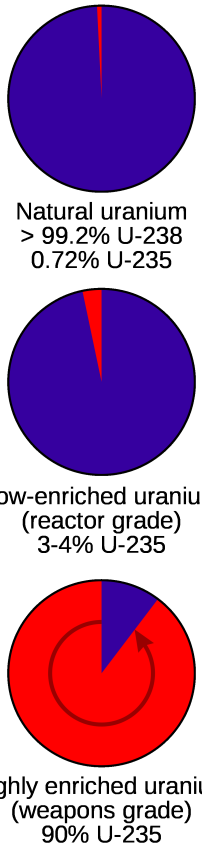
Enriched uranium

Enriched uranium is a type of uranium in which the percent composition of uranium-235 has been increased through the process of isotope separation. Natural uranium is 99.284% U^{238} isotope, with U^{235} only constituting about 0.711% of its weight. U^{235} is the only nuclide existing in nature (in any appreciable amount) that is fissile with thermal neutrons.

Enriched uranium is a critical component for both civil nuclear power generation and military nuclear weapons. The International Atomic Energy Agency attempts to monitor and control enriched uranium supplies and processes in its efforts to ensure nuclear power generation safety and curb nuclear weapons proliferation.

During the Manhattan Project enriched uranium was given the codename oralloy, a shortened version of Oak Ridge alloy, after the location of the plants where the uranium was enriched.[*citation needed*] The term oralloy is still occasionally used to refer to enriched uranium. There are about 2,000 tonnes (t, Mg) of highly enriched uranium in the world, produced mostly for nuclear weapons, naval propulsion, and smaller quantities for research reactors.

The U^{238} remaining after enrichment is known as depleted uranium (DU), and is considerably less radioactive than even natural uranium, though still very dense and extremely hazardous in granulated form – such granules are a natural by-product of the shearing action that makes it useful for armor-penetrating weapons and radiation shielding. At present, 95% of the world's stocks of depleted uranium remain in secure storage.



Proportions of uranium-238 (blue) and uranium-235 (red) found naturally versus enriched grades

Grades

Slightly enriched uranium (SEU)

Slightly enriched uranium (SEU) has a ^{235}U concentration of 0.9% to 2%. This new grade can be used to replace natural uranium (NU) fuel in some heavy water reactors like the CANDU. Fuel designed with SEU could provide additional benefits such as safety improvements or operational flexibility, normally the benefits were considered in safety area while retaining the same operational envelope. Safety improvements could lower positive reactivity feedback such as reactivity void coefficient. Operational improvements would consist in increasing the fuel burnup allowing fuel costs reduction because less uranium and fewer bundles are needed to fuel the reactor. This in turn reduces the quantity of used fuel and its subsequent management costs.[*citation needed*]

A drum of yellowcake (a mixture of uranium precipitates)

Reprocessed uranium (RepU)

Reprocessed uranium (RepU) is a product of nuclear fuel cycles involving nuclear reprocessing of spent fuel. RepU recovered from light water reactor (LWR) spent fuel typically contains slightly more U-235 than natural uranium, and therefore could be used to fuel reactors that customarily use natural uranium as fuel, such as CANDU reactors. It also contains the undesirable isotope uranium-236 which undergoes neutron capture, wasting neutrons (and requiring higher U-235 enrichment) and creating neptunium-237 which would be one of the more mobile and troublesome radionuclides in deep geological repository disposal of nuclear waste.

Low-enriched uranium (LEU)

Low-enriched uranium (LEU) has a lower than 20% concentration of ^{235}U. For use in commercial light water reactors (LWR), the most prevalent power reactors in the world, uranium is enriched to 3 to 5% ^{235}U. Fresh LEU used in research reactors is usually enriched 12% to 19.75% U-235, the latter concentration being used to replace HEU fuels when converting to LEU.

Highly enriched uranium (HEU)

Highly enriched uranium (HEU) has a greater than 20% concentration of ^{235}U or ^{233}U. The fissile uranium in nuclear weapons usually contains 85% or more of ^{235}U known as weapon(s)-grade, though for a crude, inefficient weapon 20% is sufficient (called weapon(s)-usable); in theory even lower enrichment is sufficient, but then the critical mass for unmoderated fast neutrons rapidly increases, approaching infinity at 6% ^{235}U. For criticality experiments, enrichment of uranium to over 97% has been accomplished.

A billet of highly enriched uranium metal

The very first uranium bomb, Little Boy dropped by the United States on Hiroshima in 1945, used 64 kilograms of 80% enriched uranium. Wrapping the weapon's fissile core in a neutron reflector (which is standard on all nuclear explosives) can dramatically reduce the critical mass. Because the core was surrounded by a good neutron reflector, at explosion it comprised almost 2.5 critical masses. Neutron reflectors, compressing the fissile core via implosion, fusion boosting, and "tamping", which slows the expansion of the fissioning core with inertia, allow nuclear weapon designs that use less than what would be one bare-sphere critical mass at normal density. The presence of too much of the ^{238}U isotope inhibits the runaway nuclear chain reaction that is responsible for the weapon's power. The critical mass for 85% highly enriched uranium is about 50 kilograms (110 lb), which at normal density would be a sphere about 17 centimetres (6.7 in) in diameter.

Later US nuclear weapons usually use plutonium-239 in the primary stage, but the secondary stage which is compressed by the primary nuclear explosion often uses HEU with enrichment between 40% and 80% along with the fusion fuel lithium deuteride. For the secondary of a large nuclear weapon, the higher critical mass of less-enriched uranium can be an advantage as it allows the core at explosion time to contain a larger amount of fuel. The ^{238}U is not fissile but still fissionable by fusion neutrons.

HEU is also used in fast neutron reactors, whose cores require about 20% or more of fissile material, as well as in naval reactors, where it often contains at least 50% ^{235}U, but typically does not exceed 90%. The Fermi-1 commercial fast reactor prototype used HEU with 26.5% ^{235}U. Significant quantities of HEU are used in the production of medical isotopes, for example molybdenum-99 for technetium-99m generators.

Enrichment methods

Isotope separation is difficult because two isotopes of the same elements have very nearly identical chemical properties, and can only be separated gradually using small mass differences. (^{235}U is only 1.26% lighter than ^{238}U.) This problem is compounded by the fact that uranium is rarely separated in its atomic form, but instead as a compound ($^{235}UF_6$ is only 0.852% lighter than $^{238}UF_6$.) A cascade of identical stages produces successively higher concentrations of ^{235}U. Each stage passes a slightly more concentrated product to the next stage and returns a slightly less concentrated residue to the previous stage.

There are currently two generic commercial methods employed internationally for enrichment: gaseous diffusion (referred to as *first* generation) and gas centrifuge (*second* generation) which consumes only 2% to 2.5%[1] as much energy as gaseous diffusion. Later generation methods will become established because they will be more efficient in terms of the energy input for the same degree of enrichment and the next method of enrichment to be commercialized will be referred to as *third* generation. Some work is being done that would use nuclear resonance; however there is no reliable evidence that any nuclear resonance processes have been scaled up to production.

Diffusion techniques

Gaseous diffusion

Gaseous diffusion is a technology used to produce enriched uranium by forcing gaseous uranium hexafluoride (*hex*) through semi-permeable membranes. This produces a slight separation between the molecules containing ^{235}U and ^{238}U. Throughout the Cold War, gaseous diffusion played a major role as a uranium enrichment technique, and as of 2008 accounted for about 33% of enriched uranium production, but is now an obsolete technology that is steadily being replaced by the later generations of technology as the diffusion plants reach their ends-of-life.

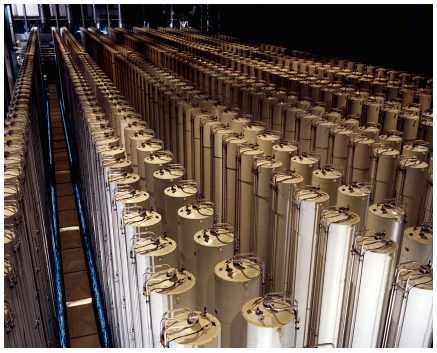
Thermal diffusion

Thermal diffusion utilizes the transfer of heat across a thin liquid or gas to accomplish isotope separation. The process exploits the fact that the lighter ^{235}U gas molecules will diffuse toward a hot surface, and the heavier ^{238}U gas molecules will diffuse toward a cold surface. The S-50 plant at Oak Ridge, Tennessee was used during World War II to prepare feed material for the EMIS process. It was abandoned in favor of gaseous diffusion.

Centrifuge techniques

Gas centrifuge

The gas centrifuge process uses a large number of rotating cylinders in series and parallel formations. Each cylinder's rotation creates a strong centrifugal force so that the heavier gas molecules containing ^{238}U move toward the outside of the cylinder and the lighter gas molecules rich in ^{235}U collect closer to the center. It requires much less energy to achieve the same separation than the older gaseous diffusion process, which it has largely replaced and so is the current method of choice and is termed *second generation*. It has a separation factor per stage of 1.3 relative to gaseous diffusion of 1.005, which translates to about one-fiftieth of the energy requirements. Gas centrifuge techniques produce about 54% of the world's enriched uranium.



A cascade of gas centrifuges at a U.S. enrichment plant

Zippe centrifuge

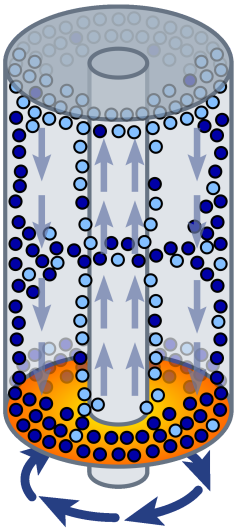


Diagram of the principles of a Zippe-type gas centrifuge with U-238 represented in dark blue and U-235 represented in light blue

The Zippe centrifuge is an improvement on the standard gas centrifuge, the primary difference being the use of heat. The bottom of the rotating cylinder is heated, producing convection currents that move the ^{235}U up the cylinder, where it can be collected by scoops. This improved centrifuge design is used commercially by Urenco to produce nuclear fuel and was used by Pakistan in their nuclear weapons program.

Laser techniques

Laser processes promise lower energy inputs, lower capital costs and lower tails assays, hence significant economic advantages. Several laser processes have been investigated or are under development. Separation of Isotopes by Laser Excitation (SILEX) is well advanced and licensed for commercial operation in 2012.

Atomic vapor laser isotope separation (AVLIS)

Atomic vapor laser isotope separation employs specially tuned lasers[2] to separate isotopes of uranium using selective ionization of hyperfine transitions. The technique uses lasers which are tuned to frequencies that ionize ^{235}U atoms and no others. The positively charged ^{235}U ions are then attracted to a negatively charged plate and collected.

Molecular laser isotope separation (MLIS)

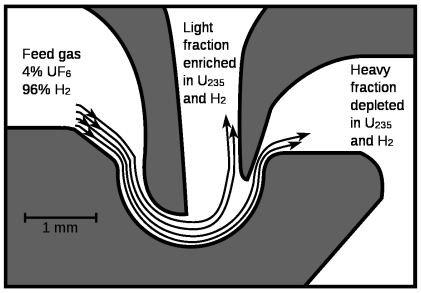
Molecular laser isotope separation uses an infrared laser directed at UF_6, exciting molecules that contain a ^{235}U atom. A second laser frees a fluorine atom, leaving uranium pentafluoride which then precipitates out of the gas.

Separation of Isotopes by Laser Excitation (SILEX)

Separation of isotopes by laser excitation is an Australian development that also uses UF_6. After a protracted development process involving U.S. enrichment company USEC acquiring and then relinquishing commercialization rights to the technology, GE Hitachi Nuclear Energy (GEH) signed a commercialization agreement with Silex Systems in 2006.Wikipedia:Link rot GEH has since built a demonstration test loop and announced plans to build an initial commercial facility. Details of the process are classified and restricted by intergovernmental agreements between United States, Australia, and the commercial entities. SILEX has been projected to be an order of magnitude more efficient than existing production techniques but again, the exact figure is classified. In August, 2011 Global Laser Enrichment, a subsidiary of GEH, applied to the U.S. Nuclear Regulatory Commission (NRC) for a permit to build a commercial plant. In September 2012, the NRC issued a license for GEH to build and operate a commercial SILEX enrichment plant, although the company had not yet decided whether the project would be profitable enough to begin construction, and despite concerns that the technology could contribute to nuclear proliferation.[3]

Other techniques

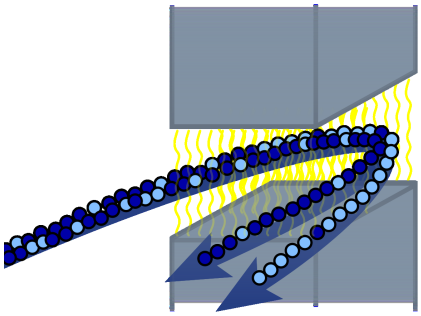
Aerodynamic processes



Schematic diagram of an aerodynamic nozzle. Many thousands of these small foils would be combined in an enrichment unit.

Aerodynamic enrichment processes include the Becker jet nozzle techniques developed by E. W. Becker and associates using the LIGA process and the vortex tube separation process. These aerodynamic separation processes depend upon diffusion driven by pressure gradients, as does the gas centrifuge. They in general have the disadvantage of requiring complex systems of cascading of individual separating elements to minimize energy consumption. In effect, aerodynamic processes can be considered as non-rotating centrifuges. Enhancement of the centrifugal forces is achieved by dilution of UF_6 with hydrogen or helium as a carrier gas achieving a much higher flow velocity for the gas than could be obtained using pure uranium hexafluoride. The Uranium Enrichment Corporation of South Africa (UCOR) developed and deployed the continuous Helikon vortex separation cascade for high production rate low enrichment and the substantially different semi-batch Pelsakon low production rate high enrichment cascade both using a particular vortex tube separator design, and both embodied in industrial plant. A demonstration plant was built in Brazil by NUCLEI, a consortium led by Industrias Nucleares do Brasil that used the separation nozzle process. However all methods have high energy consumption and substantial requirements for removal of waste heat; none is currently still in use.

Electromagnetic isotope separation



Schematic diagram of uranium isotope separation in a calutron shows how a strong magnetic field is used to redirect a stream of uranium ions to a target, resulting in a higher concentration of uranium-235 (represented here in dark blue) in the inner fringes of the stream.

In the electromagnetic isotope separation process (EMIS), metallic uranium is first vaporized, and then ionized to positively charged ions. The cations are then accelerated and subsequently deflected by magnetic fields onto their respective collection targets. A production-scale mass spectrometer named the Calutron was developed during World War II that provided some of the ^{235}U used for the Little Boy nuclear bomb, which was dropped over Hiroshima in 1945. Properly the term 'Calutron' applies to a multistage device arranged in a large oval around a powerful electromagnet. Electromagnetic isotope separation has been largely abandoned in favour of more effective methods.

Chemical methods

One chemical process has been demonstrated to pilot plant stage but not used. The French CHEMEX process exploited a very slight difference in the two isotopes' propensity to change valency in oxidation/reduction, utilising immiscible aqueous and organic phases. An ion-exchange process was developed by the Asahi Chemical Company in Japan which applies similar chemistry but effects separation on a proprietary resin ion-exchange column.

Plasma separation

Plasma separation process (PSP) describes a technique that makes use of superconducting magnets and plasma physics. In this process, the principle of ion cyclotron resonance is used to selectively energize the ^{235}U isotope in a plasma containing a mix of ions. The French developed their own version of PSP, which they called RCI. Funding for RCI was drastically reduced in 1986, and the program was suspended around 1990, although RCI is still used for stable isotope separation.

Separative work unit

"Separative work" – the amount of separation done by an enrichment process – is a function of the concentrations of the feedstock, the enriched output, and the depleted tailings; and is expressed in units which are so calculated as to be proportional to the total input (energy / machine operation time) and to the mass processed. Separative work is *not* energy. The same amount of separative work will require different amounts of energy depending on the efficiency of the separation technology. Separative work is measured in *Separative work units* SWU, kg SW, or kg UTA (from the German *Urantrennarbeit* – literally *uranium separation work*)

- 1 SWU = 1 kg SW = 1 kg UTA
- 1 kSWU = 1 tSW = 1 t UTA
- 1 MSWU = 1 ktSW = 1 kt UTA

The work W_{SWU} necessary to separate a mass F of feed of assay x_f into a mass P of product assay x_p, and tails of mass T and assay x_t is given by the expression

$$W_{\mathrm{SWU}} = P \cdot V(x_p) + T \cdot V(x_t) - F \cdot V(x_f)$$

where $V(x)$ is the value function, defined as

$$V(x) = (1 - 2x) \ln\left(\frac{1-x}{x}\right)$$

The feed to product ratio is given by the expression

$$\frac{F}{P} = \frac{x_p - x_t}{x_f - x_t}$$

whereas the tails to product ratio is given by the expression

$$\frac{T}{P} = \frac{x_p - x_f}{x_f - x_t}$$

For example, beginning with 102 kilograms (225 lb) of NU, it takes about 90 SWU to produce 10 kilograms (22 lb) of LEU in ^{235}U content to 4.5%, at a tails assay of 0.3%.

The number of separative work units provided by an enrichment facility is directly related to the amount of energy that the facility consumes. Modern gaseous diffusion plants typically require 2,400 to 2,500 kilowatt-hours (kW·h), or 8.6–9 gigajoules, (GJ) of electricity per SWU while gas centrifuge plants require just 50 to 60 kW·h (180–220 MJ) of electricity per SWU.

Example:

A large nuclear power station with a net electrical capacity of 1300 MW requires about 25 tonnes per year (25 t/a) of LEU with a ^{235}U concentration of 3.75%. This quantity is produced from about 210 t of NU using about 120 kSWU. An enrichment plant with a capacity of 1000 kSWU/a is, therefore, able to enrich the uranium needed to fuel about eight large nuclear power stations.

Cost issues

In addition to the separative work units provided by an enrichment facility, the other important parameter to be considered is the mass of natural uranium (NU) that is needed to yield a desired mass of enriched uranium. As with the number of SWUs, the amount of feed material required will also depend on the level of enrichment desired and

upon the amount of ^{235}U that ends up in the depleted uranium. However, unlike the number of SWUs required during enrichment which increases with decreasing levels of ^{235}U in the depleted stream, the amount of NU needed will decrease with decreasing levels of ^{235}U that end up in the DU.

For example, in the enrichment of LEU for use in a light water reactor it is typical for the enriched stream to contain 3.6% ^{235}U (as compared to 0.7% in NU) while the depleted stream contains 0.2% to 0.3% ^{235}U. In order to produce one kilogram of this LEU it would require approximately 8 kilograms of NU and 4.5 SWU if the DU stream was allowed to have 0.3% ^{235}U. On the other hand, if the depleted stream had only 0.2% ^{235}U, then it would require just 6.7 kilograms of NU, but nearly 5.7 SWU of enrichment. Because the amount of NU required and the number of SWUs required during enrichment change in opposite directions, if NU is cheap and enrichment services are more expensive, then the operators will typically choose to allow more ^{235}U to be left in the DU stream whereas if NU is more expensive and enrichment is less so, then they would choose the opposite.

- Uranium enrichment calculator designed by the WISE Uranium Project [4]

Downblending

The opposite of enriching is downblending; surplus HEU can be downblended to LEU to make it suitable for use in commercial nuclear fuel.

The HEU feedstock can contain unwanted uranium isotopes: ^{234}U is a minor isotope contained in natural uranium; during the enrichment process, its concentration increases but remains well below 1%. High concentrations of ^{236}U are a byproduct from irradiation in a reactor and may be contained in the HEU, depending on its manufacturing history. HEU reprocessed from nuclear weapons material production reactors (with an ^{235}U assay of approx. 50%) may contain ^{236}U concentrations as high as 25%, resulting in concentrations of approximately 1.5% in the blended LEU product. ^{236}U is a neutron poison; therefore the actual ^{235}U concentration in the LEU product must be raised accordingly to compensate for the presence of ^{236}U.

The blendstock can be NU, or DU, however depending on feedstock quality, SEU at typically 1.5 wt% ^{235}U may used as a blendstock to dilute the unwanted byproducts that may be contained in the HEU feed. Concentrations of these isotopes in the LEU product in some cases could exceed ASTM specifications for nuclear fuel, if NU, or DU were used. So, the HEU downblending generally cannot contribute to the waste management problem posed by the existing large stockpiles of depleted uranium.

A major downblending undertaking called the Megatons to Megawatts Program converts ex-Soviet weapons-grade HEU to fuel for U.S. commercial power reactors. From 1995 through mid-2005, 250 tonnes of high-enriched uranium (enough for 10,000 warheads) was recycled into low-enriched-uranium. The goal is to recycle 500 tonnes by 2013. The decommissioning programme of Russian nuclear warheads accounted for about 13% of total world requirement for enriched uranium leading up to 2008.

The United States Enrichment Corporation has been involved in the disposition of a portion of the 174.3 tonnes of highly enriched uranium (HEU) that the U.S. government declared as surplus military material in 1996. Through the U.S. HEU Downblending Program, this HEU material, taken primarily from dismantled U.S. nuclear warheads, was recycled into low-enriched uranium (LEU) fuel, used by nuclear power plants to generate electricity.

- A uranium downblending calculator designed by the WISE Uranium Project [5]

Global enrichment facilities

The following countries are known to operate enrichment facilities: Argentina, Brazil, China, France, Germany, India, Iran, Japan, the Netherlands, North Korea, Pakistan, Russia, the United Kingdom, and the United States. Belgium, Iran, Italy, and Spain hold an investment interest in the French Eurodif enrichment plant, with Iran's holding entitling it to 10% of the enriched uranium output. Countries that had enrichment programs in the past include Libya and South Africa, although Libya's facility was never operational. Australia has developed a laser

enrichment process known as SILEX, which it intends to pursue through financial investment in a U.S. commercial venture by General Electric. It has also been claimed that Israel has a uranium enrichment program housed at the Negev Nuclear Research Center site near Dimona.

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External links

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