in response to increased uranium price in the market.

Secondary Sources of Uranium

Secondary supplies today account for the equivalent of about 17,000 tU per year. This will drop sharply in 2014 when the supply of blended-down Russian high-enriched uranium to USA ceases, but in most scenarios will recover to at least 16,000 tU/yr. by 2020.

A major secondary supply of uranium is provided by the decommissioning of nuclear warheads by the USA and Russia. Since 2000, 13% of global uranium requirement has been provided by this ex-military material. Other sources of uranium include government and utility stockpiles and a very large amount of depleted uranium left over from historic enrichment, which can be re-enriched with more efficient processes. A little comes from recycled uranium from reprocessing used fuel.

Central Asia's uranium mines

Kazakhstan

Kazakhstan has been an important source of uranium for more than fifty years. Uranium exploration started in 1948 and economic mineralization was found in several parts of the country. This supported various mines in hard rock deposits. Some 50 uranium deposits are known, in six uranium provinces. In the early 1970s, successful tests on in situ leaching (ISL) led to further exploration being focused on two sedimentary basins with ISL potential. Up to 2000 twice as much uranium was mined from hard rock deposits as sedimentary ISL sands, but almost all production is now from ISL mines, some relatively small. Over 2001-2010 production rose from 2000 to 17,800 tU/yr, making Kazakhstan the world's leading uranium producer (33% of total in 2010), and further mine development is under way with a view to increasing production. All uranium is exported.

Kazatomprom is the national atomic company set up in 1997 and owned by the government. It controls all uranium exploration and mining as well as other nuclear-related activities. It aims to add value to the fuel chain and it is developing its fuel fabrication facilities so that fuel assemblies, rather than just fuel, could account for most sales by 2015. Kazatomprom has forged many international agreements on all aspects of nuclear power, and many of the mining operations are run as joint ventures with Russian, Chinese, Canadian and French companies.

In the Caspian province, the Prikaspisky Combine operated a major mining and processing complex in the 1960s, the first major mine in Kazakhstan. It was privatized as Kaskor in 1992 and operations ceased in 1994.

All except one of the operating and planned ISL mines are in the central south of the country. Mines in the Stepnoye area have been operating since 1978, those in the Tsentralnoye area since 1982 - both in the Chu-Sarysu basin/ province, which has more than half the country's known resources. There are 14 mines here. Mines in the Western (No.6) area of the Syrdarya basin/ province have operated since 1985, and today it has seven mines. One further ISL mine is in the Northern province.

The diversity, complexity and size of Kazakh uranium mining can be seen from WNA's Kazakhstan paper.

Table 3. Kazakh Uranium Resources in Southern provinces

|  |  |
| --- | --- |
| **Chu-Sarysu province** |  |
| **Northern (Stepnoye) group** | 750,000 tU |
| **Eastern (Tsentralnoye) group** | 140,000 tU |
| Syrdarya province |  |
| **Western (# 6)** | 180,000 tU |
| **Southern (Zarechnoye)** | 70,000 tU |

this being 72% of total Kazakh U resources and all suitable for acid ISL recovery.

Russia

AtomRedMetZoloto (ARMZ) is the state corporation which took over all uranium exploration and mining assets in 2007, as a subsidiary of Atomenergoprom, the state-owned Russian atomic energy company. It inherited 19 projects with a total uranium resource of about 400,000 tons, of which 340,000 tons are in Elkon uranium region and 60,000 tons in the Streltsovskiy and Vitimskiy regions.

Uranium production is increasing. In 2010 Russia produced some 3500 tons of uranium, mostly from several large underground mines operated by Priargunsky in the Streltsovskiy district of the Transbaikal or Chita region of SE Siberia near the Chinese and Mongolian borders. These deposits were discovered in 1967 and have been the major source of production since.

A lesser amount of production is from new operations at Khiagda in Buryatiya about 500 km northwest of Priargunsky's operations, and Dalur in the Kurgan region between Chelyabinsk and Omsk, just east of the Urals. Both are low-cost in situ leach (ISL) operations

Most of the future production is set to come from the massive Elkon project with several mines in the Sakha Republic (Yakutia) some 1200 km north-northeast of the Chita region. There is huge investment to bring these into production, which would ramp up from 2013 to 3000 tU in 2015, and 5000 tU/yr. by 2024.

Uzbekistan

During the Soviet era, Uzbekistan provided much of the uranium to the Soviet military-industrial complex. Today the state-owned Navoi company operates several uranium mines there, producing about 2400 tU/yr.

North America's Uranium Mines

Canada

In Canada, uranium ores first came to public attention in the early 1930s when the Eldorado Gold Mining Company began operations at Port Radium, Northwest Territories, to recover radium. A refinery to produce radium was built at Port Hope, Ontario, some 5000 km away. Radium is one of the decay products of uranium and is therefore found in all uranium ores. As its name suggests it is highly radioactive. It had niche applications in the early part of the 20th century, for example as luminous paint, before the dangers of radiation became widely known. Hence a market for radium existed before uranium was in demand.

Exploration for uranium began in earnest in 1942, in response to a demand for defense purposes. By 1956 thousands of radioactive occurrences had been discovered and three years later 23 uranium mines with 19 treatment plants were in operation. The main production centre was around Elliot Lake in Ontario, but northern Saskatchewan hosted some plants. This first phase of Canadian uranium production peaked in 1959 when more than 12,000 tons of uranium was produced. This uranium yielded more in export revenue than any other mineral export from Canada that year.

In response to the development of civil nuclear power, uranium exploration revived during the 1970s, with the focus on in northern Saskatchewan’s Athabasca Basin. The Rabbit Lake, Cluff Lake and Key Lake mines started up 1975 to 1983. Exploration expenditure in the region peaked at this time, resulting in the discoveries of Midwest, McClean Lake and Cigar Lake. Then in 1988 the newly-formed Cameco Corporation discovered the massive McArthur River deposit.   
As earlier in Australia, there was a period in the early 1990s when the Saskatchewan government considered phasing out uranium mining in the province, but this policy was abandoned after a joint federal-Saskatchewan study found that the benefits of mining outweighed the impacts, and that any impacts could indeed be minimized. Today the government actively supports uranium mining in the province.

Canada's share of known world uranium resources is currently about 8%, but it produces about one fifth of the mined uranium supply making it the second largest producer in the world behind Kazakhstan. Most uranium is exported, but about one fifth is used domestically.

Canada has made a transition from second-generation uranium mines (started 1975-83) to new high-grade ones, all in northern Saskatchewan, making its uranium mining operations among the most advanced in the world.

Cameco operates the McArthur River mine, which started production at the end of 1999. Its ore is milled at Key Lake, which once contributed 15% of world uranium production but is now mined out. Its other former mainstay is Rabbit Lake. Areva's Cluff Lake mine is now closed, and is being decommissioned.

Cameco's Rabbit Lake mine was brought into production in 1975. Most of the deposit has been mined out. Production from underground mining continues at over 1000 tU/yr but will phase out by about 2015.

McArthur River has enormous high-grade reserves of over 20% uranium ore at a depth of about 600 meters. It opened at the end of 1999 and is now the largest uranium mine in the world by a wide margin. Remote-control raise-boring methods are used for mining and the ore is trucked 80 km south to the modified Key Lake mill, where it is blended with "special waste rock" to produce 7200 tU/yr. Tailings are deposited in a mined-out pit. Cameco is the operator and majority owner, with Areva (30.2%) as partner.

Areva Resources operates the McClean Lake mine which commenced operation in mid 1999. It has new plant and other infrastructure and uses the first mined-out pit for tailings disposal (the ore having been stockpiled). McClean Lake involves four open pits and later will become an underground mine. Annual production depends critically on ore grade being treated, though the mine has recently been relicensed to produce as much as 3100 tU/yr. Denison Mines owns 22.5% of it.

Cigar Lake will be a 450 m deep underground mine in poor ground conditions, using ground freezing and high-pressure water jets for excavation of ore. High-grade ore slurry from remote mining will be trucked for treatment at Areva's expanded McClean Lake mill, 70 km northeast, and to Cameco's Rabbit Lake mill 70 km east, to produce 7000 tU/yr from about 2013. A major flood in 2006 and another in 2008 set the project back several years and pushed costs up from C$660 million to more than C$1.8 billion. The joint venture is managed by Cameco which holds 50%, and Areva holds 37%.

Areva's Midwest mine was to be underground, utilizing ground freezing and water jet boring, but is now proposed as a large open pit. The ore will be milled at McClean Lake nearby, to produce 2200 tU/yr. Start-up has been postponed due to cost increases.

Areva's large Kiggavik deposit in the Nunavut Territory has evident potential, as do several other smaller but significant deposits.

USA

In the 1950s, the USA had a great deal of uranium mining, promoted by federal subsidies. Peak production was 16,800 tU in 1980, when there were over 250 mines in operation. This number abruptly dropped to 50 in 1984, when 5700 tU was produced, and then there was steady decline to 2003, with most US uranium requirements being imported. By 2003 there were only two small operations producing a total of well under 1000 tU/yr, though more recently the sector has recovered, buoyed by higher uranium prices, so that in 2008 no fewer than 15 mines (10 underground and 5 ISL)operated for at least part the year and produced 1500 tU.

Cameco operates the Smith Ranch-Highland mine in Wyoming and the Crow Butte mine in Nebraska, both of them small ISL operations. Uranium One operates the Christiansen Ranch ISL mine in Wyoming. Mestena Uranium's Alta Mesa ISL plant in South Texas is also operational.

Conventional (non-ISL) uranium mining has returned to the USA after many years. One company, Denison Mines, operates mines on the Colorado Plateau and Henry Mountains in Utah. The ore is processed at its White Mesa mill in south-eastern Utah. White Canyon Uranium operates the Daneros mine in Utah, with ore toll milled at White Mesa. Several other projects are under development, though some projects and mines have been put on standby pending market improvements.

Australia's Uranium Mines

The first major producer of uranium in Australia was the Government-owned Rum Jungle project in the Northern Territory, which operated from 1954 to 1971. It was closely followed by Radium Hill in South Australia, then Mary Kathleen in Queensland.

As a result of intensive exploration in the late 1960s Australia began to emerge as a potential major source of uranium for the world's nuclear electricity production. At the beginning of the 1970s a series of important discoveries was made, particularly in the Northern Territory. Names like Ranger, Jabiluka and Nabarlek, all in the Northern Territory; Yeelirrie in Western Australia; Olympic Dam (with Roxby Downs town) in South Australia became familiar.

During this period many deposits were identified, however further uranium mining operations were not permitted by the government until after the findings of the Ranger Uranium Environmental Inquiry (also known as the Fox inquiry). This inquiry represented a major turning point in the history of the Australian uranium mining industry and provided the basis of subsequent Australian policy. It found that the impacts of uranium mining were manageable but that the sale of uranium needed to be carefully regulated, and that the rights of indigenous communities needed to be protected. Since then five uranium mines have operated, and several more are proposed.

Today Australia’s share of the world's known uranium resources is about one third and it produces about 16% of the world's mined uranium. All uranium is exported - a total of about 10,000 tons per year of uranium oxide - U3O8 (8500 tU).

Mary Kathleen had a second production phase from 1974 to the end of 1982.

The Nabarlek mine was the first of the uranium deposits discovered in the late 1960s to early 1970s to come into production. The main orebody, which contained about 9300 tons of uranium, was mined by open pit and the ore stockpiled all in one year in 1979. The sore was then processed from 1980 to 1988. The Narbarlek mine site is significant because it was the first site to be rehabilitated according to modern principles and practice.

Ranger, owned by Energy Resources of Australia Ltd (ERA) and located about 230 kilometers east of Darwin in the Northern Territory was next. Mining commenced in 1980 and is continuing on the second of two orebodies, producing about 4500 tons of uranium per year.

Olympic Dam, 265 km north of Port Augusta in South Australia, commenced operations in 1988 and became part of BHP-Billiton in 2005 when Western Mining Corporation was taken over. It is potentially the world's largest uranium producer, with total resources of 2.45 million tons of uranium. The mine produces about 3500 tU/yr and there are plans for a very major expansion which could see an increase in production to 16,100 tU/yr.

Beverley, the country's first mine to utilize in situ leaching, commenced operation in South Australia in 2000. It is a small in situ leach (ISL) mine producing about 600 tU/yr, owned by Heathgate Resources.

Honeymoon in South Australia is the second ISL mine, producing about 340 tU/yr from 2011. It is a joint venture between Uranium One Inc of Canada and Mitsui of Japan.

ERA also owns the Jabiluka uranium orebody, adjacent to Ranger. This is one of the world's larger known uranium deposits, but development will not proceed until aboriginal landholders agree.

In Western Australia there are also plans to start mining Yeelirrie from about 2014 at 2000 tU/yr, and smaller operations are planned at Lake Way & Centipede, and Lake Maitland.

Africa's uranium mines

Uranium mining has a long and interesting history in Africa. Significant quantities of the mineral have previously come out of the Congo and Gabon. Today uranium is mined in Namibia, Niger, South Africa and Malawi.

The DR Congo, or Belgian Congo as it was then known, provided much of the uranium for the Manhattan Project in the early 1940s particularly from the Shinkolobwe mine in Katanga. There was some uranium mining subsequently by Union Miniere, to independence in 1960, when the shafts were sealed and guarded. About 25,000 tU was produced in the two decades until then.

In Gabon, the Mounana uranium deposits were discovered in 1956 by French Atomic Energy Commission (CEA) geologists and were mined from 1960 to 1999, producing nearly 28,000 tons of uranium from underground and open pit mining. The best known of these deposits is Oklo, discovered in 1968, which is famous for its fossil nuclear reactors, where the natural conditions about two billion years ago created at least 17 self-sustaining nuclear reactors in the wet sandstone orebody.

Namibia has two large uranium mines capable of producing 10% of world output. In 1966 Rio Tinto took over the low-grade Rossing deposit, 65 km inland from Swakopmund. Rossing Uranium Ltd was formed in 1970 (now 68.6% Rio Tinto) and the company has mined the deposit from 1976 as a large-scale open pit in very hard rock. Rossing produced 3083 tU in 2010, making it the third largest uranium mine in the world. Langer Heinrich is 50 km south-southeast of Rossing and 80 km from the coast. It is being mined by Paladin Energy Ltd, producing about 1350 tU/yr.

There are several promising developments in Namibia, including Extract Resources' Husab project on the Rossing South deposit, which promises to become one of the world's largest uranium mines.

Niger has two significant long-running mines, Akouta and Arlette supplying 6% of the world's mined uranium. The Société des Mines de l'Air (SOMAIR) started production from the Arlette deposit in 1971, by open cut mining. It produces about 1700 tU/yr. The Compagnie Miniere d'Akouta (COMINAK) started production from the Akouta deposit in the 1970s. This is an underground operation at a depth of about 250 meters. Production is about 1400 tU/yr.

In South Africa, uranium production has generally been a by-product of gold or copper mining. In 1951, a company was formed to exploit the uranium-rich slurries from gold mining and in 1998 this became a subsidiary of AngloGold Ltd. It produces about 500 tU/yr from material trucked in from various gold mines and from Palabora copper mine.

In Malawi, Paladin Energy has developed the Kayelekera uranium mine where production is expected to ramp up to 1460 tU/yr about mid 2012.

In the Central African Republic, Areva is developing the Bakouma project, and is ramping up production from open pit mining to 1200 tU/yr.

In Zambia, Equinox Minerals is developing the Lumwana project, which is primarily a copper mine with discrete uranium ore. Uranium ore is being stockpiled, but there is no treatment plant yet.

Issues related to uranium mining

Safeguards to Prevent Military Use

Among uranium-exporting countries, Australia and Canada have some of the strictest conditions relating to the use of its uranium. These safeguards (inspections and accounting procedures) ensure that exported uranium is used for peaceful purposes only and is not diverted for military purposes or used in a way which adds to the proliferation of nuclear weapons.

Bilateral agreements to this effect between the Australian and Canadian Governments and each country wishing to import their uranium are therefore necessary before sales contracts can be completed. Such agreements are in addition to the application of International Atomic Energy Agency (IAEA) safeguards administered under the Nuclear Non-Proliferation Treaty. The further transfer of nuclear material is only permitted to countries which have bilateral safeguards agreements with Australia or Canada.

Australia, Canada and Kazakhstan are now the world's major producers and exporters of uranium. In addition to providing further diversification and strength to their domestic economies, it gives all three countries a voice in the framing of international nuclear policies and safeguards. It also reduces the need for buyers to seek uranium from countries with less effective safeguards.

Some uranium basics:

The atomic number of uranium is 92, meaning that it has 92 protons and occupies place number 92 in the periodic table. It occurs naturally in six isotopes, U-233 to U-238 and therefore contains between 141 and 146 neutrons. The most common isotope is U-238 with a relative abundance of 99.3%. The second most common is U-235 with a relative abundance of 0.7% and the rest occur in trace amounts. All isotopes of uranium are radioactive and over time they decay to other lighter elements. However the rate of decay is slow; the radioactive half-life of U-238 is 4.47 billion years, meaning that it takes this much time for half of any given sample of U-238 to break down. The half-life of U-235 is 704 million years which means that most of the Earth's original U-235 has already decayed away.

A further property of U235 is that it is fissile and so neutrons emitted during fission can cause other U235 nuclei to fission also, releasing a lot of energy. This reaction is the basis of operation for the world’s current nuclear power stations and is the major reason why uranium is a valuable mineral resource.