A storage site has been chosen för final storage of nuclear waste in Sweden. It's expected to be in operation around 2023. The site chosen is at the Forsmark site.

This is an article is in progress, so it will be extended and corrected or improved otherwise in the near future.

The need for storage

Fact of life. Nuclear waste is here and we need to take care of it. **The question is not if, but how** . Another question is how much?

What is special about nuclear waste

Nuclear waste is radioactive, that is it emits different types of radiation. This radiation can be either particles, that is α (nucleus of Helium), β (electrons or positrons),or electromagnetic waves called γ (gamma) radiation. The particles have very short range neither can penetrate skin but both can cause burns on unprotected skin or be very dangerous if inhaled or absorbed in the body by some means. Gamma radiation has a long range, very similar to X-rays. Gamma radiation can pass trough significant amount of matter, so it can affect the human body without inhalation or other means of uptake by the body.

- A raincoat will protect against alpha and beta particles, but it will not protect against gamma.
- Alfa and beta radiation can affect the body mainly trough inhalation or indegestion.

How does it arise?

Nuclear power today is produced by ***fission of heavy atoms*** by ***neutrons***. In the fission process an atom absorbs a neutron, gets instable and splits in two or more fractions. Neutrons are nuclear particles having the mass of a proton but no charge. Because neutrons lack charge they are neither affected by the electron cloud surrounding the nuclei of the atoms nor are they repelled by the the core of the atom which is always positively charged. For that reason neutrons can easily interact with the nuclei of atoms, causing nuclear reactions. Fission is one of the possible reactions.

The nuclei of atoms consists of a number of protons and a number of neutrons. Certain combinations of numbers of neutron to number of protons are stable, other combinations are instable. Fission produces a large number of different nuclei, many of these will be instable.

Instable atoms will, over time, convert to stable atoms. This is achieved by emitting particles. These particles may be nuclei of helium (which we call alpha particles) , or electrons (which we will call beta particles). The electron has a buddy called positron which is exactly like an electron but has an opposite charge. The particles emitted have a certain energy. It is also possible for a nuclear reactio to relesase energy, in form of electromagnetic waves also called photons. This radiation is called gamma.

There are other particles that can be emitted, neutrons are quite useful, without them we would not have nuclear power. Neutrons are also quite nasty, however, because they can penetrate heavy materials easily and also because they can introduce secondary nuclear reactions in matter. Fortunately, neutrons are produced only by the fission reaction in the power plant, so once the plant is stopped, or the fuel taken out of the reactor, neutron radiation will no longer be a problem (there will be a few neutrons caused by high energy photons, but they can be ignored as a health risk).

Decay and half-life

Radioactivity decays. If an atom is unstable it will sooner or later convert to a more stable state. When this happens is stochastic (meaning random), if we have a large number of atoms there will be a time interval when half of the atoms have converted, so we only have half of the radioactivity left. The time we call half-life. So the amount of reactivity left after a number of "half-lifes" is:

1	1/2
2	1/4
3	1/8

So we can just wait for N half-lifes (where N is a reasonably large number) and the problem will go away. Unfortunately this is not that easy, because spent nuclear fuel contains a lot of different kind of nuclei with different half-lifes, some very short, some very long. Most problematic are the nuclei with intermediate (neither very short nor very long) half-lifes. The ones with short half-life emit lots of radiation but decay (go away) rapidly. The ones with long half-life last for very long but emit very little radiation.

Overview of storage

It is said that spent nuclear fuel needs to be stored for 100000 years. Two simple reflections:

- The radioactivityof nuclear waste decays rapidly so the issue is much more grave now than it will be in 100, 1000, 10000 or 100000 years.
- Although 100000 years is very long in comparison with time our civilisation had existed it is not a very long time on the geological time scale. Most of earth has been around for a much longer time, like 4 thousand million years.

Basically, after 100 000 years the radioactivity of the fuel has decayed to a level compatible with uranium ore.

Initially, spent fuel is stored at the plant until it's transferred to CLAB (Central Storage for (radio)Active Fuel). At CLAB the fuel is stored for around 30 years. In this time radioactivity has decayed so much that the fuel does not need auxilary cooling. It is also much less (several orders of magnitude less) dangerous than it was upon removal from the reactor. When fuel no longe needs auxilary cooling, that is can be cooled by natural means, it can be moved to final storage.

The final storage is intended to contain the radiocative isotopes in the fuel and to shield the fuel from any agressive environmental factors. Many factors were taken into count:

- Water entering the storage
- Glacial periodes (ice ages)
- Earth quakes

Barriers

Much of the philosophy in nuclear power is based on barrierrs. We try to construct systems which are inherently safe. Would any system fail another system takes over and "contains" the damage. We also strive to make these systems inherently safe, so they would depend on physics only. No human intervention would be needed. These principles apply even more to final deposition.

The barriers in the proposed final storage in Sweden are:

- The fuel itself
- The copper capsule
- The bentonite bed
- The rock

Would any of these barriers fail then next one is going to imit the consequences.

The fuel

Nuclear fuel in Swedish light water reactors is a ceramic material, uranium dioxide. Ceramics are resilient and don't dissolve in water easily. They do crack, however. The fuel in the spent storage will have significant amount of cracks and it is feasible that significant amount of radiation could escape the fuel if no other barriers would exist. Most of the radioactive isotopes would still be contanied in the fuel, however.

The copper capsule

The fuel elements will be stored in solid copper capsules. The copper plays several different roles. It does protect the fuel. Copper is very ductile so it can be bent without cracking. It is also very resistent to corrosion, especially in environments containing very little oxygen. The capsule has an insert of cast iron to increase mechanical strength and protect the fuel.

Corrosion

It has been calculated that corrosion would be on the order of 0.02 mm in 100000 years. The capsule itself is 50 mm thick. This calculation is based on the environment that is expected. Calculations om more corrosive environment indicate that corrosion would reduce the thickness by 4.4 mm.

Leaks

Calculations are based on the assumption that a small fraction of the capsules may develop leaks. If the capsule only has a small leak it will be filled up with liquid (if liquid would be present). Once the capsule is filled up there is equilibrium and the liquid would essentially stay where it is. Transport of oxidants and actinides would depend on diffusion.

The bentonite bed

A special form of cl,y called bentonite, will be used to imbed the capsules. Bentonite has several interesting proprties in this context. In contact with water it swells and get a jelly like consistence, thus holding water but also tightening possible cracks in the rock. Would radiactive materials leave the capsule, they would only migrate much slower than the waterfront, perhaps 1000 times slower due to a phenomena called retention.

The rock

The rock serves at least three purposes:

- It protects the deposition site against environmental factors, like ice cover during an ice age.
- It only allows very small amounts of water to enter the deposition site.
- Would the the fuel leak, the radiocative materials would move much slower than water because of the aforementioned retention effect. An estimate that radiactive substances would,

on avarage, be retarded by a factor of on thousand.

The characteristics of the rock were thoroughly investigated at the candidate storage sites. The idea was to find a place with very few cracks, far from now cracks and fault zones.

Can we predict for 100000 years?

Yes and no. Earth has been around for 4 billion years (in US-speak) or as we say 4 10^9 years (which we estimate from geological findings, radioactive decay and cosmic science). So the planet we are living on has a long history. We can, to a significant extent, draw conclusions about the future by studying the past.

What we can learn from the natural reactor in Gabon

Something like 2 billion (2 10^9) years ago mother nature built a lightwater reactor in Gabon. Today it would not work, but at that time Uranium did contain on the order of 3% of the ^{235}U isotope which is usable to get self sustained chain reaction in lightwater reactors. The reason that todays uranium contains only 0.7% ^{235}U is because it's radioactive, so it decays. This natural reactor in Gabon, known as the Oklo reactor, produced all isotopes we have in todays reactor including a significant amount of plutonium. Thus the migration of these materials could be studied in geological materials two billion years old. The findings are that most fission products and actinides just moved a few centimetres in the passage of time.