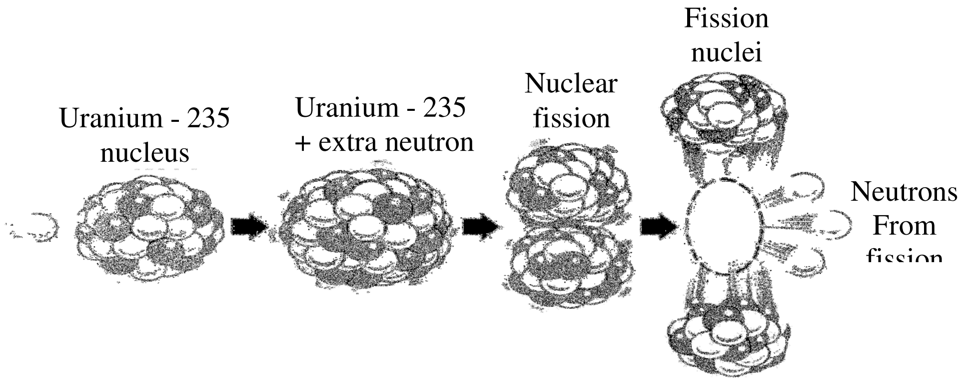
Energy resources and Policy
Handout:
Nuclear power

1. Basic principles

Uranium exists most commonly in the stable isotope U_{238}, but naturally-occurring uranium deposits contain a small amount of the less stable U_{235} (about 0.7%). If a U_{235} nucleus is struck by a neutron, it may split (nuclear fission) with the release of energy in the form of heat. The process emits further neutrons, 2 or 3 on average, which are then available to collide with further U_{235} nuclei. The possibility of a chain reaction therefore arises.



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To sustain a chain reaction in natural uranium is difficult, as the U_{235} nuclei are thinly spread; it can be achieved if a moderator is used to slow down the free neutrons, making them less likely to be captured by the abundant U_{238} nuclei. Common moderating substances are water, heavy water (deuterium) and graphite. A better performance is achieved if the fuel is enriched to increase the proportion of U_{235}: a fairly lengthy and energy-intensive process. Packages of enriched fuel, normally in the form of cylindrical rods, are then manufactured for use in power stations.

With 2 to 4% of U_{235} in the mixture a chain reaction is easily sustained, but over a period of time the number of fissionable nuclei diminishes and the fuel becomes depleted. Eventually it must be removed and replaced with new fuel elements. The depleted fuel still contains substantial amounts of U_{235} and also some plutonium Pu_{239}, so the fuel can be re-processed and the fissionable contents returned to the fuel production cycle.

If a more heavily enriched fuel is used from the start, the reaction may produce a large number of fissionable plutonium nuclei. If the rate of production exceeds the rate of consumption of the U_{235}, we have a breeder reactor.

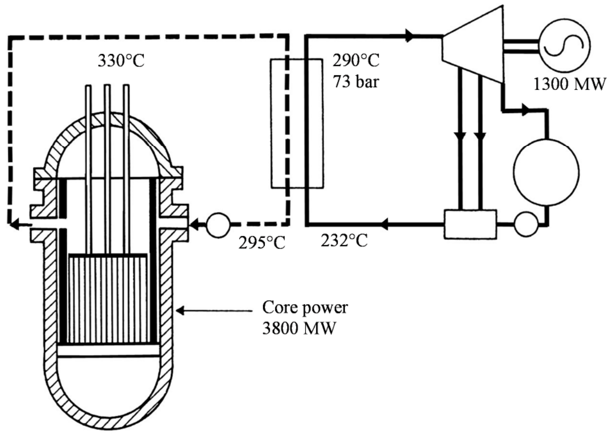
In any reactor, the reactivity is adjusted by control rods of a neutron-absorbing substance such as boron; lowering these rods into the core reduces the activity. The heat from the core is absorbed by a coolant and eventually generates steam for turbo-generators, similar to those in coal-burning power plant. For all thermal energy conversion the efficiency of the process depends upon the temperatures used. The theoretical maximum is the Carnot efficiency, given by

$$1 - \frac{T_2}{T_1}$$

where T_1 is the temperature at which heat is absorbed and T_2 is the temperature at which heat is rejected to the surroundings (in degrees absolute). There is clearly an advantage in supplying heat at the highest possible value of T_1. But high temperatures place stresses on materials with implications for reliability and safety, so a compromise must be reached. For good reasons, nuclear reactors are designed with quite moderate values of T_1 and so have a fairly low thermal efficiency.

2. Conventional thermal reactors

The most common configuration is the pressurised water reactor (PWR), developed originally in the USA for the propulsion of submarines. Water is used as both moderator and coolant, with the water in the core in liquid form at about 150 bar, 330°C, enclosed in a steel pressure vessel. Boiling water reactors have also appeared: a UK variant used heavy water as the moderator, while the Russian RBMK used graphite. Thermal efficiencies for these reactors are around 35%.



Typical pressurised water reactor

The Canadians developed a unique design using heavy water as both moderator and coolant. The UK has traditionally specialised in gas-cooled reactors, with the early Magnox design followed by the advanced gas-cooled reactor (AGR: e.g. Hunterston A and B, respectively). Both types used graphite as the moderator and CO_2 as the coolant at about 25 bar, 370°C (Magnox) and 40 bar, 650°C (AGR). Thermal efficiencies were about 32% and 41% respectively.

Recent renewed interest in nuclear power technology has resulted in a number of novel designs offering improved efficiency and safety.

3. Breeder reactors

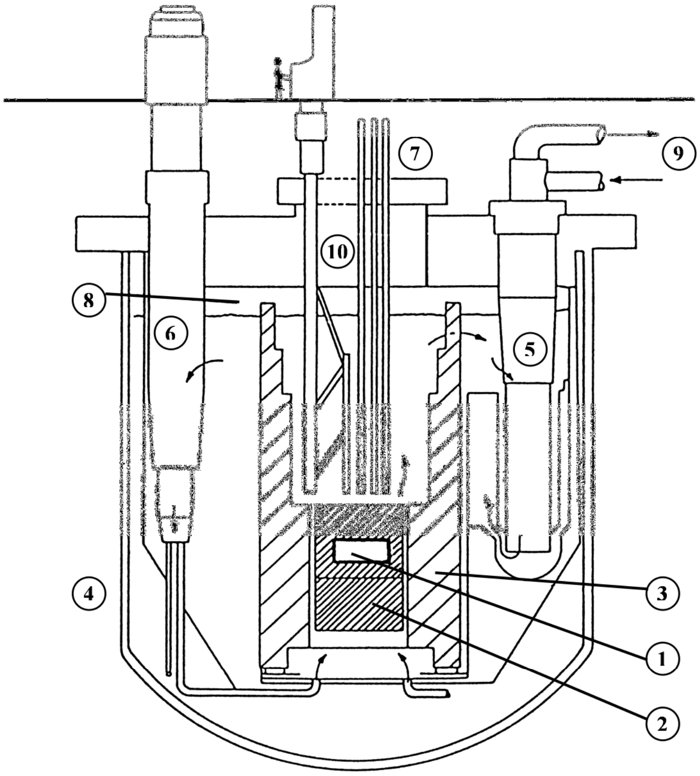
Thermal reactors convert a little U_{238} into fissionable plutonium, but overall no more than 2% of the natural uranium resource is utilised – and this resource is decidedly limited. Breeder reactors promise a much more efficient exploitation of uranium, and have been the subject of research and development in the UK, USA, France, Japan and the former Soviet Union. They require an initial charge of highly enriched fuel (25 to 50% of U_{235}), and therefore have a very high power density. Good heat transfer to the coolant is essential, so liquid metal (sodium) is commonly used. There is no moderator and the core is surrounded by a 'blanket' of natural uranium (largely U_{238}) in which new plutonium fuel is 'bred'. The sodium coolant can approach 600°C but is at ambient pressure.

Technical difficulties and poor performance have hampered development so far (the UK has abandoned work on breeders altogether). But some say that without a stock of breeder reactors, supplying fuel for more numerous thermal power plants, nuclear power will remain a relatively small contributor to our energy needs.

4. The fuel cycle

Processes involved in the use of conventional thermal reactors are shown in the diagram. Mining and separation yields the ore U_3O_8 (yellowcake). Releases of radon gas can be a hazard to workers at this stage.

Re-processing makes more efficient use of the fuel and is potentially profitable, but poses some environmental risks. The USA does not re-process its fuel; the UK does, and performs this service for some other nations as well. If breeder reactors were widely used, there would be transportation of large extra quantities of plutonium for use in thermal reactors, bringing increased environmental concerns.



Components of Fast Reactor prototype at Dounreay, Scotland:

1. core
2. blanket & reflector
3. neutron shield
4. sodium filled stainless steel reactor vessel
5. primary heat exchanger
6. primary sodium pump
7. control rods
8. argon gas above sodium in reactor vessel
9. secondary sodium pipes to and from steam generator
10. refuelling machine

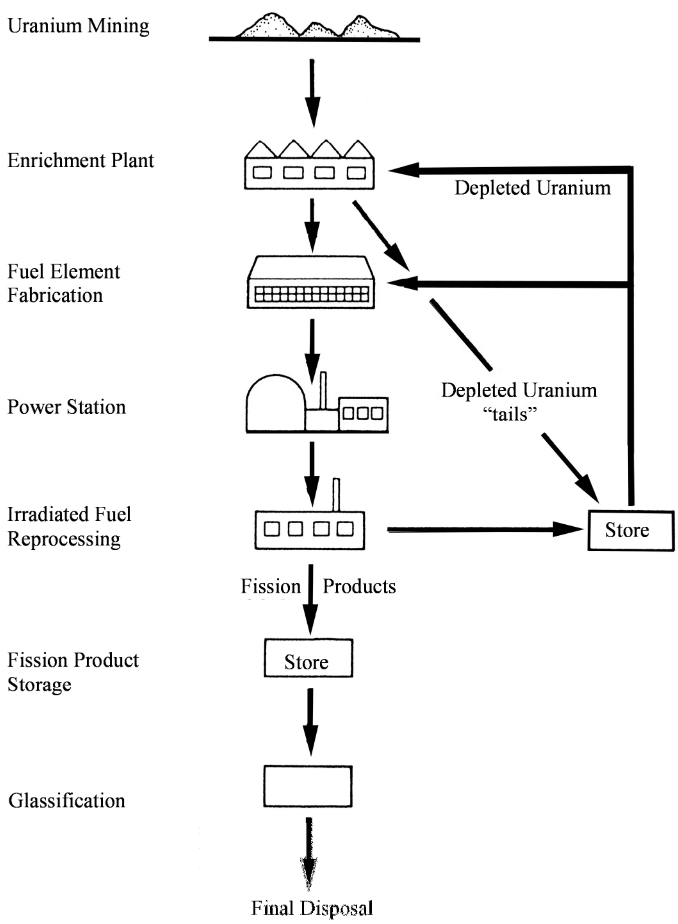
Storage of high-level waste is presently closely monitored in sites above ground; vitrification and deep burial remains the preferred final method. Selection of sites for deep burial is understandably problematic!

5. Isotopes

The radio-activity of unstable isotopes is indicated by their half-life: the period over which the activity declines by 50%. A variety of such isotopes is produced in the fission process. Very short half-lives pose little threat as the isotope will largely decay before it can reach the environment. Very long ones suggest a material which is fairly inactive. Such substances offer no immediate threat and may be handled safely if care is taken. The problem arises if they are ingested, either directly or through the food chain.

Isotope	Half-life	Comment
Iodine 137	23 seconds	
Bromine 87	1 minute	
Iodine 131	8 days	Concentrates in milk, causes thyroid cancer

Strontium 90	28 years	Enters food chain, lodges in bones
Caesium 137	30 years	Concentrated by marine creatures
Carbon 14	5800 years	Basis of 'carbon dating'
Plutonium 239	24000 years	Considered highly toxic if inhaled as dust



6. Significant accidents

1957 Windscale (now re-named Sellafield). Fire resulting in emission of iodine isotopes. Some contamination of agricultural land and milk supplies.

1979 Three Mile Island, near Harrisburg, USA. Destruction of Pressurised Water Reactor by interruption of cooling supply to core. Minor radioactive release, no injuries. Brought development of nuclear power in USA to a halt for over 20 years.

1986 Chernobyl, near Kiev, USSR. Explosion and fire in RBMK reactor. Massive release of radioactive material, around 30 immediate fatalities, many more early deaths from contamination. More than 100 000 people evacuated from the region. Pollution of large area of Western Europe.

A number of other significant accidents and releases of radioactive material are now known to have occurred within the former Soviet Union, but details were kept secret at the time.

7. De-commissioning

Commercial nuclear reactors have a maximum working life of 30 to 40 years, after which they are shut down and dismantled. The primary heat-producing circuit through the reactor core remains highly radio-active for some time; expert opinion presently indicates that it may not be approached safely for at least 100 years. The site must therefore be securely maintained for this period, until final demolition is possible.

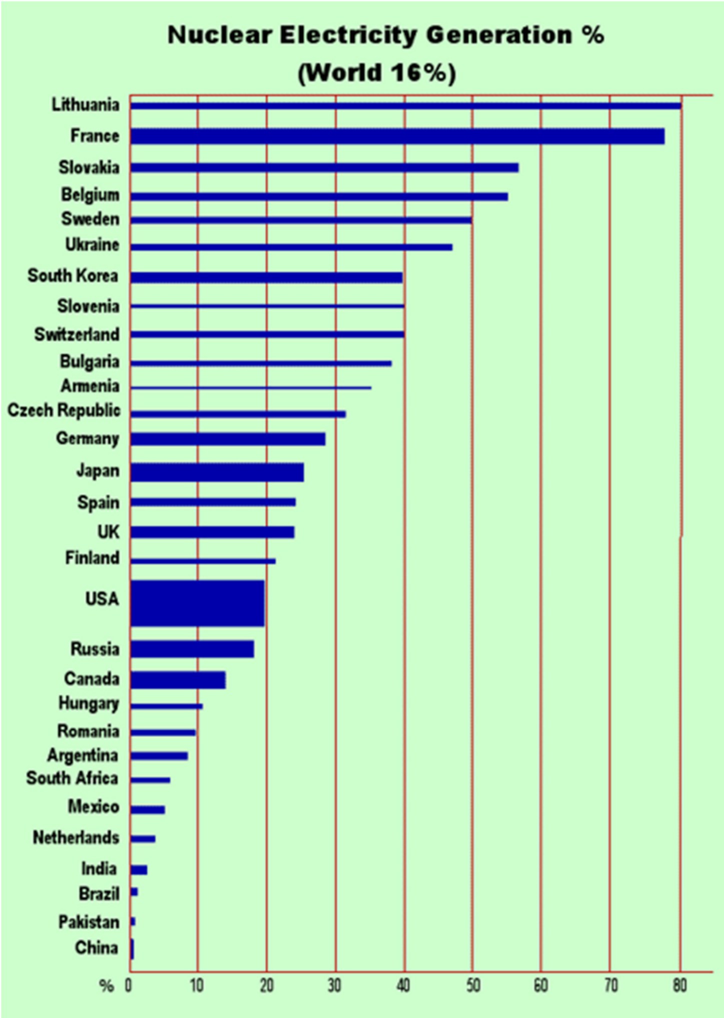
De-commissioning and the management of high-level waste products are major concerns for the future of nuclear power. Each has security implications, and each is a significant factor in overall costs. The present uncertainty over costs for de-commissioning and waste management makes meaningful comparisons with other energy technologies difficult, and is deterring private investment.

8. Now and the future

Attitudes to nuclear power vary greatly around the world. In Europe, a number of countries with substantial nuclear capacity (Germany, Spain, Sweden) have bowed to public opinion and halted their development programmes. The UK remains undecided. France by contrast produces nearly 80% of its electricity from nuclear sources and intends to continue in the future. The map below shows the number of commercial nuclear reactors presently operating in European countries.

World-wide, there are 435 commercial nuclear reactors with 370 GW total capacity, presently producing about 16% of the world's electricity. S. Korea and Japan already have substantial capacity and plan to maintain or expand this. Significant expansion is expected in China and India.

The diagram below shows the percentage of electrical power produced from nuclear sources, for all countries where nuclear reactors are installed (the area of the bars in the chart gives an idea of the total installed nuclear capacity in each country).



9. Fusion

All of the above relates to nuclear **fission**. Fusion is the thermo-nuclear process which occurs deep within the Sun and other stars. For creation in a controlled environment, the most promising reaction seems to be the fusing of deuterium and tritium isotopes of hydrogen to form helium nuclei. Very high temperatures (about 10^8 °C) are required for initiation. The basic fuel is abundant and cheap, and emissions are likely to be much less harmful than in fission processes. But so far, despite great efforts by the scientific and engineering community, progress has been frustratingly slow. At the moment we have only one operating fusion reactor at our disposal, and that is 150.10^6 km away!