World Nuclear Association

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Uranium Enrichment

(updated October 2013)

- **Most of the 500 commercial nuclear power reactors operating or under construction in the world today require uranium 'enriched' in the U-235 isotope for their fuel.**
- **The main commercial process employed for this enrichment involves gaseous uranium in centrifuges. An Australian process based on laser excitation is under development in the USA.**
- **Prior to enrichment, uranium oxide must be converted to a fluoride so that it can be processed as a gas, at low temperature.**
- **From a non-proliferation standpoint, uranium enrichment is a sensitive technology needing to be subject to tight international control.**

Uranium found in nature consists largely of two isotopes, U-235 and U-238. The production of energy in nuclear reactors is from the 'fission' or splitting of the U-235 atoms, a process which releases energy in the form of heat. U-235 is the main fissile isotope of uranium.

Natural uranium contains 0.7% of the U-235 isotope. The remaining 99.3% is mostly the U-238 isotope which does not contribute directly to the fission process (though it does so indirectly by the formation of fissile isotopes of plutonium). Isotope separation is a physical process to concentrate ('enrich') one isotope relative to others. Most reactors are Light Water Reactors (of two types - PWR and BWR) and require uranium to be enriched from 0.7% to 3% to 5% U-235 in their fuel.

Uranium-235 and U-238 are chemically identical, but differ in their physical properties, notably their mass. The nucleus of the U-235 atom contains 92 protons and 143 neutrons, giving an atomic mass of 235 units. The U-238 nucleus also has 92 protons but has 146 neutrons - three more than U-235, and therefore has a mass of 238 units.

The difference in mass between U-235 and U-238 allows the isotopes to be separated and makes it possible to increase or "enrich" the percentage of U-235. All present enrichment processes, directly or indirectly, make use of this small mass difference.

Some reactors, for example the Canadian-designed Candu and the British Magnox reactors, use natural uranium as their fuel. (For comparison, uranium used for nuclear weapons would have to be enriched in plants specially designed to produce at least 90% U-235.)

Enrichment processes require uranium to be in a gaseous form at relatively low temperature, hence uranium oxide from the mine is converted to uranium hexafluoride in a preliminary process, at a separate conversion plant.

International Enrichment Centres, Multilateral approaches

Following proposals from the International Atomic Energy Agency (IAEA) and Russia, and in connection with the US-led Global Nuclear Energy Partnership (GNEP), there are moves to establish international uranium enrichment centres. These are one kind of multilateral nuclear approaches (MNA) called for by IAEA. Part of the motivation for international centres is to bring all new enrichment capacity, and perhaps eventually all enrichment, under international control as a non-proliferation measure. Precisely what "control" means remains to be defined, and will not be uniform in all situations. But having ownership and operation shared

among a number of countries at least means that there is a level of international scrutiny which is unlikely in a strictly government-owned and -operated national facility.

The first of these international centres is the International Uranium Enrichment Centre (IUEC) at Angarsk in Siberia, with Kazakh, Armenian and Ukrainian equity so far. The centre is to provide assured supplies of low-enriched uranium for power reactors to new nuclear power states and those with small nuclear programs, giving them equity in the project, but without allowing them access to the enrichment technology. Russia will maintain majority ownership, and in February 2007 the IUEC was entered into the list of Russian nuclear facilities eligible for implementation of IAEA safeguards. The USA has expressed support for the IUEC at Angarsk. IUEC will sell both enrichment services (SWU) and enriched uranium product.

In some respects this is very similar to what pertains now with the Eurodif set-up, where a single large enrichment plant in France with five owners (France - 60%, Italy, Spain, Belgium and Iran) is operated under IAEA safeguards by the host country without giving participants any access to the technology - simply some entitlement to share of the product, and even that is constrained in the case of Iran. The French Atomic Energy Commission proposed that the new Georges Besse II plant which replaces Eurodif should be open to international partnerships on a similar basis, and minor shares in the Areva subsidiary operating company Societe d'Enrichissement du Tricastin (SET) have so far been sold to GDF Suez, a Japanese partnership, and Korea Hydro and Nuclear Power (KHNP) - total 10%.

The three-nation Urenco set-up is also similar though with more plants in different countries - UK, Netherlands and Germany, and here the technology is not available to host countries or accessible to other equity holders. Like Russia with IUEC, Urenco (owned by the UK and Netherlands host governments plus E.On and RWE in Germany) has made it plain that if its technology is used in international centres it will not be accessible. Its new plant is in the USA, where the host government has regulatory but not management control.

A new Areva plant in the USA has no ownership diversity beyond that of Areva itself, so will be essentially a French plant on US territory. The only other major enrichment plant in the Western world is USEC's very old one, in the USA.

The Global Laser Enrichment project which may proceed to build a commercial plant in the USA has shareholding from companies based in three countries: USA (51%), Canada (24%) and Japan (25%).

Enrichment Processes

A number of enrichment processes have been demonstrated historically or in the laboratory but only two, the gaseous diffusion process and the centrifuge process, are operating on a commercial scale. In both of these, UF_6 gas is used as the feed material. Molecules of UF_6 with U-235 atoms are about one percent lighter than the rest, and this difference in mass is the basis of both processes. Isotope separation is a physical process.*

*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 aqueous (III valency) and organic (IV) phases.

Large commercial enrichment plants are in operation in France, Germany, Netherlands, UK, USA, and Russia, with smaller plants elsewhere. New centrifuge plants are being built in France and USA. Several plants are adding capacity.

World Enrichment capacity - operational and planned (thousand SWU/yr)

country	company and plant	2012	2015	2020
France	Areva, Georges Besse I & II	2500	7000	8200

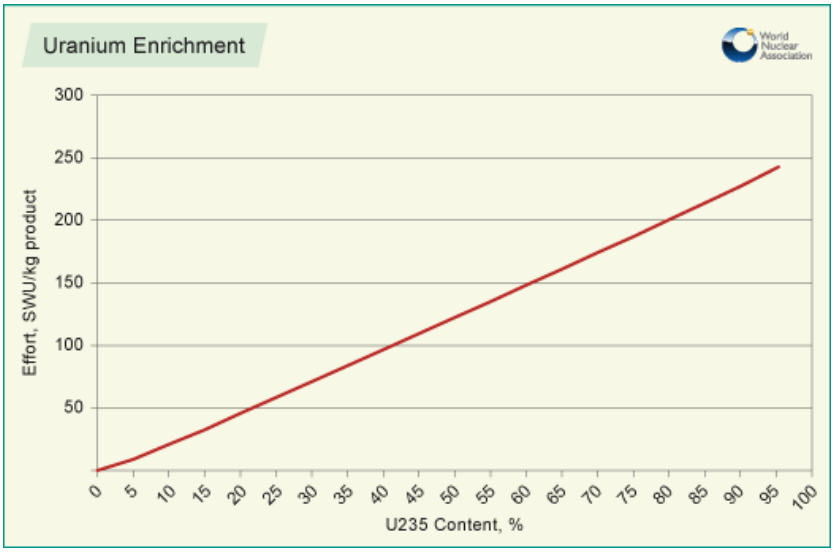
Germany-Netherlands-UK	Urenco: Gronau, Germanu; Almelo, Netherlands; Capenhurst, UK	12,800	14,200	15,700
Japan	JNFL, Rokkaasho	150	150	1500
USA	USEC, Paducah & Piketon	5000*	3800	3800
USA	Urenco, New Mexico	2000	5700	5700
USA	Areva, Idaho Falls	0	1500	3300?
USA	Global Laser Enrichment	0	1000?	3000?
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	25,000	30,000	37,000
China	CNNC, Hanzhun & Lanzhou	1500	3000	8000
Pakistan, Brazil, Iran	various	100	500	1000?
	total SWU approx	**49,000**	**65,000**	**87,200**
	Requirements (*WNA reference scenario*)	47,143	51,425	59,939

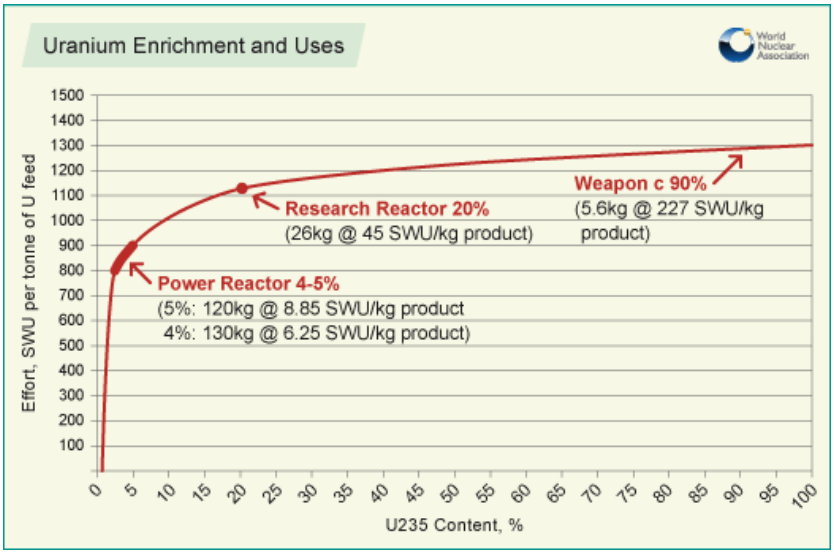
source: WNA Market Report 2011 & 2013. At end of 2012 Iran had about 9000 SWU/yr capacity operating, according to ISIS and other estimates. diffusion, due to close mid 2013*

'Other' includes Resende in Brazil, Kahutab in Pakistan, Rattehallib in India and Natanz in Iran.

The feedstock for enrichment consists of uranium hexafluoride (UF6) from the conversion plant. Following enrichment two streams of UF_6 are formed: the enriched 'product' containing a higher concentration of U-235 which will be used to make nuclear fuel, and the 'tails' containing a lower concentration of U-235, and known as depleted uranium (DU). The tails assay (concentration of U-235) is an important quantity since it indirectly determines the amount of work that needs to be done on a particular quantity of uranium in order to produce a given product assay. Feedstock may have a varying concentration of U-235, depending on the source. Natural uranium will have a U-235 concentration of approximately 0.7%, while recycled uranium will be around 1% and tails for re-enrichment around 0.25-0.30%. The capacity of enrichment plants is measured in terms of 'separative work units' or SWU. The SWU is a complex unit which indicates the energy input relative to the amount of uranium processed, the degree to which it is enriched (ie the extent of increase in the concentration of the U-235 isotope relative to the remainder) and the level of depletion of the remainder - called the 'tails'. The unit is strictly: Kilogram Separative Work Unit, and it measures the quantity of separative work performed to enrich a given amount of uranium a certain amount when feed and product quantities are expressed in kilograms. The unit 'tonnes SWU' is also used.

For instance, to produce one kilogram of uranium enriched to 5% U-235 requires 7.9 SWU if the plant is operated at a tails assay 0.25%, or 8.9 SWU if the tails assay is 0.20% (thereby requiring only 9.4 kg instead of 10.4 kg of natural U feed). There is always a trade-off between the cost of enrichment SWU and the cost of uranium.





The first graph shows enrichment effort (SWU) per unit of product. The second shows how one tonne of natural uranium feed might end up: as 120-130 kg of uranium for power reactor fuel, as 26 kg of typical research reactor fuel, or conceivably as 5.6 kg of weapons-grade material. The curve flattens out so much because the mass of material being enriched progressively diminishes to these amounts, from the original one tonne, so requires less effort relative to what has already been applied to progress a lot further in percentage enrichment.. The relatively small increment of effort needed to achieve the increase from normal levels is the reason why enrichment plants are considered a sensitive technology in relation to preventing weapons proliferation, and are very tightly supervised under international agreements. Where this safeguards supervision is compromised or obstructed, as in Iran, concerns arise.About 140,000 SWU is required to enrich the annual fuel loading for a typical 1000 MWe light water reactor at today's higher enrichment levels. Enrichment costs are substantially related to electrical energy used. The gaseous diffusion process consumes about 2500 kWh (9000 MJ) per SWU, while modern gas centrifuge plants require only about 50 kWh (180 MJ) per SWU.

Enrichment accounts for almost half of the cost of nuclear fuel and about 5% of the total cost of the electricity generated. In the past it has also accounted for the main greenhouse gas impact from the nuclear fuel cycle where the electricity used for enrichment is generated from coal. However, it still only amounts to 0.1% of the carbon dioxide from equivalent coal-fired electricity generation if modern gas centrifuge plants are used, or up to 3% in a worst-case situation.

The utilities which buy uranium from the mines need a fixed quantity of enriched uranium in order to fabricate the fuel to be loaded into their reactors. The quantity of uranium they must supply to the enrichment company is determined by the enrichment level required (% U-235) and the tails assay (also % U-235). This is the contracted or transactional tails assay, and determines how much natural uranium must be supplied to create a quantity of Enriched Uranium Product (EUP) - a lower tails assay means that more enrichment services (notably energy) are to be applied. The enricher, however, has some flexibility in respect to the operational tails assay at the plant. If the operational tails assay is lower than the contracted/transactional assay, the enricher can set aside some surplus natural uranium, which it is free to sell (either as natural uranium or as EUP) on its own account. This is known as underfeeding. The opposite situation, where the operational tails assay is higher, requires the enricher to supplement the natural uranium supplied by the utility with some of its own - this is called overfeeding. In either case, the enricher will base its decision on the plant economics together with uranium and energy prices. UxC estimates that with an optimum tails assay of 0.23% in 2013, the enrichers have the potential to contribute up to 7700 tU per year to world markets by underfeeding.

Obsolete diffusion plants have been retired, except for some belated activity at Paducah into 2013.

Supply source:	2000	2010	projected 2017
Diffusion	50%	25%	0
Centrifuge	40%	65%	93%
Laser	0	0	3%
HEU ex weapons	10%	10%	4%

The three enrichment processes described below have different characteristics. Diffusion is flexible in response to demand variations and power costs but is very energy-intensive. With centrifuge technology it is easy to add capacity with modular expansion, but it is inflexible and best run at full capacity with low operating cost. Laser technology can strip down to very low level tails assay, and is also capable of modular plant expansion.

Gaseous diffusion process

Commercial uranium enrichment was first carried out by the diffusion process in the USA. It has since been used in Russia, UK, France, China and Argentina as well. It is a very energy-intensive process, requiring about 2400 kWh per SWU*. USEC says that electricity accounts for 70% of the production cost at its Paducah plant, which is the last one operating.

* It has been estimated that 7% of total US electricity demand was from enrichment plants at the height of the cold war, when 90% U-235 was required, rather than the reactor grades of 3-4 percent for power generation.

In recent years only the USA and France used the process on any significant scale. Russia phased it our in 1992. The last of three large plants in the USA originally developed for weapons programs had a capacity of some 8 million SWU per year and was operated since 1993 by USEC. It was used to enrich some high-assay tails to mid 2013 before being finally shut down after 60 years operation. At Tricastin, in southern France, a more modern diffusion plant with a capacity of 10.8 million kg SWU per year had been operating since 1979 (see photo above). This Georges Besse I plant could produce enough 3.7% enriched uranium a year to fuel some ninety 1000 MWe nuclear reactors. It was shut down in mid 2012, after 33 years continuous operation. Its replacement (GB II, a centrifuge plant - see below) has commenced operation.

In recent years the gaseous diffusion process has accounted for about 25% of world enrichment capacity. However, though they have proved durable and reliable, gaseous diffusion plants reached the end of their design life and the focus is on centrifuge enrichment technology which has replaced them.

The large Georges Besse I enrichment plant at Tricastin in France (beyond cooling towers)
The four nuclear reactors in the foreground provide over 3000 MWe power for it.

The diffusion process involves forcing uranium hexafluoride gas under pressure through a series of porous

membranes or diaphragms. As U-235 molecules are lighter than the U-238 molecules they move faster and have a slightly better chance of passing through the pores in the membrane. The UF_6 which diffuses through the membrane is thus slightly enriched, while the gas which did not pass through is depleted in U-235.

This process is repeated many times in a series of diffusion stages called a cascade. Each stage consists of a compressor, a diffuser and a heat exchanger to remove the heat of compression. The enriched UF6 product is withdrawn from one end of the cascade and the depleted UF6 is removed at the other end. The gas must be processed through some 1400 stages to obtain a product with a concentration of 3% to 4% U-235. Diffusion plants typically have a small amount of separation through one stage (hence the large number of stages) but are capable of handling large volumes of gas.

Centrifuge process

The gas centrifuge process was first demonstrated in the 1940s but was shelved in favour of the simpler diffusion process. It was then developed and brought on stream in the 1960s as the second-generation enrichment technology. It is economic on a smaller scale, eg under 2 million SWU/yr, which enables staged development of larger plants. It is much more energy-efficient than diffusion, requiring only about 50-60 kWh per SWU.

The centrifuge process has been deployed at a commercial level in Russia, and in Europe by Urenco, an industrial group formed by British, German and Dutch governments. Russia's four plants at Seversk, Zelenogorsk, Angarsk and Novouralsk account for some 40% of world capacity*. Urenco operates enrichment plants in UK, Netherlands and Germany and is building one in the USA.

* In 2012 Russia was commissioning 8th generation centrifuges with service life of up to 30 years. The last 6th & 7th generation ones were installed in 2005, and 8th generation equipment has been supplied since 2004 to replace 5th generation models with a service life of only 15 years.

In Japan, JNC and JNFL operate small centrifuge plants, the capacity of JNFL's at Rokkasho was planned to be 1.5 million SWU/yr. China has two small centrifuge plants imported from Russia. One at Lanzhou is 0.5 million SWU/yr and the other main one at Hanzhun is operating at 1.0 million SWU/yr since 2011. Brazil has a small plant which is being developed to 0.2 million SWU/yr. Pakistan has developed centrifuge enrichment technology, and this appears to have been sold to North Korea. Iran has sophisticated centrifuge technology which is operational, with estimated 9000 SWU/yr capacity. .

In both France and the USA plants with 6th generation Urenco centrifuge technology are now being built to replace ageing diffusion plants, not least because they are more economical to operate. As noted, a centrifuge plant requires as little as 50 kWh/SWU power (Urenco at Capenhurst, UK, input 62.3 kWh/SWU for the whole plant in 2001-02, including infrastructure and capital works).

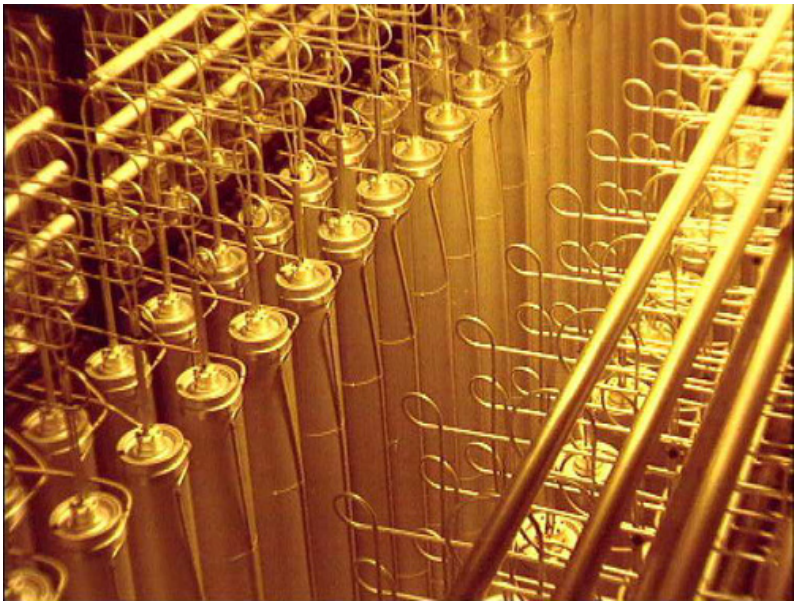
Areva's new EUR 3 billion French plant - Georges Besse II - started commercial operation in April 2011 and will ramp up to full capacity of 7.5 million SWU/yr in 2016. In October 2013 it had 4.6 million SWU/yr online.

Urenco's new $1.5 billion National Enrichment Facility in New Mexico, USA commenced production in June 2010. Full initial capacity of 3 million SWU/yr is expected to be reached in 2013, and 5.7 million SWU/yr is planned for 2015 - enough for 10% of US electricty needs.

Following this, Areva is planning to build a $2 billion, 3.3 million SWU/yr Eagle Rock plant at Idaho Falls, USA which might commence construction in 2015, with first production in 2018. In 2009 it applied for doubling in capacity to 6.6 million SWU/yr.

USEC has been building its American Centrifuge Plant in Piketon, Ohio, on the same Portsmouth site where the DOE's experimental plant operated in the 1980s as the culmination of a very major R&D program. Operation from 2012 was envisaged, at a cost of $3.5 billion then estimated. It is designed to have an initial

annual capacity of 3.8 million SWU, though its licence application is for 7 million SWU to allow for expansion. Authorisation for enrichment up to 10% was sought - most enrichment plants operate up to 5% U-235 product, which is becoming a serious constraint as reactor fuel burnup increases. A demonstration cascade started up in September 2007 with about 20 prototype machines, and a lead cascade of commercial centrifuges started operation in March 2010. These are very large machines, 13 m tall, each with about 350 SWU/yr capacity. However the whole project was largely halted in July 2009 pending further finance. A total of $1.95 billion had been spent from May 2007 to December 2010, and a further $2.8 billion cost was then projected. In March 2010 the DOE made $45 million available to USEC for continued development.



A bank of centrifuges at a Urenco plant

Like the diffusion process, the centrifuge process uses UF^6 gas as its feed and makes use of the slight difference in mass between U-235 and U-238. The gas is fed into a series of vacuum tubes, each containing a rotor 3 to 5 metres tall and 20 cm diameter.* When the rotors are spun rapidly, at 50,000 to 70,000 rpm, the heavier molecules with U-238 increase in concentration towards the cylinder's outer edge. There is a corresponding increase in concentration of U-235 molecules near the centre. The countercurrent flow set up by a thermal gradient enables enriched product to be drawn off axially, heavier molecules at one end and lighter ones at the other.

* USEC's American Centrifuges are more than 12 m tall and 40-50 cm diameter. The Russian centrifuges are less than one metre tall. Chinese ones are larger, but shorter than Urenco's.

The enriched gas forms part of the feed for the next stages while the depleted UF_6 gas goes back to the previous stage. Eventually enriched and depleted uranium are drawn from the cascade at the desired assays.

To obtain efficient separation of the two isotopes, centrifuges rotate at very high speeds, with the outer wall of the spinning cylinder moving at between 400 and 500 metres per second to give a million times the acceleration of gravity.

Although the volume capacity of a single centrifuge is much smaller than that of a single diffusion stage, its capability to separate isotopes is much greater. Centrifuge stages normally consist of a large number of centrifuges in parallel. Such stages are then arranged in cascade similarly to those for diffusion. In the centrifuge process, however, the number of stages may only be 10 to 20, instead of a thousand or more for diffusion.

Laser processes

Laser enrichment processes have been the focus of interest for some time. They are a possible third-generation technology promising lower energy inputs, lower capital costs and lower tails assays, hence significant economic advantages. One of these processes is almost ready for commercial use. Laser

processes are in two categories: atomic and molecular.

Development of the Atomic Vapour Laser Isotope Separation (AVLIS, and the French SILVA) began in the 1970s. In 1985 the US Government backed it as the new technology to replace its gaseous diffusion plants as they reached the end of their economic lives early in the 21st century. However, after some US$ 2 billion in R&D, it was abandoned in USA in favour of SILEX, a molecular process. French work on SILVA has now ceased, following a 4-year program to 2003 to prove the scientific and technical feasibility of the process. Some 200kg of 2.5% enriched uranium was produced in this.

Atomic vapour processes work on the principle of photo-ionisation, whereby a powerful laser is used to ionise particular atoms present in a vapour of uranium metal. (An electron can be ejected from an atom by light of a certain frequency. The laser techniques for uranium use frequencies which are tuned to ionise a U-235 atom but not a U-238 atom.) The positively-charged U-235 ions are then attracted to a negatively-charged plate and collected. Atomic laser techniques may also separate plutonium isotopes.

The main molecular laser process to enrich uranium is SILEX, which utilises UF6 and is now known as Global Laser Enrichment (GLE). In 2006 GE Energy entered a partnership with Australia's Silex Systems to develop the third-generation SILEX process. It provided for GE (now GE-Hitachi) to construct in the USA an engineering-scale test loop, then a pilot plant or lead cascade, which could be operating in 2012, and expanded to a full commercial plant. Apart from US$ 20 million upfront and subsequent payments, the license agreement would yield 7-12% royalties, the precise amount depending on how low the cost of deploying the commercial technology. In mid 2008 Cameco bought into the GLE project, paying $124 million for 24% share, alongside GE (51%) and Hitachi (25%). (Earlier, in 1996 USEC had secured the rights to evaluate and develop SILEX for uranium but baled out of the project in 2003.)

GE referred to SILEX, which it rebadged as GLE, as "game-changing technology" with a "very high likelihood" of success. GE-Hitachi is completing the test loop program, the initial phase of which has already been successful in meeting performance criteria, and engineering design for a commercial facility has commenced. GEH is operating the GLE test loop at Global Nuclear Fuel's Wilmington, North Carolina fuel fabrication facility - GNF is a partnership of GE, Toshiba, and Hitachi.

In October 2007 the two largest US nuclear utilities, Exelon and Entergy, signed letters of intent to contract for uranium enrichment services Global Laser Enrichment LLC (GLE). The utilities may also provide GLE with support if needed for development of a commercial-scale GLE plant. In August 2010 TVA agreed to buy $400 million of enrichment services from GLE if the project proceeds.

In mid 2009 GEH submitted the last part of its licence application for this GLE plant, which was expected to take the NRC about 30 months to process. At the end of February 2012 NRC published a favourable environmental review of the project, and its safety evaluation found that its programs for the physical protection of special nuclear material and classified matter, material control and accounting provided an adequate basis for both safety and safeguards of facility operations. Following a July review by the NRC Atomic Safety and Licensing Board, a full licence to construct and operate a plant of up to 6 million SWU/yr was issued in September 2012. GLE will now decide in the light of commercial considerations on whether to proceed with a full-scale enrichment facility at Wilmington. The project, enriching up to 8% U-235, could be operational from 2014, and ramp up to annual capacity of 6 million separative work units (SWU) in 2020.

Applications to silicon and zirconium stable isotopes are also being developed by Silex Systems near Sydney.

CRISLA is another molecular laser isotope separation process which is the early stages of development. In this a gas is irradiated with a laser at a particular wavelength that would excite only one of the isotopes. The entire gas is subjected to low temperatures sufficient to cause condensation on a cold surface or coagulation

in the gas. The excited molecules in the gas are not as likely to condense as the unexcited molecules. Hence in cold-wall condensation, gas drawn out of the system is enriched in the isotope that was laser-excited.

Electromagnetic process

A very early endeavour was the electromagnetic isotope separation (EMIS) process using calutrons. This was developed in the early 1940s in the Manhattan Project to make the highly enriched uranium used in the Hiroshima bomb, but was abandoned soon afterwards. However, it reappeared as the main thrust of Iraq's clandestine uranium enrichment program for weapons discovered in 1992. EMIS uses the same principles as a mass spectrometer (albeit on a much larger scale). Ions of uranium-238 and uranium-235 are separated because they describe arcs of different radii when they move through a magnetic field. The process is very energy-intensive - about ten times that of diffusion.

Aerodynamic processes

Two aerodynamic processes were brought to demonstration stage around the 1970s. One is the jet nozzle process, with demonstration plant built in Brazil, and the other the Helikon vortex tube process developed in South Africa. Neither is in use now, though the latter is the forerunner of new R&D. They depend on a high-speed gas stream bearing the UF6 being made to turn through a very small radius, causing a pressure gradient similar to that in a centrifuge. The light fraction can be extracted towards the centre and the heavy fraction on the outside. Thousands of stages are required to produce enriched product for a reactor. Both processes are energy-intensive - over 3000 kWh/SWU. The Helikon Z-plant in the early 1980s was not commercially oriented and had less than 500,000 SWU/yr capacity. It required some 10,000 kWh/SWU.

The Aerodynamic Separation Process (ASP) being developed by Klydon in South Africa employs similar stationary-wall centrifuges with UF6 injected tangentially. It is based on Helikon but pending regulatory authorisation it has not yet been tested on UF6 - only light isotopes such as silicon. However, extrapolating from results there it is expected to have an enrichment factor in each unit of 1.10 (cf 1.03 in Helikon) with about 500 kWh/SWU and development of it is aiming for 1.15 enrichment factor and less than 500 kWh/SWU. Projections give an enrichment cost under $100/SWU, with this split evenly among capital, operation and energy input.

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 aqueous (III valency) and organic (IV) phases.

Enrichment of reprocessed uranium

In some countries used fuel is reprocessed to recover its uranium and plutonium, and to reduce the final volume of high-level wastes. The plutonium is normally recycled promptly into mixed-oxide (MOX) fuel, by mixing it with depleted uranium.

Where uranium recovered from reprocessing used nuclear fuel (RepU) is to be re-used, it needs to be converted and re-enriched. This is complicated by the presence of impurities and two new isotopes in particular: U-232 and U-236, which are formed by or following neutron capture in the reactor, and increase with higher burn-up levels. U-232 is largely a decay product of Pu-236, and increases with storage time in used fuel, peaking at about ten years. Both decay much more rapidly than U-235 and U-238, and one of the daughter products of U-232 emits very strong gamma radiation, which means that shielding is necessary in any plant handling material with more than very small traces of it. U-236 is a neutron absorber which impedes the chain reaction, and means that a higher level of U-235 enrichment is required in the product to compensate. For the Dutch Borssele reactor which normally uses 4.4% enriched fuel, compensated enriched reprocessed uranium (c-ERU) is 4.6% enriched to compensate for U-236. Being lighter, both isotopes tend to concentrate in the enriched (rather than depleted) output, so reprocessed uranium which is re-enriched for fuel must be segregated from enriched fresh uranium. The presence of U-236 in particular

means that most reprocessed uranium can be recycled only once - the main exception being in the UK with AGR fuel made from recycled Magnox uranium being reprocessed. U-234 is also present in RepU, but as an alpha emitter it does not pose extra problems. Traces of some fission products such as Tc-99 may also carry over.

All these considerations mean that only RepU from low-enriched, low-burnup used fuel is normally recycled directly through an enrichment plant. For instance, some 16,000 tonnes of RepU from Magnox reactors* in UK has been used to make about 1650 tonnes of enriched AGR fuel, via two enrichment plants. Much smaller quantities have been used elsewhere, in France and Japan. Some re-enrichment, eg for Swiss, German and Russian fuel, is actually done by blending RepU with HEU.

* since Magnox fuel was not enriched in the first place, this is actually known as Magnox depleted uranium (MDU). It assayed about 0.4% U-235 and was converted to UF6, enriched to 0.7% at BNFL's Capenhurst diffusion plant and then to 2.6% to 3.4% at Urenco's centrifuge plant. Until the mid 1990s some 60% of all AGR fuel was made from MDU and it amounted to about 1650 tonnes of LEU. Recycling of MDU was discontinued in 1996 due to economic factors.

A laser process would theoretically be ideal for enriching RepU as it would ignore all but the desired U-235, but this remains to be demonstrated with reprocessed feed.

Tails from enriching reprocessed uranium remain the property of the enricher. Some recycled uranium has been enriched by Tenex at Seversk for Areva, under a 1991 ten-year contract covering about 500 tonnes UF6. French media reports in 2009 alleging that wastes from French nuclear power plants were stored at Seversk evidently refer to tails from this.

Enrichment of depleted uranium tails

Early enrichment activities often left depleted uranium tails with about 0.30% U-235, and there were tens of thousands of tonnes of these sitting around as the property of the enrichment companies. With the wind-down of military enrichment, particularly in Russia, there was a lot of spare capacity unused. Consequently, since the mid 1990s some of the highest-assay tails have been sent to Russia by Areva and Urenco for re-enrichment by Tenex. These arrangements however cease in 2010, though Tenex may continue to re-enrich Russian tails. Tenex now owns all the tails from that secondary re-enrichment, and they are said to comprise only about 0.10% U-235.

After enrichment

The enriched UF^6 is converted to UO^2 and made into fuel pellets - ultimately a sintered ceramic, which are encased in metal tubes to form fuel rods, typically up to four metres long. A number of fuel rods make up a fuel assembly, which is ready to be loaded into the nuclear reactor.

Environmental Issuses

With the minor exception of reprocessed uranium, enrichment involves only natural, long-lived radioactive materials; there is no formation of fission products or irradiation of materials, as in a reactor. Feed, product, and depleted material are all in the form of UF6, though the depleted uranium may be stored long-term as the more stable U^3O^8.

Uranium is only weakly radioactive, and its chemical toxicity - especially as UF^6 - is more significant than its radiological toxicity. The protective measures required for an enrichment plant are therefore similar to those taken by other chemical industries concerned with the production of fluorinated chemicals.

Uranium hexafluoride forms a very corrosive material (HF - hydrofluoric acid) when exposed to moisture,

therefore any leakage is undesirable. Hence:

- in almost all areas of a centrifuge plant the pressure of the UF_6 gas is maintained below atmospheric pressure and thus any leakage could only result in an inward flow;
- double containment is provided for those few areas where higher pressures are required;
- effluent and venting gases are collected and appropriately treated.

Sources:

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