

# Getting to the Core of **THE NUCLEAR FUEL CYCLE**

From the mining of uranium  
to the disposal of nuclear waste



**IAEA**

International Atomic Energy Agency

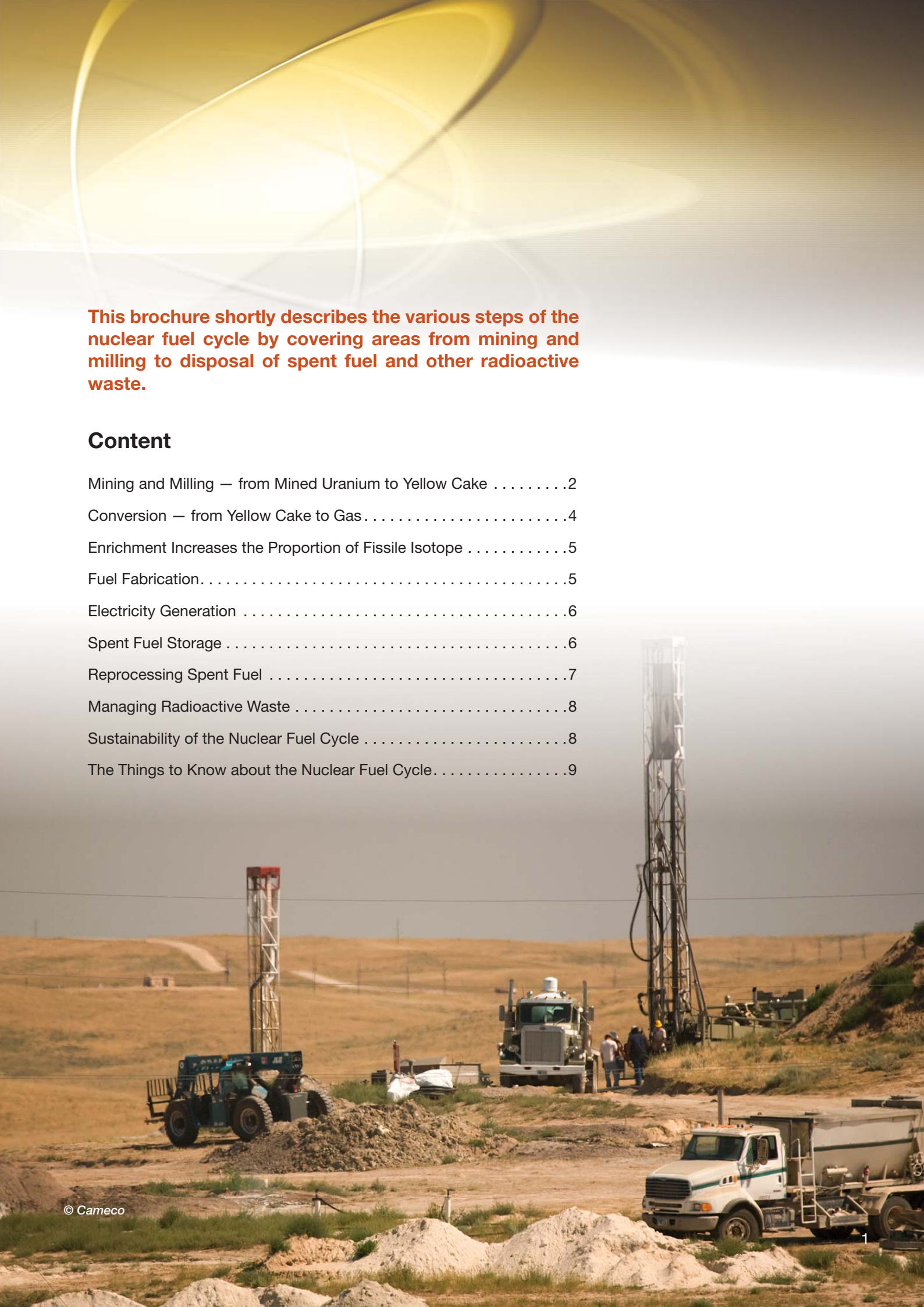
# Getting to the Core of the Nuclear Fuel Cycle

*The various activities associated with the production of electricity from nuclear reactors are collectively referred to as the nuclear fuel cycle.*

**This brochure shortly describes the various steps of the nuclear fuel cycle by covering areas from mining and milling to disposal of spent fuel and other radioactive waste.**

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# Getting to the Core of the Nuclear Fuel Cycle

*The nuclear fuel cycle is an industrial process involving various activities to produce electricity from uranium in nuclear power reactors. The cycle starts with the mining of uranium and ends with the disposal of spent fuel and other radioactive waste.*

The raw material for today's nuclear fuel is uranium. It must be processed through a series of steps to produce an efficient fuel for generating electricity. Spent fuel needs to be taken care of for reuse and disposal.

The nuclear fuel cycle includes the 'front end', i.e. preparation of the fuel, the 'service period', in which fuel is used during reactor operation to generate electricity, and the 'back end', i.e. the safe management of spent fuel including reprocessing and reuse and disposal.

If spent fuel is not reprocessed, the fuel cycle is referred to as an 'open' or 'once-through' fuel cycle; if spent fuel is reprocessed, and partly reused, it is referred to as a 'closed' nuclear fuel cycle.

The nuclear fuel cycle also includes transport of the fuel materials between processing steps, as well as any related research and development activities.

## Mining and Milling — from Mined Uranium to Yellow Cake

The raw material for today's nuclear fuel is uranium, which is a relatively common metal that can be found throughout the world. Uranium is present in most rocks and soils, in many rivers and in sea water. Uranium is about 500 times more abundant than gold and about as common as tin. The largest producers of uranium are currently Australia, Canada and Kazakhstan.

The concentration of uranium in the ore can range from 0.03 to 20%.

Conventional mining can be by open cut or underground methods. Uranium ore can come from a mine specifically for uranium, or as a by-product from mines with a different main product such as copper, phosphate or gold.



The mined uranium ore is crushed and chemically treated to separate the uranium, usually by the addition of acid or alkali. The remaining crushed rock, called 'tailings', must be appropriately disposed of.

Alternatively, for in situ leach mining, acidic or alkaline mining solution is passed directly through the underground ore body via a series of bores or wells and uranium is brought to the surface in a dissolved state for purification. No tailings are produced by this method.

The final result is 'yellow cake', a powder form of uranium oxide ( $U_3O_8$ ) or similar compounds. In yellow cake, which can actually vary in colour from yellow, orange to almost black depending on its exact chemical composition, the uranium concentration is raised to more than 80%.

Milling and purification are generally carried out at or close to a uranium mine. Sometimes, two or more operations may send ore or partially processed uranium to a central facility. After processing, the yellow cake concentrate is securely packed and shipped to a conversion facility.

*Uranium is a common, slightly radioactive material that occurs naturally in the Earth's crust.*



*In a mill, uranium is extracted from crushed ore to enable the conversion process. Yellow cake, the result of milling, is packaged into special steel drums before shipping.*

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*The conversion phase mostly deals with converting yellow cake to the gaseous form to allow enrichment.*

## Conversion — from Yellow Cake to Gas

In general, conversion is a process in which the uranium is converted to a form suitable either for fuel fabrication or enrichment. A minority of nuclear power plants do not require enriched uranium and for these power plants, the yellow cake ( $U_3O_8$ ) is converted to uranium dioxide ( $UO_2$ ) at the conversion plant.

Most power plants, however, require enriched uranium. As enrichment — the next step of the nuclear fuel cycle — requires the material to be in the gaseous form, the yellow cake is converted into uranium hexafluoride ( $UF_6$ ).

$UF_6$  is a gas at relatively low temperature. The gas is fed into large cylinders where it solidifies. The cylinders are loaded into strong metal containers and shipped to an enrichment plant.



*It takes about 10 kg of natural uranium to make 1 kg of uranium enriched to 5%.*  
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## Enrichment Increases the Proportion of Fissile Isotope

Natural uranium consists primarily of two isotopes: 99.3% is  $^{238}\text{U}$  and 0.7% is  $^{235}\text{U}$ . The fission process, by which heat energy is released in a nuclear reactor, takes place mainly with  $^{235}\text{U}$ . As most nuclear power plants require fuel with a  $^{235}\text{U}$  concentration of 3–5%, the proportion of the  $^{235}\text{U}$  isotope must be increased. This process is known as enrichment.

Uranium is enriched in  $^{235}\text{U}$  by introducing the gas into fast spinning cylinders (centrifuges), where heavier isotopes are pushed out to the cylinder walls. Uranium can also be enriched using older technology — known as diffusion — by pumping  $\text{UF}_6$  gas through porous membranes that allow  $^{235}\text{U}$  to pass through more easily than heavier isotopes, such as  $^{238}\text{U}$ . The older diffusion plants are energy intensive and are being phased out to be replaced by far more energy efficient centrifuge enrichment technology.

After enrichment, the  $\text{UF}_6$  is converted to uranium dioxide ( $\text{UO}_2$ ) in powder form, suitable for fuel fabrication.

## Fuel Fabrication

All of the current generation of power reactors use uranium dioxide ( $\text{UO}_2$ ) fuel in the form of ceramic pellets. To make these pellets, ceramic-grade  $\text{UO}_2$  powder is pressed into a cylinder about the size of a fingertip. These pellets are then sintered (baked) at high temperatures to form the ceramic, which is much like making any other ceramic items.

With a melting point around  $2800^\circ\text{C}$ , ceramic pellets can operate at high temperatures. They are also a ‘barrier’ containing radioactivity within the reactor fuel. One uranium pellet contains approximately the same amount of energy as 800 kg of coal or 560 L of oil.

After sintering, the pellets are milled to a very precise size and shape, and loaded into long metal tubes to form fuel elements. These tubes are generally made of zirconium alloys. They hold the fuel pellets and contain any radioactive gases released from the fuel pellets. Many such fuel elements make up a fuel assembly. Fuel assemblies are carefully designed to allow transfer of heat to the cooling water, which flows through them carrying away the heat from the fuel elements during reactor operation.

*Fuel is reactor specific. The fuel assemblies also vary in size.*  
© TVO



# Getting to the Core of the Nuclear Fuel Cycle

*A nuclear power plant produces electricity by  
(1) heating water to  
(2) generate steam that  
(3) makes the turbine rotate to  
(4) enable the generator to produce electricity.*

## Electricity Generation

A nuclear power plant is much like any gas- or coal-fired power plant. Water is heated to produce steam at extremely high temperatures and pressures. This steam is used to drive turbines which then turn generators, producing the electrical energy we use every day.

The significant difference between fossil fuel and nuclear power plants is the source of heat. In a fossil fuel plant, the heat is produced by burning gas or coal. In a nuclear plant, the heat is generated by the fission of some of the uranium in the nuclear fuel assemblies.

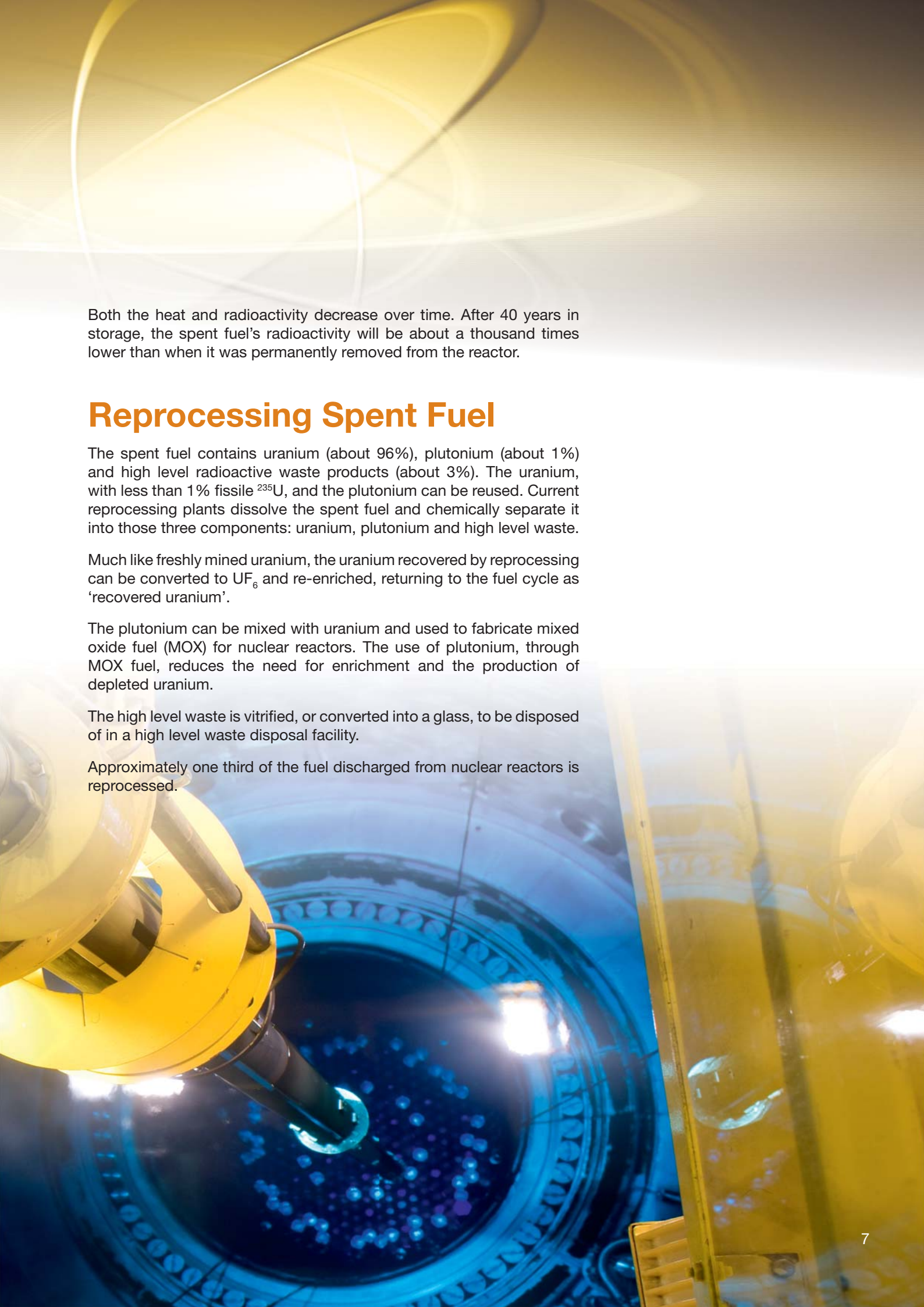
When the nucleus of an atom of, for example,  $^{235}\text{U}$  absorbs a neutron, it may split (or fission) into two pieces, giving off energy as heat and a few more neutrons to continue this nuclear chain reaction. This chain reaction is controlled to produce exactly the desired amount of energy.

Nuclear fuel is typically used in the reactor for 3–6 years. About once a year, 25–30% of the fuel is unloaded and replaced with fresh fuel.

## Spent Fuel Storage

After their useful life of 3–6 years, fuel assemblies are removed from the reactor. After their permanent removal, they are stored under water, which provides both cooling and radiation shielding. Later, for longer term storage, spent fuel assemblies can be moved to another pool for wet storage or to air-cooled, shielded buildings or casks for dry storage.





Both the heat and radioactivity decrease over time. After 40 years in storage, the spent fuel's radioactivity will be about a thousand times lower than when it was permanently removed from the reactor.

## Reprocessing Spent Fuel

The spent fuel contains uranium (about 96%), plutonium (about 1%) and high level radioactive waste products (about 3%). The uranium, with less than 1% fissile  $^{235}\text{U}$ , and the plutonium can be reused. Current reprocessing plants dissolve the spent fuel and chemically separate it into those three components: uranium, plutonium and high level waste.

Much like freshly mined uranium, the uranium recovered by reprocessing can be converted to  $\text{UF}_6$  and re-enriched, returning to the fuel cycle as 'recovered uranium'.

The plutonium can be mixed with uranium and used to fabricate mixed oxide fuel (MOX) for nuclear reactors. The use of plutonium, through MOX fuel, reduces the need for enrichment and the production of depleted uranium.

The high level waste is vitrified, or converted into a glass, to be disposed of in a high level waste disposal facility.

Approximately one third of the fuel discharged from nuclear reactors is reprocessed.

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## Managing Radioactive Waste

In broad terms, radioactive waste is grouped into low, intermediate and high level waste. As some countries use more detailed categorization, the common principle determining the type of waste is the radioactive content and half-life, i.e. the time taken for the waste to lose half of its radioactivity.

Spent fuel (when declared as waste) and high level waste can be safely disposed of deep underground, in stable rock formations such as granite, thus eliminating the health risk to people and protecting the environment. This waste will be packed in durable containers and buried deep in geological formations chosen for their favourable stability and geochemistry, including limited water movement. These geological formations have stability over hundreds of millions of years, far longer than the spent fuel and the high level waste are dangerous for. The first disposal facilities are planned to be in operation around 2020 in Finland and Sweden.

In addition to spent fuel and high level waste, each of the nuclear fuel cycle steps as well as decommissioning of a nuclear facility generate low and/or intermediate level radioactive waste. This includes, for example, water purification resins, paper tissues, used gloves, discarded tools and equipment. It also includes waste from hospitals that use radioisotopes to diagnose and treat cancer, for example.

Low and intermediate level waste is not disposed of conventionally as normal refuse but is carefully segregated, measured for radioactivity and placed into engineered and monitored waste disposal facilities.

## Sustainability of the Nuclear Fuel Cycle

About 14% of electricity consumption in the world is covered by nuclear energy. While many countries are embarking on nuclear energy — or wish to keep the option open of doing so in the future — the increasing use of nuclear power puts stringent demands on the nuclear fuel cycle. Concerted efforts are needed, for example, to increase sustainable uranium production; to better utilize uranium resources; to improve nuclear fuel performance; and to properly manage spent fuel through long term storage as well as reprocessing and recycling.

In addition to these fields, the IAEA supports its Member States to develop materials, fuels and fuel cycles for new, innovative nuclear reactors, which would be more efficient in utilizing uranium fuel, using thorium as a safe and sustainable alternative, while reducing the amount of radioactive waste generated.

The sustainability of nuclear energy has its roots in sustainable nuclear fuel cycle activities. Together with other international organizations, the IAEA is committed to helping countries to maintain or exceed current levels of safety while keeping the electricity production economically competitive.

## The Things to Know about the Nuclear Fuel Cycle

- The nuclear fuel cycle consists of several steps: mining, milling, conversion, enrichment, fuel fabrication and electricity generation.
- The front end of the nuclear fuel cycle produces nuclear fuel for electricity generation.
- The back end of the cycle covers all aspects of spent fuel management, including disposal and/or recycling of the fuel and other waste.
- All steps of the nuclear fuel cycle generate radioactive waste which has to be managed responsibly and in an environmentally sustainable manner.
- The raw material for today's nuclear fuel is uranium which is processed into a form suitable for fuel fabrication.
- The biggest uranium producers are Australia, Canada and Kazakhstan.
- Many countries are either embarking on nuclear energy or wish to keep the option open of doing so in the future. Hence, concerted efforts are needed to ensure that every step of the nuclear fuel cycle is sustainable without posing an undue burden on the environment.





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