

## Isotope enrichment: how does it work? Do you see it as part of a future new-generation nuclear fuel cycle?

Mined uranium ore comprises 0.7% of the U235 isotope, the rest being U238. U235 is much more unstable and undergoes fission more readily, and is a much better fuel for a reactor. Enrichment of uranium is undertaken to increase the amount of U235 to 3-5%, which is needed in most current reactor designs. For comparison, uranium used for nuclear weapons, for which enrichment technology was developed, would have to be enriched in plants specially designed to produce at least 90% U235.

### Enrichment methods

There are currently two main commercial methods to enrich uranium: gaseous diffusion and gas centrifugation. Both use uranium hexafluoride ( $UF_6$ ) as the feed, which is converted to uranium dioxide after enriching.

The enrichment process removes about 85% of the U238 by separating gaseous uranium hexafluoride into two streams: one stream is enriched to the required level, while the other stream is depleted in U235 and is known as 'tails'. The tails comprises roughly 99.75% U238 and is of no further use for energy. Such 'depleted uranium' is used in metal form in yacht keels, as counterweights, and as radiation shielding, as it is 1.7 times denser than lead.

Once the uranium hexafluoride has been enriched to the required extent, it can be converted to enriched uranium dioxide by heating it with hydrogen and steam, with waste products of hydrogen fluoride gas and uranium hexafluoride. Fluorine is the most reactive of all the elements, reacting, often explosively, with almost all other elements. Both fluorine and hydrogen fluoride attack glass, and cause very severe burns if they come in contact with skin. These chemical hazards pose more of a risk than radiation does when enriching the fuel, and are extremely harmful to the environment if releases occur.

### Gaseous diffusion

In the gaseous diffusion process, U235 and U238 atoms are separated by feeding  $UF_6$  in gaseous form through a series of porous walls or membranes.

Because the lighter U235 particles travel faster than U238 particles, more of them penetrate each membrane. This is repeated through hundreds of membranes until the correct enrichment level is reached. The high amount of energy required to force the UF<sub>6</sub> through the membranes makes the gaseous diffusion process expensive.

## Centrifuges

In this process, the gaseous UF<sub>6</sub> is placed in a centrifuge. The rapid spinning flings the heavier U238 atoms to the outside of the centrifuge, leaving the UF<sub>6</sub> in the centre enriched with a higher proportion of U235 atoms. The enrichment level achieved by a single centrifuge is insufficient to obtain the desired concentration of U235. Therefore a number of centrifuges are connected together in an arrangement known as a cascade. The U235 concentration gradually increases to 3 – 5% as it passes through the cascade.

This method has a significant cost advantage over gaseous diffusion, as it requires about 2% of the energy needed to perform gaseous diffusion. As Fishlock notes (Fishlock, 2004) it has become the dominant method of enrichment.

There are also other techniques that can be used to enrich uranium:

## Electromagnetic Isotope Separation (EMIS)

EMIS uses the same principles as a mass spectrometer (albeit on a much larger scale). Ions of U238 and U235 are separated because they describe arcs of different radii when they move through a magnetic field (Frejaques et al., 1975).

A major problem with this method is that less than half of the UCl<sub>4</sub> feed is converted to the desired U ions, and less than half of the desired U ions are collected. Recovering unused material from the interior surfaces of the tanks is laborious, time-consuming process that reduces the effective output of an EMIS facility.

EMIS is both energy intensive and labour intensive, and not economically competitive with other enrichment technologies.

## Aerodynamic/Jet Nozzle: stationary wall centrifuge

Although not in common use, techniques using gas flow and pressure gradients have been developed (Roux and Grant, 1975), including the separation nozzle process and the vortex tube separation process. These

aerodynamic separation processes depend upon diffusion driven by pressure gradients, and can be thought-of as a non-rotating centrifuge.

For both of these processes, the high proportion of carrier gas required in relation to  $UF_6$  process gas results in high specific-energy consumption and substantial requirements for removal of waste heat.

## Is enrichment necessary?

The question that must be answered is “Is enrichment necessary for a future new-generation nuclear fuel cycle?”. At the present time the answer appears to be Yes, due to reactor designs and the cost of refuelling more frequently if unenriched uranium is used.

Enrichment accounts for almost half of the cost of nuclear fuel and about 5% of the total cost of the electricity generated (WNA, 2003), which encourages the use of less enriched fuel.

Since the late 1960s reactor designs that can work on unenriched uranium have been in existence, such as the CANDU™ design (CANada Deuterium Uranium). However this design hasn't been without problems, and has raised some proliferation concerns due to the high content of plutonium in the spent fuel. It also needs refuelling more frequently than would be needed with an enriched fuel, which means that for cost-efficient operation a reactor design where you can refuel online without shutting the reactor down is necessary.

CANDU reactors, due to their low neutron absorption, also show possibility with burning exhausted fuel from pressurised water reactors (PWR) and other reactor designs (Whitlock, 2000) without re-enrichment. They are also well adapted for consuming plutonium (Brogden, 1996). There is currently a lot of weapons-grade plutonium that needs disposing of, and it would make economic sense to use it as an alternative fuel to produce electricity.

Another possibility is the development of fast breeder reactors (FBR), where the  $U_{238}$  is converted into more fissile material. These have a major problem in that they can be used to produce plutonium – indeed the major use of breeder reactors currently is for military purposes, and designs like this would not do anything to reduce the proliferation of nuclear weapons. However they do have the advantage of utilising uranium at least 60 times more efficiently than a normal reactor (UIC, 2005). Lead can be used as a coolant in FBRs:  $Pb_{208}$  (54% of naturally-occurring lead) is transparent to neutrons, which provides obvious efficiency achievements. A downside in the current commercial market is the cost of FBRs, although as the price of uranium

increases they become more favourable. Development is underway on a European design (Lefevre et al., 1996).

The European Pressurised Water Reactor (EPR) design (EDF, 2005), which is currently being constructed in Finland and France requires less enrichment of fuel than current designs, and this may be the way forward. This reactor is one of the 'third generation' designs, which is a transitory reactor based on current principles but with improvements. It has also been designed to consume a very large proportion of mixed oxide (MOX) fuels, reusing much of the plutonium which results from the fission (Barbrault, 1994, Youinou et al., 2003).

The threat of nuclear proliferation (John Deutch, 2003) is one of the biggest arguments against isotope enrichment. The same technology used to produce low enriched uranium (LEU) suitable for use in nuclear power stations can be used to produce highly enriched uranium (HEU), suitable for nuclear weapons.

Is there any way enrichment can be done such that it cannot be siphoned off for weapons production? One proposed way forward is to centralise fuel processing and waste storage internationally (Li, 1995). This would mean that the mass expected could be compared with the mass arriving. However, there are still large security concerns about this, and even greater political ones, since citizens are not in favour of their country being a nuclear store for others.

There is also difficulty in that countries looking for increased independence from the big suppliers, seeking commercial opportunities or an independent nuclear weapons capability will still build their own enrichment plants (McCombie and Chapman, 2004).

With the threat of terrorist attacks growing, enrichment plants and the transport of nuclear material are increasingly being seen as a liability.

## Technological solutions

New burnable poisons (materials that absorb neutrons and then transmute to weak absorbers after absorbing a neutron) for use in reactor fuel are being developed that have ideal lifetimes to be consumed at the correct rate – otherwise they negate the neutron emissions when the fuel is less active and mean it must be replaced before it's fully consumed.

One new design of reactor is the Pebble Bed, into which MIT has conducted research (Kadak et al., 2001). This reactor design is promising because it

operates at a low temperature (~800C) and can never meltdown. The fuel is also very difficult, if not impossible, to reprocess which prevents problems of nuclear proliferation.

Fuel cladding that doesn't absorb so many neutrons is being developed, reducing need for enrichment, as there are more free neutrons to cause fission reactions. Research into alternative fuels such as thorium also continues (Pereira and Leite, 1998, Morozov et al., 1999, Cerullo et al., 1994).

Atomic and molecular laser isotope separation (LIS) techniques use lasers to selectively excite atoms or molecules containing one isotope of uranium so that they can be preferentially extracted. Although LIS appears promising, the technology has proven to be extremely difficult to master and may be beyond the reach of even technically advanced states (Ramakoteswara Rao, 2003).

## Conclusion

Isotope enrichment will remain part of the nuclear power cycle for the foreseeable future, but work is under way to replace it when technologically possible. This will enable unstable countries to have access to nuclear power without the need to buy pre-enriched fuel from other countries (which is more expensive), or constructing their own enrichment programme, with obvious fears about nuclear weapons proliferation.

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