THE NUCLEAR FUEL CYCLE

Reference to Vattenfall AB

Environmental Product Declarations

S-P-00021 and S-P-00026

2010

TABLE OF CONTENTS

Illustrations are mostly from Vattenfall but some are from open websites.

1 OVERVIEW

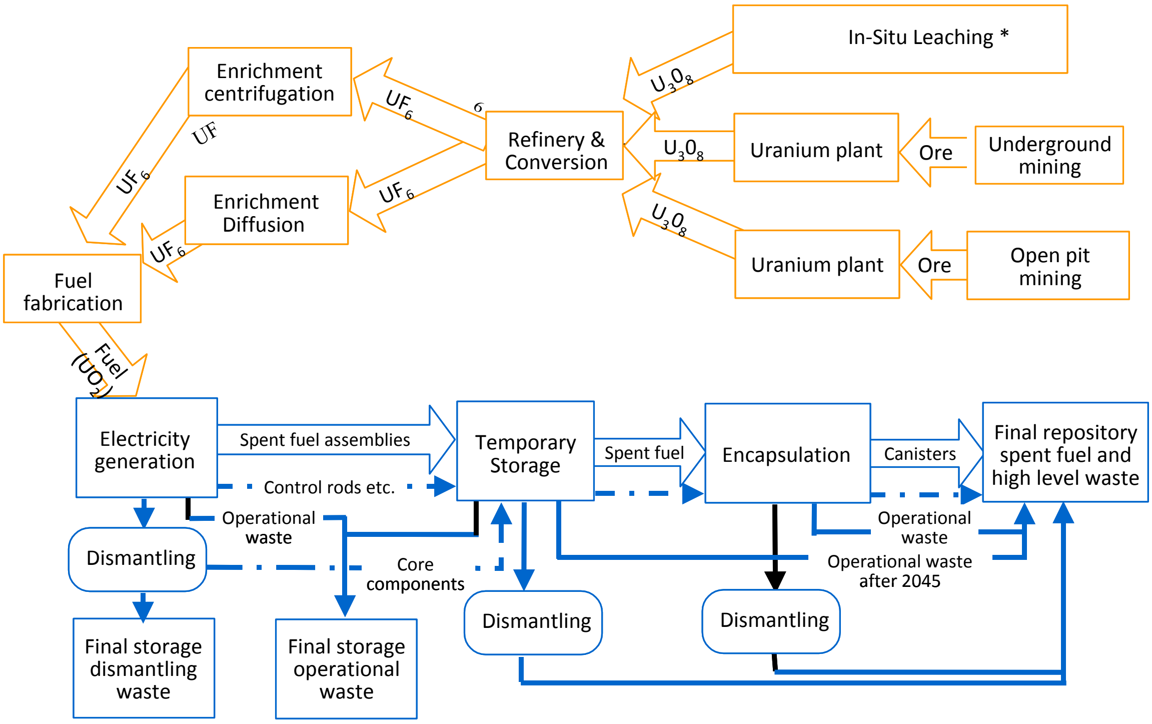
This document is a presentation of the nuclear fuel cycle for electricity generation at Vattenfall's nuclear power plants in Sweden.

Uranium

Oil, coal, natural gas, and uranium are energy resources, which can be processed into fuels for electricity generation. The fuel for a nuclear power plant is uranium, which is relatively abundant in the Earth's crust. Uranium is 500 times more common than gold and about as common as tin. Natural uranium consists of the isotopes U-238 (approx. 99.3%) and U-235 (approx. 0.7%), and traces of U-234. Staying in the proximity of, or even holding, natural uranium is not dangerous from a purely radiation point of view, but it is a chemically toxic, heavy metal that is hazardous if allowed to enter the body.

From mining to electricity and final repository

The flow chart below illustrates the various steps of the nuclear fuel cycle from mining to final repository.



*) Vattenfall has at present no contracts on in-situ leaching.

Figure 1.1 The various steps in the Nuclear Fuel Cycle.

2 URANIUM EXTRACTION

Uranium is extracted from the Earth's crust in different ways, Open Pit Mining, Under-ground Mining and In-Situ Leaching. The mining method for uranium does not differ appreciably from those of iron or copper mining. The choice of mining method basically depends on relative costs and factors such as size, shape, depth, and concentration of the ore deposits. Several substances are often extracted from the same mine in order to achieve a profitable operation. Environmental, health, and safety aspects are similar irrespective of the type of ore being mined.

2.1 Open Pit Mining

The ore is hauled to a mill, normally located close to the mine. In the mill the ore is crushed, pulverized, and mixed with water to a feed slurry. The uranium oxide is leached with sulfuric acid and the uranium bearing solution is separated from the sand. The solution is cleaned and treated with ammonia to yield a uranium dioxide powder, with uranium content of approximately 70% "yellowcake". The U_3O_8 powder is packed in steel drums and sealed for shipment. Uranium dioxide is weakly radioactive and a person standing one meter from such a drum is exposed to radiation corresponding to about half of that received from cosmic radiation inside a commercial airplane at an altitude of 10 000 meters.

The remaining slurry is pumped from the mill to a tailings pond. The processes in the mine and in the mill generate waste such as chemicals, sand and water. The water is cleaned and neutralized by adding lime and barium chloride and the solids are allowed to precipitate before the water is released. The solid waste is deposited in depleted open pit mines. After an open pit mine has been decommissioned the site it is reclaimed by covering it with excavation material, landscaping and revegetating it to a condition as closely as possible resembling the predevelopment (baseline) state. Another purpose of the finishing operation is to reduce radon gas emissions to levels at or below natural levels.

2.2 Underground Mining

Several mining techniques are used, and the choice of mining method depends on the characteristics of the ore body. In mines with high uranium concentration, only mechanized and automated mining is used because of excessive radon radiation. The Olympic Dam mine, primarily copper, in Australia for example, utilizes a variant of sublevel open stooping, in which blocks of mineralized ore are systematically blasted and the ore recovered for crushing below ground. The crushed ore is then hoisted up one of the shafts to the surface stockpile. Further processing is the same as for open pit mining, see above.

2.3 In-Situ Leaching

In-Situ is Latin and means “in position”. The In-Situ Leaching method, ISL for short, is used in North America as well as in Australia and in the former Soviet Union. Diluted sulfuric acid, alkali solution or water is circulated through porous ore underground dissolving the uranium, which can be extracted from the slurry after it has been pumped to the surface. Uranium daughters, such as radium, remain where they were thus avoiding any additional release of radon gas into the biosphere. ISL mines consist of well fields, pipelines, a compact and simple uranium extraction plant, and drying facilities.

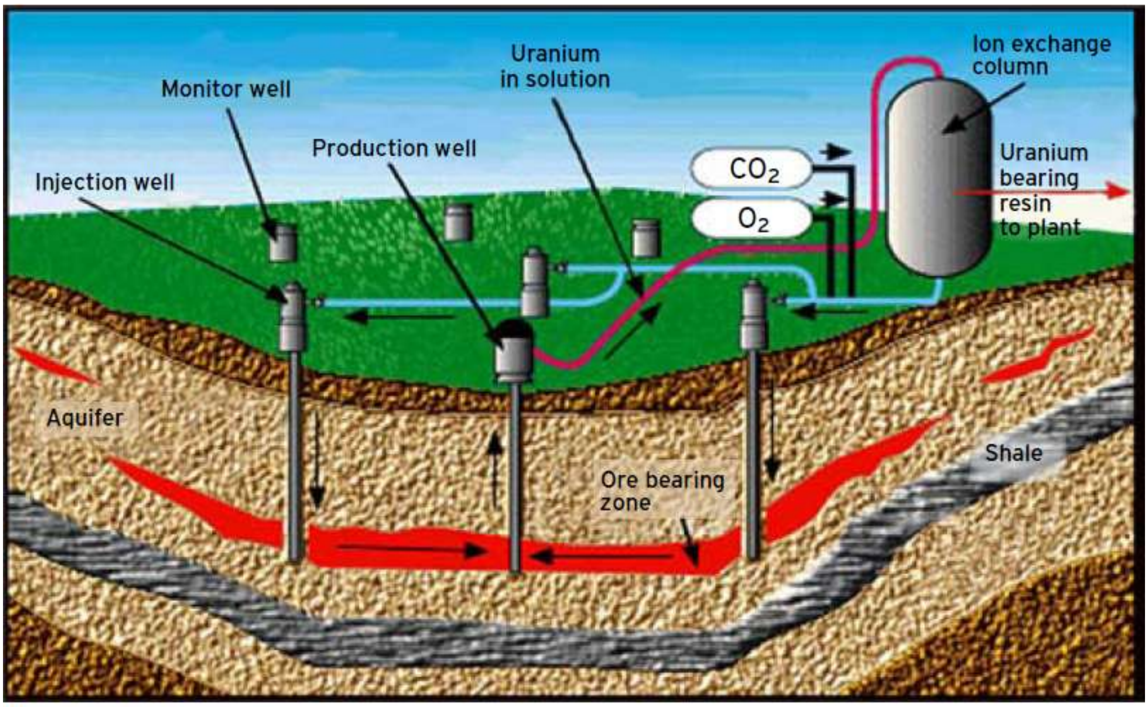


Figure 2.1. In-Situ-Leaching.

3 CONVERSION

3.1 Refinery

The uranium concentrate, must be further refined before it can be used as fuel for nu- clear reactors. Neutron absorbents must be removed, as they would otherwise block the chain reaction in the reactor thus stopping the fission process. The feed for a refinery is uranium concentrate, and the output is pure UO3.

The refinery process consists of the following steps:

- Nitric acid is added, yielding a uranyl nitrate solution
- Solids are extracted from the uranyl nitrate solution in three steps
- Water is vaporized, yielding a concentrated uranyl nitrate hexahydrate solution
- Concentrated uranyl nitrate hexahydrate is heated to yield uranium trioxide (UO3)

Most of the nitric acid added in the first step is separated in the last step and recirculated.

3.2 Conversion

Conversion is performed in two steps. First, hydrofluoric acid is added to uranium trioxide (UO_3) to yield uranium tetrafluoride (UF_4). Then UF_4 reacts with fluorine gas to yield hexa fluoride gas (UF_6). UF6 changes states readily within a small temperature range. The UF6 gas is passed through several filters and finally through cold traps, and collected as crystalline UF6. The UF6 is liquefied by heating and drained into specially designed steel cylinders for shipment, and it solidifies when pressurized.

4 ENRICHMENT

Most nuclear reactors require fuel with a U-235 content of 3–5%. At room temperature UF_6 is a solid, similar to paraffin. At 65°C and warmer UF_6 is a gas and can be enriched either by gaseous diffusion or by gas centrifugation. Both processes enrich UF_6 from 0,7% U-235 to the required level (the rest of the uranium is U-238). The uranium is kept as UF_6 and cooled to solid form before shipment to fuel fabrication facilities.

4.1 Gaseous Diffusion

The gaseous UF_6 is passed through a fine porous filter, and as U-235 is slightly lighter than U-238 the gas on the other side of the filter is slightly enriched. This must be repeated 1 400 times in order to yield the required 3–5% of U-235. The method is very energy-intensive as it consumes 3–4% of the electricity generated. The output is enriched UF_6 with 3–5% U-235 and a depleted fraction, in which the content of U-235 varies inversely with world uranium prices.

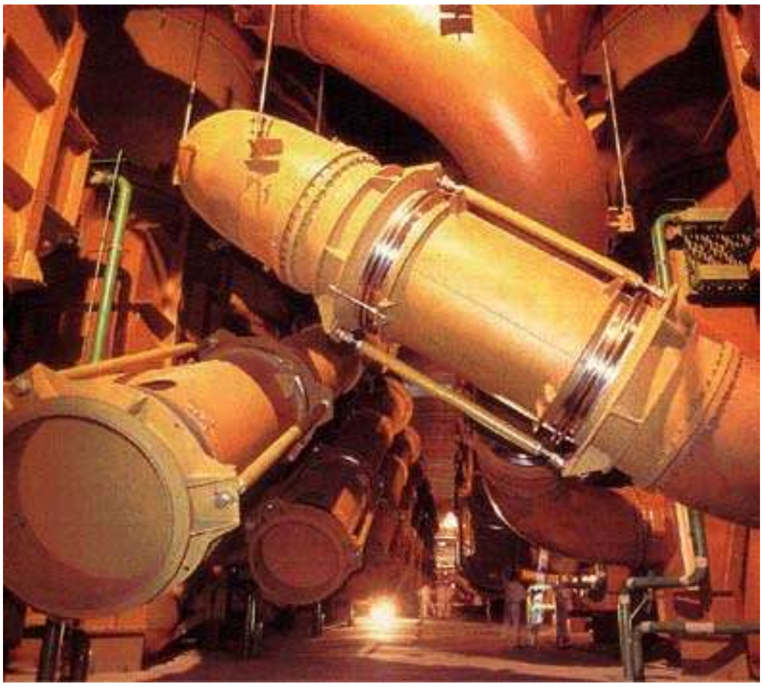


Figure 4.1. Tubing and filters for UF_6 enrichment.

4.2 Gas Centrifugation

The isotope U-238 is heavier than the isotope U-235 and the centrifugal forces will tend to separate the two isotopes by throwing the heavier U-238 towards the outer wall of the centrifuge. A centrifuge comprises a vacuum casing containing a cylindrical rotor, 1–2 meters long and 15–20 cm in diameter, rotating at 50,000–70,000 rpm in an extremely low friction environment. Gaseous UF6 is fed into the rotor where it picks up the rotational motion. The centrifugal forces push the heavier U-238 closer to the wall, where the gas is depleted of U-235 whereas nearer to the axis the gas is enriched in U-235.

The process is further enhanced by the gas flow inside the rotor caused by an axial temperature gradient, which causes gas depleted in U-235 to flow upwards along the rotor wall and gas enriched in U-235 to flow downwards along the axis. The two gas flows are removed through pipes at each end of the centrifuge.

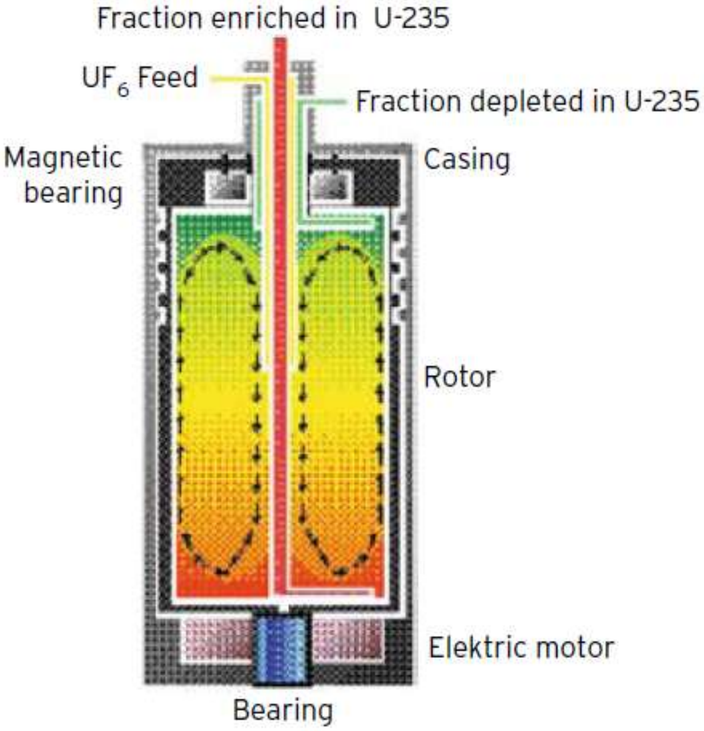
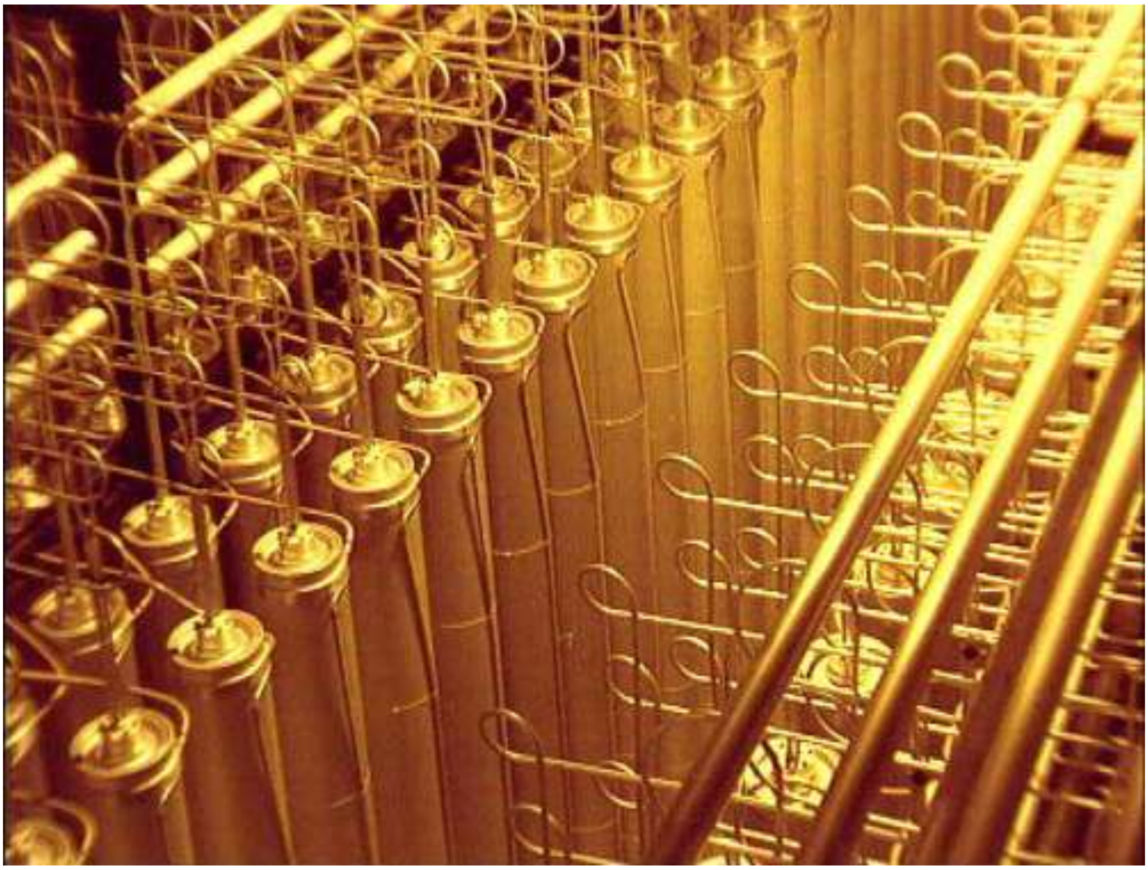


Figure 4.2. The centrifuge.

In order to reach the required content of 3–5% U-235, centrifuges must be cascaded, since the enrichment from a single one is minute. The depleted fraction contains 0.2–0.4% depending on world uranium prices.



Figur 4.3. Cascaded centrifuges, which can run maintenance free for more than 10 years. This method is energyware efficient, consuming approximately 0.1% of the electricity generated.

5 FUEL FABRICATION

The uranium arrives as enriched, solid UF_6 at the fuel fabrication facility, where it is heated into gaseous state. Ammonia, gaseous oxygen, and gaseous hydrogen are added to yield uranium dioxide powder. The UO_2 powder is compressed into cylindrical pellets weighing 6–7 grams.

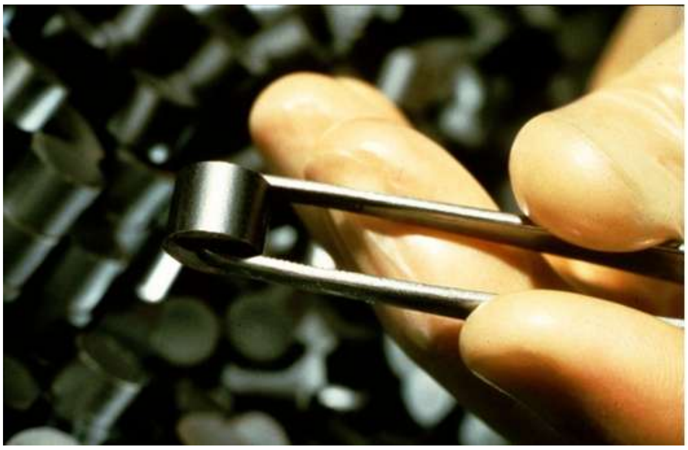


Figure 5.1. UO_2 pellets.

The pellets are sintered to a structure resembling ceramics and are ground to final dimension, after which 300–370 of them are placed in zirconium alloy (zircaloy) tubes approximately 3,7 meters in length.

Figure 5.2. Fuel rods

The tubes are pressurized with helium and sealed to form fuel rods, which are then bundled into fuel assemblies in which the number of rods depends on the design of the reactor. A boiling water reactor (BWR) holds between 400 and 700 fuel assemblies comprising a maximum of 70 000 fuel rods. A pressurized water reactor (PWR) holds some 160 fuel assemblies with a maximum of 42 000 fuel rods.

Zircaloy is an alloy of zirconium (98%), tin (1,5%), and small amounts of iron, nickel, and chromium. It does not absorb neutrons, is very resistant to corrosion, and it withstands high temperatures, all of which makes it particularly suited for deployment in nuclear reactors.

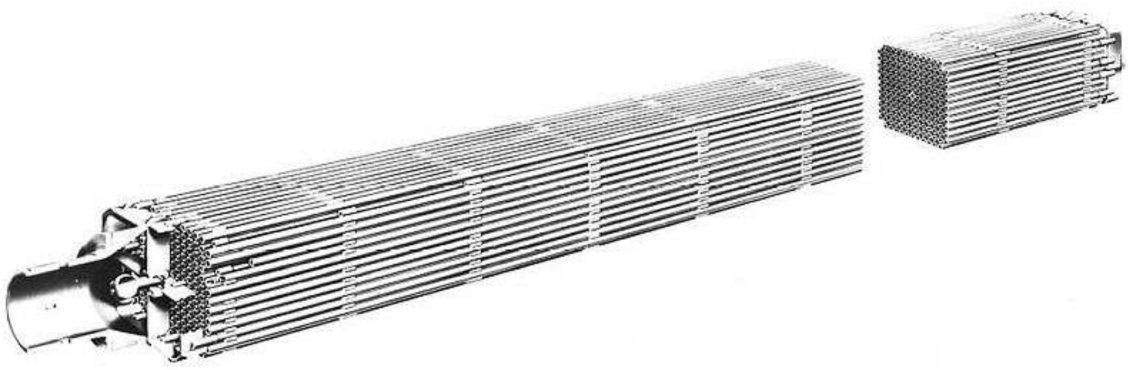


Figure 5.3. Fuel assembly

The fuel factory also fabricates control rods, mainly made from stainless steel. Control rods for BWRs have small cavities filled with boron carbide and hafnium oxide. PWRs use control rods with an alloy of indium, cadmium, and silver encapsulated in the stainless steel.

6 ELECTRICITY GENERATION

In a nuclear reactor neutrons are used to split uranium nuclei (fission). The fission releases energy in the form of kinetic energy of the fission particles, as well as in the form of radiation. The energy is transformed to heat, which in turn is used to heat the water in the reactor. The steam drives a turbine connected to a generator, which converts the energy to electricity. After passing through the turbine the steam is condensed to water in a condenser through heat exchange with a cooling agent (seawater), and after filtering the water is recirculated into the reactor.

Vattenfall's nuclear reactors are light water reactors (LWR), and normal desalinated water is used as the cooling agent. There are two main types of LWRs, (the aforementioned BWR and PWR), pictures below.

Pressurized Water Reactor, PWR

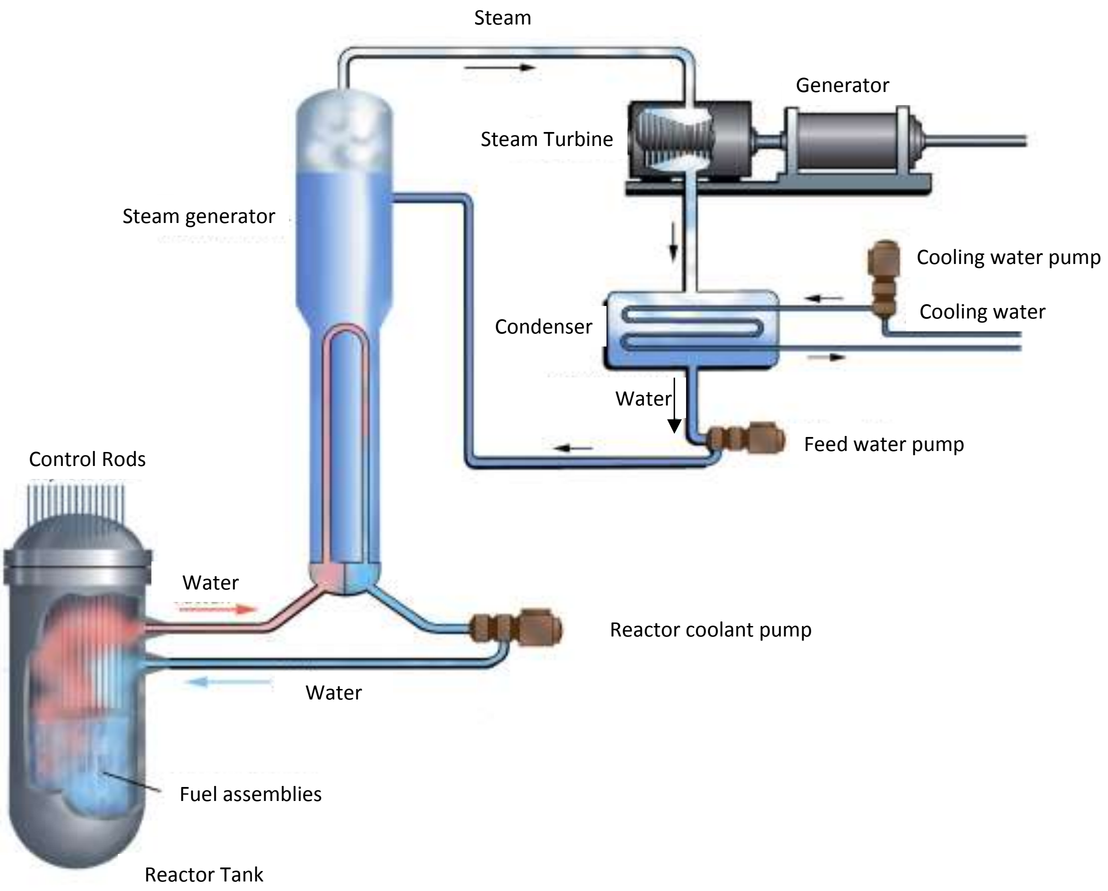


Figure 6.1. Basic PWR.

Boiling Water Reactor

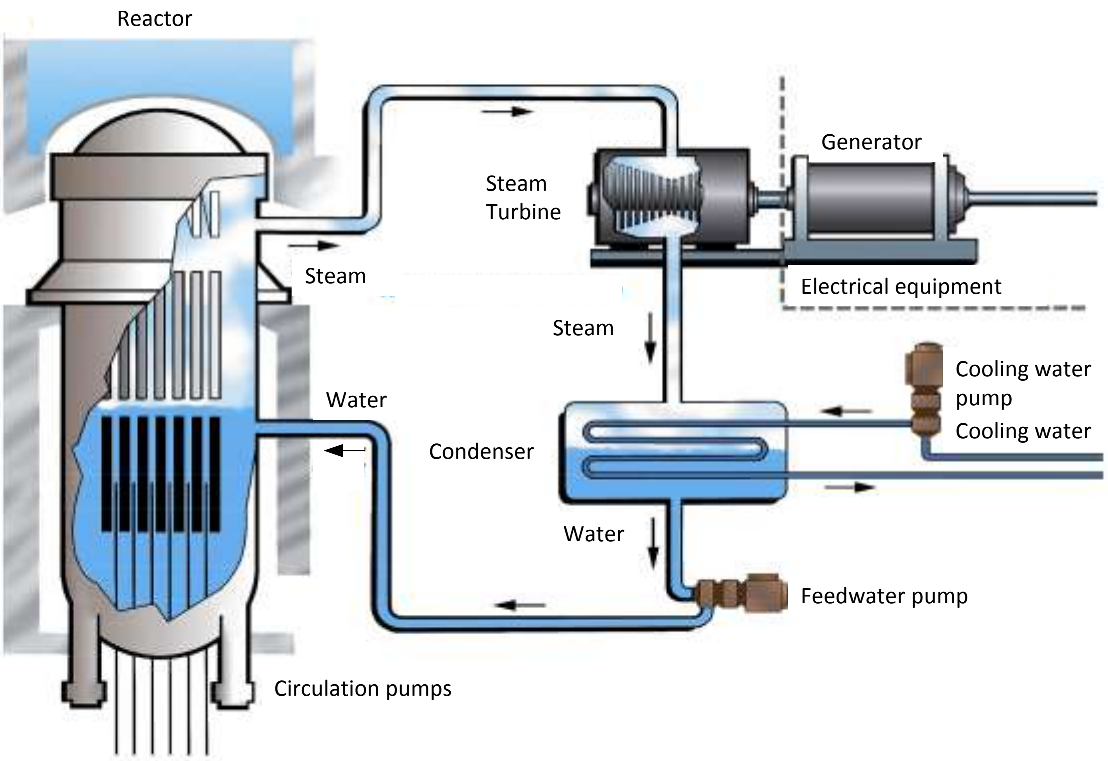


Figure 6.2. Basic BWR.

The nuclear reaction is the same in both types of reactor. Neutrons collide with uranium nuclei, which split and release energy. The fissions release new neutrons, which collide with more uranium nuclei and thus the process continues. The process in both reactor types is controlled with control rods. In PWRs the reactor water has neutron-absorbing additives (boron) as well.

In BWRs the reactor water is heated until it vaporizes in the reactor itself. In PWRs the reactor water is pressurized in the reactor without vaporization, and the superheated water flows to a steam generator where the heat is exchanged with another water circuit. That water is vaporized and the steam drives a steam turbine as in the case of BWRs.

The main difference between BWR and PWR is that PWRs have two water circuits – one for reactor water and the other one for feed water to the steam cycle. The water in the PWR is never vaporized and it does not drive the steam turbine. Because the water is not vaporized in the PWR the reactor vessel can be smaller than that of a BWR. On the other hand a PWR building is larger than a BWR building as it must also accommodate steam generators and other equipment.

7 WASTE MANAGEMENT

7.1 Overview

Operation of a nuclear power plant generates solid waste, some of which is more or less radioactive. This waste is categorized into operational waste, decommissioning waste, and spent nuclear fuel. The radioactive waste categories are divided into low, intermediate, and high level radioactive waste. Depending on the amount of time the substances in the waste remain radioactive yet another classification is short-lived and long-lived waste. The spent fuel and control rods are high level waste. The operational waste is low and intermediate level waste and consists of protective equipment, tools, and replaced components from active areas of the nuclear power plant as well as filter substances.

Low level waste is treated either inside the nuclear power plant and subsequently stored in a separate waste burying facility at the site, or processed together with the intermediate level waste. After sorting and cleaning some low level waste will display such a low activity as to be processed as normal non-active waste. This type of waste (exempt waste) may be reused or deposited in a normal facility.

Intermediate level waste and some low level waste is transferred to SFR (Final Repository for Radioactive Operational Waste), located under sea level at Forsmark. The waste will be stored and isolated until the radioactivity has decayed to a safe level. Calculations indicate that in 500 years time the waste will radiate less than the surrounding rock.

Spent fuel is high level waste and is kept at the nuclear power plant for one year, and after that for 30-35 years at CLAB (Central Interim Storage Facility for Spent Nuclear Fuel), and finally encapsulated and placed in a final repository.

Other waste, e.g. non-radioactive waste is also generated.

7.2 SFR

The Final Repository for Radioactive Operational Waste, SFR, is located in the vicinity of the nuclear power plant at Forsmark. SFR is a common facility for final storage of short-lived low and intermediate level waste of Swedish origin. SFR is located in bedrock more than 50 meters below the seafloor, the depth of water being 5 meters.

Figure 7.1 . SFR receiving station and the three reactor blocks of Forsmark in the distance.

The operation of a nuclear power plant generates various types of radioactive waste, on one hand spent fuel which is high level and long-lived, and on the other operational waste which is low or intermediate level and short-lived. Only low and intermediate level waste is stored at SFR. The intermediate level waste consists mainly of ion exchange resins. Radioactive material adheres to the walls of pipes, valves, pumps, etc., and this is taken care of as the components are replaced. Most of this waste is low level waste. This category also includes everything used in areas where radioactive material may be present, e.g. tools, protective equipment, etc.

During operation the parts of the nuclear power plant in and around the reactor vessel are irradiated by the nuclear activity. Radioactive material is spread to other sections of the power plant by the coolant. Therefore these parts must be treated as radioactive waste when the nuclear power plant is decommissioned. This type of waste is short lived and of low and intermediate level and will be deposited in an expansion of SFR with a special permit from the Swedish Government.

When the waste arrives at SFR it is encapsulated in protective containers. The intermediate level waste is molded in concrete or asphalt as well. Other low level waste is incinerated and arrives at the facility in metal containers. Thus there is no free radioactivity anywhere at SFR.

The facility is accessible from the surface via two parallel tunnels about one kilometer in length. The present storage areas consist on one hand of four160 meters long rock vaults and on the other of a 70 meters high chamber which houses a concrete silo.

Low level waste is stored in intact transportation containers in one of the four rock vaults. The waste in this section of the facility is handled without radiation shielding and moved out with normal forklifts.

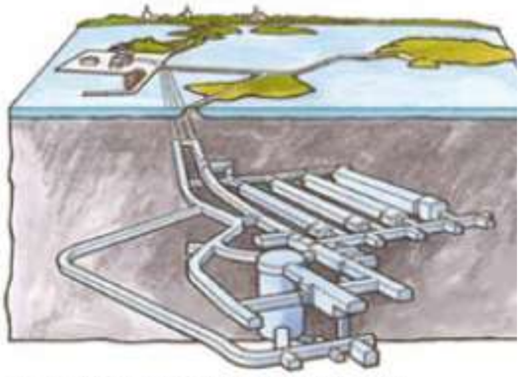


Figure 7.2. Sketch over the SFR facility.

Figures 7.3 Rock vaults at SFR.

Three of the rock vaults receive intermediate level waste, requiring radiation shielding. Two of these vaults are used for storage of dried ion exchange resins in concrete tanks. In a cylindrical chamber there is a 50 meters high concrete silo (with an inner diameter of 26 meters). This silo is intended for storage of intermediate level waste, and is mainly utilized for spent filters.

7.3 CLAB – Central Interim Storage for Spent Nuclear Fuel

Central Interim Storage Facility for Spent Nuclear Fuel is located on the Simpevarp peninsula in close proximity to the Oskarshamn nuclear power plant (OKG). CLAB has a receiving area at surface level where containers arrive and the spent fuel unloaded under water. The storage is located in two rock vaults, the ceilings being 25–30 meters below ground level. The vaults are 120 meters long and each contains four storage pools and one reserve pool.

Figure 7.4. CLAB with reactor blocks Oskarshamn 1 and 2 in the distance.

The spent fuel has been stored for at least 9 months in the storage pools at the power plants before it is transferred to CLAB. During this time the major portion of the radioactivity of the fuel will have decayed. The radioactivity in the fuel is, however, still very high and the fuel must be shielded and cooled. Spent fuel is shipped to CLAB enclosed in heavy shipping containers, casks, which shield from radiation and protect against damage. These containers are robust and designed to withstand large external forces, such as a drop from a height of 9 meters and a pressure corresponding to a depth of 4 000 meters of water. At CLAB the spent fuel is stored in deep pools of water.

The water provides shielding of radiation as well as cooling. After 30-35 years of storage at CLAB the radioactivity has decreased by approximately 90%, but the spent fuel still requires shielding. At this point the spent fuel will be encapsulated for storage in final repository.

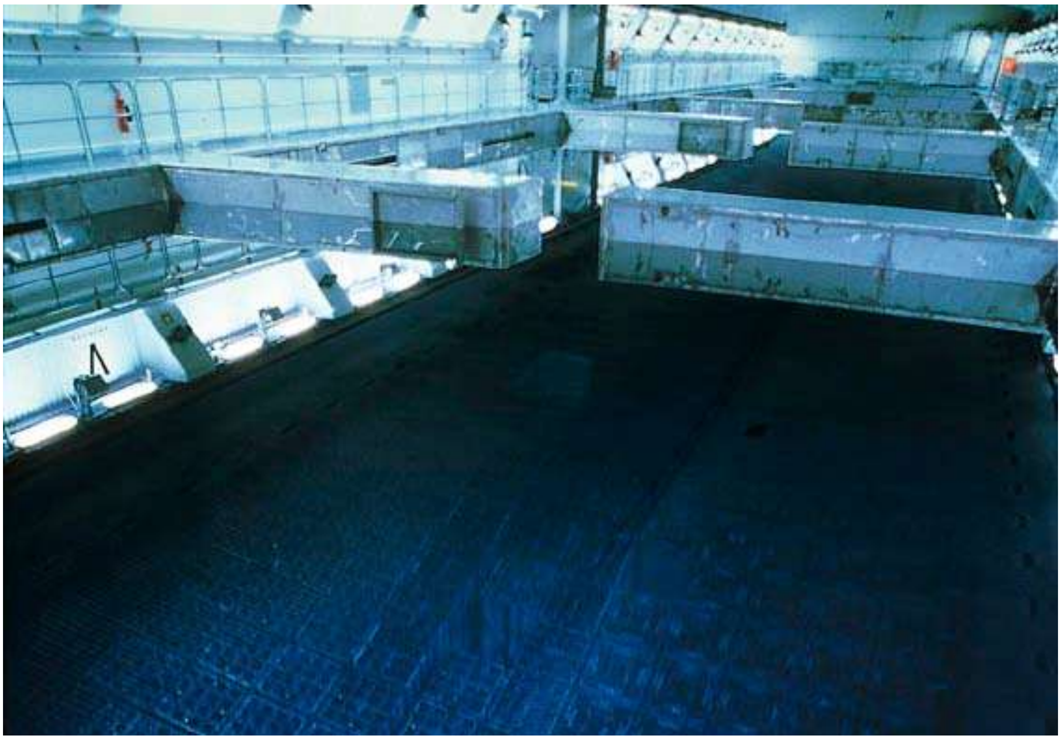


Figure 7.5. Pools at CLAB.

7.4 Encapsulation

Encapsulation will be performed in a separate facility close to CLAB. The encapsulation facility receives spent fuel from the storage pools at CLAB. The spent fuel is placed in copper canisters after checking and drying, whereupon the canisters are sealed, possibly even filled with noble gas. The seals are checked and the canister cleaned before being placed in an intermediate storage awaiting transfer to deep repository. Encapsulation will be performed by remote control in well-shielded areas. The shipment will utilize the same type of containers as those used for shipment of spent fuel from the nuclear power plants to CLAB. At a later stage the encapsulation facility will process other long-lived waste, such as core components, control rods, and other parts, which have been activated by neutron irradiation. The plan is to encapsulate these components in concrete.

7.5 Final Repository

The Final repository will be built in the vicinity of Forsmark’s nuclear power plant. The copper canister is one of the most important barriers, as it must isolate the spent fuel from the ground water for a very long time. The canister must remain watertight; it must neither be damaged by corrosion, nor by the mechanical stress in the final repository.

In order to achieve this the plan is to construct the canister with an outer casing of copper for protection against corrosion, and an inner housing of cast iron or steel for mechanical stability. Copper corrodes very slowly in the non-acid and oxygen depleted ground water deep in Swedish crystalline bedrock. Any oxygen is rapidly consumed by some of the hundreds of species of microbes populating the ground water seeping through the bedrock since thousands of year. Studies show that the canister will remain watertight for at least one million years, which is considerably longer than the 100 000 years during which the spent fuel placed in canister radiates more than rich uranium ore.

The canister will be placed in final repository at approximately 500 meters depth in bedrock, where they will be embedded in special clay, bentonite, which swells in water and thus will fill the space between the rock and the canister. The location of the final repository in Sweden is not yet determined.

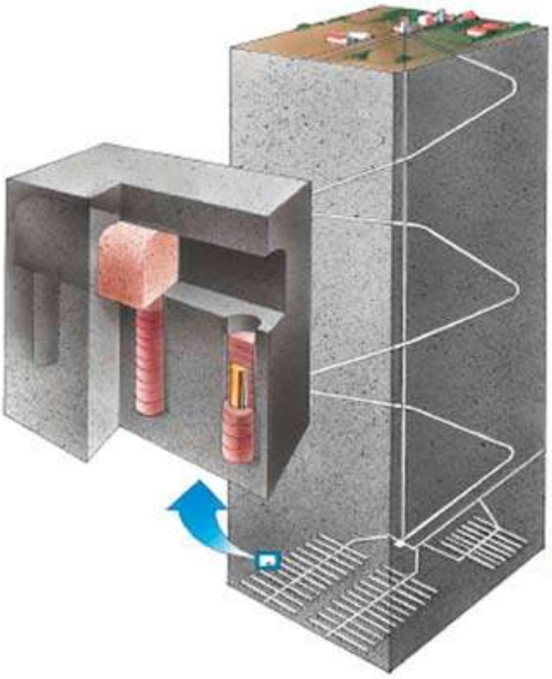


Figure 7.6. Canister for final repository. Figure 7.7. Final repository.

7.6 Other Waste

Solid waste

Solid waste is classified and sorted as much as possible and each type is processed separately. Asbestos and hardened epoxies are collected and transported in containers to a dedicated local facility. Neon and mercury lamps are collected and processed in a recycling facility. Domestic waste and industrial waste, such as building material, plastics, and exempt items, is compressed, packaged, and removed in accordance with local regulations. Garden waste is chipped and reused on the premises.

Filter substances

Inactive or extremely low level filter substances are stored in cases. Samples are taken and activity checked before the cases are emptied. After reporting to SSM (Swedish Radiation Safety Authority) the cases are deposited in an on-site burial facility and immediately backfilled.

Oil waste

Oil waste is collected in dedicated tanks. Full tanks are transported by an authorized contractor, either for destruction or incineration.

Hazardous waste

All other waste classified as hazardous to health, safety, and environment is collected. When suitable quantities are accumulated, they are removed by an authorized contractor for destruction.

8 TRANSPORTATION

8.1 Fuel transports

Transportation of nuclear fuel is by road, sea, or rail depending on the location of the mine and on which facilities are involved before the fuel is deployed in the reactor. The fuel (se chapter 1 on chemical form) does not require radiation shielding and is shipped in steel drums.

8.2 Intermediate and Low Level Waste

Shipments of intermediate level waste, mainly ion exchange resins, utilize heavy steel containers that provide the required radiation shielding. These containers have a gross weight of 120 tons each and hold approximately 25 cubic meters of waste. Low level waste does not require radiation shielding and can be shipped in standard containers.

8.3 Spent Fuel

A purpose-built, diesel powered, rollon/rolloff ship named Sigyn is used for the shipment of spent fuel from Swedish nuclear power plants to CLAB. Her capacity is 30 tons of spent fuel per trip. The spent fuel is placed in special shipment containers prior to loading.

Figure 8.1. M/S Sigyn.

The spent fuel is placed in cylindrical steel containers. The walls of these containers are very thick (approximately 30 cm) to shield the radiation from the fuel. Because the fuel is also very hot the containers are equipped with a large number of cooling flanges made of copper. The gross weight of the container is 80 tons and it is designed to with- stand more strain than can be expected during shipment including the pressure equivalent of a depth of 4 000 meters of water. The removal of all spent fuel from a nuclear reactor to CLAB requires 6–10 annual shipments.

Figure 8.3. Transport cask for spent nuclear fuel.

The transportation of canisters from CLAB to the final repository in Forsmark will utilize the same type of containers as those used for shipments to CLAB. Shipment from CLAB to Forsmark will be made by Sigyn or a similar purpose vessel, and of course with truck the short distance on land.

9 OWNERSHIP OF URANIUM

Procurement of nuclear fuel requires permit issued by the Swedish Government in accordance with present legislation (Kärntekniklagen). Permits are only granted to operators of nuclear power plants. The operators FKA and Ringhals have received permits and are the owners of the uranium from cradle to grave. This responsibility starts at excavation and does not end until the final repository has been sealed. SKB has a permit to operate on behalf of FKA and Ringhals AB.