Nuclear Fuel

Its Nature and Disposal

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Spent nuclear fuel under water exhibits a blue glow

by Francois Mellet

Uranium in nature is a slightly radioactive metal that occurs throughout the Earth's crust. It occurs in most rocks, in concentrations of 2 to 4 parts per million. Uranium is about 500 times more abundant than gold, and is as common in the Earth's crust as tin, tungsten and molybdenum. It is also naturally present in most soils, as well as in many rivers and in sea water. It is found in concentrations of about four parts per million (ppm) in granite, which makes up 60% of the Earth's crust. Uranium concentration can be as high as 400 ppm (0.04%) in fertilizers, and in some coal deposits the Uranium concentrations can rise to greater than 100 ppm (0.01%).

In South Africa and Namibia where the concentration of Uranium in the ground is sufficiently high, the mining of various ores to process and to extract uranium for eventual use as nuclear fuel, is economically feasible.

Francois Mellet is an electrical engineer whose career started in Eskom. He progressed to spend ten years in Koeberg Nuclear Power Station as a commissioning and project engineer. He later spent a year in the nuclear environment in France, Germany, Belgium and the United Kingdom. He then spent five years as maintenance manager at the coal-fired Matimba Power Station. Francois then spent nearly a decade in International Risk Control Africa where he worked in a diversity of sectors. From 2002 he has been working on a project in France to design and develop an underground research laboratory, leading to the construction of a longterm storage facility for high level nuclear waste. The client is ANDRA (National Agency for Nuclear Waste Storage).

The earth's Uranium (chemical symbol U) was apparently formed in supernovae up to about 6.6 billion years ago. Its radioactive decay provides the main source of heat inside the earth, causing convection of molten rock and consequent continental drift. As decay proceeds, Uranium eventually becomes lead, so the lead in the final product progressively increases in relative abundance. Rather interesting is that lead is scientifically used to shield living organisms from the radio-active effects of different nuclear sources

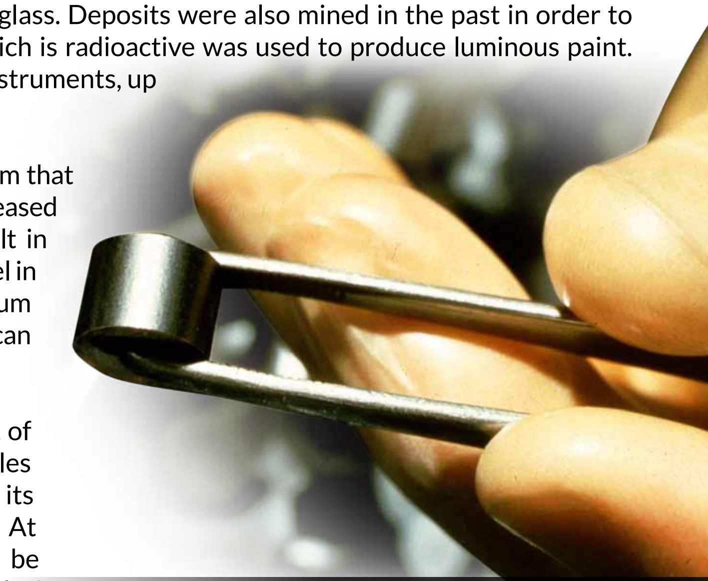
Uranium was discovered by Martin Klaproth, a German chemist, in 1789 in the mineral pitchblende, and was named after the planet Uranus. Being relatively soluble, in contrast to thorium, it is also found in the ocean, at an average concentration of 3 parts per billion.

Light elements such as hydrogen and helium are found in abundance all over the universe. However for the heavier elements to form, such as Uranium and gold, the giant gravitational fields found amongst stars are required. As layers of matter are crushed together by gravitational force, a star can explode, forming many of the heavier elements. Such an explosion is known as a supernova. Fragments from such an explosion can later be drawn together by gravity to form planets, containing materials 'like uranium and gold.'

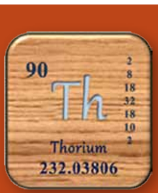
In the past, from as early as 79AD, Uranium was also used to colour glass. Deposits were also mined in the past in order to obtain its decay product, Radium. From the later 1800's, Radium which is radioactive was used to produce luminous paint. This paint was used particularly on the dials of watches and aircraft instruments, up to the 1950's, so that they could be read in the dark.

For many years after the Second World War, virtually all of the Uranium that was mined was used in the production of nuclear weapons, but this ceased to be the case in the 1970's when nuclear power reactors were built in significant numbers. Today the only substantial use for Uranium is as fuel in nuclear reactors; mostly for electricity generation. The isotope of Uranium called Uranium-235 is the only naturally-occurring material which can sustain a fission chain reaction, releasing large amounts of energy.

Small amounts of radioactive fission products in the fuel can leak out of the fuel cladding into the reactor water, in the form of small particles and debris. These can lodge on surfaces of the reactor vessel and in its internal structures, and also in those of adjoining pipes and vessels. At decommissioning, much of this radioactive debris is loose and can be washed or scrubbed away to form a sludge that can then be disposed of. Some of it is more firmly stuck and cannot be so easily removed.



A pellet of Uranium Oxide which goes into the Zirconium tubes which makes up a fuel element.



- Thorium (Th) is more abundant in nature than Uranium.
- Thorium is fertile rather than fissile, and can only be used as a fuel in conjunction with a fissile material such as recycled Plutonium.
- Thorium fuels can breed fissile Uranium-233 to be used in various kinds of nuclear reactors.

Uranium

is one of the heaviest of all the naturally-occurring elements and has a density of 18.7gm/cm^3. Its melting point is 1132°C.

While nuclear power for the production of electricity is the predominant user of Uranium, one can also use the heat from nuclear fission directly for industrial processes, and for marine propulsion, such as in nuclear submarines and nuclear powered surfaced warships. Another class of specialist nuclear reactors is important for making a range of commercial radio-isotopes, such as our own South African SAFARI-1 reactor which produces life-saving medical isotopes. SAFARI-1 has been in operation for over 50 years.

In nature, Uranium produces so little radio-activity that its ore can be safely handled with bare hands. Before it can be used in a reactor for electricity generation, however, the ore must undergo a series of processes to produce a useable nuclear fuel.

Like many other natural elements, Uranium occurs in slightly differing forms known as isotopes. These isotopes differ from each other in the number of neutrons in the nucleus. Natural Uranium (Unat), as found in the Earth's crust, is a mixture of three isotopes: Uranium-238 (U-238), accounting for 99.275%; U-235 at a concentration of 0.720%; and traces of U-234 at 0.005%. Uranium ore is processed in South Africa into a yellow oxide power which is then exported. It is known as: Yellowcake. Its chemical composition is U_3O_8. In popular and commercial literature it is something written like this: U3O8.

For most of the world's reactors, the next step in making a useable fuel is to convert the uranium oxide into a gas, Uranium Hexafluoride (UF_6). Since this form of Uranium is a gas, it can be fed into enrichment devices that require a gas flow, such as a centrifuge or the South African developed Vortex tube system. The process of Uranium enrichment increases the proportion of the U-235 isotope from its natural level of 0.7% to 3 to 10%, depending on the type of reactor it will be used in. This enrichment enables greater technical efficiency in reactor design and operation, particularly in larger reactors, and also allows the use of ordinary water as a process controller or moderator. Submarines and ships operate using enrichment levels ranging all the way up to 96%. Note that weapons-grade Uranium is typically 80%-95% enriched.

Illustration of a PWR fuel element of an array of 17x17 zircalloy tubes of 3.4m in length. Illustration shows Uranium oxide Fuel Pellets being loaded into the tubes.

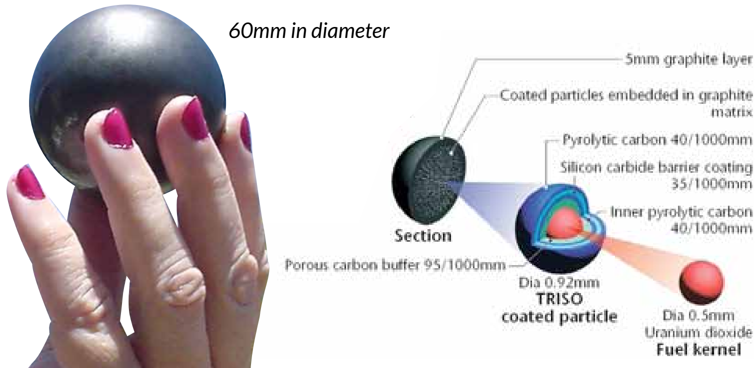
The World Nuclear Association predicts that global Uranium demand will increase by 48% by 2023, as a result of the approximately 70 nuclear reactors currently under construction globally.

The Pebble Bed Modular Reactor (PBMR) type of power plant is fuelled and moderated by graphite fuel spheres, each containing Tri-structural-isotropic (TRISO) coated, low-enriched, Uranium Oxide fuel particles. TRISO fuel is a type of micro fuel particle, coated with four layers of three materials. These particles are less than 1mm in diameter. They are all embedded in a graphite ball about the size of a cricket ball.

TRISO fuel particles are the size of poppy seeds. Break one open, and it looks like the inside of a tiny jaw-breaker sweet. An outer shell of carbon coats a layer of silicon carbide, which coats another layer of carbon and the uranium centre — where the energy-releasing fission happens.

TRISO fuel particle

A TRISO particle of Uranium has its own containment layers. It is about 1mm in diameter.



PBMR fuel ball containing 9gm of Uranium, made at Necsa

There are 15000 fuel particles per fuel sphere, called a Pebble. It is the size of a cricket ball. Each fuel pebble contains 9gm of Uranium, and this Uranium contains enough electrical generation capacity to sustain a family of four for a year. Five tons of coal would be required to generate the same amount of electricity as one pebble's energy.

In South Africa, much of the productive ground for Uranium production is the gold fields in the Witwatersrand Basin. Uranium is frequently found as a by-product of gold mining. Klerksdorp, Welkom, Carletonville, Parys and Evander are towns strongly associated with gold mines.

A 1000MW nuclear power plant will produce 20 tons of spent fuel per annum, compared to a typical similar coal-fired unit in South Africa, which would produce 1.4 million tons of ash in a similar period. Therefore a nuclear plant produces 70 000 times less waste by volume.

Nuclear Waste

Operational nuclear waste is produced at any facility which uses radioactive material, such as a power station, research reactor, or nuclear medicine center.

Low Level Waste (LLW) is produced from ongoing operational and maintenance activities, as well as the de-commissioning of certain equipment during or at the end of power station life. This consists of gloves, jackets, swabs and anything which may have come into contact with radioactive material, and so may have some smear of radioactive material on it.

Intermediate Level Waste (ILW) is based on concentrations of radioactive materials in liquids or filter materials. These materials are deposited in pipes or similar and are then normally placed in high-density concrete containers, which are then stored in near-surface disposal facilities. "Near-surface" means: some 30 to 50m below ground.

For a power station reactor, once the inner fuel elements in the centre of the reactor core are exhausted (due to higher neutron flux in the core centre) the reactor commences a power coast-down towards a re-fuelling outage. The spent fuel elements are then removed and replaced with new fuel elements. The spent fuel should not be regarded as nuclear waste at this stage, since there are still very valuable materials in the spent fuel. This spent fuel can then be reprocessed, to separate the various valuable materials such as Plutonium-239, in the spent fuel. This Plutonium can be further used in other types of reactors.

Spent fuel is referred to as High Level Waste (HLW) and it is extremely dangerous if not handled correctly. The governments of most countries in the world have not yet authorized the long-term storage of HLW in their countries. The first two countries to gain government authorization were Finland and Sweden. Their repositories are underground, in ground that is permanently wet, so the regular pumping out of water is required, while the tunnels are filled with spent fuel. In South Africa's case the likely ground for such a High Level Waste repository is extremely dry, so no water pumping would be necessary.

During the early years of Koeberg Nuclear Power Station, fuel elements were being imported from the USA and France. In order to secure the sustainable operation of our only nuclear power production unit, a strategic decision was made to manufacture South Africa's own fuel assemblies.

Production of low-enriched Uranium (3.25%) commenced in August 1988 at Valindaba, part of the Pelindaba site of Necsa near Pretoria. There was also a Zircaloy Tubing facility at Pelindaba used to produce the cladding tubes for the fuel assemblies fabricated for the Koeberg reactors.

The first complete Koeberg fuel loading with locally manufactured fuel, took place in 1991 on Koeberg Unit 2, when a third of the 157 fuel assemblies were replaced during a re-fueling outage. This was an extremely proud moment for South African nuclear engineering!

Enrichment activities at the plant were terminated in October 1995, due to political and economic reasons.

Reprocessing

When highly radioactive spent fuel is produced, two options face the government concerned. One is to store the spent fuel underground, while the other is to reprocess the spent fuel to extract the remaining valuable materials. Of course the spent fuel is highly radioactive, so reprocessing is a complex and dangerous process.

Once all materials of value have been removed from the spent fuel; the remaining material may then be considered as "nuclear waste".

Spent fuel can be safely handled and transported in a controlled manner under the supervision of nuclear professionals.

At present South Africa has an operational nuclear waste repository site at Vaalputs in the Northern Cape, for Low and Intermediate Level Nuclear Waste storage. This facility is ideally located 100km south-east from the town of Springbok in a very dry region, with rainfall of 74mm per annum. With low inhabitance of less than 1 person per km^2, low seismicity and a stable weather system, the area is ideal. Over the last 30 years there has been a utilization of only 500-1000 hectares of the extremely large site of 10 000 hectares. This is a very economical site, run since 1986 by a South African team from the local region.

First South African made fuel element for Koeberg Nuclear Power Station, 1989.

France has their low and intermediate level nuclear waste facilities located within 5 km of populated towns, in very wet regions by European standards, where extensive concrete and clay-engineered solutions are required.
For the High Level Waste, high cost experimentation has been ongoing for the last 16 years in France, to find a solution to store the waste in sedimentary clay rock. This Underground Research Laboratory (URL) is at a depth of 500m and is located within 2.5 km of surrounding villages. The final solution design is now complete and is planned to also be at a depth of 500m, covering an area of 15km^2 of tunnels. The budgeted cost is a figure of some 25 billion Euros over the next 150 years.

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