Chapter 8 Nuclear Energy

Realising nuclear energy

In Chapter 3 we described how each nucleus remains at the centre of its atom, effectively without activity of any kind over aeons in time, aside from the slow gyration of its spin (if any) in passing magnetic fields and radiowaves, as occurs in MRI. But Figure 4 shows that in principle large amounts of energy could be released from nuclei, either through the fission of the heaviest or through the fusion of two of the lightest. Yet to a good approximation this does not happen at all, except in the extraordinary conditions at the centre of the Sun.

Some numbers on nuclear fission illustrate the point. Of all naturally occurring nuclei, only uranium-238 and uranium-235 undergo spontaneous fission. The half-life of uranium-238 is 4.5×10^{9} years but the proportion that decays naturally by fission is only 5.4×10^{-7}. The numbers for uranium-235 are 0.7×10^{9} years and 2.0×10^{-9}. So the fission rate for a uranium-238 nucleus is 8×10^{-17} per year, and for a uranium-235 the rate is 2×10^{-18} per year. These rates are exceptional – only one in a million uranium-238 nuclei has fissioned since the Earth was formed, and the rate for uranium-235 is even smaller. In fact natural (spontaneous) fission was only discovered in 1940, two years after neutron-induced fission was found by Hahn, Strassman and Meitner in Berlin. (Of course the conjunction of the date, December 1938, with the location was part of the drama to come.) But why are nuclei so reluctant to release their energy by fission?

The answer turns out to be closely related to the reason why the Sun has to be so hot at its centre to achieve fusion. The diagram in Figure 19a shows a nucleus, as a whole on the left and divided into two halves at progressively larger separations towards the right. The potential energy of the halves is the sum of the longrange electrical repulsion of their electric charge and the short-range nuclear attraction, both sketched in Figure 19b on different scales. The curves in Figure 19c and 19d show the net potential energy composed of these two effects added together, for the fusion of two light nuclei and the fission of one heavy nucleus, respectively. When the halves are in contact the nuclear force dominates, but if they are slightly separated they are too far apart

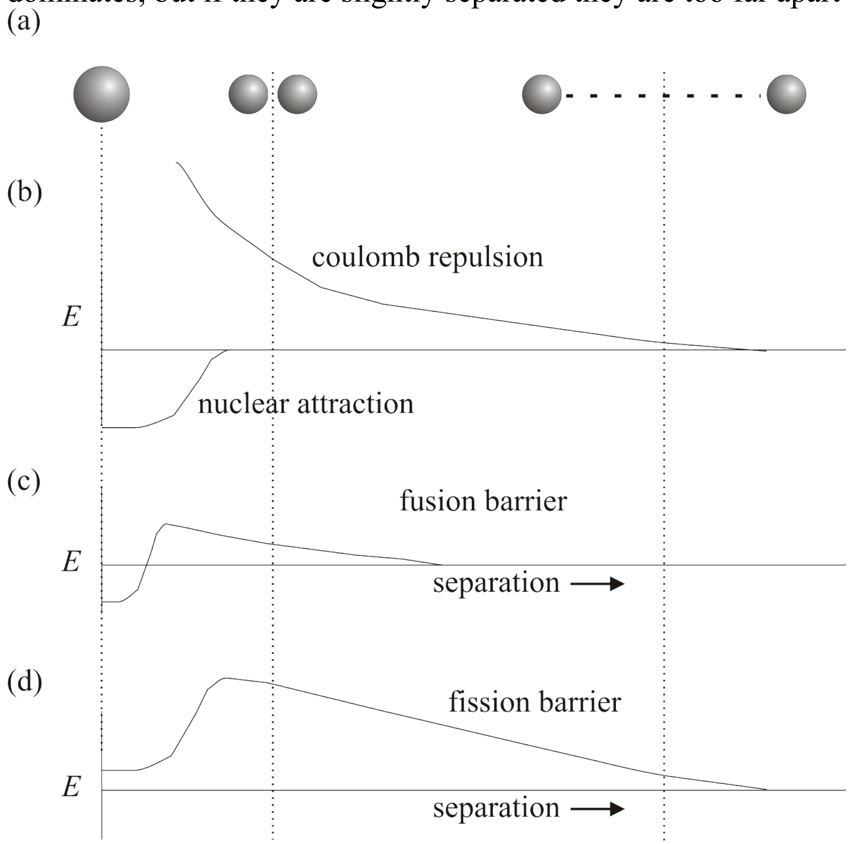

Figure 19 The energy of two halves of a nucleus, together (left), just separated (centre), and far apart (right). (a) Diagrams. (b) The two energy components, the repulsive and the attractive, not to scale. (c) The net energy sketched for the fusion of two light nuclei. (d) The net energy sketched for the fission of one heavy nucleus into two halves.

to feel anything except the disruptive influence of the electrical repulsion. As a result the energy curve forms a big 'hill', separating the condition of a single nucleus from that of two well separated halves. This hill is electrical in origin and is called the coulomb barrier, after Charles Coulomb, an 18th century pioneer in the field of electrostatics.

For fission to occur – for the two halves to separate – they have to have the lowest E when separated *and* be able to get over, or through, this barrier. The hill obstructs the change that delivers the energy.[44] Once through the barrier the two halves can slide down the remaining slope, rapidly gaining kinetic energy as they move further apart.

For fusion the problem is the other way around – the two smaller nuclei have to have the lowest E when together *and* be able to get inwards through the barrier, from right to left as shown. The curve for fusion is different in detail to the fission curve because the charges and distances are smaller. Only when they are very close together can the two halves feel the superior attraction of the nuclear force and slide down with the energy of the combined nucleus. To extract energy from fusion the barrier may be surmounted by extreme temperature and pressure, as happens in the Sun. The challenge of fusion power is to do this on Earth under controlled conditions for power generation. An important element of the nuclear story, looking to the future, is that fusion-based nuclear power stations are expected well within the next 50 years [45]. On the other hand schemes for fusion that circumvent the barrier by some 'cunning plan' or magical discovery are not expected to work.[45]

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[44] Quantum mechanics helps. It is possible for particles to *tunnel* through the hill permitting slow leakage, otherwise the barrier would be even more effective. A similar effect permits slow alpha decay. Tunnelling rates depend exponentially on the height of the hill. Quantum tunnelling is also important in electronics.

[45] A well known recent 'breakthrough' called Cold Fusion professed to do this, but, predictably, its hopes have not been realised.

So viable rates of fusion occur when the components are heated to give them extra energy to get inwards through the barrier. But what about fission? How may energy be delivered to the components inside a uranium nucleus to help them get out over the barrier? The answer is by absorbing a neutron. Being electrically uncharged, a neutron can enter straight through the barrier and contribute its energy towards an excited nucleus, which then has the extra energy to fission rapidly over (or through) the barrier. Furthermore, in the fission process extra neutrons are produced and these can then go on to induce further fission, and so a chain reaction may ensue.

The first man-made nuclear fission reactor had to be based on uranium-235, because no other fissile material exists in nature.[46] Uranium-235 occurs naturally as 0.7% of natural uranium. This concentration of uranium-235, on its own in a reactor, does not sustain a chain reaction, because too many neutrons are lost from the chain through absorption by the majority uranium-238. To do this a neutron *moderator* is needed as part of the reactor, as explained later, or else the concentration of uranium-235 relative to uranium-238 must be enriched. The first man-made self-sustaining nuclear reactor was built by Enrico Fermi on the site of a racquets court at the University of Chicago in December 1942.

With the first reactor came a source of neutron flux, and with these neutrons it was possible to make fissile nuclear fuels other than uranium-235. Placed in such a uranium reactor, natural thorium-232 can capture an extra neutron to make thorium-233, which decays by beta emission to uranium-233. Similarly, plutonium-239 is made from uranium-238 by neutron absorption followed by two successive beta decays. Both plutonium-239 and uranium-233 are fissile fuels that can maintain a chain reaction. Plutonium was a totally new chemical element that was not found on Earth until made artificially in 1940.

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[46] A fissile material is one that can sustain a nuclear fission chain reaction.

An important effect of the coulomb barrier is that it is very difficult to make materials radioactive. Aiming a source of ionising radiation at material does not have that effect, unless the energy is exceptional. Neutrons can do it because they get through the barrier, but beams of neutrons are not found in the environment because they are unstable and decay away in a few minutes. Electrons and gamma rays have little effect on nuclear structure, and protons and alpha particles are prevented from making other nuclei radioactive by the coulomb barrier. So, neutrons apart, the use of radiation does not make materials radioactive. This is a most important and reassuring aspect of radiation and nuclear safety. It needs to be appreciated when considering the use of processes like the irradiation of food or the sterilisation of hospital supplies.

Explosive devices

Although we are not really interested here in nuclear weapons and would rather avoid them, we need to appreciate how different their technology can be. In particular we need to understand why their fuel is different to that used in regular civil nuclear power stations.

A nuclear fission weapon relies on the rapid build-up of a neutron-induced chain reaction in high purity fissile fuel – that is uranium-235, plutonium-239 or uranium-233. Each nucleus of the fuel emits two or three further neutrons as it fissions. Each such neutron has a large chance to induce fission in a further nucleus, thereby releasing more neutrons and more energy. If the mass of fuel is small or dispersed, too many neutrons escape through the surface for this build-up to start – a condition described as sub-critical. For an explosion, two or more sub-critical masses have to be assembled to make a mass above the critical limit in which the build-up can then occur.

Timing is crucial, and the critical mass must be fully assembled before the chain reaction develops, otherwise the fuel blows itself apart before it has time to build up its full power. An efficient explosion should avoid a premature start, or *fizzle*, as it is known. This requires that the timescale of assembly be faster than the chain reaction build-up, and the mechanical dispersal be the slowest of all. This timing requirement limits the maximum size of a fission bomb – a larger one could not be assembled fast enough to avoid fizzle. The two methods of assembly that have been used are the gun barrel and the chemically driven implosion. With the gun method a sub-critical mass is fired into a hole in a second mass – this is effective with uranium-235. But for plutonium-239 it is too slow and the implosion method is required.

The chain reaction in a critical mass of fuel only begins when the first neutron appears. Where does this first neutron come from? If it comes from natural spontaneous fission its timing would be random, and, if this random rate is high, the chain reaction will start early, resulting in fizzle. Otherwise the start of the neutron build-up can be engineered with a *neutron initiator*, a neutron source made by mixing beryllium-9 with americium-241 at the critical time. Americium emits alpha radiation, and this reacts with the beryllium to give carbon-12 and the required neutron. This flux of neutrons gives the chain reaction a 'push start' just at the right time as the assembly comes together.

Table 11 Some fissionable isotopes with their fission fraction and fission rate per second for 1 kg.

Element-*A*	Half-life years	Spontaneous fission	
		Fraction	Rate per kg per second
uranium-233	2×10^{5}	1.6×10^{-12}	0.5
uranium-235	7.0×10^{8}	7×10^{-11}	0.06
uranium-238	4.5×10^{9}	5.4×10^{-7}	6
plutonium-239	2.4×10^{4}	4.4×10^{-12}	10
plutonium-240	6.6×10^{3}	5.0×10^{-8}	4.1×10^{5}
californium-252	2.6	0.03	2.3×10^{15}

So fuel for a nuclear weapon must have a high neutron-induced fission rate, but a low natural spontaneous rate. Table 11 gives spontaneous data for some isotopes of interest. With greater mass number *A* the spontaneous fission rate increases quite dramatically. So that any trace of californium-252, for instance, as an impurity in nuclear fuel would cause fizzle. Even plutonium-240 causes fizzle, unless its concentration is very low.

All of the isotopes listed in Table 11 can absorb a neutron to give an excited nucleus that then fissions. However, because the nuclear force gives an energy preference to neutrons that pair up in a nucleus (and likewise for protons), uranium-233, uranium-235 and plutonium-239 fission readily, even if the absorbed neutron has low energy. But that is not so for uranium-238 – upon absorbing a neutron it becomes uranium-239, which has an odd number of neutrons, and does not benefit from the neutron-pair premium. So it has less spare energy to overcome the coulomb barrier. As a result it usually emits a gamma ray rather than fission, unless the initial absorbed neutron is rather energetic. So uranium-238 is ruled out as a fissile fuel for weapons. However, it still has a large store of nuclear energy that can be used in civil power, and so also does thorium-232.

Uranium-233 is possible weapon fuel and it has been used in a test. However, in storage it builds up a concentration of uranium-232, which emits high energy gamma radiation. This makes it a hazardous choice as the basis of a weapons system – that is hazardous from a practicable handling and maintenance perspective.

That leaves plutonium-239 and uranium-235 as the preferred fuels for weapons. In each case weapons-grade fuel must be free of other isotopes. Uranium fuel should have more than 80% of uranium-235 to avoid neutron absorption by uranium-238; plutonium fuel should have less than 7% plutonium-240 to avoid fizzle on account of its high spontaneous fission rate. These requirements do not apply to fuel for civil power production, for which much lower purity is quite sufficient and fizzle is not relevant. The critical mass for uranium-235 is about 20 kg and for plutonium-239 about 6 kg.

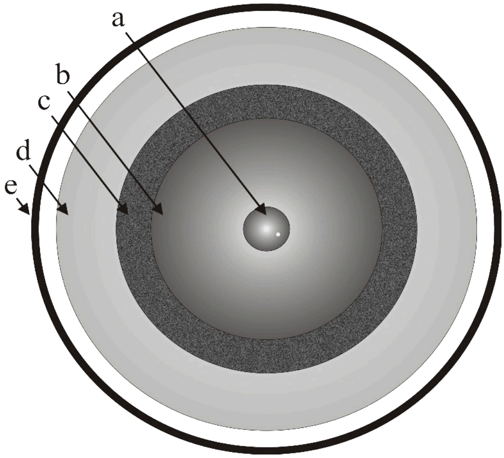


Figure 20 A diagram illustrating the relation between the components of a fission-based nuclear weapon:
a, neutron initiator;
b, fissile fuel;
c, tamper;
d, chemical explosive;
e, steel vessel.

A physical explosive device, fired by chemical implosion, has a number of concentric elements, illustrated symbolically in Figure 20. At the centre is the neutron initiator and around that the core of fissile fuel. Then comes the heavy *tamper* material with high atomic mass number that reflects neutrons back into the fuel to reduce surface losses. The chemical explosive develops implosion speeds as high as 5,000 to 7,000 metres per second to compress the fuel and the tamper inwards with a physical shock wave. The whole is encased in a steel containment vessel to reflect the initial compression wave inwards.

Enriching uranium-235 for weapons-grade fuel requires a large-scale high-technology industrial plant with an abundance of energy. Although there are a number of methods, none is easy because the two isotopes differ by only 1% in mass. In the early days the separation method used was mass spectrometry and later diffusion. The compound, uranium hexafluoride, is a gas at normal pressure and a temperature above 57°C. This makes it suitable for separation by diffusion. Being 1% lighter, the more nimble uranium-235 hexafluoride molecules are faster in the race through the diffusion tanks than those of the more ponderous uranium-238. But the difference is small and some 1400 diffusion stages are needed to reach 4% purity. For weapons-grade purity many more stages are required.

Today separation plants employ high speed centrifuges instead of diffusion. Such centrifuges were not available in the 1940s because materials technology was not developed to withstand the forces involved. Cylinders, 15–20 cm in diameter and rotating a thousand times a second, subject the uranium hexafluoride gas to an acceleration a million times gravity; this enriches the concentration of uranium-235 at the centre of the cylinder relative to the edge [46]. To make weapons-grade fuel requires many such stages, although far fewer are sufficient for civil reactor fuel. Such plant is more compact and less energy intensive than the earlier methods, and an important political question is how well it can be concealed from the eyes of neighbouring states and international inspectors.

The alternative to enriched uranium-235 is plutonium-239, also in rather pure form. This may be produced in a reactor by neutron absorption on uranium-238, followed by two successive spontaneous beta decays. However, the probability that this plutonium-239, once made in the reactor, captures a further neutron to make plutonium-240 is rather high – and plutonium-240 is a most undesirable contaminant for weapon-grade fuel because it causes fizzle. Consequently the uranium fuel (and with it the plutonium-239) has to be removed from the reactor rather frequently, before it has time to absorb the extra neutron. This is a most inefficient use of the reactor fuel – some 10 tonnes of uranium must be processed to extract a critical mass of plutonium-239. A nation state that tries to set up production of weapons-grade plutonium fuel using civil power reactors, which it claims to use for electricity generation, must spend much time shutting the reactors down for extra, and otherwise inexcusable, fuel changes. These fuel changes, and the construction of the required fuel reprocessing plant, make it obvious that plutonium fuel for weapons is being manufactured. At every reactor such activity is routinely monitored by international teams, as for weapons-grade uranium enrichment.

The first plutonium bomb was a test device called Trinity which was detonated on 16 July 1945 in the New Mexico Desert. Of the two bombs dropped on Japan on 6 August and 9 August 1945, one used plutonium and the other uranium. The result was that World War II ended on 15 August without the need for a land-based invasion of Japan.

There is a limit to the size of any nuclear fission weapon because of the difficulty of assembling a large critical mass within the time constraint – the fission bombs dropped on Japan were equivalent to 15 and 22 kilotonnes of TNT. Thermonuclear weapons based on fusion are not limited in size in this way and many were detonated in tests during the Cold War, although none has ever been used in anger. Just as a fission weapon is ignited by a chemically driven compression, the fuel for a fusion device is compressed and heated by an implosion driven by nuclear fission. This is necessary for the hydrogen to reach a sufficiently high temperature and density for long enough for the nuclei to overcome the coulomb barrier. This barrier is lowest when both nuclei have a single charge – that is hydrogen. Rather than simple hydrogen, its isotopes deuterium and tritium are used as fuel. The fusion products are helium-4 and a neutron. So the technology to build a fusion weapon requires fission as a trigger, and the feasibility of the two are closely linked.

A chemical explosion is quite distinct from a fire. In a fire the energy is released progressively over a period of time and this may be dangerous if not controlled, but an explosion is quite different, because the energy is released all at once to give a shockwave, a physical blast. Combustible materials and explosives are not the same. And so it is with nuclear energy too. The fuels can be distinct and the technology required for a civil nuclear power plant is different to that used in nuclear weapons, fission or fusion. Importantly, the design and operation of a nuclear reactor making fuel for weapons is different to a civil plant, used purely for the generation of electricity. The construction of reactors designed to produce fuel that can be used for weapons, the so-called breeder reactors, should form no part of a civil nuclear programme in the era of climate change.

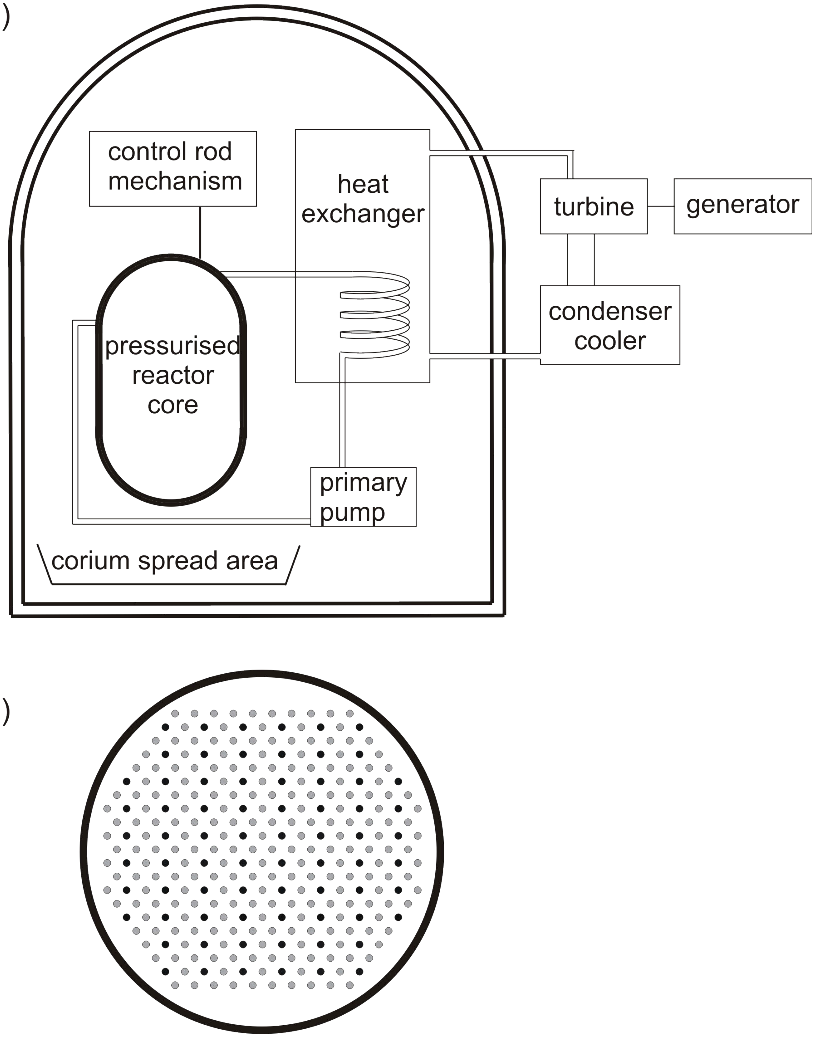
Civil power from fission

During the Cold War period many fission power reactors were designed also to produce weapon-grade fuel, and this has left an unfortunate legacy in the public mind. But the history of nuclear reactor design is a story of problems on other levels too – materials, control engineering and corporate financing.

Over the last 50 years improvements in materials technology have benefited every aspect of life. We have come to expect, for example, failure-free plastics and long-lived structures that can operate under harsh conditions. The evolution of new technologies is often painful in the development stage but successful in the end. In recent decades the tools of finite element analysis, computer simulation and monitoring systems have increased the speed and assurance with which developments are made. A good example is the diesel engine – over the last 50 years its design has been transformed. The way in which nuclear power plants can be built for efficiency and reliability is no exception.

All technologies suffer financial quakes in the development phase. For example, the IT industry has been a succession of cycles of boom and bust, ever since the first attempts to lay and operate a transatlantic cable in the middle of the 19th century. However, no one could say that it has not delivered benefits to mankind. Similar oscillations of confidence have plagued the nuclear industry, although this was made worse by the political pressure that generated links between military and civil programmes. Today, such links are undesirable, unnecessary and relatively easily monitored. They are undesirable, not least because they connect the fear of nuclear weapons with civil nuclear power in the public mind, and this has become the major image problem for nuclear power.

(a)



(b)

Figure 21 (a) The general features of a modern nuclear fission power reactor, in this case water cooled and moderated, and isolated in a double wall containment vessel. (b) A section across the pressurised reactor core vessel showing the matrix of fuel rods and neutron absorber control rods, immersed in the water as coolant and moderator. (This is a simplified sketch of the Areva EPR 1.6 GWe reactor where the pressurised core vessel is 12.7m in height [47].)

The really important safety features of a reactor are those that are responsible for the control and stability of energy production, and this depends on certain generic principles. If these fail, further safety systems ensure that the reactor contents are not released outside into the environment.

To understand the way in which a nuclear reactor works, it is instructive to follow how the energy flows, starting from the nucleus of the fuel and ending at the electric turbines that feed the power grid. First, a nucleus in a fuel rod within the reactor core absorbs a neutron and fissions, also emitting two or three neutrons which carry off the released nuclear energy. The fuel rods are surrounded by the moderator. This is made of low mass atoms, chosen to transform the released energy of the neutrons into heat. The neutrons bounce elastically off these low mass atoms, sharing their kinetic energy with them in the process. Then the material of the moderator transfers its acquired energy to the primary cooling circuit by thermal conduction or convection. A heat exchanger passes this energy onward to a secondary circuit that feeds the generating turbines. Exactly how these stages work varies with reactor design.

Figure 21a is a simplified drawing of the Areva Evolutionary Power Reactor (EPR) [47], chosen as an example of a modern design. In this case the moderator is water, which also acts as the coolant in the primary circuit. Figure 21b shows the reactor core with its matrix of fuel elements and neutron absorber rods that are inserted whenever the neutron flux is to be shutdown. Below the pressure vessel of the reactor core is the *corium spread area*, designed to retain the result of an overheated core within the double containment vessel, in the event that this should ever be necessary. The four-fold parallel safety control systems are omitted from the figure, but are described on the Areva website [47].

The nuclear fuel itself has to be replaced when 'spent'. How often this happens is determined by the structural integrity of the fuel elements and the build-up of fission products – the extent to which the fuel is fully used is called the *burn-up*, measured as a percentage or in megawatt-days per tonne. Typically fuel elements spend up to three years in the reactor core before replacement.

What properties should a good moderator have, and what other choices are there for the moderator and coolant, apart from water?

The chance of neutron-induced fission of uranium-235 or plutonium-239 is increased if the neutron energy is low. So, by lowering the neutron energy, the moderator improves the fission rate and reduces neutron absorption by uranium-238 at intermediate energies.[47] The effectiveness of its low mass atoms in slowing the energetic neutrons may be understood as follows. If two balls of equal mass collide, after the collision they will tend to share their energy equally on average, regardless of which ball had the most energy in the first place. On the other hand, if the energetic one is much lighter than the other, it simply bounces off the heavy one and there is not much sharing.[48] To maximise such energy sharing with neutrons, moderators with light atoms are chosen, such as graphite, water or heavy water.[49] An ideal moderator absorbs few neutrons, so that a chain reaction can be sustained without the need for enriched fuel. Ordinary water containing low mass hydrogen-1 is a good moderator and cheap. However, because of its neutron absorption, it requires fuel enriched up to 5%. The neutron flux is finely controlled by adding boron to the water which increases its absorption. Heavy water is not a strong absorber and does not

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[47] The problem has to be analysed carefully. The granularity of the fuel/moderator mix is important, as is the ability of the moderator to reduce the neutron energy in a small number of large steps, rather than a large number of small ones, which would increase the risk of absorption at the energy of many narrow resonances.

[48] If neutrons hit electrons, the neutrons would be cooled very efficiently indeed. But because the neutron has no charge and the electron no strong nuclear force, such collisions do not occur.

[49] In heavy water the isotope hydrogen-2, deuterium, is present in place of regular hydrogen-1. So heavy water is only 10% (20/18) denser than ordinary light water. Heavy water forms 0.015% of natural water.

require enriched fuel but it is not readily available. Graphite is not so efficient as a moderator and reactors that use it are larger. Furthermore, its crystal structure absorbs energy from the neutron bombardment. If not carefully managed, this energy[50] can be released unintentionally – this was the cause of the Windscale accident in 1957 [24].

The choice of coolant in the primary circuit depends on the core temperature and the requirement that it should not become too radioactive as it circulates through the core. Different designs use water, carbon dioxide or liquid sodium. The circulating coolant fluid has to transfer energy from the inside to the outside of the containment vessel, and the heat exchanger separates the coolant in the primary circuit from the secondary circuit that feeds the turbines. This improves the isolation of the latter from any possible radioactive contamination.

The objectives, against which any design may be assessed, are the efficient conversion of nuclear energy into electricity, the stable operation of the reactor, the containment of radioactive material, and the cost. Other factors that affect the total energy output and therefore the cost effectiveness are the refuelling cycle, the extent of maintenance shutdown periods and the working life of the reactor.

The highest efficiency at which heat can be converted into electric power is called the Carnot efficiency[51] and this depends on the absolute temperature of the thermal source. So a high working temperature of the cooling circuit is required if the conversion by the turbines is to be efficient. Although a high temperature improves efficiency, it also limits the choice of coolants and makes for a more hostile physical and chemical environment in the reactor. This affects the ageing and ease of maintenance of the reactor. The EPR design operates at a reactor pressure of 155 atmospheres and temperature of 310ºC with an efficiency of 35%. The importance of operating at high

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[50] This is called the Wigner Energy.
[51] For an ideal thermodynamic engine this is given by $1\text{-}T_1/T_2$ where T_1 is the exhaust absolute temperature and T_2 is the input absolute temperature.

temperature is evident because this efficiency is still only modest. Reactor power is quoted in GWt (gigawatts thermal) or, more often, GWe (gigawatts electric) – the ratio between these is the efficiency. This means that 65% of the total energy output is lost and is discarded as warm water to cooling towers or sea water – twice as much as the electrical energy generated. The large volumes of low-grade heat are not easy to use, but with good planning some of this surplus energy can be used to heat homes and greenhouses in the neighbourhood. The same consideration applies to fossil fuel plants. If power plants are preferentially sited far from centres of population, these options are reduced – and for political reasons this is usually the case for nuclear power plants. These are often built by the sea to take advantage of its large cooling capacity with some benefit to efficiency. The seawater is then also to hand as input to a possible linked desalination plant.

A reactor steadily delivering power needs a steady neutron flux in every part of its core. For this to be stable, each fission must produce just enough neutrons to go on to create exactly one further fission, on average. This depends on the neutron energy spectrum because that determines the balance between the rates of absorption and fission. Closely related are the temperature and density of the moderator. This raises two questions. The first is, how fast does the reactor respond to changes of absorber, for instance the position of the control rods?

In a nuclear weapon, mechanical speeds implemented by explosives are required to achieve the neutron flux change needed. Fortunately the neutron flux in a reactor behaves quite differently and responds rather slowly. This is because some fission neutrons come from the decay of short-lived neutron-rich fission products and their emission is therefore delayed. As a result, the reaction rate responds quite gently to small changes in the position of the control rods and slow mechanical feedback is sufficient.

The second question concerns stability. If the neutron flux rises a little so that the power output and the temperature increase, does the increased temperature reduce the neutron flux and re-establish equilibrium or increase the flux still further? Such temperature stability is an important requirement for any modern reactor design. For stable operation, as the temperature of the reactor increases, the neutron-induced fission rate should fall – without any intervention. This depends on the moderator and other details of the design. Early designs including that used at Chernobyl did not have this inherent stability.

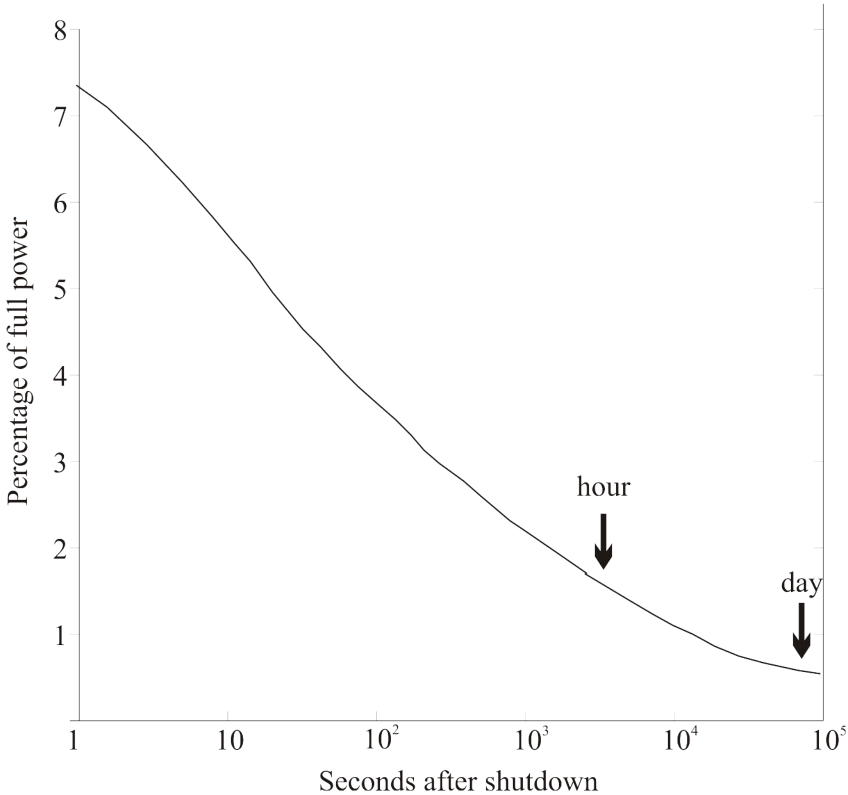

Figure 22 The decay of reactor power following shutdown (decay heat).

In the event of a power failure or other emergency, the neutron absorber rods should fall into place by default to cut the neutron flux and implement a shutdown, but cooling still has to be maintained. If the neutron flux is reduced to zero and the reactor is shut down completely, it continues to produce energy. This *decay heat* starts at 7% of the previous reactor output and decays away quickly and then more slowly, as it has contributions from many exponential radioactive decays, some with long half-lives. This fall-off is shown in Figure 22. After an hour the power drops to 2% and after a day to just over 0.5%. The consequence is that significant cooling continues to be needed following an emergency shutdown. In the EPR design this is provided by standby emergency diesel pumps backed up by extra water supplies fed by gravity. In the unlikely event that these fail and the core overheats, the reactor fuel must be contained even if the reactor pressure vessel fails. Provision is made for this extreme combination of eventualities in the form of a core spillage area within the containment vessel where hot radioactive core material (the *corium*) can cool without an environmental release of activity. More detail can be found on the Areva website [47].

Because of the release of decay heat it is difficult and inefficient to turn nuclear power plants on or off as electricity demand fluctuates. Such switching contributes to the ageing processes that eventually limit the working life of a reactor. This is why nuclear power is best used to provide the baseload supply, leaving more easily switched sources such as hydroelectric or gas plants to provide for fluctuations.

Energy without weapons

A chemical explosion is triggered by the excitation of molecules that are locked in an unstable state at normal temperatures. The excitation may be electrical or thermal, and the result of the explosion is a release of energy and gas, often nitrogen. One of the most famous such explosives, dynamite, was invented by Alfred Nobel in 1866. An obituary to him, erroneously published in 1888 while he was still alive, condemned him for this invention stating, *Le marchand de la mort est mort,*[52] and then continued,

[52] The merchant of death is dead.

> *Dr Alfred Nobel, who became rich by finding ways to kill more people faster than ever before, died yesterday.*

This is said to have brought about his decision to leave a better legacy on his death. All the great men who shared in the task of laying the foundations for nuclear technology partook of this legacy by winning the Nobel Prize.

The fuel for a simple fire based on chemical combustion is not the same as a chemical explosive. Fuels that burn are very common indeed, but fuels that explode are rather unusual. Similarly, the relatively simple fuel used for peaceful applications of nuclear technology cannot be used for nuclear explosives. So in both cases the fuels are different. In the nuclear case they require quite different levels of isotopic purity that cannot be confused unintentionally – they may be confused on purpose, of course, but that is a matter of deception and politics. The scientific signs of such deception are not easy to hide.

Uranium fuel for use in civil reactors designed simply to generate electric power needs either no enrichment in uranium-235, or an enrichment of 3–5%. Higher purity is not necessary. As for plutonium fuel, if the proportion of plutonium-240 is greater than 19%, the plutonium is termed reactor grade. Such fuels are quite safe to the extent that they cannot be used to make an effective nuclear explosion – that would require a concentration level of plutonium-240 of less than 7%. Purification of plutonium-239 by removing the plutonium-240 would be far more difficult, even than the enrichment of uranium-235 – the mass difference of the isotopes is only one part in 240, instead of three parts. Technically it would not make sense to attempt this on a practical scale.

A sub-critical mass of fuel still releases a small amount of radioactive energy in the form of alpha and beta radiation, so that it is warm, or hot in large masses if not cooled. Exceptionally, some isotopes emit gamma radiation as well and the use of these is avoided because they are hazardous. Otherwise, if shielded by a modest thickness of absorber like a glove, unused fuel may be safe to handle. In the 1950s on a visit to Harwell Queen

Elizabeth was handed a lump of pure plutonium-239 in a plastic bag and invited to feel its warmth.[53]

Depleted uranium is a substance that has caused much public concern even though it is less hazardous than natural uranium [48]. It is described as *depleted* because it is the spoil of the enrichment process. It is a useful material because it is a hard metal of exceptional density (19 times that of water). Typically it has less than half the activity of natural uranium. The alpha radiation that it emits is readily absorbed by a thin film of any material – it only forms a hazard to any extent if it is ingested. Like aluminium the bare metal is normally protected chemically by a hard natural oxide film – only in powder form is it chemically reactive. Like many other elements, for example copper, uranium would also be chemically toxic. But, because it is not absorbed by the body, copper is treated as an exceptionally safe material. With depleted uranium, it is lack of real information and confidence that is the problem. Armed forces using depleted uranium need to understand and be able to make judgements, otherwise they will not be confident with their weaponry.

The important task is to distinguish the military use of nuclear materials from their peaceful use. Compared with the production of other weapons of mass destruction, the manufacture of nuclear weapons remains difficult, and monitoring it is easier. Although the availability of civil nuclear power reactors for electricity generation is widely spread around the world, their misuse for the manufacture of weapons-grade plutonium fuel can be detected by monitoring reactor fuel changes, the choice of certain reactor designs[54], and the use of fuel reprocessing plant. Large-

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[53] This is fact. A different story is emphasised in fiction. The script of the BBC TV film, *Edge of Darkness* (1985), has the principal character, Jedburgh, dying of radiation sickness following contact with plutonium.

[54] For example, reactors moderated by heavy water can be refuelled without shutdown. But heavy water is not readily or cheaply available. It can be made by the electrolysis of large quantities of natural water, but this requires correspondingly large amounts of electric power whose use can be detected.

scale multi-stage enrichment facilities for uranium are also monitored. These tasks are carried out at the international level by the International Atomic Energy Agency (IAEA).

Another indicator of nuclear weapon production is the development of certain technologies, such as high speed centrifuges and the neutron trigger. Prior to the First Iraq War it was noticed that Saddam Hussein was acquiring this neutron trigger technology.

Waste

The severity of any waste problem depends on how much waste is generated and where it is discharged. There are other equally important questions. On what timescale is the waste released? What kind of risk does it generate? For how long does it persist as an extra hazard in the environment once released?

In Table 12 these considerations are compared for typical coal-fired and nuclear-powered electricity generating stations. The differences between the various fossil fuels – coal, oil and gas – are small (the chemical energy per ton of carbon dioxide emitted is roughly in the ratio of 1:1.7:2.2 for coal:oil:gas). The lesser effect of sulphur is omitted from the table because this can be captured and neutralised with available technology.

The production of carbon dioxide by a coal-fired power station is prodigious. The combustion of each ton of carbon creates 3.6 tons of carbon dioxide, because it locks up the oxygen too. The facts are that a gigawatt fossil fuel power station discharges over six *million* tons of carbon dioxide into the atmosphere each year and that this carbon dioxide persists there for a century or so, on average, before being reabsorbed by vegetation, oceans and soil.

Table 12 A comparison of the typical waste products generated by a large power station using either fossil fuel or nuclear fission.

	Fossil fuel	Nuclear fission
Risk due to waste if released	Climate change	Cancer and other health hazards
Quantity of waste generated by 1 GW power station per year	6,500,000 tons carbon dioxide 22,000 tons nitrous oxide (coal) 320,000 tons of ash, incl 400 tons arsenic and toxic heavy metals	27 tons high level waste (5 tons when reprocessed and vitrified) 310 tons medium level waste 460 tons low level waste
Release into the environment	carbon dioxide, nitrous oxide, immediate atmospheric release ash and heavy metals, no early release but shallow burial	no early release, but deep burial after (high level) reprocessing and vitrification
Persistence in the environment if released	carbon dioxide, about 100 years nitrous oxide, about 100 years heavy metals, indefinite	iodine and xenon, a few weeks strontium and caesium, about 100 years actinides, indefinite

Less important are the large quantities of ash containing hazardous heavy metals. These are buried in shallow landfill sites where they persist indefinitely. The numbers in Table 12 are not precise – but it is the factors of ten, a hundred, a thousand and a million that are important. For instance, the fact that gas is only half as bad as coal is almost irrelevant. The mass of carbon dioxide makes any scheme for its removal highly problematic. Even if pumped underground at high pressure, as has been suggested, it remains potentially a gas. Although out of sight if captured in this way, in reality it is stored in a pressure vessel at 50 atmospheres or more. In an earthquake or other accident such a geological container, with its pent-up internal pressure, could leak and vent its contents under pressure into the atmosphere as if it had never been stored.

The problem is described as *carbon capture*, but giving it a name does not mean that the large-scale technology is available at a realistic price. At best, it is a small component of the overall solution to the energy problem; at worst, it is an expensive idea, fraught with risk. There is already a very large charge of greenhouse gas stored in the sub-polar permafrost, and there is a significant concern that this may be released as these regions warm – storing further gases for the future seems undesirable, even if it were affordable. Buried solids such as ash or radioactive waste are quite different. They have no such hidden pressure and would not be released into the environment in the event of an earthquake.

Nuclear waste differs from fossil fuel waste in two essential ways – its quantity is small and it is not released. It is small because a nuclear power station needs only about a millionth as much fuel as a chemical power station for the same energy production (see footnote 6 on page 29). Then, unlike carbon dioxide, the waste from a nuclear power station can be stored, processed and then buried safely.

Broadly this 'spent' nuclear fuel waste has three constituents.

1. There are the actinides, comprising the unburnt fuel and various radioisotopes generated from it – essentially that part of the fuel that has not fissioned. The isotopes, including plutonium and uranium itself, may be extracted chemically by reprocessing and re-used for fuel, and as such they are very valuable. Exceptionally, if they are dispersed into the environment in a major accident, as at Chernobyl, they do not melt or vaporise and are not thrown far into the atmosphere. However, many have extremely long half-lives and so persist – although not for as long as the toxic heavy metal waste from a coal-fired plant, such as arsenic and cadmium, the power of whose chemical toxicity never diminishes at all.

2. Then there are the products of the fission itself. As the process of fission suggests, these have atomic masses that are about half of that of uranium. Many decay quite quickly to more stable isotopes. The faster decay processes are the source of the decay heat that follows the chain reaction (Figure 22). Of most concern are those with longer half-lives, in particular strontium-90 and caesium-137 with half-lives of about 30 years. So after the initial rapid decline, the activity of fission products falls by a factor two every 30 years.

3. Finally there are a few volatile products of nuclear fission with shorter half-lives. Examples are iodine-131 and xenon-133 with half-lives of a week or so. These decay away completely in a few months. Some are vented into the atmosphere in harmless quantities but others are removed by filtering and the filters buried as low level waste. Other fission products are less significant, either because they are less volatile or because they have short half-lives.

More generally, radioactive materials are managed with one of four strategies: 1, reprocess and re-use; 2, concentrate and contain; 3, dilute and disperse; 4, delay and decay.

Low level waste comes largely from laboratories, hospitals and industry. It consists of conventional garbage, tools, clothing and filters, contaminated by small quantities of mostly short-lived isotopes. It is not dangerous to handle and is safely disposed of by diluting and burying in relatively shallow sites [49]. It may be that with a more relaxed attitude to radiation some of this waste will not be seen to require disposal separate from other forms of waste. Such decisions will reduce costs.

Intermediate level waste includes resins, chemical sludges and reactor components, as well as contaminated materials from decommissioning. It makes up 7% of the volume, and 4% of the activity, of all radioactive waste. It may be solidified in concrete or bitumen. Generally short-lived waste from reactors is buried, but longer-lived waste from reprocessing is concentrated ready for later burial deeper underground [49].

In the event of the accidental dispersal of fission products, as happened at Chernobyl, land contaminated by caesium-137 is treated with regular potassium fertiliser to reduce its uptake into the food chain by dilution – caesium has a similar chemistry to potassium. In the same way, lime is used to dilute the effect of strontium-90 – calcium and strontium are chemically similar. Generally the dilution and dispersal strategy is not applied to high concentrations of these isotopes.

Spent fuel elements and their support cladding are the most radioactive types of waste. They are handled with strategies 4, 1 and 2, in succession. When the elements are withdrawn from the reactor, or it is shut down, the decay of neutron-rich fission-product nuclei continues and significant power is still released. Such materials are cooled for about 5 years by keeping them separated in large tanks of water, which also absorbs the emitted radiation in complete safety.[55] The materials may then be reprocessed to extract the actinides which can be recycled to make new fuel elements, such as MOX, composed of mixed oxides of uranium and plutonium. Of course the fraction of the spent fuel that has not fissioned and so can be recycled depends on the burn-up. In modern reactors the burn-up is still low but this could become higher in the future.

Having already given up their fission energy, fission products cannot be recycled. Their activity falls rapidly in the first 10 years. After that the radioactivity is largely due to strontium-90 and caesium-137, which decay with a 30-year half-life. So their activity drops by a factor of 10 after 100 years and 1,000 after 300 years. Long before that, after reprocessing these products can be chemically encapsulated by vitrification. The resulting ceramic blocks are extremely strong and resistant to leaching by ground water, or other mechanical or chemical attack. They are stored for 30–50 years above ground while they are naturally air-cooled, and then will be placed underground in a suitable deep mine or depository where they will maintain their integrity long after their radioactivity has faded away. In a few hundred years the radioactivity of the waste will drop to a level that can be found elsewhere in the Earth's crust. The reprocessing and vitrification of waste in this way is a mature technology that has an accident-free record of several decades. Only now is the earliest high level nuclear waste ready for disposal in a deep underground depository.[56]

An underground site for the long-term deposit of waste needs to be constructed, but this is not difficult or critical – not critical

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[55] For example, the entire stock of used fuel from 15 years of operation of the Sizewell B power station is safely stored in a single tank that is less than half full.

[56] In some cases extra expense is involved in the disposal of the earliest 'legacy' waste, for instance the fuel rods from the Windscale Fire of 1957. However, this work is now in hand. Benefiting from 50 years of experience, the disposal of waste from the plants of today will not incur such exceptional costs.

because the long-lived activity should have been removed by reprocessing. Radiation due to the vitrified fission products is a modest and contained hazard that requires security for a time that may be long in everyday terms, but is very short compared with the life of the blocks. Nevertheless, massive provision is being made for waste in some countries. In Finland a deep depository is under construction. A 5 m wide and 6.5 m high tunnel follows a helical path down to a depth of 500 m within structurally sound rock. Copper canisters containing nuclear waste will be placed in horizontal shafts that will be filled and sealed with clay. Use of the depository is expected to start in about 2020.

In the USA a depository at Yucca mountain in Nevada is due to receive its first nuclear waste by 2017. Matched to current safety regulations, such facilities may be thought overspecified. Such extraordinary precautions are not required and the expense could be reduced. The scale of these resources is primarily aimed at reassuring public opinion, rather than the provision of necessary safety. Such priorities cannot be afforded, and, in any case, it would seem that they are not effective at providing this reassurance. [Note added in proof, May 2009: It is reported that the US may discontinue the Yucca project and, perhaps, may recycle spent fuel, which has not been US policy in the recent past because of its association with weapons-grade plutonium production.]

In addition, there remains the need for public education. Also important is the need for technical continuity of know-how and recorded data. Inventories of radioactive materials and where they are stored, need to be maintained. Such records tend to have a short life compared with the physical and chemical integrity of any deposit. This short life is of most concern in countries where political stability is uncertain and social responsibility is short term. In any case depositories should be deep enough and burial irreversible, so that it matters somewhat less if records are lost during the few hundred years needed for the activity of the reprocessed waste to die away.