Nuclear Power Science and Technology

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KREMESTI ENVIRONMENTAL CONSULTING

PASSION FOR CHEMISTRY

Main Modules

- Nuclear Fuel
- Radioactive Decay
- Nuclear Waste Immobilization and Disposal
- Radiation Shielding and Protection
- Reactor Physics, Criticality and Design
- Nuclear Fuel Cycle
- Decommissioning, Waste and Environmental Management
- Criticality Safety Management
- Severe Accidents

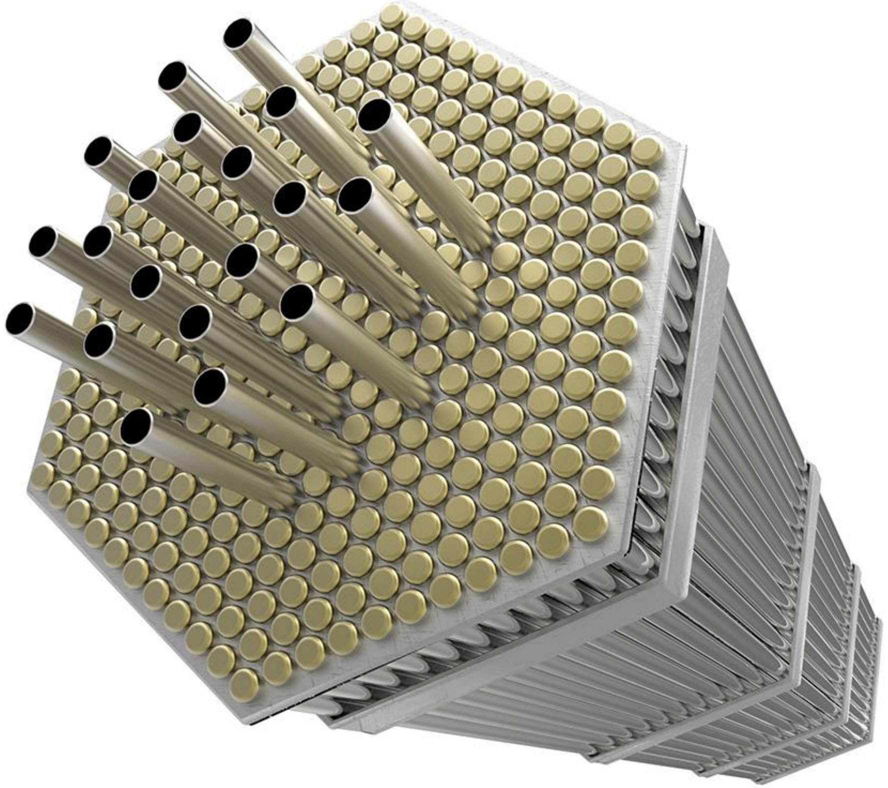
Nuclear Fuel

- Uranium is the most widely used fuel by nuclear power plants for nuclear fission. Nuclear power plants use a certain type of uranium—U-235—as fuel because its atoms are relatively easy to split apart. Although uranium is about 100 times more common than silver, U-235 is relatively rare at just over 0.7% of natural uranium. Uranium concentrate is separated from uranium ore at uranium mills or from a slurry at in-situ leaching facilities. It is then processed in conversion and enrichment facilities, which increases the level of U-235 to 3%–5% for commercial nuclear reactors and made into reactor fuel pellets and fuel rods in reactor fuel fabrication plants.

Nuclear Fuel Cycle - Fuel Fabrication

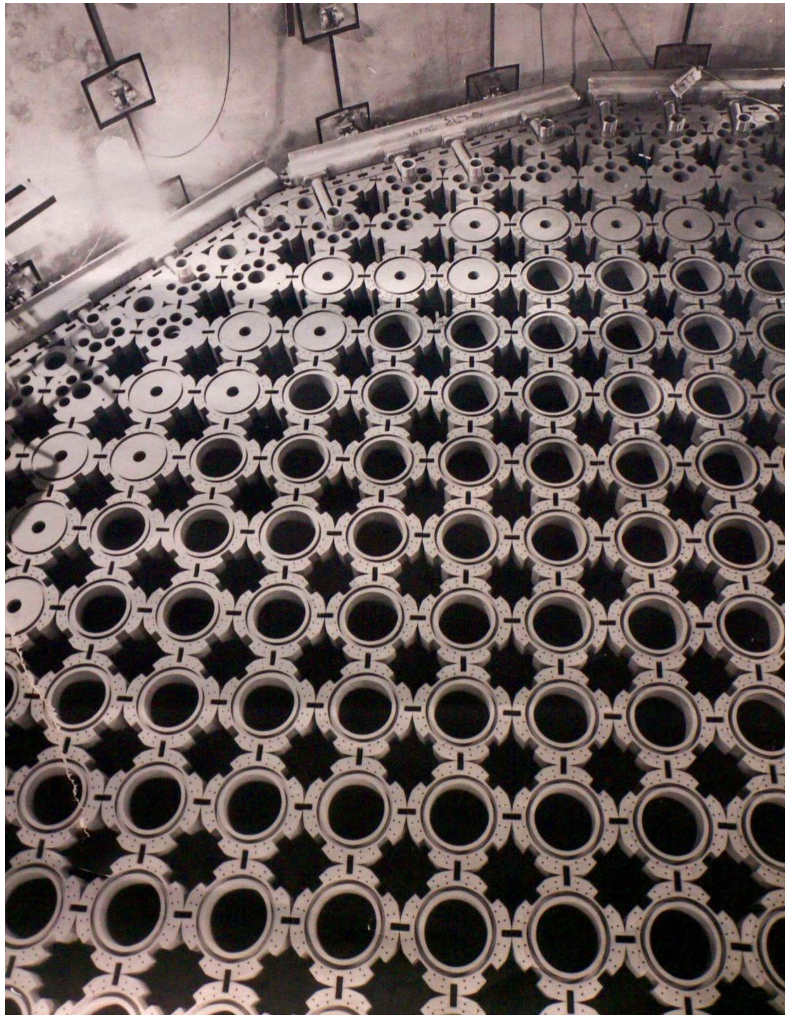
- Reactor fuel is generally in the form of ceramic pellets that contain Uranium. These are formed from pressed uranium oxide (UO_2), which is sintered (baked) at a high temperature (over 1400°C). The pellets are then encased in metal tubes to form fuel rods, which are arranged into a fuel assembly ready for introduction into a reactor. The dimensions of the fuel pellets and other components of the fuel assembly are precisely controlled to ensure consistency in the characteristics and behaviour of the fuel.
- In a fuel fabrication plant great care is taken with the size and shape of processing vessels to avoid criticality (a limited chain reaction releasing radiation). With low-enriched fuel criticality is very unlikely, but in plants handling special fuels for research reactors this is a vital safety consideration.
- Some 27 tonnes of fresh enriched fuel is required each year by a 1000 MWe reactor.

Nuclear Rods Contain Uranium Pellets



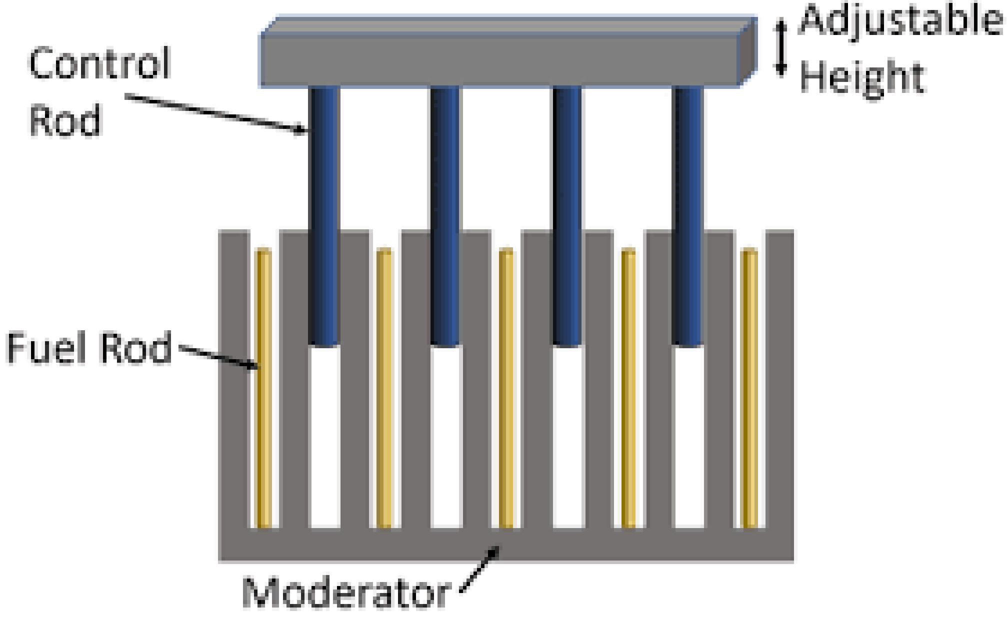
Graphite blocks in nuclear Reactor Cores

- Graphite bricks are used in the core of all of the UK's Advanced Gas-Cooled Reactors (AGRs). They act as a moderator, helping to keep the nuclear reaction going, and perform an important safety function: they reduce the speed of neutrons and allow a nuclear reaction to be sustained.



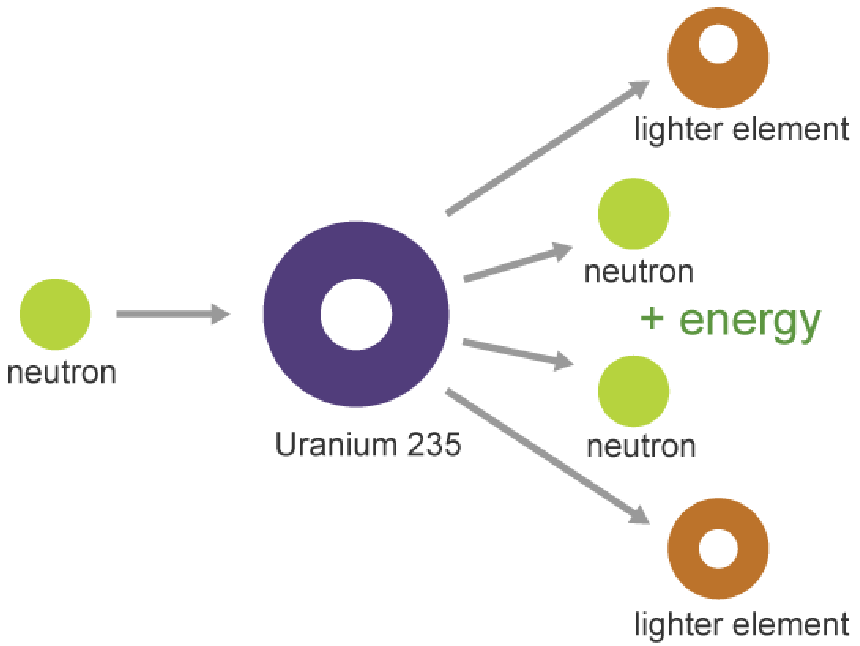
Power Control Rods

- Control rods are rods, plates, or tubes containing a neutron absorbing material (material with high absorption cross-section for thermal neutron) such as boron, hafnium, cadmium, etc., used to control the power of a nuclear reactor. A control rod is removed from or inserted into the reactor core to increase or decrease the reactor's reactivity (increase or decrease the neutron flux). This, in turn, affects the reactor's thermal power, the amount of steam produced, and hence the electricity generated.



Nuclear Fission Reaction

- During nuclear fission, a neutron collides with a uranium atom and splits it, releasing a large amount of energy in the form of heat and radiation. More neutrons are also released when a uranium atom splits. These neutrons continue to collide with other uranium atoms, and the process repeats itself over and over again.



How fission splits the uranium atom

Source: Adapted from National Energy Education Development Project (public domain)

The Uranium Fission Reaction

- 92 U-235 + 1 neutron → 36 Kr-92 + 56 Ba-141 + 3 neutrons + energy
- Both the barium and krypton isotopes subsequently decay and form more stable isotopes of Neodymium and Yttrium, with the emission of several electrons from the nucleus (beta decays). It is the beta decays, with some associated gamma rays, which make the fission products highly radioactive.

Radioactive Decay

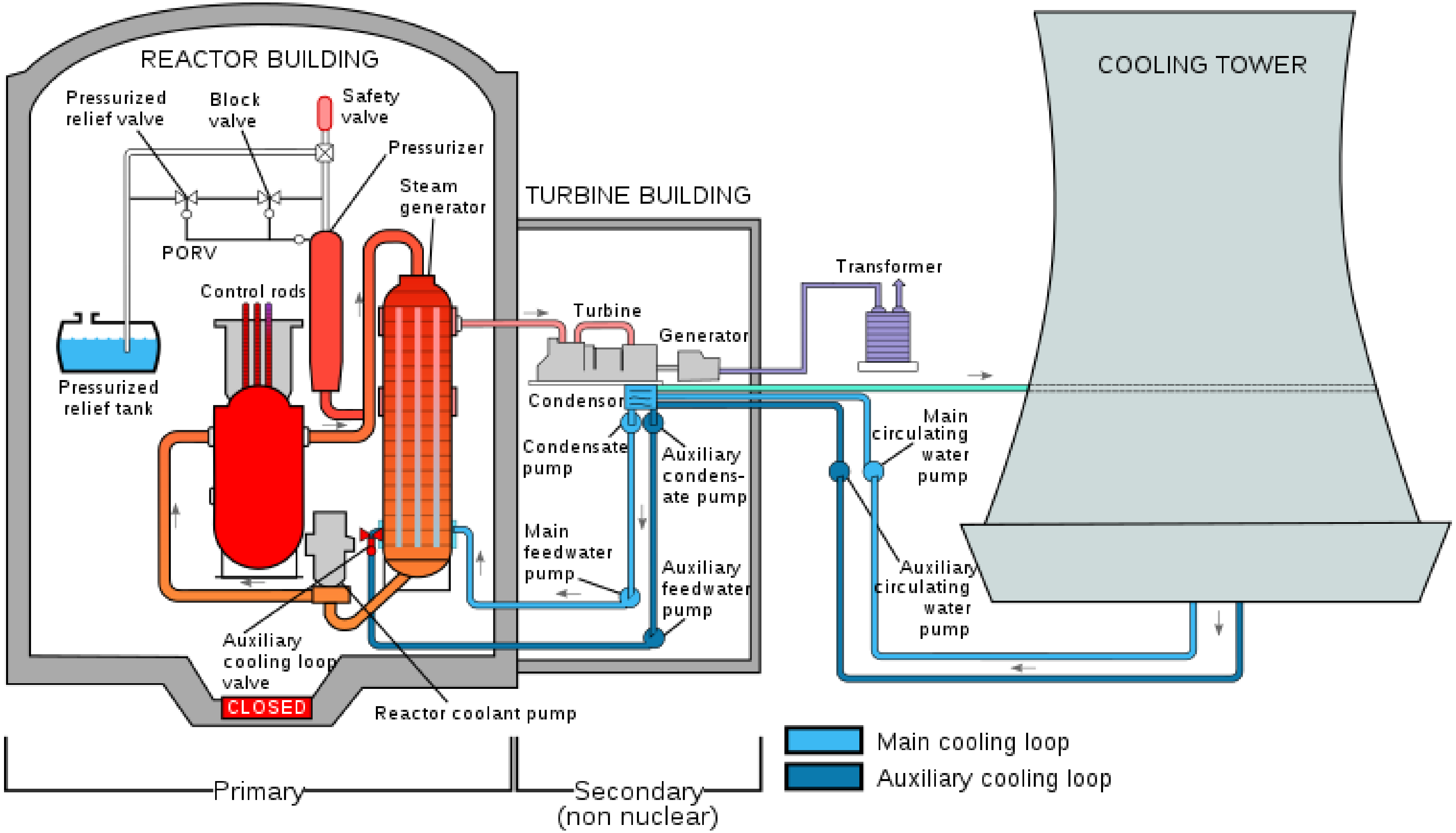
- Radioactive Decay releases radiation which is dangerous if exposed to:

This radiation can be emitted in the form of particles or electromagnetic waves:

1. positively charged alpha particles,
2. negatively charged beta particles,
3. gamma rays
4. x-rays

Notice the difference between particles and electro-magnetic rays.

Nuclear PWR Power Station Schematic



Criticality

- Criticality is the normal operating condition of a nuclear reactor, in which nuclear fuel sustains a fission chain reaction. A reactor achieves criticality (and is said to be critical) when each fission releases a sufficient number of neutrons to sustain an ongoing series of nuclear reactions.
- The International Atomic Energy Agency defines the *first criticality date* as the date when a nuclear reactor is made critical for the first time. This is an important milestone in the construction and commissioning of a nuclear power plant.

Nuclear Power Plant Safety Engineering

- Interesting video from Canadian Nuclear Safety Commission - CNSC

https://www.youtube.com/watch?v=yx_XoqXNtRM

- Nuclear plants internationally follow IAEA safety standards.

Nuclear Waste Immobilization and Disposal

- Nuclear waste must be processed to make it safe for storage, transportation, and final disposal, which includes its conditioning, so it is immobilized and packaged before storage and disposal.
- Nuclear waste immobilization is the conversion of waste into a safer waste form by solidification, embedding, or encapsulation that reduces the potential for migration or dispersion of radionuclides during operational and disposal stages of waste lifecycle.
- Immobilization of waste is achieved by its chemical incorporation into the structure of a suitable matrix (typically cement, glass, bitumen, or ceramic) so it is captured and unable to escape.

Radiation Shielding and Protection

Shielding from Nuclear Radiation:

- Barriers of lead, concrete, or water provide protection from penetrating gamma rays. Gamma rays can pass completely through the human body; as they pass through, they can cause damage to tissue and DNA.
- To reduce typical gamma ray intensity by a factor of a billion, according to the American Nuclear Society, thicknesses of the shield need to be about 13.8 feet of water, about 6.6 feet of concrete, or about 1.3 feet of lead.

Nuclear Fuel Cycle - Power generation and burn-up

- Several hundred fuel assemblies make up the core of a reactor. For a reactor with an output of 1000 MWe, the core would contain about 75 tonnes of low-enriched uranium. In the reactor core the U-235 isotope fissions or splits, producing a lot of heat in a continuous process called a chain reaction. The process depends on the presence of a moderator such as water or graphite, and is fully controlled.
- Some of the U-238 in the reactor core is turned into plutonium and about half of this is also fissioned, providing about one-third of the reactor's energy output (or more than half in CANDU reactors).
- As in fossil-fuel burning electricity generating plants, the heat is used to produce steam to drive a turbine and an electric generator. Through this process, a 1000 MWe unit provides over 8 billion kilowatt hours (8 TWh) of electricity in one year.
- To maintain efficient reactor performance, about one-third of the spent fuel is removed every year or 18 months, to be replaced with fresh fuel.e The length of fuel cycle is correlated with the use of burnable absorbers in the fuel, allowing higher burn-up.
- Typically, some 44 million kilowatt-hours of electricity are produced from one tonne of natural uranium. The production of this amount of electrical power from fossil fuels would require the burning of over 20,000 tonnes of coal or 8.5 million cubic metres of gas.

Nuclear Fuel Cycle - Power generation and burn-up - II

- An issue in operating reactors, and hence specifying the fuel for them, is fuel burn-up. Fuel burn-up is measured in gigawatt-days (thermal) per tonne and its potential is proportional to the level of enrichment. To date a limiting factor has been the physical robustness of fuel assemblies, and hence burn-up levels have been limited to about 40 GWd/t, requiring only around 4% enrichment. With the advancement of equipment and fuel assemblies, 55 GWd/t is now possible (with 5% enrichment), and 70 GWd/t is in sight (though this would require 6% enrichment). The benefit of increased burn-up is that operation cycles can be longer – around 24 months – and the number of fuel assemblies discharged as used fuel can be reduced by one third. Associated fuel cycle cost is expected to be reduced by about 20%.
- In CANDU reactors using natural uranium, burn-up is much less, about 7.5 GWd/t, but in terms of efficiency this is equivalent to almost 50 GWd/t for enriched fuel.

Burn Up - Continued

- Burn-up in GWd/t is the conventional measure for oxide fuels, and 60 GWd/t U is equivalent to about 6.5 atomic percent burn-up (*i.e.* about 6.5% of the original uranium atoms are burned directly, or indirectly via transformation to fissile plutonium). (With metal fuels, the atomic percent metric is used, and a new light water reactor metal fuel is targeting 21 atomic percent burn-up when it is deployed in 2020s.)
- As with coal-fired power stations, about two thirds of the heat produced is released, either to a large volume of water (from the sea or large river, heating it a few degrees) or to a relatively smaller volume of water in cooling towers, using evaporative cooling (latent heat of vaporization).

Nuclear Fuel Cycle - Used fuel

- With time, the concentration of fission fragments and heavy elements in the fuel will increase to the point where it is no longer practical to continue using it. So after 18-36 months the used fuel is removed from the reactor. The amount of energy that is produced from a fuel assembly varies with the type of reactor and the policy of the reactor operator. Used fuel will typically have about 1.0% U-235 and 0.6% fissile plutonium (almost 1% Pu total), with around 95% U-238.f The balance, about 3%, is fission products and minor actinides.
- When removed from a reactor, the fuel will be emitting both radiation, principally from the fission fragments, and heat. It is unloaded into a storage pond immediately adjacent to the reactor to allow the radiation levels to decrease. In the ponds, the water shields the radiation and absorbs the heat, which is removed by circulating the water through external heat exchangers. Used fuel is held in such pools for several months and sometimes many years. It may then be transferred to naturally-ventilated dry storage, generally on site.

Nuclear Fuel Cycle - Used fuel

- Depending on the policies of particular countries, some used fuel may be transferred to central storage facilities. Whilst there is a clear incentive for interim storage, used fuel must ultimately either be reprocessed in order to recycle most of it, or prepared for permanent disposal. The longer it is stored, the easier it is to handle, due to decay of radioactivity.

There are two options for used fuel:

- Reprocessing to recover and recycle the usable portion of it.
- Long-term storage and final disposal without reprocessing.

Decommissioning, Waste and Environmental Management

- Decommissioning refers to the administrative and technical actions taken to remove all or some of the regulatory controls from an authorized nuclear facility so the facility and its site can be reused.
- Decommissioning includes activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management.

Decommissioning of Nuclear Power Station in the UK by EDF - Main Steps

- There are around 300 fuel channels in each reactor, all of which need to be carefully emptied.
- A de-fuelling machine removes the fuel assembly from a channel and each fuel element is transferred to a cooling pond where it stays for a minimum of 90 days.
- Once cooled, the fuel is removed from the pond, packaged, and loaded into a container called a flask. The flask is transported by train to Sellafield in Cumbria where it is further cooled and stored until it is safe to be disposed of.

Nuclear Waste Disposal in the UK

- Management of High Level (Spent Nuclear Fuel) Waste:

This is a process called 'vitrification' and converts the waste into a stable, solid form for long-term storage and disposal. This process takes place at the Sellafield site in Cumbria, UK.

GDF Onkalo - Finland

- The Onkalo spent nuclear fuel repository (GDF = Geological Disposal Facility) is a deep geological repository for the final disposal of spent nuclear fuel (400-500 m deep). It is near the Olkiluoto Nuclear Power Plant in the municipality of Eurajoki, on the west coast of Finland.
- It is being constructed by Posiva, and is based on the KBS-3 method of nuclear waste burial developed in Sweden by Svensk Kärnbränslehantering AB (SKB). The facility is expected to be operational in 2023.

KBS-3

- The method is based on three protective barriers that prevent radiation from the nuclear waste reaching the geosphere. The three barriers are:
- copper canisters,
- Bentonite clay and
- the bedrock.

- KBS is a Swedish abbreviation of kärn-bränsle-säkerhet, nuclear fuel safety)

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