Chapter 18
Uranium and Thorium Resources

J. Stephen Herring

Glossary

Cross section	Probability of neutron interaction with a nucleus, expressed in terms of area, in units of barns (b). One barn equals 1.0×10^{-24} cm^2.
Enrichment	The fraction of an isotope, usually fissile ^{235}U, in a mass of uranium. Enrichment is commonly quoted as the weight percent of the particular isotope. Natural uranium has an enrichment of 0.711 wt%, commercial reactor fuel is 3–5% enriched, and depleted uranium is 0.2–0.3% ^{235}U.
Enrichment tails (also depleted uranium)	The uranium remaining after the enrichment of natural uranium into fuel, today about 0.3% ^{235}U, earlier 0.2–0.25% ^{235}U.
Fractionation	Crystallization from a magma in which the initial crystals are prevented from equilibrating from the parent liquid, resulting in a series of residual liquids of more extreme composition than would have resulted from continuous reaction [1].
Highly enriched uranium (HEU)	Uranium containing more that 20 wt% ^{235}U.
J_{th}	Joule (i.e., Watt-second) thermal. One British thermal unit (BTU) equals 1,055 J_{th}.
Log-normal distribution	Distribution of the form $f(x) = e^{-(\ln x)^2}$. In the present usage, the tonnage of an element available at concentration c, $T(c)$, is

---

This chapter was originally published as part of the Encyclopedia of Sustainability Science and Technology edited by Robert A. Meyers. DOI:10.1007/978-1-4419-0851-3

J.S. Herring (✉)
Idaho National Laboratory, Idaho Falls, ID, USA
e-mail: J.Herring@inl.gov

N. Tsoulfanidis (ed.), *Nuclear Energy: Selected Entries from the Encyclopedia of Sustainability Science and Technology*, DOI 10.1007/978-1-4614-5716-9_18,

	given by $T(c) = C_1 e^{-(\ln c_o - \ln c)^2}$, where c_o is the average crustal abundance and C_1 is a constant.
Low-enriched uranium (LEU)	Uranium containing less than 20 wt% ^{235}U.
Mafic	Composed chiefly of dark ferromagnesian minerals.
MOX	Mixed oxide fuel, usually consisting of a ceramic mixture of uranium dioxide and plutonium dioxide.
MSWU	Mega-separative work unit, a million separative work units. A separative work unit is the separative work that must be done to one kilogram of a mixture of isotopes to change its separation potential by one unit. The separation potential, a dimensionless function, is defined by $\phi\ (x_k) = (2x_k - 1) \ln \frac{x_k}{1-x_k}$, where x_k is the atomic fraction of the isotope, k. See Benedict 1981, p. 667 for a more complete definition [2].
Pegmatite	An exceptionally coarse-grained igneous rock, with interlocking crystals, often found at the margins of batholiths.
Placer	A mineral deposit at the surface formed by sedimentary concentration of heavy mineral particles from weathered debris.
Quad	Quadrillion (i.e., 10^{15}, also written 1E15) British thermal units. One quad = 1.055×10^{18} J_{th}.
t	Metric ton, also used in *Mt*, million metric tons, and *Tt*, trillion metric tons (teratons).
Unconformity	A break or gap in the geologic record, such as an interruption in the normal sequence of deposition of sedimentary rocks, or a break between eroded metamorphic rocks and younger sedimentary strata [1].
Yellowcake	A concentrate of uranium ore, containing 80–90% U_3O_8. Yellowcake ranges from yellow to black, depending on impurities, processing temperature, and degree of hydration [3]. Although uranium prices are sometimes colloquially cited as “dollars per pound of yellowcake,” the actual prices are $ per lb of U_3O_8, where all of the uranium is assumed to be present in the yellowcake as that oxide.

Definition of the Subject

Uranium is a widely distributed element which is essential, at least in the near term, to the use of nuclear fission as a source of energy. Uranium is ubiquitous in the earth because of the wide variety of minerals in which it can occur, and because of the variety of geophysical and geochemical processes that have transported it since the primordial formation of the earth from the debris of supernovae. Uranium is approximately as common in the earth's crust as tin or beryllium, and is a minor constituent in most rocks and in seawater. The average crustal abundance of uranium is 2.76 weight parts per million (wppm), higher than the average concentrations of such economically important elements as molybdenum (1.5 wppm), iodine (0.5 wppm), mercury (0.08 wppm), silver (0.07 wppm), and gold (0.004 wppm).

Introduction

Beginning with the discovery of nuclear fission, uranium has been seen as a valuable but scarce resource. Uranium-235 (^{235}U) is the only naturally occurring isotope that can be made to fission with thermal neutrons. Consequently, the resources of uranium have been believed to inherently limit the sustainability of nuclear energy. There have been two periods of extensive exploration for uranium, in the 1950s and in the 1970s, both followed by long periods of severe contraction in the market and in exploration activity. With the peak of uranium prices to about $350/kg in 2007, there was an increased effort in exploration. However, that exploration quickly resulted in increased known reserves in several deposits and the return of prices to about $140/kg. Today, exploration activity is at a moderate level for several reasons: (1) deposits found during earlier exploration periods have proven to be larger than initially estimated, (2) nuclear energy is growing, but not as rapidly as earlier forecast, (3) improved nuclear fuel management techniques and materials are allowing higher burnup and longer operating cycles, and (4) the conversion ("downblending") of highly enriched uranium of military origin to civilian purposes has postponed the need for large amounts of newly mined natural uranium.

Concern that uranium would soon be exhausted was one of the driving forces in the development of fast breeder reactors, particularly in the 1960s and 70s. Fast breeder reactors convert the fertile isotope ^{238}U into the fissile isotope ^{239}Pu. These concerns also led to the development of thermal breeder reactors capable of converting thorium into the fissile, but not naturally occurring, isotope ^{233}U. Thorium, consisting almost entirely of the isotope ^{232}Th, is about four times more abundant than uranium and thus may represent a source of nuclear fuel in the distant future.

Estimates of Uranium Reserves

The importance of the overall uranium and thorium resource is demonstrated by the attention given to the estimates by such international agencies as the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD). The estimates of these organizations are based on information provided by the member states and backed by research from others. The results are regularly compiled in the "Red Book" [4].

However, the estimates of uranium resources in the Red Book are based on the known and expected reserves that can be economically extracted using present or near-future technology. Because of the wide range of uranium concentrations in various minerals, the cost of extraction serves as the independent variable against which resources are estimated. Any reported amount of reserves/resources should be accompanied by the estimated cost of recovery of those reserves.

The Red Book [4] estimates the economically recoverable uranium reserves based on current and prospective mining projects ("Total Identified Resources Reasonably Assured and Inferred") as of January 2009 are 5.4 million metric tons (Mt) of uranium of the best-proven category recoverable worldwide at a marginal cost of $<$\$130/kg of uranium metal. When the high-cost category (between \$130/kg and \$260/kg of U metal) is added, the total identified resources are estimated to be 6.3 Mt. Total undiscovered resources (prognosticated resources and speculative resources) as of January 2009 were estimated to be 10.4 Mt. The 2008 consumption of natural uranium by the 438 reactors worldwide was 59,065 t, and consequently, these total identified resources could be expected to last about 100 years at current rates and 250 years if speculative resources are included. These ratios of identified and speculative resources to consumption rate are longer than those for nearly all metals and fossil fuels, with the exception of coal.

Low market prices, the slow growth of nuclear power, and the downblending of highly enriched uranium (HEU) have in the past resulted in both very low levels of exploration and little effort in the development of advanced extraction technologies. Downblending agreements with the Russian Federation are due to expire in 2013. The discovery of additional total identified resources has shown a strong correlation with exploration expenditures, averaging 0.65 kg of additional resources per exploration dollar from 1987 to 2005 and 0.32 kg/exploration dollar from 2005 to 2009, following the uranium price increases after 2005 [5]. Those transient price increases led to an increase in the average annual expenditures for exploration from \$127 million/year for 1987–2005 to \$1.1 billion/year for 2005–2009.

It is important to note that uranium today is used overwhelmingly in the light water reactor fuel cycle, where only about 1.1–1.5% of the ultimate energy of the mined uranium is extracted via fissioning of ^{235}U and the small amounts of ^{239}Pu bred in situ. The rest of the uranium remains either in the used fuel or in the depleted uranium tails remaining after enrichment. Of the 1.8 Mt of uranium mined worldwide since 1945, the location of all but about 1,500 t is known. Only the location of that uranium dispersed either in nuclear explosions or as armor-piercing projectiles is not known. The inventory of used fuel and of depleted uranium represents a very significant resource that could become fuel for fast breeder reactors.

While uranium is an essential input for the production of nuclear energy, the costs of natural uranium are a minor component of the overall cost. Today, at uranium prices of about \$140/kg U (\$53/lb of U_3O_8), the natural uranium required for the light water reactor (LWR) fuel cycle is responsible for only about 2.5–3% of generating costs. The fuel cost is 15–20% of the generating costs, but those costs include conversion of the uranium ore to UF_6, enrichment of the natural uranium, production of the ceramic UO_2 fuel pellets, and fabrication of the fuel assemblies. A tenfold increase in the cost of natural uranium would not be welcome, but would not fundamentally change the economics of nuclear power. A tenfold increase in uranium prices would, at first estimate, be expected to increase the cost of nuclear electricity by 25–30%. However, a more detailed calculation, optimizing the ^{235}U content of the depleted uranium tails and adjusting fuel management for a higher priced resource, would result in an increase in the cost of electricity significantly less than 20%.

This entry discusses uranium resources in a global sense, beyond the official estimates of the IAEA and the OECD. As an introduction to that discussion, the origins of the earth's present inventory of uranium, the geophysical and geochemical processes that serve to concentrate uranium into economically viable deposits, and the technologies now being used for the extraction and concentration of uranium ores are described. Finally, the potential impacts of technologies now under development and the overall impact of the cost of uranium on the cost of energy from nuclear fission will be reviewed.

Thorium as a Nuclear Fuel

For the foreseeable future, uranium will probably continue to be the only source of nuclear energy. Nevertheless, for completeness, thorium resources should also be considered because of thorium's unique characteristics as a nuclear fuel. There are basically four reasons for considering thorium resources within the overall discussion of nuclear fuel resources. First, thorium is about 3.9 times more abundant than uranium, on a mass basis, as indicated both by samples of the continental crust and by spectroscopy of supernova debris, from which planets are formed. Secondly, because similarities of the geochemistry and mineralogy of thorium and the lanthanides, thorium and the lanthanides (often called the "rare earth elements") are often found in the same ore bodies. Since the lanthanides are of increasing technical and strategic importance due to their widespread use in magnets and electronics, thorium is often treated as a waste since it has only a small market and since it is radioactive. Thus research on the efficient separation and purification of thorium could enhance both rare earth and thorium resources. Third, thorium can be directly substituted in the UO_2 crystal, making it a long-term supplement for uranium for in situ ^{233}U breeding. Thorium, as ThF_4, can also be used in the molten salt reactor in combination with UF_4, where the uranium would be a mixture of ^{233}U, ^{235}U, and ^{238}U. Finally, because thorium has only one oxide, ThO_2, which has high thermal stability, it can serve as a very robust matrix for actinide transmutation, after which the ThO_2 would serve as the waste form for the transmutation targets.

Thorium averages 12 parts per million in the earth's crust, and is the 39th most abundant of the 78 crustal elements. Soil commonly contains an average of 6 wppm of thorium. When thorium is used as a nuclear fuel, much less plutonium and other minor transuranics (i.e., neptunium, americium, curium, berkelium, ...) are produced than are produced in uranium fuel cycles. The reduced production of transuranics occurs for two reasons. First, the fissile product of neutron absorption by ^{232}Th is ^{233}U, which is further down the actinide series from plutonium and the minor actinides, and secondly, the fission to capture ratio of ^{233}U is approximately nine, while that of ^{239}Pu is about three, thus resulting in lower production of the transuranics.

The generation of thorium deposits occurs in a fundamentally different manner from deposits of uranium. Uranium has some nine oxides and is dissolved or precipitated depending on the oxygen content and pH of the groundwater. Thus deposits are often formed where there is a decrease in the oxygen content of groundwater. Thorium, on the other hand, has only one oxide, ThO_2, which is very refractory and insoluble. Thus thoria (along with many of the lanthanide oxides) is not dissolved in erosion by groundwater and flowing rivers. The surviving grains, containing the thoria from the base rock, form into alluvial deposits of monazite sands.

Thorium occurs as the ores thoriatite (ThO_2), thorite ($ThSiO_4$) and mainly as monazite ((Ce, La, Nd, Th)PO_4). Thorium and its compounds have been produced primarily as a by-product of the recovery of titanium, zirconium, tin, and rare earths from monazite, which contains 6–8.5 wt% thorium oxide. Only a small portion of the thorium produced is consumed. Limited demand for thorium, relative to the demand for rare earths, has continued to create a worldwide oversupply of thorium compounds and mining residues. Most major rare-earth processors have switched feed materials to thorium-free intermediate compounds to avoid the handling of radioactive thorium. Excess thorium not designated for commercial use is either disposed of as a radioactive waste or stored for potential use as a nuclear fuel or other applications. Increased costs to comply with environmental regulations and potential legal liabilities and costs to purchase storage and waste disposal space were the principal deterrents to its commercial use. Health concerns associated with thorium's natural radioactivity have not been a significant factor in switching to alternative nonradioactive materials. US consumption of thorium, all for nonenergy uses, has decreased from 11.4 t (thorium content) to 0.7 t since 1997. The principal applications of thorium today make use of the very high melting point of ThO_2 (3,300°C, the highest of all binary oxides) and of the electron emitting capability of thorium when alloyed with tungsten for use in filaments for high-powered magnetrons for radar.

In the short term, thorium is available for the cost of extraction from rare-earth processing wastes. In the longer term, large resources of thorium are available in known monazite deposits in India, Brazil, China, Malaysia, and Sri Lanka. The world total thorium resources identified and prognosticated amounts to 3.6 million tons Th. Though reported values vary because of the difficulty in measuring such low concentrations, ^{232}Th is present in seawater at only about 0.050 wppb, due primarily to the insoluble nature of its only oxide, ThO_2. Thus the recovery of thorium from seawater is not a realistic option.

Because ^{232}Th is the only isotope of natural thorium, there are no enrichment plant tails from thorium nuclear fuel. Therefore, the cost of thorium in a mixed thorium-uranium LWR fuel or in a pure thorium-^{233}U fuel cycle is relatively small. However, the cost of chemically processing of ThO_2-based fuel and the separation of ^{233}U is significant.

Energy Content of Uranium and Thorium

Uranium has 18 known isotopes, none of which are stable and only two of which have half-lives longer than a million years, ^{235}U (704 Ma) and ^{238}U (4.47 billion years). Only ^{235}U, which is about 0.711 wt% (0.720 atom%) of natural uranium, is fissile, i.e., will fission using thermal (i.e., low velocity) neutrons. Uranium-238, which is by far the dominant isotope at 99.2745 wt%, will fission if struck by high-energy neutrons. However, ^{235}U is the only naturally occurring isotope of any element capable of sustaining a neutron chain reaction in a suitably designed reactor.

^{238}U is a fertile isotope and can be transformed into ^{239}Pu through the capture of a neutron and two subsequent beta decays, as shown in the following reaction:

$$^{238}\mathrm{U}(n,\gamma)^{239}\mathrm{U} \xrightarrow[\beta^- t_{1/2} = 23.5\ \text{min}]{}$$

$$^{239}\mathrm{Np} \xrightarrow[\beta^-\ t_{1/2} = 2.35\,\text{days}]{}$$

$$^{239}\mathrm{Pu} \xrightarrow[\sigma_{f\ \text{thermal}} = 750b]{} \text{fission}$$

where β^- indicates a beta decay with electron emission and $\sigma_{f\ \text{thermal}}$ is the fission cross section in barns at a neutron energy of 0.025 eV.

Thorium has 25 isotopes, of which only the non-fissile isotope ^{232}Th is long-lived, with a half-life of 14 billion years. However, in the reaction shown below, ^{232}Th can be transmuted into ^{233}U, a fissile isotope:

$$^{232}\mathrm{Th}(n,\gamma)^{233}\mathrm{Th} \xrightarrow[\beta^- t_{1/2} = 22.3\ \text{min}]{}$$

$$^{233}\mathrm{Pa} \xrightarrow[\beta^-\ t_{1/2} = 27.0\ \text{days}]{}$$

$$^{233}\mathrm{U} \xrightarrow[\sigma_{f\ \text{thermal}} = 531\,b]{} \text{fission}$$

The fission energy of ^{233}U is 190 MeV and that of ^{239}Pu is 200 MeV. If 1 kg of thorium were bred into ^{233}U, the fission energy available would be 78.9 × 10^{12} $J_{thermal}$ (78.9 TJ_{th}). The fission energy in 1 kg of natural uranium, bred to ^{239}Pu, is 80.4 TJ_{th}. Thus thorium and uranium are quite similar in maximum energy content, but uranium is far more important in the near term because ^{235}U is a naturally occurring fissile isotope.

Global Estimates of Overall Uranium and Thorium Resources

Uranium and thorium have two unique characteristics when compared with other fuels. First, their energy is contained in the nucleus, rather than in the chemical bonds between the atoms, as is the case with fossil fuels. Thus, chemical reactions within the earth, due to pressure, high temperatures, or the presence of oxygen, have no effect on the nuclear energy available from uranium or thorium. In contrast, exposure of fossil fuels to the oxygen in the atmosphere or to volcanic activity releases the energy stored in their chemical bonds. The vast majority of the solar energy originally stored in fossil fuels through photosynthesis of the source biomass has been lost in chemical reactions with the atmosphere, groundwater, and lava.

A second, less obvious, characteristic of uranium and thorium is that they are constantly signaling their presence via the products of radioactive decay. Everyone is familiar with pictures of the prospector with a Geiger counter searching for uranium. Gamma rays and beta particles can be detected with a handheld instrument if the uranium ore is at the surface. However, even as little as a meter of overlying soil will shield the gammas and beta particles from the counter. Therefore, any ore deposits more than a meter below the surface will have to be detected through well logs or core samples or via their gravitational or magnetic signatures, rather than through their radiation.

Astrophysical Origins of Uranium

Uranium, thorium, and all other elements heavier than nickel result from the sudden collapse of massive stars as supernovae. The lifetime of stars and the results of these gravity-driven implosions are very dependent on the stars' initial mass. A star having the mass of our sun lasts for about ten billion years but can only produce elements up to iron. A star having ten solar masses lasts for only 10 Ma until it explodes as a supernova, producing all the elements in the periodic table.

The groundbreaking work by Burbidge, Burbidge, Fowler, and Hoyle [6] led to the realization that all of the elements heavier than nickel are the result of less than a minute of tremendous neutrino and neutron fluxes during the collapse and explosion of a supernova [7]. The nuclide distribution as a function of time in a supernova has been simulated [8] and indicates that isotopes with the maximum

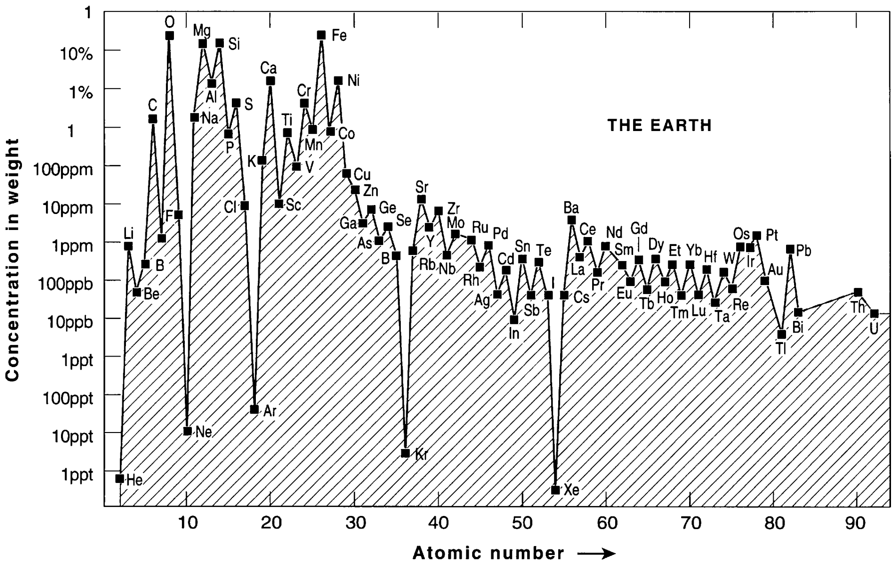


Fig. 18.1 Composition of the bulk silicate Earth

number of neutrons ("the neutron drip edge") form during few seconds of intense activity at the center of the imploding supernova. From this nuclear modeling of a supernova explosion, it can be inferred that uranium and thorium are about seven orders of magnitude below silicon in the composition of the supernova debris – the material from which planets are formed. This is in rough agreement with Bulk Silicate Earth model, shown in Fig. 18.1.

Earlier studies are also in agreement. Urey cites estimates by Goldschmidt of the primordial abundance of 41 weight parts per billion (wppb) for uranium and 106 wppb for thorium. Alpher's theoretical curves and Harrison S. Brown's observed astrophysical data show uranium approximately 6.5 orders of magnitude less abundant than silicon, resulting in a primordial abundances of 57 wppb. Deffeyes, accounting for the decay of uranium since the expansion of the primordial neutron gas, estimates global uranium abundance at 10.5 wppb [9].

Recent work on the physics of supernova collapse offers some insight into the expected global inventories of uranium and thorium. These two elements, and all other elements heavier than nickel, are formed in a few seconds of extremely violent conditions during the collapse and explosion of massive stars. During the last few minutes of such a massive star's evolution, hydrogen, helium, and all of the elements lighter than nickel at the center of the star are depleted through fusion reactions. With no more energy available for continued fusion reactions, the center cannot withstand the outer shells of material, and the matter in the center is compressed to a degenerate state in which matter is broken into the constituent particles, primarily neutrons and neutrinos. The torrent of neutrons from the center of the supernova irradiates the infalling outer layers of stellar material, producing heavier isotopes at a rate faster than the radioactive decay of those isotopes. The result is the production of isotopes stretching from nickel through uranium and beyond, all saturated with neutrons.

This type of supernova explosion is estimated to occur, somewhere in the universe, at the rate of one per second. Obviously, most such explosions are too distant or masked by dust clouds and are not detected from the earth. Since the beginning of the universe, some interstellar material has gone through multiple cycles of collapse, explosion, dispersal, and accretion into new stars.

The hydrodynamic instabilities of the implosion result in a wide variation in the shapes of the resulting nebulae. Nevertheless, neutron transport and reaction codes have been developed to estimate the distribution of isotopes resulting from a supernova implosion. Wanajo and others [8] have modeled the first few seconds of isotope production and shown that the uranium mass should be about seven orders of magnitude less than that of silicon. Since the chemical and planetary accretion characteristics of silicon, uranium, and thorium are similar, and since the earth is about 10% silicon, one would expect that the overall concentration of uranium in the earth is about 10 wppb. The geoneutrino data from KamLAND and from newer detectors indicate that the global uranium inventory is, in fact, about 10 wppb.

Therefore, based on these astrophysical models, it is fairly clear that the earth taken as uniform body contains about 10 wppb uranium and about 40 wppb thorium. Stated in other terms, the present global inventory is thus 63 Tt (63×10^{12} t) of uranium and approximately 400 Tt of thorium. Although this inventory is a vast amount of both elements, if uranium and thorium had a uniform distribution throughout the earth, as assumed in the cold accretion model, concentrations of uranium and thorium would be far too small to be economically extracted.

Geoneutrino Estimates of Uranium and Thorium

In the last 20 years, however, another decay product of the 4.5 billion year half-life of ^{238}U and the 14.2 billion year half-life of ^{232}Th has been used to estimate the total global inventory of uranium and thorium. These particles, called neutrinos, are extremely difficult to detect and most neutrinos pass completely through the earth without interacting. Thus neutrino detectors are usually a thousand tons in mass and must be located deep underground to avoid unwanted signals caused by cosmic rays.

Neutrinos occur in three types: electron, muon, and tau. Each of the three types has a corresponding antineutrino. Neutrinos originating within the earth, termed *geoneutrinos*, are actually electron antineutrinos primarily resulting from the decay of ^{40}K, ^{238}U, and ^{232}Th. Geoneutrinos provide a means for estimating the total uranium and thorium content of the earth and also may provide limited information on the location of those resources. These elementary particles have been measured over the past decade by massive detectors in Japan, Canada, and Europe in an effort to differentiate the radiogenic and gravitational components of the total geothermal energy flux through the earth's surface [10]. Neutrino and antineutrino fluxes have also been measured to understand neutrino oscillations, to investigate solar fusion processes, and as a first signal of supernova events. Neutrinos (and antineutrinos) travel close to the speed of light, have a small mass (<2 eV), and lack an electric charge. When an electron antineutrino collides with a proton, the result is a neutron and a positron (i.e., an antielectron). This reaction, known as the neutron inverse β decay, was used in the first detection of the neutrino in the Cowan–Reines experiment of 1956. Following the neutron inverse β decay, the positron reacts with a nearby electron to produce two 511 keV gamma rays. The neutron is absorbed by a hydrogen nucleus, releasing a characteristic 2.2 MeV gamma with a mean delay of $\sim$200 μs. Circuitry in the detector registers a neutrino event through the delayed emission of a 2.2 MeV gamma following two 511 keV gammas.

The KamLAND (the Kamioka Large Antineutrino Detector), in central Japan, consists of a 18 m diameter spherical vessel which in turn contains a 13 m diameter nylon balloon. The balloon contains approximately 1,000 t of a liquid scintillator (mineral oil, benzene, and fluorescent compounds). The volume between the balloon and the spherical vessel contains highly purified oil which shields the balloon from external radiation and provides buoyancy to support the liquid scintillator. About 1,900 photomultiplier tubes are mounted on the inner surface of the spherical vessel. Surrounding the spherical vessel is a water Cherenkov detector which provides additional shielding and acts as a muon veto counter.

The decay chain of ^{238}U into ^{206}Pb results in six antineutrinos, one antineutrino for each beta decay. Similarly, the decay of ^{232}Th in ^{208}Pb results in four antineutrinos [11]. Because the neutron inverse β decay requires an electron antineutrino threshold energy of 1.80 MeV, KamLAND cannot detect ^{40}K antineutrinos, but antineutrinos from both ^{238}U and ^{232}Th are within the range of this instrument.

The overall results of the KamLAND geoneutrino study [12] show that the sum of the global U and Th inventory is approximately 30×10^{16} kg. Since the global Th/U mass ratio is 3.9, the global U inventory is about 6×10^{16} kg or $\sim$10 ppb of the mass of the earth. The geoneutrino signal also indicates that the majority of the uranium is in the upper continental crust (UCC) and that relatively little of the inventory is in the oceanic crust, the mantle, or the core. The partitioning of the uranium among the upper, middle, and lower continental crust and the upper mantle occurs via geochemical processes [13].

Thermal models of the earth point to inevitable melting of the earth soon after its accretion due to gravitation energy and due to radioactive decay of uranium, thorium, and potassium. Because of its large ionic size and heating due to radioactive decay, uranium is transferred into low melting temperature fractions and out of the earth's core and mantle into the crust. These geochemical and geophysical models predict that two thirds of initial 63 Tt of uranium present in the earth are now concentrated in the crust, which constitutes only 0.4% of the earth's total mass. The low uranium and high iron concentrations predicted for the earth's mantle and core have been supported by concentrations in iron meteorites and in mantle issuing

Table 18.1 The main properties of geoneutrinos

Decay	Q (MeV)	$\tau_{½}$ (10^9 year)	E_{max} (MeV)	ε_H (W/kg)	$\epsilon_{\bar{\nu}_e}$ (kg^{-1} s^{-1})
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^4He + 6\,e + 6\,\bar{\nu}_e$	51.7	4.47	3.26	0.95×10^{-4}	7.41×10^7
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^4He + 4\,e + 4\,\bar{\nu}_e$	42.7	14.0	2.25	0.27×10^{-4}	1.63×10^7
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}_e$	1.32	1.28	1.31	0.36×10^{-8}	2.69×10^4

$\bar{\nu}_e$ denotes electron antineutrinos
where:
Q is the energy release for the overall decay chain
$\tau_{½}$ is the half-life of the parent isotope
E_{max} is the maximum antineutrino energy in the decay chain
ε_H is the heating rate, per kg of the parent isotope
$\epsilon_{\bar{\nu}_e}$ is the electron antineutrino source rate, per kg of the parent isotope

Table 18.2 U, Th, and K global inventories, radiogenic heating, and neutrino luminosities according to the Bulk Silicate Earth (BSE) model

	m (10^{17} kg)	H_R (10^{12} W)	L_ν (10^{24} s^{-1})
U	0.8	7.6	5.9
Th	3.1	8.5	5.0
^{40}K	0.8	3.3	21.6

from oceanic spreading zones (0.1 ppm U), compared with U concentrations in magma and crust in subduction zones, (2 ppm U).

Preliminary results from the newer antineutrino detector Borexino at Gran Sasso in the Apennines [14] generally confirm the KamLAND results but indicate a geoneutrino flux 60% higher. Because of very low radioactive contamination in the materials of construction for Borexino, a signal-to-noise ratio of 50:1 was achieved. This greater sensitivity allowed the Borexino researchers to place an upper bound on the power of any critical fissioning zones in the core at 3 TW, significantly below the indicated global radiogenic heat production of about 18 TW. Collection of geoneutrino data by Borexino is continuing.

Geoneutrino data collected to date indicates that the uranium content of the earth is several orders of magnitude greater than conventional resource estimates. Limited geoneutrino data and an understanding of geochemical processes suggest that most of that uranium content is in the upper continental crust. This data provides some confidence that, with further local exploration or advanced extraction technologies, sufficient uranium could be found for several centuries of expanded nuclear power (Tables 18.1 and 18.2).

The overall results of the KamLAND geoneutrino study [10, 12] show that the sum of the U and Th inventory is 3E17 kg and since the global Th/U mass ratio is 3.9, the global U inventory is 6E16 kg or 10 ppb of the mass of the earth, in agreement with the supernova production ratio with silicon. Further note that the geoneutrino signal indicates that the majority of the uranium is in the upper continental crust and that relatively little of the inventory is in the oceanic crust. The partitioning of the uranium into the UCC via geochemical process is discussed in the next section.

Mechanisms for the Concentration of Uranium

Unlike other energy resources such as coal or petroleum, the resources of uranium are not fundamentally changed by geological processes. Whereas petroleum might be lost through evaporation or combustion or a natural gas reservoir may vent into the atmosphere, uranium is lost only through radioactive decay or through the relatively rare formation of a natural reactor. Therefore the primordial inventory of uranium, reduced by radioactive decay, remains present somewhere in the earth. The crucial question is “where?”

The natural distribution of elements in the earth’s crust is controlled by two major factors. The first is the set of ambient geological fractionating processes that leads to regions of depletion and concentration of the element. The second factor includes the overall geochemical characteristics of the element. Elements that are concentrated by a small number of fractionation processes can be expected to have a multimodal distribution, with a peak in the tonnage versus grade curve for each of the modes of geochemical concentration. For elements having a large number of applicable concentration processes, the peaks overlap and the resulting tonnage versus grade curve takes on a log-normal characteristic. For example, the element chromium, whose distribution at high concentrations is solely governed by fractional crystallization in mafic magmas (i.e., high in magnesium and iron), one would expect a bimodal distribution of concentrations, with one peak at the average crustal abundance and the high concentration peak at the mafic fractionation concentration. On the other hand, most elements, uranium included, can undergo a wide variety of fractionating processes, and deposits would be expected over a wide range of concentrations. In this latter case, the tonnage versus grade distribution would be expected to be log-normal. Bear in mind that geological conditions change over time and therefore the distribution patterns have varied with time.

In considering uranium in particular, it is important to examine the tectonic and igneous processes that have redistributed the uranium within the crust. In the past four billion years, the most important processes are continental accretion and plate tectonics. In the accretion process, crust formed into masses of continental dimensions. In the second, continuing, process, the continental crust and the oceanic crust have taken on quite different characteristics in terms of uranium concentration.

Igneous Processes

Igneous processes begin with the melting of mantle rocks at depths of 60–200 km, followed by the migration of less dense liquids to the surface. The migration of these less dense minerals to the surface is a predominant process in the formation of the continental crust. The extruded liquid forms crust in two general locations, at mid-oceanic ridges, where the upwelling material forms new oceanic crust and in subduction zones, where the oceanic crust plunges back into the mantle, usually passing under the edge of a continent.

The behavior of uranium in igneous processes is dominated by two characteristics of the element. In the +4 oxidation state, the condition expected in the earth's mantle, the U^{+4} ion has an ionic radius of 97×10^{-12} m (picometers, pm) about the same as Na^{+1} ion (97 pm). Other ions common in the core and mantle are significantly smaller in radius: Fe^{+2}, 74 pm; Ni^{+2}, 69 pm, Mg^{+2}, 66 pm; and Al^{+3}, 51 pm. Thus, like sodium and the other large ions, uranium ions selectively enter partial melts within the mantle and are transported to the surface.

The second characteristic of uranium is its radioactivity, serving as a source of heat for melting the mantle and core. Like Th^{+4} (ionic radius 102 pm) and K^{+1}(133 pm), these heat-producing elements are readily fractionated out of the mantle and toward the surface. Deffeyes notes that the earth would be a radically different place if the heat-producing elements had small radii, since the geothermal energy source would then be located deep within the core and the convection currents driving plate tectonics would be much stronger [15].

The rocks forming the oceanic crust at mid-oceanic ridges are characterized by a uniform uranium concentration of about 0.1 wppm. Conversely, the crust formed above subduction zones is characterized by uranium concentrations of about 2 wppm. The wide difference in concentration is due to the differences in the source materials and to the different chemistry. The upwelling mantle at the oceanic ridge has a uranium concentration of about 0.005 wppm, while the subduction zones have as their source material oceanic crust and bits of continental crust, with an average uranium concentration of about 0.1 wppm. The continuous upwelling at the oceanic ridges serves as a mechanism for depleting the core and mantle of uranium and incorporating that uranium in the oceanic crust. The relatively low concentration of uranium in the oceanic crust is augmented with uranium from continental runoff, which subsequently precipitates in the ocean basins. At the subduction zones, the oceanic crust is again subjected to partial melting and the uranium is again fractionated in the melt and transported to the surface.

Average Vertical Distribution of Uranium and Thorium

As a result of the various igneous processes, the average concentration of uranium is highest at the surface of the continental crust and decreases approximately exponentially with depth.

Table 18.3 Sources of heat in the upper continental crust

Isotope	Thermal output
U-238	0.095 mW/kg
Th-232	0.027 mW/kg
K-40	3.6 nW/kg

Table 18.4 Temperature distribution depth parameter

Location	h_r (m)
Sierra Nevada	10,000
Eastern USA	7,500
Norway and Sweden	7,200 ± 700
Eastern Canadian Shield	7,100 ± 1,700
Canadian Appalachians	10,000 ± 2,000
US Appalachians	8,100 ± 1,300

In the other references the depth parameter is denoted as D, rather than h_r

The anticipated variation of uranium concentration with depth is given by the equation $U(z) = U(z = 0)\, e^{(-z/h_r)}$, where z is the depth in m, h_r is the depth parameter (discussed below), and $U(z)$ is the concentration at depth z, in wppm. $U(z = 0)$ is the average continental crustal abundance of uranium at the surface, 2.76 wppm.

This approximation is based on the presence of heat-producing elements, U-238, Th-232, and K-40, in the continental crust, measurements of the thermal conductivity of the crustal materials, and the linear temperature distribution with depth measured at many locations. The heat produced in the crust is divided about evenly between U-238 and Th-232, since the crustal abundance mass ratio between Th and U is 3.9. K-40 is about four orders of magnitudes lower, although potassium has a crustal abundance of 2.1%, since K-40 is only 117 ppm of natural potassium and the thermal energy output of K-40 is about four orders of magnitude below U-238 and Th-232, as shown by Lachenbruch, below [16] [17] (Table 18.3).

Obviously, this method assumes one-dimensional heat transport and a fairly uniform thermal conductivity, without a significant contribution from flowing fluids. A more recent review by Brady et al. [18] provides more details on the technique.

Several measured values of the depth parameter are listed in Table 18.4. [19].

If a depth parameter of 8,500 m is assumed, based on the above data, then 11% of the crustal uranium inventory would be expected to be within 1,000 m of the surface and 21% within 2,000 m.

Geochemical Beneficiation Processes

Uranium occurs in ores such as uraninite [UO_2, pitchblende], carnotite [$K_2(UO_2)_2V_2O_8{\cdot}3(H_2O)$], autunite [$Ca(UO_2)_2(PO_4){\cdot}11(H_2O)$], uranophane [$Ca(UO_2)_2$

$(HSiO_4)_2 \cdot 5H_2O$), davidite [Ce0.75La0.25Y 0.75U0.25$Ti_{15}Fe_3$ + 5O38 and $La_{0.7}Ce_{0.2}Ca_{0.1}Y_{0.75}$ $U_{0.25}Ti_{15}Fe_3$ + 5O38], torbernite [$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$], and other minerals containing U_3O_8 (actually a stable complex oxide of $U_2O_5 \cdot UO_3$).

The governing characteristic in the geochemical transport of uranium is the fact that uranium is highly soluble in oxidizing environments and essentially insoluble in reducing environments. The change in the earth's atmosphere from a reducing to an oxidizing condition about 1.8 billion years ago is thus responsible for a fundamental change in the dominant processes in uranium transport. In the earlier age, igneous processes and fractionation of uranium in partial melts due to its large ionic size were dominant. In the last 1.8 billion years the transport of uranium by means of groundwater oxygenated at the surface has been dominant.

Thus, in the period more than 1.8 billion years ago, uranium was primarily concentrated in placer deposits as a chemically inert and physically dense phase. Because of the low solubility of uranium in reducing environments, rivers, lakes, groundwater, and thus the sea contained very low uranium concentrations. The placer deposits at Elliott Lake, Canada and at Witwatersrand, South Africa are typical of the deposits formed during this period.

With the dominance of photosynthesis in the last 1.8 billion years, the atmospheric and groundwater conditions have been oxidizing and uranium minerals have been highly soluble in the sedimentary weathering cycle. Placer deposits no longer formed and, in fact, began to dissolve. The uranium content of rivers, lakes, and groundwater increased and gradually, the uranium concentration in the oceans also increased. Nevertheless, the uranium concentration remained well below saturation.

In a few isolated locations, however, oxidation of organic-rich beds by groundwater led to locally reducing conditions. In these locations, the uranium ions or their complexes would reach supersaturation and re-precipitate. An important example of this re-precipitation is in the Mesozoic sandstones of the Colorado Plateau. The uranium ores are found in organic-rich zones where the oxygen in groundwater was removed by carbon-rich debris. Precipitation of uranium has also occurred where restricted circulation in the oceans and organic-rich sediments led to anoxic conditions. Good examples are the black Chatanooga Shale and the phosphorite shale of the Phosphoria Formation [9].

Specific Deposit Types

Before the discovery of the McArthur River deposit, the highest grade uranium ores were obtained from igneous sedimentary deposits such as Great Bear Lake in Canada, Joachimsthal in the Czech Republic, and Katanga in the Congo. The deposits at Oklo in the Gabon Republic in Africa were of high enough concentration and the uranium, 1.7 billion years ago, contained 3% ^{235}U rather than the present 0.711% such that several critical natural reactors occurred in the deposit.

The reactor zones released about 15,000 MW-years of fission energy over the course of about 250,000 years. These deposits were formed by the movement of hot water through fractures in blocks of rock heated by their own uranium and thorium content.

Precambrian sandstones overlie much older Precambrian granites and metamorphic rocks. At the interface, there is a discontinuity in the age of the rocks. This type of discontinuity is termed an unconformity. Unconformity deposits, such as those in Saskatchewan and northern Australia occur where uranium from the sandstone, has formed into veins in the open spaces of the interface, and has been heated to temperatures of several hundred degrees Celsius.

Roll-Front Deposits

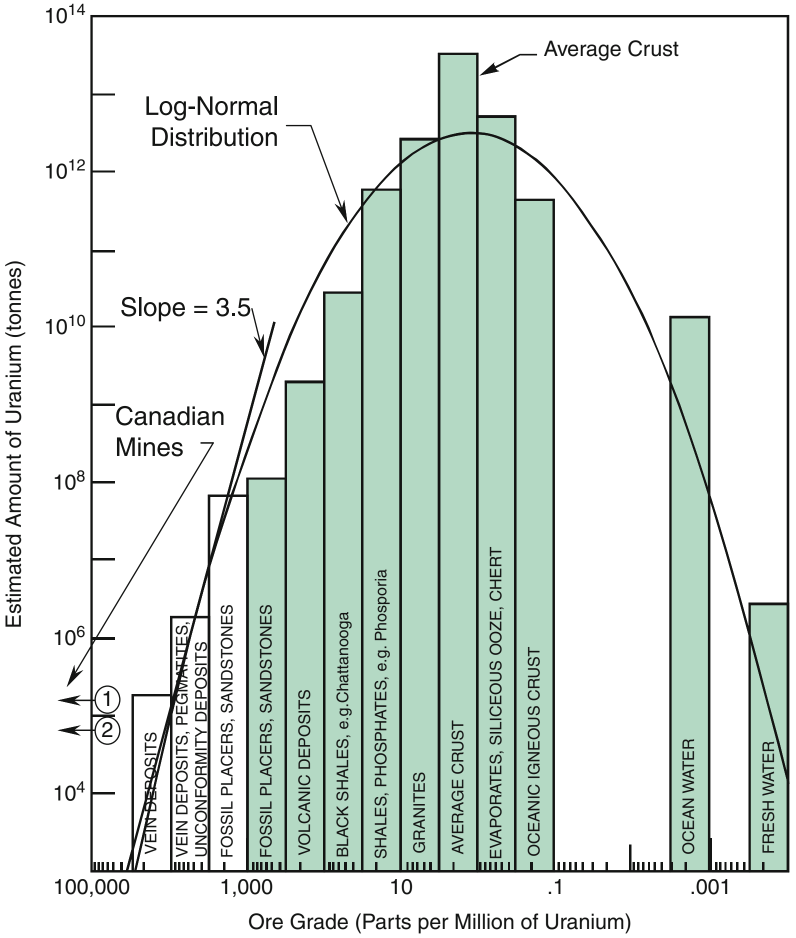
As mentioned earlier, uranium oxide precipitates when the solution enters a reducing environment. The uranium oxide can be redissolved in situ by oxygenated leach solutions. In sandstone deposits, the uranium minerals have been deposited in the interstices between the sand grains. The deposits are often moving very slowly through the sandstone because of the flow of groundwater, much like the movement of a front through a liquid chromatography column. Oxygenated water from the surface enters the sandstone where reducing agents, such as sulfides or organic matter, are located in the interstitial spaces. The organic carbon in one pore volume of sandstone can remove all the oxygen dissolved in 50,000 pore volumes of oxygenated groundwater.

Therefore, the front between the oxygenated groundwater and oxygen-free groundwater moves slowly through the sandstone. Uranium dissolved at the surface and uranium dissolved from the sandstone by the oxygenated groundwater is swept along and precipitated at the front. Upstream of the front the uranium is present in the groundwater as the soluble hexavalent uranyl carbonate complex. As the oxygen is removed from the groundwater at the front, the soluble hexavalent uranium is reduced to the insoluble quadrivalent state.

The quadrivalent uranium precipitates in the form of the mineral uraninite (UO_2). Thus the location of ore bodies is often associated with deposits of carbonaceous materials where the carbon, in much larger quantities compared with the uranium, has removed the oxygen from the groundwater.

Based on the various modes for the formation of uranium ore bodies, reviewing the large body of prior research, Deffeyes and MacGregor estimated the uranium content of the various crustal regimes in a report for the USDOE in 1978 [9].

The distribution of mass versus grade for the various types of uranium deposits is shown in Fig. 18.2 with additional data [9, 15]. The three gray bars on the left (grade $>$1,000 ppm U) indicate deposits of the type now mined for uranium alone. The expected log-normal distribution is shown and the mass and grade of two Canadian mines discovered since 1978 are also indicated: (1) the McArthur River deposit, 137,000 t U of proven reserves averaging 18 wt% U and (2) the Cigar Lake deposit,



(after Deffeyes 1978, 1980)

Fig. 18.2 Distribution of uranium in the Earth's crust

90,000 t U at an average grade of 17 wt% U. Other known larger, but lower grade deposits, such as Olympic Dam in Australia, have not been shown.

Present mining activities are recovering uranium at market prices of $150/kg from ores containing 0.027–20% U_3O_8. Given the log-normal distribution and the known quantities of the various uranium mineralizations, a tenfold increase in the price of uranium (and thus a tenfold decrease in economically viable ore grade) would result in a 300-fold increase in the amount of uranium available. Equivalently, the World Nuclear Association (formerly the Uranium Institute) estimates that a doubling of uranium prices would result in a tenfold increase in supply [5] (WNA 2010).

'The slope of the log-normal curve at presently mined grades is also shown in Fig. 18.2. This slope, about +3.5, indicates that for a doubling of the cost of mining (i.e., mining ore at half the present concentration), the economically available resources of uranium would increase by more than an order of magnitude $(2^{3.5} \approx 11)$. This estimate presumes a continuation of present mining techniques and does not consider the increased using of in situ leaching and recovery of uranium as a by-product in gold, copper, and phosphate mining.

Unconventional Resources

Existing Enrichment Tails

Another potential source of uranium is the re-enrichment of depleted uranium by using today's overcapacity of enrichment. Because of low price of natural uranium in recent years, many enrichment plants have been operating with tails assays of up to 0.3% ^{235}U. The 1.18 million tons of depleted uranium currently stored at enrichment plants could therefore supplant a few hundred thousand tons of natural uranium if demand required. The inventory of depleted uranium is expected to increase by about 51,400 t U/year though at least 2010. The enrichment capacity in 2010 was reported to be 57 MWSU/year compared with an annual demand of 49 MWSU/year. The present spare capacity in enrichment plants in the world, around 8 MSWU/year, theoretically represents an equivalent of around 3,000 tons/year of natural uranium if this spare capacity was utilized for enrichment of depleted uranium with an assay of 0.3% and a new tails assay of 0.1%.

The economics of re-enrichment depend on the ^{235}U assay of the depleted uranium and the relationship between the price of uranium and the cost of enrichment services. A tails assay of above 0.3% is preferable if re-enrichment of depleted uranium is to be considered a possibility. Re-enrichment of depleted uranium for the production of low-enriched uranium (LEU) in the Russian Federation has taken place for several years in times of excess enrichment capacity. However, decreasing amounts of excess enrichment capacity makes re-enrichment a marginal source of light water reactor fuel. On the other hand, the eventual use of enrichment tails as breeding blankets for fast reactors, as will be discussed shortly, represents a large long-term source of fuel.

Gold and Phosphate Tailings

In addition to the discovery of new resources through increased exploration, improvements in mining technology are also lowering the cost of previously high-cost deposits. In particular, in situ leaching (ISL) is of growing significance and could be applied to existing gold and phosphates tailings piles. The resource base of 16.2 million tons U does not include uranium in gold and phosphate tailings. The phosphate deposits are estimated at 22 million t U.

Uranium from Seawater

The recovery of uranium from seawater places an upper limit on the cost of uranium. Uranium is dissolved in seawater at 3 mg/m^3 (3 wppb) and represents a well-known resource of 4.2 billion tons, 250 times the known land-based resource. The uranium content of the oceans is relatively constant and large-scale extraction can be done without local depletion of the resource. Since only about 3% of global population lives in landlocked countries, extraction of uranium from seawater is truly the bounding cost for uranium.

New Technologies for Uranium Extraction

The current prices for uranium provide little motivation for the development of new extraction technologies. However, regulations to minimize the impact of mining on the environment and radiation exposure to workers have led to the use of technologies where uranium is extracted in situ or where ores previously mined for another element are processed for uranium extraction. In addition, the technologies described above for the extraction of uranium from seawater could have a major impact in minimizing environmental impact and radiation exposure.

In Situ Leaching

During conventional mining, the rock of the ore body is removed from the ground, transported to a mill, and treated to remove the minerals of economic value. The opening of the mine, the transport of the ore, the milling and the disposal of remaining treated rock can create severe environmental impacts. In situ leaching (ISL), sometimes known as solution mining, involves the use of liquids to dissolve the desired elements from the ore body without removing it from the ground. The liquid is pumped through the ore body and returned to the surface, where the desired elements are removed from the solution by precipitation, by electrochemistry, or other means. The leaching liquid is then returned to the ore body and the process is repeated. ISL eliminates the need to remove large quantities of ore from ground and to transport it to the mill, thus minimizing surface disturbance. ISL also eliminates the need to dispose of the tailings or waste rock. However, for ISL to be effective, the ore body must be permeable to the flow of the leaching liquid. Furthermore, the ISL site must be located so as not to contaminate ground water away from the ore body.

Today, because of its reduced surface impact and lower cost, ISL is used for 85% of US uranium production. Most of the operations in Wyoming, Nebraska, and Texas are less than 10 years old. Worldwide, about 16% of world uranium production uses ISL, including all the production in Uzbekistan and Kazakhstan.

ISL can be used to extract uranium from deposits below the water table in permeable sand or sandstone, provided that the deposit is confined above and below by impermeable strata. Suitable candidates are often roll-front deposits as described earlier. The uranium mineral are usually uranium oxide or uranium silicate coatings on the individual sand grains. The ISL process replicates, in a few months, the conditions that led to the formation of the roll-front deposit in the sandstone initially.

There are two types of ISL, depending on the chemistry of the deposit and groundwater. When the ore body is limestone or gypsum, i.e., containing significant amounts of calcium, then an alkaline leaching agent such as sodium bicarbonate and CO_2 must be used. Otherwise an acid leaching agent, such as weak sulfuric acid plus oxygen at a pH of 2.5–2.8 (about the same as vinegar) is preferred. ISL in Australia is primarily acid, while ISL in the USA is primarily alkaline.

Generally the uranium is extracted by progressively drilling wells into the deposit on a rectangular grid with $\sim$30-m spacing. The leaching fluid is pumped into four wells surrounding a central extraction well, into which a submersible pump has been lowered. The wells are cased to assure that the fluids do not enter strata above the deposit. In the USA the production life of an individual alkaline ISL well is typically 6–10 months. The most successful operations have extracted 80% of the uranium from the ore. Production life is often limited when the sandstone is plugged by mobilized clay and silt. Sometimes the blockages can be dislodged by reversing the flow through the field or by increasing the injection pressure.

The uranium is recovered from the extracted solution in an ion exchange or solvent extraction process. Solvent extraction is preferred if the groundwater is saline, while ion exchanges is most effective if the chloride content is below 3,000 ppm. With alkaline leaching, ion exchange is effective until the total dissolved solids reach 3,000 ppm. The uranium is then stripped from the resin or solution for further processing [20].

Before the process solution is reinjected, it is reoxygenated or recharged with sulfuric acid, for alkaline or acidic processes respectively. About 1% of the process solution is bled off to maintain a pressure gradient toward the wellfield. The pressure gradient ensures that groundwater from any surrounding aquifer flows into the wellfield and that ISL mining solutions does not enter the aquifer.

Recovery of Uranium from Seawater

The recovery of uranium from seawater is highly speculative and may never prove to be economic. One cubic meter of seawater contains 3 mg of natural uranium, which can deliver 244 MJ_{th} in a breeder or about 2.5 MJ_{th} in a present day LWR. Simple calculations show that the pumping energy needed in an extraction plant could easily consume all the energy available, particularly in the LWR case. Thus seawater extraction conceptual designs relying on ion exchange or adsorption have utilized ocean currents or wave action to move the seawater past the uranium-collecting surfaces.

However, the magnitude of the seawater resource places an upper limit on the cost of uranium for several reasons. First, seawater is available to nearly all countries of the world at virtually the same uranium concentration and without local depletion due to the extraction of uranium. Secondly, because no group of countries can form a cartel over the uranium supply if seawater extraction is practiced, the price of uranium is unlikely to be driven artificially high through market manipulation. Furthermore, the only present limitation on the extraction of uranium from seawater is knowledge of the technology and resins. Thus one would expect that, if conventional sources of uranium become limiting, a healthy competition in research and development would drive down the cost of extraction.

Uranium recovery from seawater has been studied in Japan for a very long term or to face a very strong development of fission energy. In a laboratory scale experiment performed by the Japan Atomic Energy Agency (JAEA) where uranium is trapped by an amidoxime adsorbent which has been prepared on nonwoven polyethylene material with the aid of radiation-induced cografting. This experiment, 7 km offshore from Sekine-Hama in Aomori Prefecture, Japan, produced more than 1 kg of U on 350 kg of nonwoven fabric during a total submersion time of 240 days [21]. However, at this stage of the study, it is difficult to predict the practical application of uranium recovery from seawater. An economic assessment has been reported indicating a possible cost for this uranium process in a 1,000-t U/year commercial plant of approximately \$600/kgU [22].

Impact of Uranium Scarcity and Higher Extraction Costs

Table 18.5 shows the approximate impact of increases in the price of natural uranium on the cost of electricity from a light water reactor. In this set of calculations, the cost of natural uranium is set at \$140/kg U (approx. average price of domestic U to US utilities, 2011), \$500/kg U, representing an optimistic cost of extraction from seawater and \$1,000/kg U, representing a more pessimistic (or perhaps more realistic) cost for extraction from seawater. Two burnups are shown for each uranium price, 45 MW-day (thermal) per kg of initial uranium (MW-day/kg) and 60 MW-day/kg. The specific power of the fuel remains constant at 37.9 kWth/kg of initial uranium, as does the interest charged on the fuel during the fuel cycle. In the cases with higher cost uranium, the tails assay ("Tails U-235 content") to optimize the balance between raw materials and enrichment costs. As shown in the last two lines of the table, an increase in the cost of natural uranium from \$140/kg U to \$1,000/kg U results in an increase in the cost of electricity of

Table 18.5 Impact of uranium costs on the cost of electricity

Impact of uranium costs on the cost of electricity

			Uranium from unconventional sources				
	Current uranium prices		Optimistic: \$500/kg		Pessimistic: \$1,000/kg		
	UO_2 fuel 45 MWd/kg	UO_2 fuel 60 MWd/kg	UO_2 fuel 45 MWd/kg	UO_2 fuel 60 MWd/kg	UO_2 fuel 45 MWd/kg	UO_2 fuel 60 MWd/kg	Units
Specific power	37.9	37.9	37.9	37.9	37.9	37.9	kWth/kg
Cycle parameters							
Total cycle length	3.6	4.8	3.6	4.8	3.6	4.8	years
Capacity factor	90%	90%	90%	90%	90%	90%	
Effective full power days	1183	1578	1183	1578	1183	1578	efpd
Burnup	45	60	45	60	45	60	MWd/kg ihm
Feed U-235 content	0.711%	0.711%	0.711%	0.711%	0.711%	0.711%	wt%
Product U-235 enrichment	4.00%	5.34%	4.00%	5.34%	4.00%	5.34%	wt%
Tails U-235 content	0.25%	0.25%	0.20%	0.20%	0.10%	0.10%	wt%
Separative work	5.874	8.692	6.546	9.636	8.953	13.020	kg-SWU/kg fuel
Natural uranium	8.089	10.964	7.439	10.050	6.385	8.569	kg/kg fuel
	0.180	0.183	0.166	0.168	0.142	0.143	kg/MWd
Rates							
Interest rate	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	/year
Natural uranium	\$140	\$140	\$500	\$500	\$1,000	\$1,000	/kg U
Conversion U3O8 to UF6	\$54	\$54	\$193	\$193	\$385	\$385	/lb U3O8
	\$11	\$11	\$11	\$11	\$11	\$11	/kg natural U
Separative work	\$150	\$150	\$150	\$150	\$150	\$150	/kg-SWU
Costs							
Natural uranium	\$1,132	\$1,535	\$3,719	\$5,025	\$6,385	\$8,569	/kg fuel

(continued)

Table 18.5 (continued)

Impact of uranium costs on the cost of electricity

			Uranium from unconventional sources				
	Current uranium prices		Optimistic: $500/kg		Pessimistic: $1,000/kg		
	UO_2 fuel 45 MWd/kg	UO_2 fuel 60 MWd/kg	UO_2 fuel 45 MWd/kg	UO_2 fuel 60 MWd/kg	UO_2 fuel 45 MWd/kg	UO_2 fuel 60 MWd/kg	Units
Separative work	$881	$1,304	$982	$1,445	$1,343	$1,953	/kg fuel
Conversion	$89	$121	$82	$111	$70	$94	/kg fuel
Fabrication	$500	$500	$500	$500	$500	$500	/kg fuel
Total cost	$2,602	$3,459	$5,283	$7,081	$8,298	$11,116	/kg fuel
Interest during use	$234	$415	$475	$850	$747	$1,334	/kg fuel
Total fuel cost	$2,837	$3,874	$5,758	$7,931	$9,045	$12,450	/kg fuel
	$63.19	$64.73	$128.27	$132.50	$201.48	$208.00	/MWth-day
	$0.772	$0.790	$1.566	$1.618	$2.460	$2.540	/million BTU
	$7.81	$8.00	$15.86	$16.38	$24.91	$25.72	/MWe-h
COE increase due to high uranium prices			$8.05	$8.38	$16.91	$17.71	/MWe-h
			0.8	0.84	1.69	1.77	cents/kWe-h

about \$0.018/kW-h. For comparison, an increase in the prices of natural gas of \$2.80 per million BTU, as has occurred five times since 2005, also results in an increase in the cost of electricity of \$0.018/kW-h.

Uranium Compared with Future Energy Needs

A simple calculation is needed to place the magnitude of current uranium mining in perspective. If it is assumed that the world population reaches a steady-state level of 10 billion and each of those people consumes energy at the average rate of a US resident in 2011, then the total annual world consumption of energy would be about 3.7×10^{21} J_{th}. While that high rate of consumption would probably not be sustainable for a variety of other reasons, the required natural uranium input to a system of fast reactors to produce 3.7×10^{21} J_{th} would be about 45,000 t U. Average worldwide uranium usage, from both mining and the downblending of HEU, is now about 59,000 t U/year [4].

The Need for Fast Reactors

The early development of fast breeder reactors and of thermal breeder reactors using thorium was driven in part by the apparent global scarcity of fissile isotopes to fuel a rapidly growing set of nuclear reactors. Slow growth in nuclear power and large discoveries of natural uranium in a few regions of the world have reduced the global urgency for breeding more fissile material. In those regions of the world lacking known uranium resources, particularly Europe and Japan, there has been continuing interest in the development of sodium-cooled fast breeder reactors. Such reactors reduce the need for natural uranium by a factor of ~50, compared with light water reactors and thus the cost and availability of natural uranium is a much smaller consideration.

However, beyond the breeding of fissile isotopes, the use of a fast neutron spectrum offers unique capabilities for the consumption of the long-lived actinides, particularly plutonium, neptunium, americium, and curium.

In the long term, the capability of a fast reactor to make use of both ^{238}U and ^{235}U will be critical in meeting future energy needs. However, in the next century, fast reactors will be crucial for the management of actinides and the reduction of the long-term radiotoxicity of the nuclear fuel cycle by at least two orders of magnitude.

Table 18.6 Comparison with fossil reserves

Coal		909	Billion tons
	=	2.01E + 22	Jth
	=	19,089	Quadrillion BTU (quad)
Petroleum		1340	Billion barrels
	=	8.20E + 21	Jth
	=	7,772	Quad
Natural gas		6261	Trillion cubic feet
	=	6.84E + 21	Jth
		6,480	Quad
Total fossil reserves		3.52E + 22	Jth
	=	33,341	Quad
Uranium		5.404	Million t natural U
	+	1.2	Million t depleted U
	=	2.33E + 21	Jth in LWRs
	=	2211	Quad in LWRs
	=	5.36E + 23	Jth in fast reactors
	=	508,000	Quad in fast reactors

Comparison of Fossil Fuel and Uranium Reserves

It is interesting to compare the cited uranium known reserves and the inventory of depleted uranium with the estimated reserves of coal, oil, and natural gas. In Table 18.6, the reserves of fossil fuels and uranium are compared on the basis of known, economically recoverable reserves.

Fossil fuel reserves are those of the World Energy Council, the *Oil & Gas Journal*, and *World Oil* [23]. In the use of Table 18.6, the caveat cited above applies. Resources of both fossil fuels and of uranium are undoubtedly much larger than the reserves cited. Nevertheless, it is noteworthy that the uranium resources are energetically equivalent to about 20% of natural gas or oil resources, even with the use of LWRs only. The 1.2 million tons of depleted uranium currently in storage itself represents an energy source larger than the fossil reserves if used in a fast reactor.

Future Directions

Uranium is ubiquitous in the continental crust and concentrated in economically recoverable deposits by several relatively well-understood processes. Today uranium is being mined from the richest and most convenient of the deposits though little exploration has taken place in the last 20 years. Uranium and thorium are often being extracted as by-products of mining for other elements. It is likely that other similarly rich deposits exist in relatively unexplored regions of Asia and Africa.

Prices in the present uranium market are dominated by large discoveries in the last 20 years and by the conversion of military HEU to civilian purposes.

The continued use of nuclear energy and the end of downblending can be expected to raise uranium prices, encourage exploration, and return the uranium to a slightly higher-priced equilibrium.

However, because of the wide range of igneous and geochemical processes that are responsible for the formation of uranium deposits, it can be expected that uranium will be found in significant quantities with renewed exploration.

Emerging technologies for the extraction of uranium, particular in situ leaching, will make resources in sandstone and shale economically recoverable and minimize the surface disruption due to open pit mining and the occupational radiation exposures of underground mining.

In more distant future, the extraction of uranium from seawater will make this fuel available to virtually every nation. While extraction from seawater is likely to be five to ten times more expensive than uranium is today, the overall increase in the cost of electricity or other energy products would be minimal.

Therefore, the need for fast reactors in the near term, with a global view in mind, is not driven by a scarcity of uranium but rather by a need to effectively manage the long-lived actinides in spent fuel. A fast neutron spectrum is uniquely capable of fissioning the higher actinides and reducing the long-term radiotoxicity and volume of the nuclear fuel cycle. Likewise, although thorium is more abundant than uranium, the primary use of thorium will probably not be for the breeding of ^{233}U, but rather as a host material for the transmutation of the higher actinides in fast neutron spectrum reactors.

There are many challenges in the development of safe, proliferation-resistant, and economical reactors and fuel cycles. Fortunately, the uranium and thorium resources do not appear to be a near-term limitation.

Bibliography

1. Bates RL, Jackson JA, American Geological Institute (eds) (1984) Dictionary of geological terms, 3rd edn. Anchor Books, New York
2. Benedict M, Pigford TH, Levi HW (1981) Nuclear chemical engineering. McGraw-Hill, New York
3. NRC Glossary (2011) Yellowcake. http://www.nrc.gov/reading-rm/basic-ref/glossary/yellowcake.html. Updated 27 May 2011
4. OECD Nuclear Energy Agency, International Atomic Energy Agency (2010) Uranium 2009: resources, production and demand: a joint report. OECD, Paris
5. World Nuclear Association (2010) Supply of uranium, Dec 2010. www.world-nuclear.org/info/inf75.html
6. Burbidge EM, Burbidge GR, Fowler WA, Hoyle F (1957) Synthesis of the elements in stars. Rev Mod Phys 29(4):547
7. Burrows A (2000) Supernova explosions in the Universe. Nature 403:727–733, 17 Feb 2000
8. Wanajo S et al (2003) The r-process in supernova explosions from the collapse of O-Ne-Mg cores. Astrophys J 593:968–979, 20 Aug 2003
9. Deffeyes KS, MacGregor ID (1978) Uranium distribution in mined deposits and in the Earth's crust: final report. GJBX–1(79). Dept of Geological and Geophysical Sciences, Princeton University, Princeton. Prepared for the USDOE, Grand Junction Office, Aug 1978

10. Araki T et al (2005) Experimental investigation of geologically produced antineutrinos with KamLAND. Nature 436:499–503, 28 Jul 2005
11. Fiorentini G, Lissia M, Mantovani F, Vannucci R (2004) Geo-Neutrinos: a short review. arXiv: hep-ph/0409152v1, 14 Sep 2004
12. Enomoto S, Ohtani E, Inoue K, Suzuki A (2005) Neutrino geophysics with KamLAND and future prospects. arxiv.org/ftp/hep-ph/papers/0508/0508049.pdf
13. Herring JS (2004) Uranium and thorium resources. In: Cleveland CJ (ed) The encyclopedia of energy. Academic, Amsterdam/Boston
14. Borexino Collaboration (2010) Observation of geo-neutrinos. Phys Lett B 687:299–304
15. Deffeyes KS, MacGregor ID (1980) World uranium resources. Sci Am 242(1):66–76
16. Lachenbruch AH (1968) Preliminary geothermal model of the Sierra Nevada. J Geophys Res 73(22):6977–6989, 15 Nov 1968
17. Lachenbruch AH (1970) Crustal temperature and heat production: implications of the linear heat-flow relation. J Geophys Res 75(17):3291–3300, 10 June 1970
18. Brady RJ, Ducea MN, Kidder SB, Saleeby JB (2006) The distribution of radiogenic heat production as a function of depth in the Sierra Nevada Batholith, California. Lithos 86:229–244
19. Schubert G, Turcotte DL, Olson P (2001) Mantle convection in the Earth and planets. Cambridge University Press, Cambridge/New York, p 146
20. World Nuclear Association (2010) In situ leach (ISL) mining of uranium. http://www.world-nuclear.org/info/inf27.html. Updated Mar 2010
21. Seko N et al (2003) Aquaculture of uranium in seawater by fabric-adsorbent submerged system. Nucl Technol 144:274–278
22. Joint Nuclear Energy Action Plan, Fuel Cycle Technology Working Group (2010) Uranium extraction from seawater, 1st information exchange meeting. Lawrence Berkeley National Laboratory, Berkeley, Meeting record, 24–25 June 2010
23. EIA (2010) Annual energy review 2009, DOE/EIA-0384(2009). Energy Information Administration, US Department of Energy, Washington, DC, Aug 2010