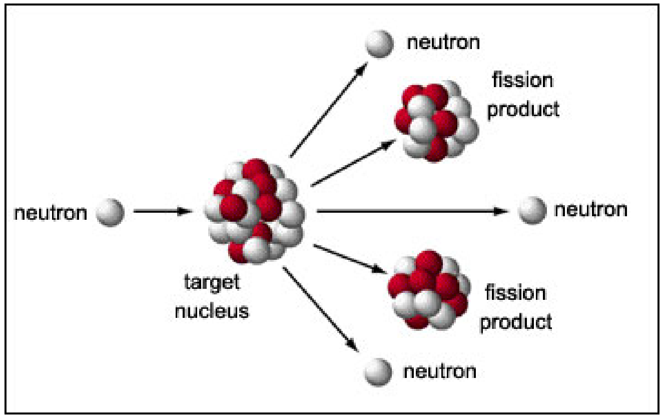
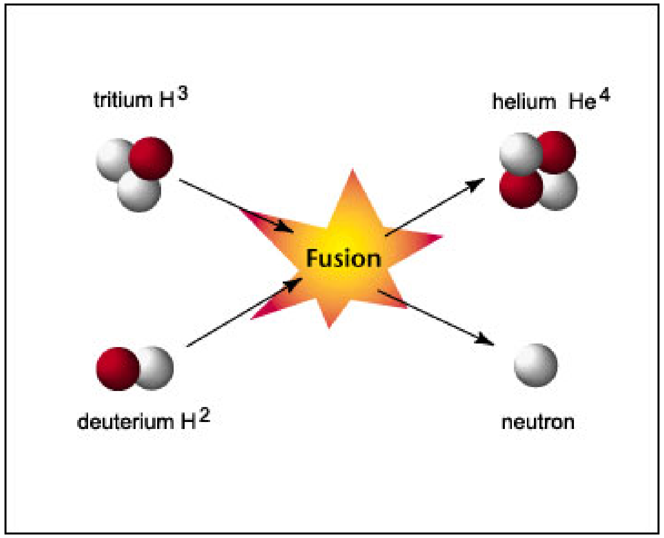
24. Nuclear?

Nuclear power comes in two flavours:

1. Nuclear fission. Split up heavy nuclei into medium-sized nuclei, thereby releasing energy.

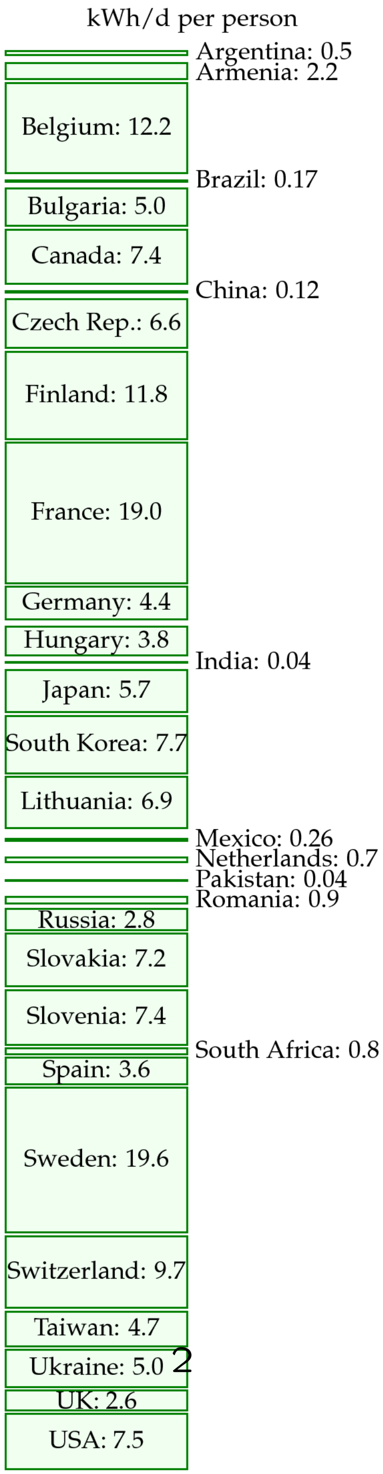


2. Nuclear fusion. Fuse light nuclei into medium-sized nuclei, thereby releasing energy.



Nuclear energy available per atom is roughly one million times bigger than the chemical energy per atom of typical fuels ⇒ The amounts of fuel and waste that must be dealt with at a nuclear reactor can be up to one million times smaller than the amounts of fuel and waste at an equivalent fossil-fuel power station.

Nuclear power generates up to 20 kWh/d per person in several countries (see figure on the right).



“Sustainable” power from nuclear fission

If we leave aside for a moment the usual questions about safety and waste-diposal and try to answer the question: *Could humanity live for generations on fission?* To estimate a “sustainable” power from uranium, we will take the total recoverable uranium in the ground and in seawater, divide it fairly between 6 billion humans, and ask **“How fast can we use this if it has to last for 1000 years?”**

Phosphate deposits contain uranium at low concentration and are more expensive to exploit than conventional reserves. Most of the uranium is in the oceans which contain 3.3 mg of uranium per m^3 of water. However, no one has yet demonstrated uranium-extraction from seawater on an industrial scale.

	million tons uranium
World total (conv. reserves)	4
Phosphate deposits	22
Seawater	4500

We will consider two ways to use reactors: **(a)** the widely used *once-through method* gets energy mainly from ^{235}U (which makes just 0.7% if uranium), and discards the remaining ^{238}U; **(b)** *fast-breeder reactors* which convert the ^{238}U to fissionable plutonium-239 and obtain roughly 60 times as much energy from the uranium.

SUPERPHENIX: The largest fast-breeder reactor ever built. Installed power of 1200 MW.

Question I: What is the rate (in kWh/d per person) at which we can use power from fissionable fuels assuming we only rely on once-through reactors and only use uranium from the ground.

Additional data: A once-through one-gigawatt nuclear power station uses 162 tons of uranium per year.

Answer to Question I

(i) Number of one-gigawatt reactors that could run for 1000 years with the uranium from the ground:

$$\frac{\text{reserves uranium}}{\text{yearly consumption reactor}\times 1000} = \frac{27\times 10^6}{162\times 1000} \simeq 167.$$

(ii) Power of one-gigawatt reactor in kWh/d per person:

$$\frac{10^9\times 24}{6\times 10^9\times 1000} = 0.004 \text{ kWh/d per person.}$$

(iii) The rate at which fissionable fuels can be used in a sustainable way: $167 \times 0.004 =$ 0.668 kWh/d per person.

Note: There are currently 369 GW of nuclear reactors.

Question II: What is the rate (in kWh/d per person) at which we can use power from fissionable fuels assuming we only use uranium from the ground and fast-breeder reactors?

Question III: What is the rate (in kWh/d per person) at which we can use power from fissionable fuels assuming that we only rely on fast-breeders and that we can extract 5% of the uranium contained in seawater?

Question IV: What is the rate (in kWh/d per person) at which we can use power from fissionable fuels assuming that we only rely on once-through reactors and that we can extract all the uranium contained in seawater?

Answer to Question II: $0.668 \times 60 =$ 40 kWh/d per person

Answer to Question III: $40 \times \frac{4500 \times 0.05 + 27}{27} =$ 373.3 kWh/d per person

Answer to Question IV: $0.668 \times \frac{4500+27}{27} =$ 112 kWh/d per person

Question: What can be concluded from these numbers?

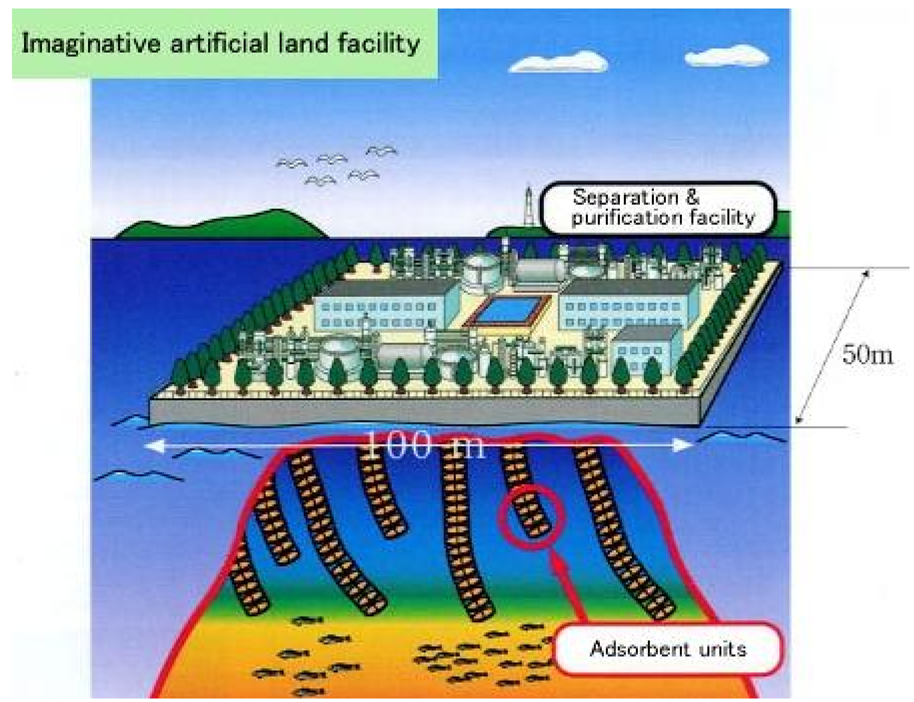
1. The rate at which once-through reactors can produce energy in a sustainable way is well below the 125 kWh/d per person of primary energy consumption of Europe.

2. Fast-breeder reactors could produce a significant percentage (30%) of the 125 kWh/d per person of primary energy consumption of Europe using only mined uranium .

3. By extracting only a small percentage of the uranium contained in sea water and using fast-breeder reactors, it would be possible to produce much more than 125 kWh/d per person in the next one thousand years.

Uranium extraction from seawater

Uranium is extracted using **high-surface-area materials** that have a high-affinity with uranium. These materials trap uranium in water. Once the uranium is trapped, it is extracted using simple chemical reactions. This process is five to ten times more expensive than extracting uranium from ore.

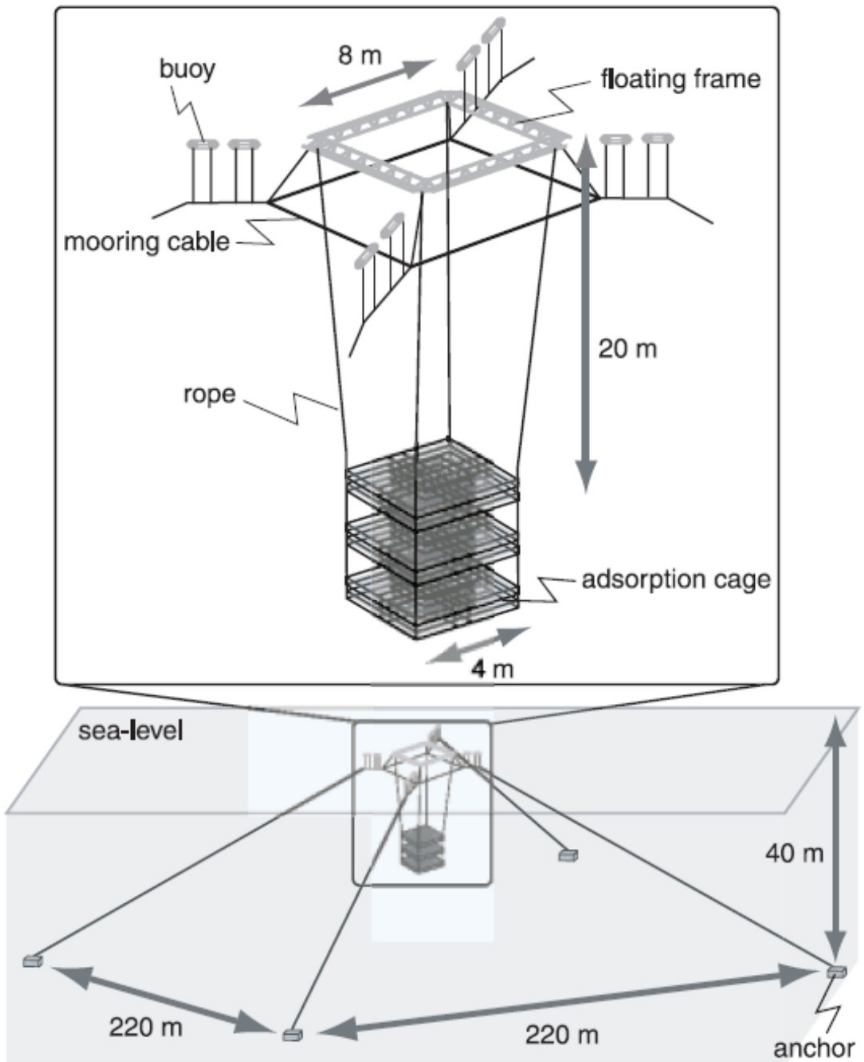


How big would these uranium extraction facilities be?

For producing 125 kWh/d per person with fast-breeder reactors, $\frac{125}{0.004} = 31,250$ one-gigawatt reactors are needed. A one-gigawatt fast-breeder reactor uses $\frac{160}{60} \simeq 2.666$ tons of uranium per year $\Rightarrow$ 83,333 tons of uranium would have to be harvested each year.

Let us estimate the size of the uranium harvesting facility required to extract this amount of uranium from the oceans each year.

For coming up with this estimation, we will first describe a **Japanese experiment** for which around 1 kg of uranium was collected in 240 days.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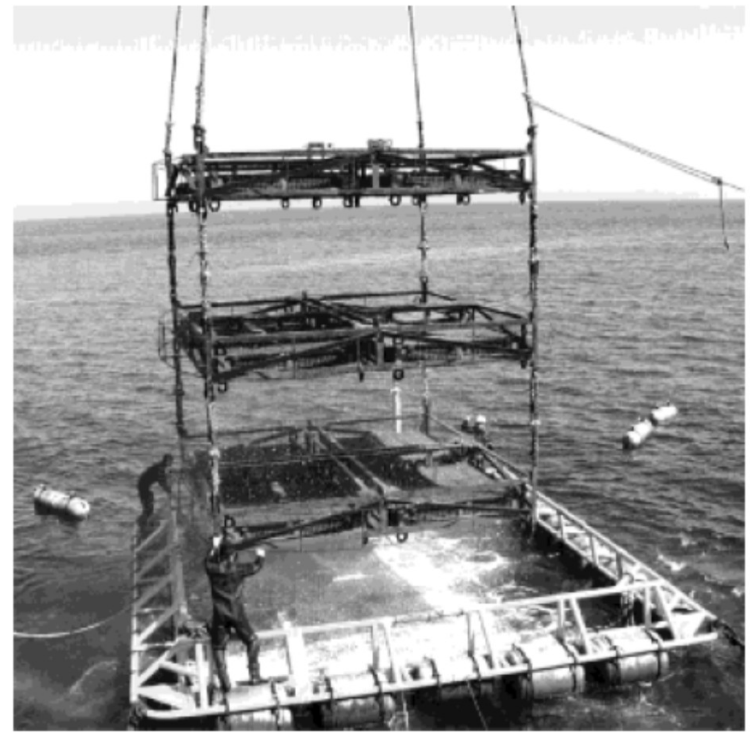


The **Japanese experiment** has extracted 1 kg of uranium in 240 days. This figure corresponds to 1.6 kg per year. The ocean surface covered by the Japanese experiment is $8 \times 8 = 64$ m^2 $\Rightarrow$ We assume that we can extract $\frac{1.6}{64} = 0.025$ kg of uranium per year per m^2 of ocean.

To extract 83,333 tons of uranium, we would therefore need $\frac{83333 \times 1000}{0.025 \times 1000 \times 1000} \simeq 3333$ km^2 of ocean.

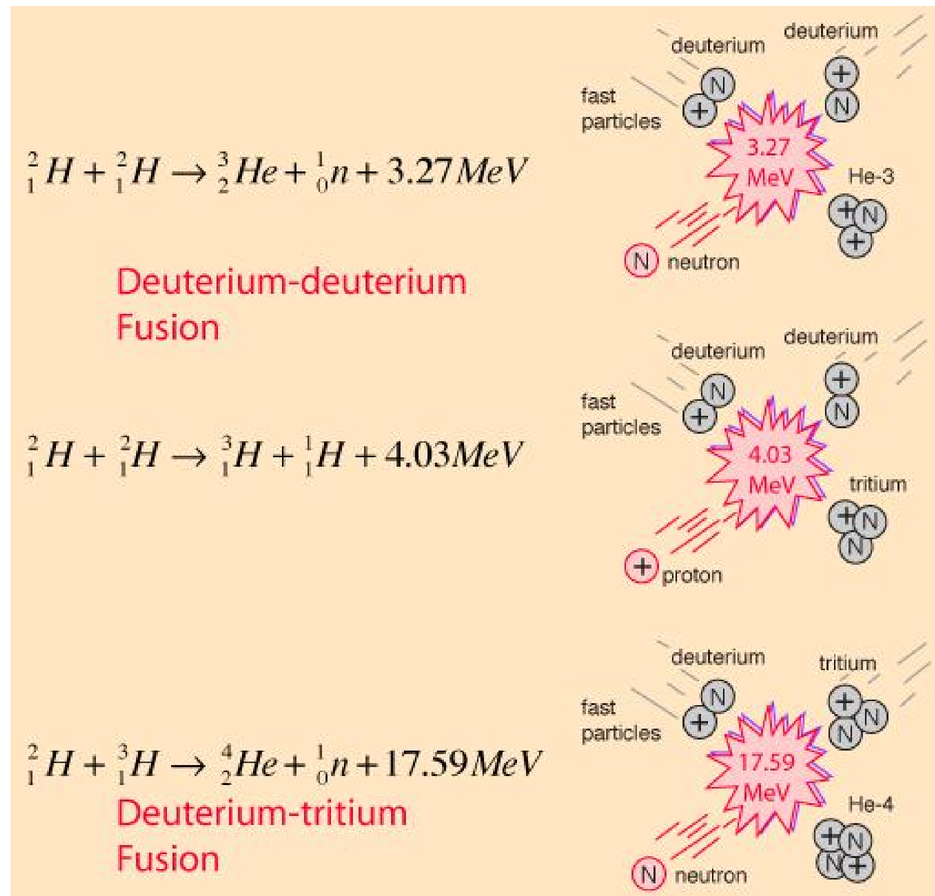
Notice that 3,333 km^2 corresponds to $\frac{3{,}333 \times 1000 \times 1000}{6 \times 10^9} = 0.555$ m^2 per person.

Sustainable power from nuclear fusion

The two fusion reactions that are considered the most promising are:

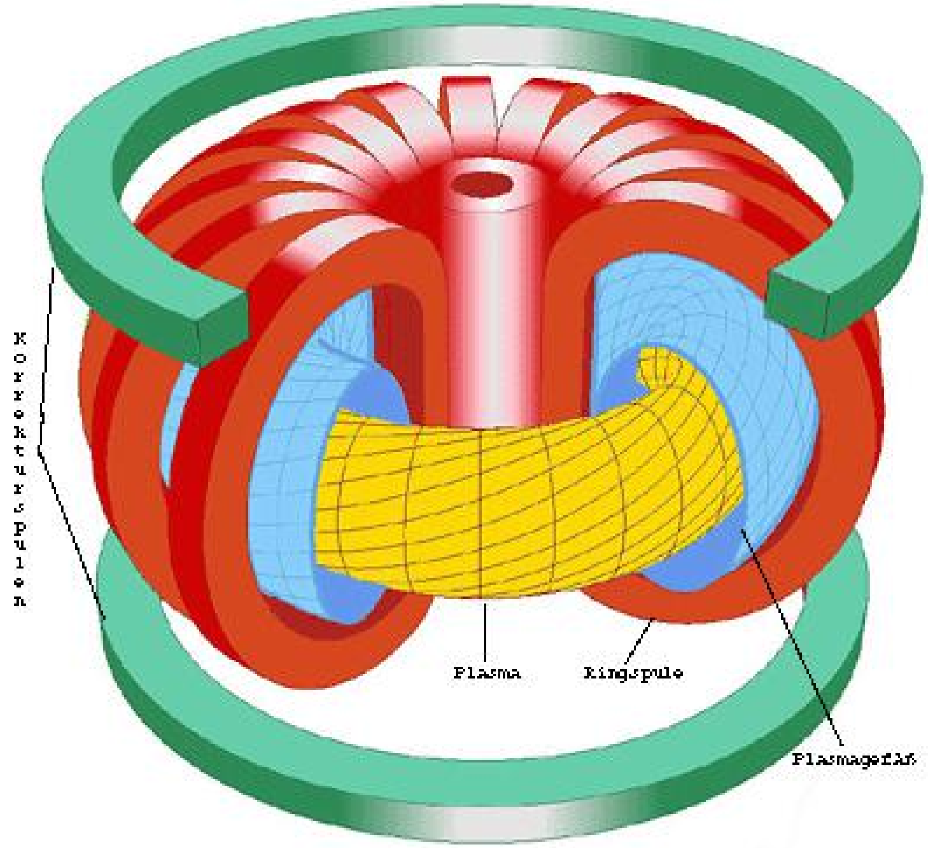
1. The **DT** reaction, which fuses deuterium (D or ^{2}H) with tritium (T or ^{3}H), making helium.

2. The **DD** reaction, which fuses deuterium with deuterium to produce helium.



The ITER project

ITER is an international project to design and build an experimental fusion reactor based on the "tokamak" concept. The ITER prototype will use the DT reaction. The DT reaction is preferred over DD, because the DT reaction yields more energy and requires a temperature of "only" 100 million °C to get it going, whereas the DD reaction requires 300 million °C.



The ITER fusion reactor itself has been designed to produce 500 MW of output power for 50 MW of input power. The first commercial demonstration fusion power plant, named DEMO, is proposed to follow on from the ITER project to bring fusion energy to the commercial market.

More about the DT reaction

Tritium is a radioactive element which has a rather small half-life (approximately 12.32 years) and cannot be found in large quantities in nature.

It can however be produced by bombarding $^6_3$Li by neutrons (or $^7_3$Li (something that people from the Los Alamos National Laboratory did not know before the Castle Bravo bomb explosion - *http://en.wikipedia.org/wiki/Castle_Bravo#Cause_of_high_yield*)).

The amount of power that can be delivered by DT fusion is therefore limited by the amount of lithium available. It can be computed that if the 9.5 million tons in lithium deposits were devoted to fusion over 1000 years, the power delivered would be around 10 kWh/d per person. However, by exploiting just 5% of all the lithium from seawater, more than 2000 kWh/d per person over a period of 1000 years could be generated.

Deuterium-deuterium reaction

Question: How fast (in kWh/day per person) can we use deuterium-deuterium fusion if it has to last for one thousand years and if we assume that we can recover 5% of the deuterium contained in oceans?

Data: The fusion of two deuterium atoms (^2_1H) releases 3.27 MeV. 1 eV $= 1.6 \times 10^{-19}$ J. 1 mole $= 6.022 \times 10^{23}$ atoms. Volume of water in oceans $\simeq$ 1.3 billion cubic kilometres. 33 g of deuterium in every ton of water.

First, we compute the energy delivered by fusing 1 mole of deuterium: $3.27 \times 10^6 \times 1.6 \times 10^{-19} \times \frac{6.022\times10^{23}}{2} = 157535520000$ J. That's 43760 kWh.

1 mole of deuterium weighs 2 g. Therefore, one m^3 of water could deliver $\frac{33}{2} \times 43760 = 722040$ kWh.

By assuming that there is only pure water in oceans, extracting 5% of the deuterium contained in oceans could lead to an energy equal to $722040 \times 0.05 \times 1.3 \times 10^9 \times 10^9 = 46933 \times 10^{18}$ kWh.

Assuming a population of six billion, this corresponds to : $\frac{469333\times10^{18}}{6\times10^9\times365\times1000}$ = **21430411 kWh/d per person over 1000 years!!!**

The waste problem

Three categories of nuclear waste:

1. Low-level waste. Contain small amounts of mostly short-lived radioactivity. Suitable for shallow land burial. To reduce its volume, it is often compacted or incinerated before disposal.

2. Intermediate-level waste. Contain higher amounts of radioactivity and in some cases requires shielding. It may be solidified in concrete or bitumen for disposal. As a general rule, short-lived waste (mainly non-fuel materials from reactors) is buried in shallow repositories, while long-lived waste (from fuel and fuel reprocessing) is deposited in geological repositories.

3. High-level waste. Contain fission products and transuranic elements generated in the reactor core. It is highly radioactive and often thermally hot. HLW accounts for over 95 percent of the total radioactivity produced in the process of nuclear electricity generation. This waste is deposited in geological repositories.

How much waste is really produced?

A typical 1000 MW nuclear reactor will generate 200-350 m^3 of low- and intermediate-level waste per year. It will also discharge about 20 m^3 (27 tonnes) of used fuel per year, which corresponds to a 75 m^3 disposal volume following encapsulation if it is treated as waste. Where that used fuel is reprocessed, only 3 m^3 of vitrified waste (glass) is produced, which is equivalent to a **28 m^3 disposal volume** following placement in a disposal canister. This compares with an average **400,000 tonnes of ash** produced from a coal-fired plant of the same power capacity.

Question: What would be the size of the cube needed to store the nuclear waste generated over one year assuming that we use nuclear power to generate 125 kWh/d per person for six billion people?

Power of one-gigawatt reactor in kWh/d per person: 0.004 kWh/d per person.
Number of reactors needed: $\frac{125}{0.004} = 31,250$
Total volume per year: $31,250 \times 28 = 875,000$ m^3 $\Rightarrow$ A cube of side length equal to $(875,000)^{\frac{1}{3}} \simeq$ 95,7 m is needed to store the nuclear waste generated over one year.

Observation: The nuclear waste problem does not seem to be that big.

The safety problem

Operation of nuclear installations comes with danger. However, nuclear power is **not infinitely dangerous**. Four main types of danger are identified:

1. The daily release of radiations by nuclear power plants.

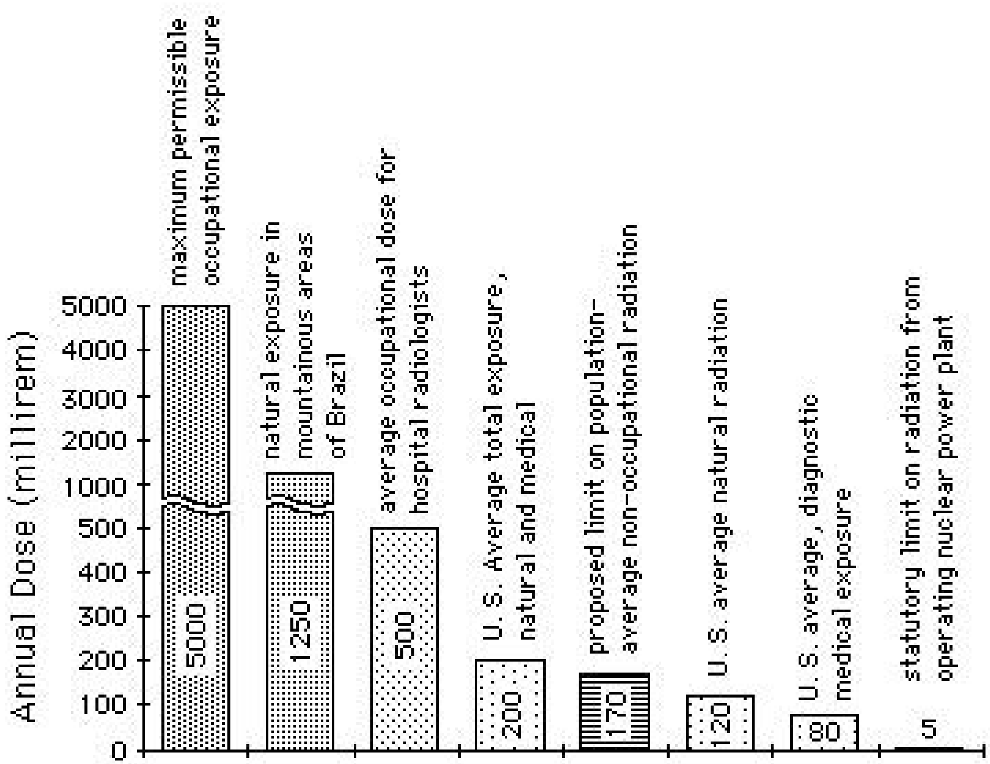
2. The accidental release of large quantities of radioactive material into the environment. The installation is still kept under control.

3. Accidents in nuclear installations that are confined to the plants and that only endanger the people working at these installations.

4. A nuclear disaster.

1. The daily release of radiations by nuclear power plants

The normal operation of nuclear plants releases radioactivity into the environment. The **millirem** is a unit of absorbed radiation dose. The risk of one millirem of radiation dose is a 1 in 8 million risk of dying of cancer if large dose effects extrapolate linearly to zero dose. The loss in life expectancy from a 1 millirem dose is about 1.2 minutes, equivalent to: (i) crossing the street three times (ii) three puffs on a cigarette (iii) 10 extra calories for an overweight person.



2. The accidental release of large quantities of radioactive material into the environment. The installation is still kept under control.

Accidental release of large quantities of nuclear material into the environment is not that rare.

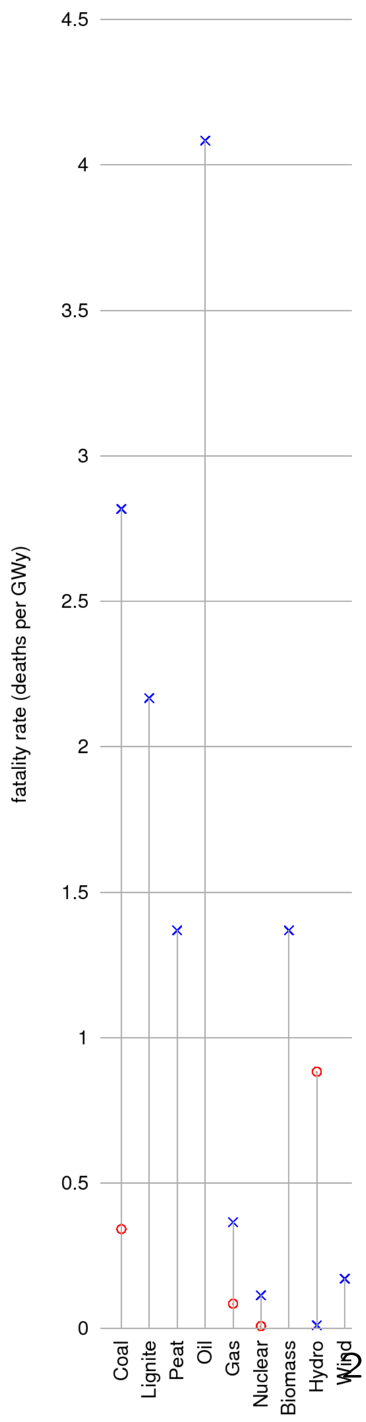
Example of accidental release: During the period August 2004 to April 2005, the THORP reprocessing facility at Sellafiled released **85,000 litres** of uranium-rich fluid into the environment. The leak was only detected by *accountancy*, when people responsible for operating the plant realized that they were getting 10% less uranium out than their clients claimed they were putting in. **Main cause:** *The plant was operated in a culture that seemed to allow instruments to operate in alarm mode rather than questioning the alarm and rectifying the relevant faults.*

Question: If we let private companies build new reactors, how can we ensure that they adhere to high-safety standards?

3. Accidents in nuclear installations that are confined to the plants and that only endanger the people working at these installations.

Unit used for measuring these dangers: **deaths per GWy (gigawatt-year)**.

The figure on the right gives the death rates of electricity generation technologies. The crosses give the European Union estimates by the ExternE project and the empty bullets give the estimates of the Paul Scherrer Institute.



4. A nuclear disaster

Chernobyl nuclear plant

Fukushima nuclear plant

Consequences of a nuclear disaster: **[A]** May kill many workers at the nuclear installation as well as people living around the installation (especially if evacuation is not carried out fast enough); **[B]** Creation of an exclusion zone around the nuclear installation; **[C]** Release of radioactive material even outside of the exclusion zone.

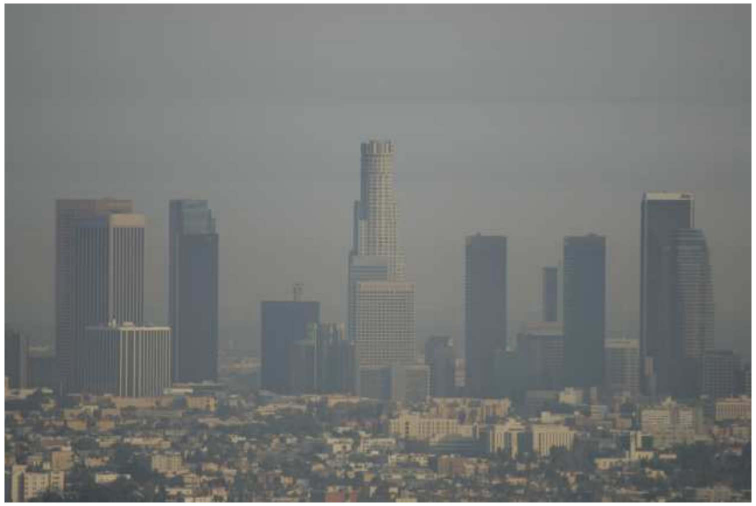
Two thought-provoking observations to rationalize the fear of nuclear disasters

Yes nuclear energy can kill many people in the aftermath of a disaster but so can renewable energy.

The **Banqiao Reservoir Dam** failed catastrophically in 1975. The dam failure killed an estimated 171,000 people and 11 million people lost their homes.

An exclusion zone is a zone where nature can flourish without being destroyed by mankind.

Chernobyl today



Los Angeles today