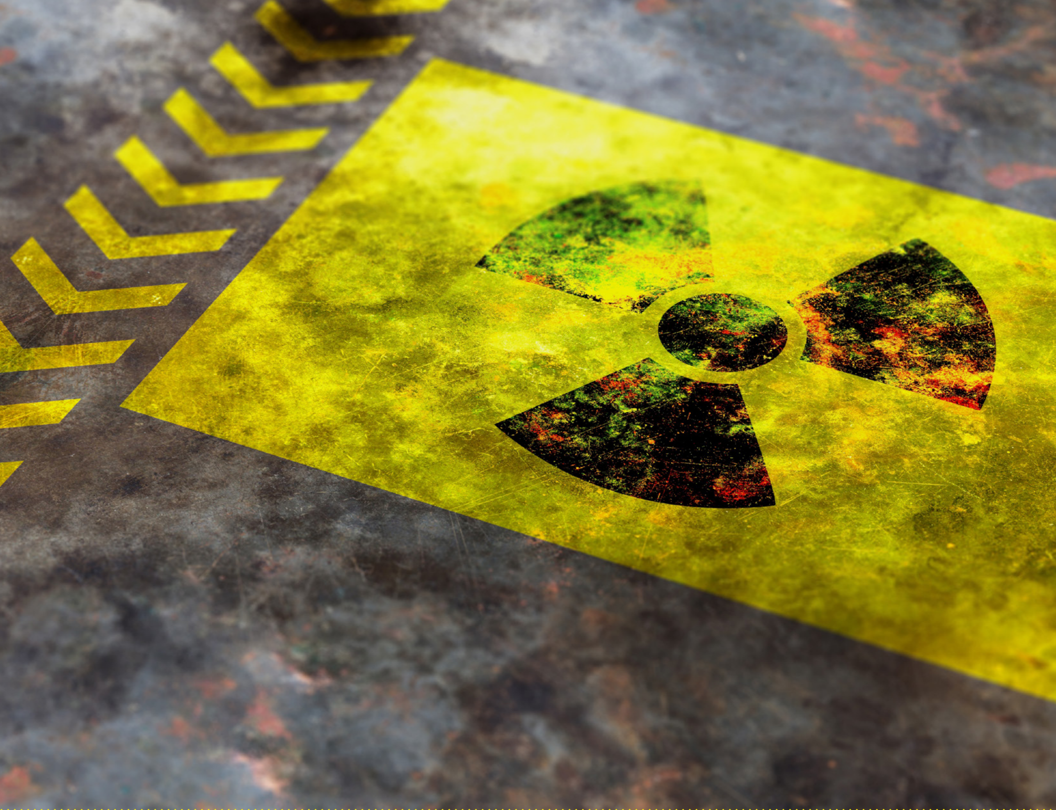


The case against nuclear power

Facts and arguments from A-Z

A PUBLICATION OF BEYOND NUCLEAR

THE URANIUM FUEL CHAIN

1. Uranium ore is mined
2. Uranium ore is milled into yellowcake
3. Yellowcake is turned into UO_2 and then a gas, UF_6
4. Gas is enriched to increase the amount of U-235
5. Enriched UF_6 is converted back to UO_2 and made into fuel assemblies
6. Fuel assemblies are loaded into power reactors to make electricity
7. Irradiated fuel is stored at the reactor site

No safe, long-term, scientifically proven waste solution

Toxic radiological and chemical exposures occur at every phase of the uranium fuel chain.

THE CASE AGAINST NUCLEAR POWER

Overview: The Nuclear Fuel Chain

In this overview, we provide a brief explanation of each phase of the nuclear fuel chain. In the ensuing chapters, we take a deeper look at the specific problems related to each of those phases, as well as the many other risks related to the use of nuclear power. In those chapters, organized alphabetically by topic, you will find greater detail, as well as the key arguments against nuclear power.

We prefer to use the term "nuclear fuel chain" rather than the more widely used "nuclear fuel cycle" which includes reprocessing and suggests a closed loop with no waste production. However, the US no longer uses reprocessing, and did so only for nuclear weapons-making purposes. In the handful of countries that do reprocess, the end product is almost entirely more radioactive waste.

A Uranium Mine

Uranium is a radioactive element. It is mined from the earth in order to be processed and enriched for nuclear reactor fuel and nuclear weapons. The two principle natural isotopes of uranium are **uranium-235** which is fissile (i.e. capable of undergoing fission) and **uranium-238** which is capable of transforming into fissile material or undergoing fission itself under special conditions. There are three kinds of uranium mine: hard rock, open pit and in-situ leach. Uranium-235 comprises less than one percent of the uranium mined from the ground.

1. **A Hard Rock or Underground Mine.** The uranium ore is extracted through deep underground tunnels and shafts. This method is selected where the ore is found deeper underground and where the environment is not suited to in-situ leaching.
2. **An Open Pit Mine.** The uranium ore is extracted from an open air pit, a method typically used when deposits exist relatively near the surface, the site is structurally unstable for tunneling, or the environment is not suited to in-situ leaching.

3. **An In-Situ Leach Mine.** This is the most commonly-used method today. The uranium is extracted using chemical solutions – usually sulfuric acid or ammonium carbonate – that are injected into an aquifer containing uranium ore. This method can only be used when the uranium deposit is located in porous rock, confined in impermeable rock layers. The process dissolves (leaches) uranium from the ore, bringing it to the surface in a liquid plume. Bore holes are drilled into the deposit and sometimes hydraulic fracturing is used to open pathways to allow the chemical solution to penetrate. In-situ leach mining uses vast quantities of – and contaminates – water supplies.

Uranium Tailings

Uranium **"tailings"** are what is left behind after the uranium to be processed into reactor fuel has been extracted. About 85 percent of the total radioactivity in the excavated ore is never used but remains in the tailings. Tailings take the form of radioactive rocks, sand and sludge, and are a serious health hazard, contaminating groundwater and drinking water and, in dry climates, dispersing on the winds.

A Uranium Mill

The uranium ore is crushed and uranium is leached from the ore and concentrated, producing a material known as **"yellowcake,"** the solid form of mixed uranium oxide. Most mills produce a compound comprised mostly of uranyl peroxide dihydrate, which is then transported to a uranium conversion plant.

A Uranium Conversion Plant

The "yellowcake" is transformed into **uranium hexafluoride** or UF_6 by reacting it with fluorine. The resulting product starts out as a gas that is then cooled to a liquid and eventually a solid. In the solid form, it can be shipped to an enrichment plant.

A Uranium Enrichment Plant[1]

Light water reactors use uranium fuel with the uranium-235 content enriched to 3-5%. (Weapons-grade uranium is enriched to 85%. The stage in between is sometime referred to as "weapons usable.") There are three potential kinds of enrichment processes:

1. **Gaseous Diffusion.** This system is no longer in use.
2. **Gas Centrifuge.** In this process, UF_6 gas is placed in a gas centrifuge cylinder and rotated at a high speed.
3. **Laser Separation.** This system is still under development.

A Fuel Fabrication Plant[2]

Low-enriched uranium, in the chemical form of uranium hexafluoride (UF_6), arrives from an enrichment plant and is converted into low-enriched uranium fuel for commercial nuclear reactors. The UF_6, in solid form in containers, is heated to gaseous form, and then the UF_6 gas is chemically processed to form **uranium dioxide** (UO_2) powder. This powder is then pressed into pellets, sintered into ceramic form, loaded into Zircaloy tubes, and constructed into fuel assemblies.

A Nuclear Power Plant

A nuclear power plant is a commercial facility that generates electricity using nuclear reactors. There are two kinds of nuclear power reactors currently in commercial operation in the United States, collectively known as "**light water reactors**". Light water reactors are divided into two different systems – **Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR)**. In both cases, the principle is the same. A nuclear power reactor splits fissile atoms to release tremendous amounts of heat, only 33% of which actually goes into electricity production. The remaining 67% must be dissipated by reactor cooling systems and discharged into the environment to prevent damage to the reactor fuel and the reactor itself.

Consequently, all nuclear power reactors are located on large bodies of water (rivers, lakes, reservoirs and oceans). The splitting of the atom not only produces heat but tremendous amounts of radiation. Under normal operations, the majority of that radiation remains inside the reactor as nuclear waste. However, a portion is routinely released into the air and water, potentially harming the environment.

The Pressurized Water Reactor[3]

The reactor core of 150-200 fuel assemblies inside the pressure vessel creates the heat for steam-driven turbines. The primary coolant loop carries the water at a pressure of more than 2,000 pounds per square inch (therefore it is never allowed to boil). It can then be heated up to 650 degrees F and transferred into a steam generator. There, the heat is transferred through the walls of thousands of tubes in the primary coolant loop, to the thousands of tubes carrying water that is allowed to boil in a secondary loop, where the water can turn to steam and drive the turbine.

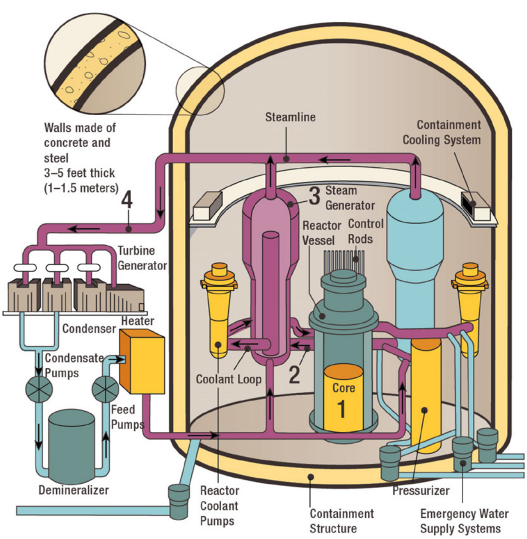


Diagram of a pressurized water reactor. (NRC)

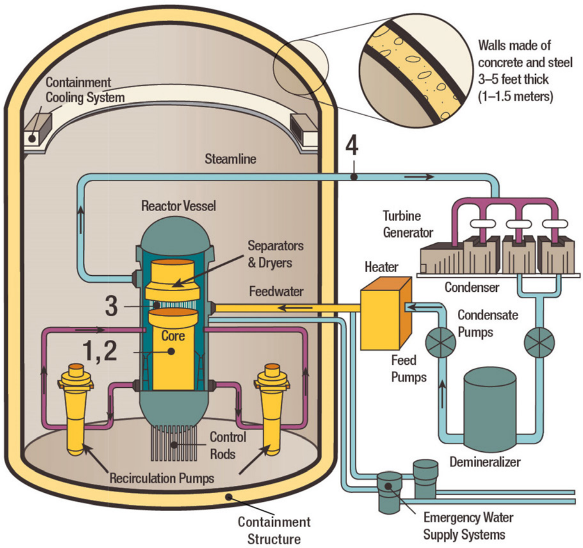


Diagram of a boiling water reactor. (NRC)

The Boiling Water Reactor[4]

A reactor core of 370-800 fuel assemblies boils the water inside the reactor vessel generating steam. Although there are more fuel assemblies in a BWR than a PWR, both reactor cores are roughly the same size – 12 feet tall by 12 feet round – and have the same weight of about 100 tons. In a BWR, a steam-water mixture is produced when very pure water (reactor coolant) moves upward through the core, absorbing heat. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation, where water droplets are removed before the steam is allowed to enter the steamline. The steamline directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.

Closed Cycle and Once-Through Cooling Systems

Nuclear reactors use either **"closed cycle"** cooling or **"once-through"** cooling. The steam leaving the main turbine is condensed and then either evaporated through cooling towers (closed cycle), or directly discharged into the river, lake or ocean (once-through) from which the cooling water was originally drawn. Closed cycle cooling utilizes "mechanical draft systems" using exhaust fans and "natural draft" through large cooling towers. The closed cycle system consumes water, evaporating it as steam. The once-through system draws in and discharges huge amounts of water – as much as a million gallons a minute. This discharged water has been heated during its passage through the nuclear plant and artificially warms the water body into which it is expelled, damaging and even destroying the immediate aquatic environment.[5] Some US reactors use a combination of both. "Direct dry cooling" systems that use air as the cooling medium, much like a car radiator, have been considered but ruled as unfeasible and impractical for nuclear power stations.

What happens at a nuclear reactor

Splitting the atom

When atoms of uranium are fissioned or split, they release energy and radiation. The enriched uranium-235 is the fuel that is housed in **fuel rods** inside **fuel assemblies** placed inside the **core** of the reactor. A 1,000 megawatt reactor contains about 90 tons of uranium in hundreds of fuel assemblies made of fuel rods.

When U-235 fissions, it produces continuous large amounts of heat and radiation in what is known as a **chain reaction**. A **moderator** is used to control the reaction and slow down the neutrons. The moderator is always water in US reactors.

Production of electricity

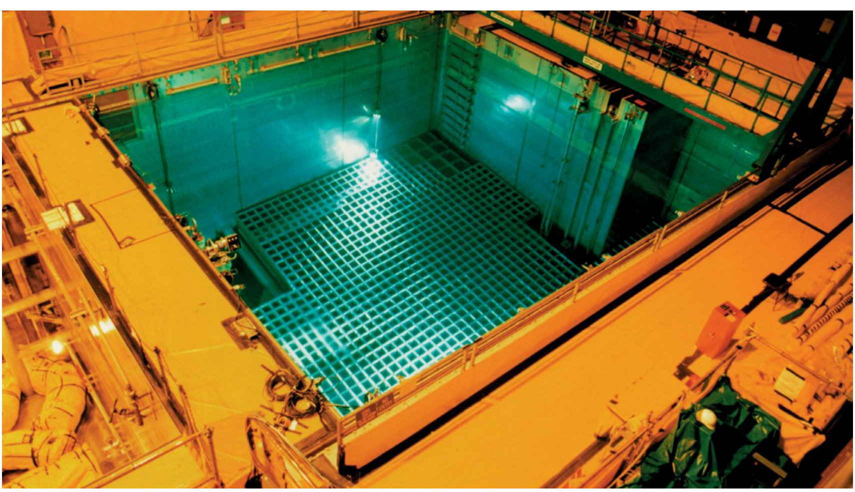
The **reactor core** is located in a steel **pressure vessel**, a primary barrier to contain radioactivity during operation. The steam drives the **turbine** to produce electricity. A typical fuel rod will be in the vessel for 6-8 years, through at least three refueling cycles.

Production of radioactive waste

As **fuel rods** go through the fission process, they become too radioactive to remain in the reactor, increasingly contaminating and degrading reactor parts and structures. Accordingly, every 18 to 24 months, reactors shut down and replace about one third of the fuel assemblies with fresh fuel. The discharged fuel assemblies are correctly termed as irradiated but often called "spent" because their uranium-235 content has been reduced. However, the term "spent" is misleading because the irradiated fuel assemblies contain byproducts from the fission process, many of which are highly radioactive and extremely thermally hot.

Fuel Pools

Irradiated fuel rods are removed from the reactor core and transferred to **fuel pools** where they must be continuously submerged, cooled and shielded under water for a minimum of five years.



Photograph of a reactor fuel pool.

These storage pools were originally designed for short-term storage of irradiated nuclear fuel, or high-level nuclear waste. The waste would then be transferred to a final geological facility, which has never materialized in the US, or used for reprocessing, an operation that was canceled in the US in 1972.

Irradiated fuel assemblies are not being removed from the storage pools at most reactor sites. Instead, they are accumulating in numbers beyond the capacity for which the pools were originally designed, and are remaining in the pools for far longer than the minimum five years, and at some sites, indefinitely. The fuel pool at the average US reactor contains more than six times as much fuel as resides in its core.

In BWRs, the irradiated fuel is transferred and congregated in densely packed water-filled storage ponds that are situated six to ten stories up in the reactor building but outside of the containment structure.

In PWRs, the irradiated fuel is transferred to densely packed water-filled storage ponds at the surface or partially below grade level in an adjacent building, but also outside of – and therefore unprotected by – the thick concrete containment walls.

High-density storage in cooling pools is dangerous because the closely packed and thermally hot fuel rods could catch on fire if cooling water drains out during an accident or sabotage.

Overheated nuclear fuel will chemically interact with steam to generate explosive hydrogen gas.

Dry Cask Storage

Theoretically, after a minimum five-year cooling period, the fuel rods can be removed from the pool and transferred into what is known as **dry cask storage**. The typical dry cask design is a vacuum-sealed steel canister inerted with helium used as an efficient "dry" coolant for the heat transfer from the nuclear waste to the outer steel cask wall.

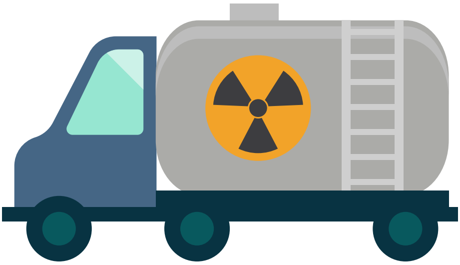
These canisters are loaded into concrete casks, vertically or horizontally, to shield against intense gamma radiation. The casks are ventilated to allow for passive cooling and are parked at the reactor sites in closely packed configurations. The fuel assemblies remain in the casks where they must continue to cool and their radiation shielded.

Cask designs in the US are certified for 20 years of high-level nuclear waste storage and can be reviewed for up to four additional 20-year extensions. Although the current cask designs are by no means adequate technically from a safety and security perspective, this method of interim storage, if properly certified, is preferable to leaving fuel in vulnerable high-density pools. Public safety experts and advocates, however, continue to lobby for more robust cask designs and "hardened onsite storage" as a necessary first line of defense against cask failure and an attack on these potentially enhanced radiological targets.

Nuclear Waste Transportation

The high-level radioactive waste produced by US nuclear power plants currently remains at the reactor sites. Plans to move it would put millions of Americans at risk since the large majority of US nuclear power plants are east of the Mississippi River and so far the only proposed permanent or "interim" dumpsites are in the American West.

This would involve transporting tens of thousands of shipments of high-level radioactive waste across vast distances through major population centers via roads, rails and waterways and past the homes and workplaces of at least 50 million people.



Even without an accident, vehicles and vessels transporting high-level radioactive waste will still expose populations to radiation through the emission of ionizing radiation known as "shine."

A transportation accident involving radioactive waste is virtually inevitable. For example, there are typically more than 400,000 large tuck crashes in the US every year. About 85,000 of these involve injuries or fatalities. Memorable train disasters, such as the July 18, 2001 Baltimore tunnel fire, also sound an ominous warning.

Even without an accident, vehicles and vessels transporting high-level radioactive waste will still expose populations to radiation through the emission of ionizing radiation known as "shine." Measurements of shine from train cars in France, carrying irradiated reactor fuel waste from a nuclear power station, showed ionizing radiation exposures at three times background at a distance of 50 meters. These doses are equivalent to the annual "allowable" dose for nuclear power plant workers. ("Allowable" does not mean "safe.")

A Nuclear Waste Dump

Ever since the first self-sustaining **chain reaction** occurred, on December 2, 1942 at the Fermi "atomic pile" in Chicago, no solution has ever been found for the "disposal" of its radioactive waste. For decades, military and commercial nuclear wastes were discarded by dumping them in barrels into the sea or into unlined earthen trenches. Today, the search continues for a suitable "burial" site.

The favored option for commercial **high-level radioactive** waste is a **deep geological repository**. High-level radioactive waste must be isolated from the environment for at least 10,000 years, a daunting technical challenge. So-called low-level waste has been taken to **regional dump sites**. Given the shortcomings of both options, we prefer the term "dump" to "repository."

"Low-Level" Radioactive Waste

"Low-level" radioactive waste (LLRW) is a misleading catchall phrase that includes radiologically toxic materials – even long-lived plutonium! LLRW is typically defined by the exclusion of what it is not. If it is radioactive waste but not irradiated nuclear fuel, transuranic waste, uranium mine or mill tailings, it is administratively classified as "low-level." Low-level waste is by far the largest volume of nuclear waste and is generated by every phase of the nuclear fuel chain.

"Low level" does not mean "low risk" for public health, safety and the environment. Nor are all low-level radioactive wastes sent to dumpsites. For example, operating reactors release large volumes of routine and permitted radioactive tritium, a clinically effective mutagen and carcinogen that makes up the reactor cooling water being continuously discharged into lakes, reservoirs, rivers and oceans.

So far, the US government has identified only one candidate site for high-level radioactive waste – on Western Shoshone land at Yucca Mountain, Nevada. However, the federal government has evaluated other potential deep geological burial sites in nearly a dozen states.

Low-level radioactive waste sent to a dumpsite typically includes items contaminated with radioactive material or that have become radioactive through exposure to neutron radiation. These include protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment and tools, luminous dials, medical tubes, swabs, injection needles, syringes, and laboratory animal carcasses and tissues.

Low-level radioactive waste is broken down into four categories, determined by the level of radioactivity being emitted, ranging from just above background levels found in nature to very high radioactivity such as filters and concentrated sludge accumulating in a nuclear power plant.

Trace amounts of plutonium, another clinically effective carcinogen even in minute doses, can be found in some of these low-level radioactive waste streams.

Low-level waste is typically stored on site by licensees to allow for radioactive decay before it is containerized and shipped to a low-level radioactive waste disposal dump site.

In the US, there are presently four operating low-level waste dumps located at Barnwell, SC; Clive, UT; Andrews, TX; and Richland, WA. There are scores of low-level radioactive waste dumps around the US that are now closed to receiving more nuclear waste but that are experiencing leakage.[6]

High-Level Radioactive Waste

High-level radioactive wastes (HLRW) are the highly radioactive materials produced as a byproduct of the fission reaction that occurs inside nuclear reactors. Because HLRW contains highly radioactive fission products, it must be isolated from the environment for hundreds of thousands of years. This requires predictably reliable technological and geological barriers not yet scientifically achieved and proven.

HLRW principally includes all of the irradiated commercial nuclear fuel. Along with uranium products, HLRW contains radioactive strontium, cesium and plutonium. In the US, all of the irradiated nuclear fuel currently remains at commercial nuclear reactor sites submerged underwater in densely-packed pools or in individual dry cask storage canisters.

So far, the US government has identified only one candidate site for high-level radioactive waste – on Western Shoshone land at Yucca Mountain, Nevada. However, the federal government has evaluated other potential deep geological burial sites in nearly a dozen states.

The US government has spent more than $9 billion in federal money on the Yucca Mountain site. In 2009, the Obama Administration defunded and stopped the federal licensing process. However, efforts are presently underway in Congress to put Yucca Mountain back on the table.

A Blue Ribbon Commission of the US Department of Energy under President Obama recommended "Consolidated Interim Storage" as a "temporary" alternative to Yucca Mountain. Considered "consent-based" volunteer sites, these have so far been

So far, the proposed high-level waste repository at Yucca Mountain consists of an engineered tunnel. At press time it remained canceled but could be revived by Republicans in the US Congress.

targeted at low-income communities of color and are essentially indefinite parking lot dumps that, if ever opened, are unlikely to remain temporary and would present serious health, safety and security risks.

Weapons-Grade Radioactive Waste

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, stores what is known as **"transuranic" waste**, principally plutonium-239, plutonium-240 and americium-24, from the US nuclear weapons program.

With the government failure to scientifically evaluate, build and open Yucca Mountain to nuclear waste storage, arguments have been made to store high-level radioactive reactor waste at WIPP, even though it is not designed to accommodate the hotter and more radioactive commercial irradiated waste fuel.

WIPP is a deep geological dump in salt dome deposits, opened in 1999. It was licensed to last 10,000 years but 15 years in suffered a serious accident that temporarily shut the facility down. In February 2014, a radioactive leak followed an earlier underground explosion and truck fire, contaminating at least 17 workers with americium-24 who were working on the surface at the time. Air sensors detected plutonium half a mile away from the site.

The WIPP accident raised serious questions about the repository's suitability to accept commercial high-level radioactive waste. Although there was an official "reopening ceremony" in January 2017, part of the site remained closed and there are continuing problems with rock falls causing tunnel collapse and roof cave-ins within the repository.[7]

Reprocessing does not reduce the volume of waste. It creates enormous amounts of radioactive sludges and liquids as well as radioactive gases that are discharged into the air and water.

Reprocessing

Reprocessing[8] does not take place in most countries, including the US. Technically, it is therefore not part of the uranium fuel chain. However, we provide an explanation here, as it is frequently offered up by nuclear proponents as a way to "close" the nuclear fuel "cycle."

Reprocessing is the **chemical separation** of **uranium** and **plutonium** contained in irradiated reactor fuel that has been removed from the reactor. The uranium and plutonium is separated from the other wastes also found in the irradiated reactor fuel.

What is plutonium-239?

Plutonium does not occur in nature. It is a man-made isotope. Plutonium (Pu-239) is formed in a nuclear power reactor by transmutation of individual atoms of one of the isotopes of uranium present in the fuel rods. Light water reactors produce considerable power by splitting plutonium atoms. In fact, during the latter months of a 18- or 24-month operating cycle, more than half of the power produced by a commercial nuclear reactor comes from plutonium rather than uranium fissions. This is why plutonium-239 is found in reactor waste fuel.

The purpose and practice of reprocessing

The original purpose of reprocessing was to extract plutonium for the manufacture of nuclear weapons. For example, the US used reprocessing in the 1940s to extract the plutonium used in the Trinity atomic bomb test. Reprocessing in the US, at the Savannah River Site in Aiken, SC, was halted by the Ford administration in 1972 due to proliferation concerns.

Reprocessing continues in the UK, Russia, and France, although the UK reprocessing plant at Sellafield is scheduled to close some time in 2018. Japan closed its Tokai reprocessing plant in 2007 and its much postponed Rokkasho reprocessing facility had not opened by press time. India and China are both intent on starting reprocessing. Reprocessing does not reduce the volume of waste. It creates enormous amounts of radioactive sludges and liquids as well as radioactive gases that are discharged into the air and water. In France, a small amount of plutonium extracted through reprocessing is re-used in a reactor fuel known as mixed-oxide fuel, or **MOX** (see below).

Mixed-Oxide Fuel (MOX)

Mixed-oxide fuel, or MOX, is not currently manufactured in the US. As with reprocessing, however, we include an explanation here in the Overview, given the US MOX fuel fabrication facility is yet to be permanently canceled and it remains necessary to debunk the false claims about a "need" for MOX fuel manufacture and use.

When nuclear promoters claim that nuclear waste can be "recycled" they are talking about MOX. Reprocessing is necessary in order to extract plutonium from irradiated reactor fuel that could then potentially be manufactured into MOX and reused in a nuclear power plant.

MOX is nuclear **fuel** that contains more than one **oxide** of fissile material, usually consisting of plutonium blended with natural uranium, reprocessed uranium, or depleted uranium.

France uses a 30% load of MOX fuel in about 20 of its commercial nuclear reactors. However, as the fission process produces plutonium, there is no net reduction of plutonium, also because irradiated MOX fuel cannot be reprocessed.

In the US, the construction of a **MOX fuel fabrication** plant has been "underway" for more than a decade. It is located near the Savannah River Site where the US used to reprocess irradiated reactor fuel, a necessary precursor to extract the plutonium for MOX.

However, the price tag for the MOX plant had ballooned to more than $17 billion by late 2017, is far behind schedule and may well be canceled.

[1] Uranium Enrichment, NRC. https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html
[2] Fuel Fabrication, NRC. https://www.nrc.gov/materials/fuel-cycle-fac/fuel-fab.html
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[6] Federal Nuclear Facility Cleanup Sites. http://www.ncsl.org/research/environment-and-natural-resources/federal-nuclear-facility-cleanup-sites.aspx
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[8] Reprocessing. Union of Concerned Scientists. https://www.ucsusa.org/nuclear-power/nuclear-plant-security/nuclear-reprocessing#.WnseFWPt-DU

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