

Chapter 6

Nuclear Energy: The Ultimate Technological Fix?

6.1 Introduction

In Chapter 3 we saw that radioactive decay of elements like uranium in the Earth's crust was partly responsible for geothermal heat. Uranium, however, can also be used as a source of energy in its own right—not from radioactive decay heat (although this has been used as an energy source in satellites), but from the heat of nuclear fission. From its origins in the development of nuclear weapons in the 1940s, nuclear fission power has been the most controversial of all energy sources, which makes it particularly difficult to forecast its future. Controversy has embroiled all aspects of nuclear power: the safety of reactors, the extent of uranium resources, the effects on health of low levels of ionising radiation, the likelihood of nuclear weapons proliferation, and the effectiveness of various nuclear waste disposal methods.

Most reactors operating today are of a type that use very little of the energy potentially available from nuclear fission of the fuel. Some efficiency improvements can be made by raising operating temperatures and leaving the nuclear fuel in the reactor for longer, but if nuclear power is to have a long-term future as a major energy source, the presently-used thermal reactors must be seen as only a transition technology to so-called fast reactors, which, it is claimed, can extend the world's limited resources of uranium by perhaps a factor of 30 [36]. If a major shift to nuclear energy demands construction of breeder reactors, the experience gained in the first half century of nuclear power plant design will be of much less use.

Because nuclear energy is an established technology, this chapter looks in detail at the operation of nuclear plants, and the numerous problems they have encountered. It also examines the prospects for both fast and fusion reactors, new technologies, which, it is claimed, can alleviate many of the difficulties facing present reactor designs.

6.2 Nuclear Energy: History and Forecasts

In 1932, Albert Einstein stated: ‘There is not the slightest indication that nuclear energy will ever be obtainable.’ Yet 24 years later, in 1956, the first nuclear power station ever connected to the grid went on line at Calder Hall in the UK [55]. However, more than one half-century later, nuclear power provided less than 6 % of total energy, a share that has fallen slightly in recent years. According to the International Atomic Energy Agency (IAEA), at the end of 2008, 438 nuclear power plants were in operation worldwide (one less than a year earlier), with a total generating capacity of 372 gigawatt (GW). A total of 44 reactors were under construction, with a combined design output of 39 GW [20, 21].

In 2008, nuclear plants supplied 9.9 EJ gross of electric power (or 13.6 % of the world’s gross electricity), down from a local peak of 10.0 EJ in 2004 [2]. In fact, nuclear power’s share of global electricity production reached 16 % as early as 1986, then held steady for two decades, before losing share in recent years.

The growth of installed global capacity since 1960 is shown in Figure 6.1. In recent years there has been a decline in output (as distinct from installed capacity), largely because of the shut-down of a number of Japanese reactors while their earthquake risk is assessed, as discussed in Section 6.4.3. Growth in nuclear power output, like installed capacity, was rapid until the late 1980s, but has only grown slowly since. Nevertheless, the availability factor (the proportion of time for which the reactor is available for generating power) has risen greatly in recent decades, as operating experience has accumulated; in the US the average capacity factor (the proportion of time for which the reactor is actually generating at design power output) rose from less than 60 % in 1980 to 91 % in 2005 [46].

In their 2009 assessment of nuclear energy, the IAEA projected that even in their high-growth scenario, nuclear’s share of global electricity generation would increase to 14.4 % by 2030, only a little above its present level. In the low-growth case, nuclear energy’s share would fall from its 2007 level of 14.2 % to 12.4 % in 2030 [20, 21]. The IAEA is not known for its pessimism in projecting the future of nuclear power—in the mid-1970s, the IAEA forecast that the year 2000 would see as much as 2500 GW of installed capacity. In fact there was only 348 GW installed by the end of 2000 [26]. Similarly, Utgikar and Scott [49] showed that the international participants in a major 1974 Delphi study on the future of energy technology greatly over-estimated the development of nuclear energy and technology in 2000.

The most recent EIA projections [11], unlike the IAEA, have taken account of the late-2008 global financial crisis. Their base case projection was similar: nuclear’s share of global electricity output falls from 15.2 % in 2006 to 11.3 % in 2030. Even in the most favourable scenario (high oil price case), nuclear’s share of global electricity in 2030 is only marginally above its present value. These low official forecasts contrast sharply with talk of a ‘nuclear renaissance’. But as Bradford [3] has pointed out, 2009, the seventh year of the nuclear renaissance in the US has seen most of the applications to build reactors delayed or cancelled, and no concrete has been poured.

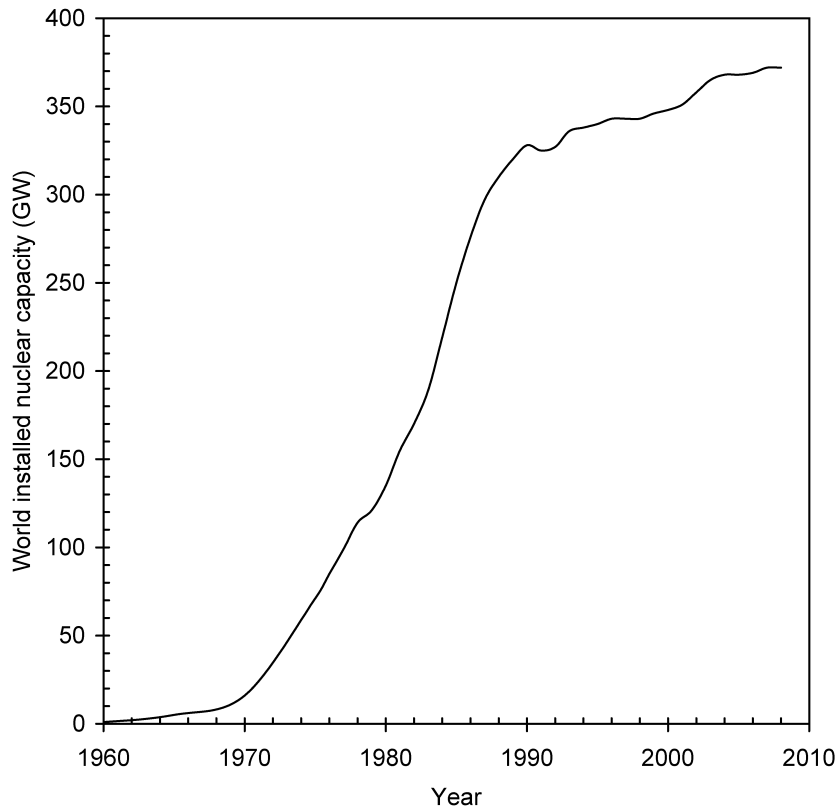


Fig. 6.1 World installed nuclear power capacity (electric), 1960-2008. Sources: [21, 55]

The prospects for rapid growth in nuclear power are not helped by escalating construction costs—in the US the cost of planned 1.0 GW nuclear plants in 2008 was estimated to be as high as US\$ 10 billion [39]. So-called extreme costs, the costs for the most expensive of a fleet of plants, are just as significant as average costs for plant construction and operation. The possibility of these very high cost plants deters private investment in nuclear power.

Another US study by Hultman and co-workers [18] analysed the levelised capital and operating costs for electricity entering the grid from 99 nuclear plants. They found that unit costs (in constant 2004 cents/kWh) for most reactors fell in the 3-8 cents/kWh range, but that 16 % had total delivered costs of over 8 cents/kWh, and 5 % were greater than 12 cents/kWh. Some very high cost reactors are to be expected for early reactors of a given general type, but these researchers found that the risk of high costs remained even after a number of reactors of the same design had been built. Nuclear power plants do not seem to follow the learning curves typical of other technologies.

Similarly, Mycle Schneider [42, 44], a French nuclear consultant, has documented the delay and cost overruns for the only two new reactors being presently

constructed in Western Europe, the first ones started since 1991. Both are being constructed by the Franco-German consortium AREVA NP, one in Finland, one in France. The 1,600 MW Finnish reactor is already several years behind schedule, and more than 50 % over its planned budget. AREVA NP has received subsidies for its construction from both the French and German governments. Worldwide, of the 35 reactors he reported under construction in August 2008, 11 had been under construction for 20 years or more. Feiveson [13] has also used the long lead times for nuclear power expansion to argue that no great expansion of nuclear power output is possible in the next decade or two.

Recently Schneider has predicted that ‘the industry will not even be able to replace the units being shut down because of ageing’ [42]. He gave several reasons why nuclear plant fleet replacement, or even up-grading of existing plants to prolong their operational life, will prove difficult. First, the slow growth in power plant construction evident over the past two decades (Figure 6.1) has resulted in many nuclear equipment suppliers leaving the market. The nuclear slowdown has led to an ageing nuclear workforce as well as an ageing fleet of reactors, so shortages in skilled workers and professionals could also limit any nuclear expansion, even if funds were available. Second, even before the global financial crisis, investors were reluctant to commit funds to nuclear plants, and given the cost data just outlined, it is not hard to see why. Given these facts, we might now reinterpret Einstein’s remark to mean that there is not much indication that nuclear’s share of global energy will ever rise much above its current value.

6.3 The Nuclear Fuel Cycle

A useful way of introducing the complex topic of nuclear energy production is to examine the so-called nuclear fuel cycle: tracking the uranium (or other nuclear) fuel from mining and milling, enrichment to fabrication of the fuel elements, loading of the fuel elements into the reactor, reactor operation, reprocessing of the spent fuel (if attempted), and finally the permanent disposal of nuclear wastes in underground storage sites. Figure 6.2 provides an idea of the fuel cycle in its ideal form. At present only a small share of spent fuel is reprocessed, and, despite the promises, no permanent high level waste storage repositories are operating.

The element uranium occurs in a number of different forms, or isotopes. Isotopes of a given element like uranium all have the same number of protons in the nucleus, but differing numbers of neutrons. The two most important isotopes of uranium (U) are U-235 and U-238. The isotopes decay naturally, U-238 with a half-life of 4.51 billion years—after 4.51 billion years half the atoms will have decayed, emitting an alpha-particle (the nucleus of a helium atom) in the process, and after another 4.51 billion years, half of the remaining atoms, and so on [57]. (Its half-life of 4.51 billion years is close to the age of the Earth itself, and about a third of the age of the universe, which explains why there is still some left.)

The nuclear fuel cycle for conventional nuclear power begins with uranium mining. Mining of uranium, either by underground or surface mining, is similar to

other mining operations, presenting similar hazards, with one important difference: the presence of radon gas. Radon is an intermediate product in the radioactive decay of U-238. After several decay steps, the chemically inert but radioactive gas radon-222 is produced, which builds up in the ore body. Being a gas, it can be inhaled, and so care must be taken to ventilate the mines well. Unfortunately, this has not always been the practice in the past—or even in some low-income, uranium-producing countries today. And for residents living near uranium mines, the threat to their health continues for many decades, even after the mines have closed down [9].

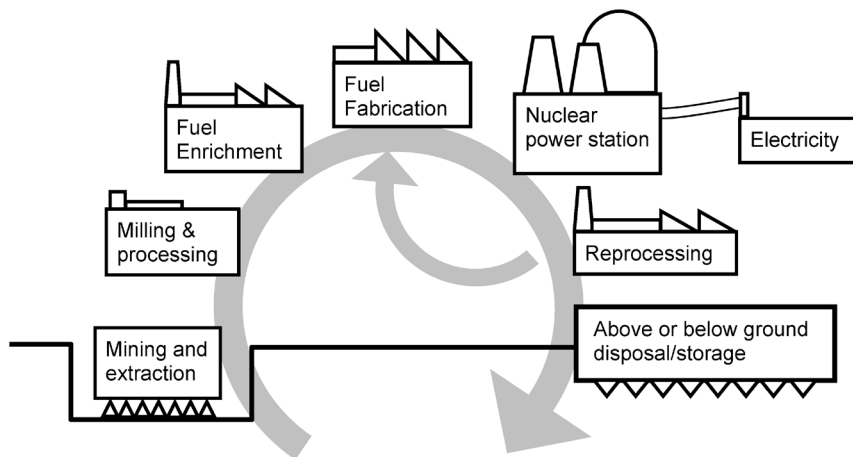


Fig. 6.2 Schematic diagram of the nuclear fuel cycle

After mining, the ore is crushed and milled to the consistency of fine sand, and the uranium extracted using chemical solvents. This ‘yellowcake’, with a chemical composition corresponding to U_3O_8 , consists of only 0.7 % of U-235, with nearly all the remainder being the more stable U-238, which cannot be directly fissioned.

The proportion of U-235 in natural uranium is too low for it to be used as a fuel in most existing reactors in operation today, so the fuel must be ‘enriched’ to raise the proportion of U-235 in the fuel to typically 3 %. For enrichment, the yellowcake is first converted to a gas (uranium hexafluoride). The slightly lighter U-235 can then be separated from U-238; the two main methods for doing so use either gaseous diffusion or gas centrifuges. Multiple passes of the gas through the enrichment plant are necessary for enrichment to even 3 %. (Some possible reactor types, including gas-cooled reactors and pressurised heavy water reactors, do not require uranium enrichment [55].)

However, the same equipment can also be used to produce highly enriched U-235, a weapons grade material (and the fissionable fuel used in the Hiroshima weapon in 1945). A civilian nuclear power program can provide an ideal cover for a highly enriched uranium program. At the very least, it leaves this option open for a country—and makes neighbouring countries think the worst about the purity

of its nuclear intentions. Enrichment, even to low levels, is also a very energy-intensive process. Although the centrifuge method is much more energy efficient, most enriched uranium is still produced in the earlier gaseous diffusion plants. Because of this reliance on inefficient technology, enrichment accounts for most of the energy inputs into nuclear power, but this should change as the centrifuge method increases its share [14].

Today's commercial nuclear power plants are nearly all fission reactors: heavy atoms (usually of uranium) are induced to undergo fission, but the products of this process have slightly less mass than the original atoms. The missing mass (m) has been converted into energy (E) in accordance with Einstein's celebrated formula $E = mc^2$, where c is the speed of light. The fission products typically include two or three neutrons emitted at high speed, which can be used to fission further uranium atoms. But since these fast neutrons are less efficient at causing fission of U-235 atoms than slower neutrons, a *moderator* is used to slow them down. Water is the most commonly used moderator, but the gases CO₂ and helium have also been used. Slow neutrons are also called thermal neutrons, and the reactors that employ them, thermal reactors.

If all neutrons emitted from the fission process could be used for fissioning further U-235 atoms, the fuel would be extremely rapidly depleted by the resulting runaway chain reaction, as happens in fission bombs. Only one neutron from each fissioning is required to maintain the chain reaction. Surplus neutrons are mopped up by neutron-absorbing control rods so that a steady rate of fissioning, and so thermal power output, is produced. (Control rods are manufactured from materials that can absorb neutrons without themselves fissioning. The light element boron is often used in the form of high-boron steel or boron carbide as absorbant [53].)

The fuel rods are removed from the core well before fission of all U-235 has occurred, because of the build-up of neutron-absorbing fission byproducts, which impede (or 'poison') the chain reaction. After removal, the irradiated spent fuel rods are placed in large water tanks to cool. The fuel rods contain most of the fission products from U-235 fission, and these are often intensively radioactive, with short half-lives. After 10 half-lives, the radioactivity of a given isotope will have decayed to less than one-thousandth of its original level (because 2^{10} equals 1024). So for isotopes with half-lives measured in days, a few months in the cooling pond will allow a great reduction in radioactivity. Some isotopes have very long half-lives—for plutonium-239, the value is 24,100 years [56]. It will take nearly 250,000 years for its radioactivity to fall to safe levels.

The long half-lives of plutonium (and other elements with even higher atomic numbers) create the need for long-term secure underground burial of high-level radioactive wastes, the final link in the fuel cycle. After more than 60 years of nuclear weapons and civilian nuclear power development, no permanent waste disposal sites have been developed. Instead, high level wastes from both the civilian and military programmes are stored above ground, as in the tanks at the Hanford reservation in Washington state in the US. These tanks, which have operating lives of only a few decades, have experienced serious leaks over the past decades. This, and the experience of other nuclear dumps and toxic waste disposal practic-

es, do not augur well for safe nuclear waste disposal. Cost-cutting has always been a feature of all toxic waste disposal.

Needless to say, we have no experience of political organisations lasting for such long time periods—they have lifetimes of a few centuries, at best. Proper disposal of our waste produces no economic benefits for future generations; for them it will be all cost. And we have no idea what the world will be like in future, since, as we saw in Chapter 2, significant climate change in the past has occurred over timespans of a decade or less. We can have no confidence that even hundreds of years from now, presently unoccupied land will remain unoccupied, or that the underground water regimes that we have observed in the past will be any guide to the future. Whether we have a ‘nuclear renaissance’ or not, the existing long-lived wastes will haunt us—or rather our descendants—for millennia.

6.4 Reactor Design

A bewildering variety of reactor types have been developed and even deployed, based on various combinations of moderator, coolant, and fuel [38]. By far the most common type are light water reactors (LWRs) [55]. In light water reactors, water serves as both the moderator for slowing the fission neutrons down, and as a coolant for carrying the heat from the reactor core to the turbines for electricity generation (see Figure 6.3). LWRs evolved from the US naval reactor program for nuclear-powered submarines. Submarine reactors require high power density, because of space limitations. Water is readily available for both moderating and cooling. These reactors are also refuelled ‘off-line’; in other words, the reactors are shut down for refuelling, which is not a problem for submarines, since they must return to port and be serviced at regular intervals anyhow. But the best design for submarine reactors is not necessarily optimal for the far larger land-based civilian power plants.

Nevertheless, LWRs today account for the great majority of global installed capacity. Ramana [37] gives the following breakdown:

- 359 LWRs, including 265 pressurised water reactors and 94 boiling water reactors
- 44 pressurized heavy water reactors
- 18 gas-cooled, graphite-moderated reactors
- 16 light-water-cooled, graphite-moderated reactors
- 2 fast breeder reactors.

A very different approach to reactor design was developed in Canada. Their CANDU (short for CANadian Deuterium Uranium) reactors use ‘heavy water’ (D_2O rather than H_2O , where deuterium (D) consists of one proton and one neutron) as moderator and coolant. D_2O occurs naturally as a very small constituent of ordinary water—one in every 3200 molecules [54]. The advantage of using heavy water is that natural uranium can fuel the reactor—in essence, the water is

‘enriched’ (by chemical and fractional distillation methods) rather than the uranium.

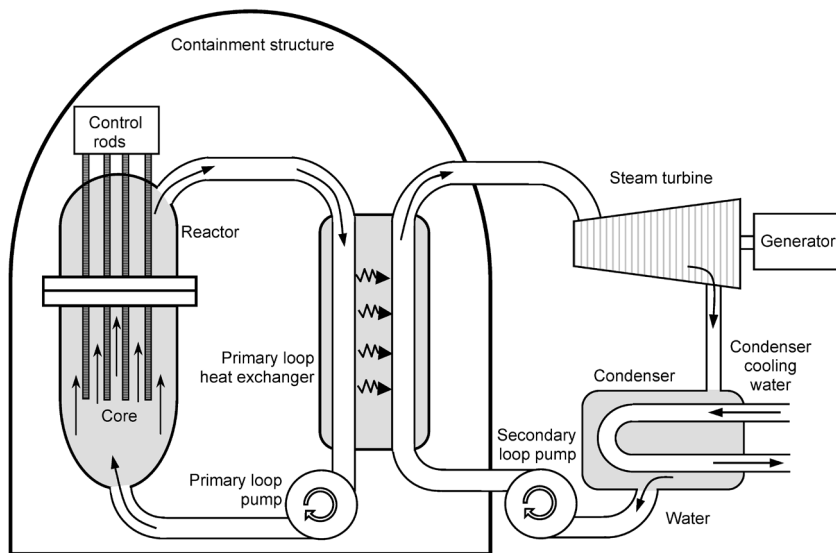


Fig. 6.3 Schematic diagram of a pressurised light water reactor

Another advantage of CANDU reactors is that they can be refuelled on-line, so need not be shut down for refuelling. Because CANDU reactors use heavy water, they produce more plutonium from their uranium fuel, adding to their weapons proliferation risk. Other reactors types, such as the Magnox reactors in the UK, also use natural uranium as fuel, but graphite to moderate the neutrons, and CO_2 as the coolant. Helium can also be used as a coolant in gas-cooled reactors.

In the three decades following the accident at the Three Mile Island (TMI) nuclear plant near Harrisburg, Pennsylvania, much of the emphasis in reactor design has been on making LWRs safer. The design aim has been to make reactors ‘inherently safe’, so that even if a loss of coolant accident occurs, the reactors can still be safely cooled. For reactors such as that at TMI, if for some reason the coolant water flow is reduced, emergency pumps are rapidly activated. If these also fail, a loss of coolant accident occurs.

Even if the fission reactions are stopped by full insertion of control rods to absorb all neutrons, much heat will still be generated in the core from decay of short-lived fission byproducts of the chain reaction. (Typically, decay thermal power output is 5-6 % of the total thermal output of the operating reactor.) The longer the fuel has been in the reactor, the greater is the decay heat power output that must be removed. If it is not continuously removed there is a danger of the fuel elements melting, with resultant damage to the reactor vessel. Safety of LWRs is not helped by the high power energy density in the reactor core.

One approach to improving safety has been the use of passive safety features, rather than reliance on active high-pressure emergency water pumps. Passive safety features rely on natural physical processes, so that even if all active systems fail, the core will not overheat. The new LWR reactor design AP600, for example, relies on a large tank filled with cold borated water (ie water containing borax). If the core pressure remains elevated, the cold water circulates as a result of negative buoyancy [34]. Convection cooling operates for as long as core cooling is needed. Inherently safe designs are even better than passive systems. Pebble bed reactors encase the fuel pellets in layers of ceramic materials that have higher melting points than can be achieved by the reactor, even without cooling.

If nuclear power is ever to be a major global energy source, it will also need to be taken up by most countries in the world, not just the present technologically advanced economies, which account for nearly all nuclear power capacity today. One proposal in the US is to construct small reactors designed to operate without major maintenance needed for up to 30 years in countries with low grid capacity requirements.

Conventional reactors can have electrical outputs of one GW or more, often too large for grids in such countries to absorb. (These small reactors are also designed to be used in settlements remote from the grid in regions such as Siberia and Alaska, with power needs as low as 10 MW.) For overseas operation, the reactors would be shipped in a supposedly ‘tamper-proof’ capsule, and then shipped back to the US at the end of their operating life. A number of other countries, including Japan, Russia and India, are also working on small reactor development for both local and export markets [29].

6.5 Difficulties with Existing Nuclear Power Programs

Nuclear power has been by far the most controversial of all energy sources. In the 1970s and 1980s, strong anti-nuclear movements developed in many countries of the OECD, around the issues of uranium mining, reactor safety and low-level radiation, nuclear proliferation and nuclear waste disposal. No doubt helped by the 1979 TMI accident and the Chernobyl disaster in 1986, these movements succeeded in producing a near-moratorium on new nuclear power plants in West European countries and the US. In this section, we explore in more detail the various reasons underlying the controversy.

6.5.1 *Uranium Resources Are Limited*

Although nuclear energy is not a carbon-based fossil fuel, and so produces no CO₂ when operating, it is, like fossil fuels, a non-renewable energy source. Like fossil fuels, we need to know what the reserves of uranium are, and for how long they will last at various usage rates. The latest official estimates gave convention-

al resources of uranium as 5.5 million tonnes (Mt) able to be mined at prices $\leq$ US\$ 130 per kg. Of this figure, reasonably assured resources were 3.3 Mt, and inferred, but yet-to-be-discovered resources were 2.2 Mt. Additionally, undiscovered resources were estimated at 10.5 Mt, for a total of 16 Mt [8].

Reactors typically use 20.7 tonnes of natural uranium to generate one TWh of electricity (0.0036 EJ) [36]. If all the 2008 global electricity production of 20,202 TWh was generated from nuclear plants, the proved recoverable reserve figure of 3.3 Mt uranium would last only 7.9 years, and the entire 16 Mt total a little over 38 years—the life of a typical reactor. On the other hand, at the 2008 rate of nuclear electricity production (2,739 TWh), 16 Mt would last for nearly 300 years. Some have argued that the official estimates are too high, and should be reduced [8, 32]. Even so, if nuclear power only maintains its present primary energy share, U-reserves should not be a problem any time soon [31].

Uranium ores presently mined are typically around 2,000 ppm, and the energy costs for mining are low compared with the energy in uranium [17, 50]. As we saw for copper [6], the energy requirements for mining and milling uranium also rise exponentially as ore grades decrease. For concentrations below 100–200 ppm, van Leeuwen and Smith [50] argued that energy costs become so high that CO₂ emissions from nuclear power plants using these low grade ores would exceed those from a natural gas plant of equal output. In addition, the environmental costs of mining, milling and disposing of the huge volumes of soil or rock involved would be large; a shift from 2,000 ppm ores to 200 ppm means that 10 times as much ore has to be processed.

To illustrate what would be needed for low grade ores, consider the energy requirements for mining existing high grade ores at South Australia's Olympic Dam mine. Once extensions are completed, this mine is expected to yield 730 thousand tonnes of refined copper and 19 thousand tonnes of uranium oxide per year. To do this it will consume almost 1.4 million litres of diesel and fuel oil per day, roughly equivalent to 2.7 % of all Australian diesel fuel consumption, and almost one % of annual electricity. Total annual greenhouse gas emissions are expected to be around 4.7 million tonnes CO₂-e [1].

Unconventional uranium resources are vastly larger than conventional resources. Phosphate rocks contain an estimated further 22 Mt of uranium. Together with shales, ore concentrations might be 10–100 ppm [17, 36]. For the very low concentrations found in phosphate rock, it seems unlikely that net energy would result from its use in the present reactor fleet [30]. The energy, economic and environmental costs would also be high, although some costs could be shared with phosphate production. The mining program required would be enormous.

But terrestrial resources are dwarfed by those of the world's oceans, which contain an estimated 4–5 billion tonnes of uranium, at 3 gram/litre. For seawater, the maximum energy density that could be obtained from the dissolved U-235 is low, 1.8 MJ/m³ of seawater [17], although using the concentrated brine from desalination plants could reduce energy needs. Just providing for the world's 2008 gross electricity production would entail processing nearly 50 thousand km³ of the ocean each year, even assuming 100 % collection. The effect on ocean surface ecosystems—and the costs of segregating depleted seawater from unprocessed seawater—would rule out such an approach.

6.5.2 Low Level Radiation

Low level ionising radiation is a potential hazard at many parts of the nuclear fuel cycle: from mining, tailings dumps, normal reactor operation, reprocessing of spent fuel, and the storage, either temporary or permanent, of high level nuclear wastes. Fear of this invisible radiation is an important driver of opposition to nuclear power. Of course, the nuclear fuel cycle for civilian power plants is only one possible source of radiation.

Other sources include wastes from military nuclear programs, medical and other X-rays, and natural background radiation. The widespread testing of nuclear weapons in the atmosphere was also an important source of radioactivity. As we have just discussed, radioactive elements are present in low concentrations in the Earth's crust, particularly in granite rock. People living in areas with such rocks receive larger than usual doses of background radiation. So do those living at high altitudes, because of increased levels of cosmic radiation [52].

An examination of the history of radiation standards shows a progressive reduction since the early 20th century in what were regarded as 'safe' dosages for both workers in the nuclear industry and the general public. It is widely agreed that setting radiation standards involves ethical problems as well as scientific ones. For example, should levels for nuclear plant workers be set at higher levels than the general public? If yes, how much more risk should they be exposed to? There is also much controversy about the dose-response curve for radiation at low levels; in other words, the adverse health effects (for example the increased risk of certain types of cancer) that can be expected for populations exposed to various levels of ionising radiation.

The currently-accepted view is the 'linear no-threshold' model, which argues that all levels of radiation cause some adverse health effects, and that the risk is directly proportional to exposure. It is based on the long-term health experiences of Japanese survivors of the nuclear weapons dropped in 1945. This view is in line with our understanding of how radiation causes damage in biological cells. A rival viewpoint, the hormesis effect, argues that low doses of many substances that are toxic at higher levels (including low level radiation) are beneficial at low levels [45]. Plainly, such a theory is convenient for the nuclear and other industries.

Reactors routinely emit small amounts of ionising radiation during normal operation. Whether this level is harmful for local residents is a controversy that has continued for several decades. The industry claims the extra dosage is negligible compared with that from background radiation and the medical and dental X-rays the public already receive, and so is of little consequence. Other researchers are not so sure: Mangano and co-workers [28] studied infant deaths and birth defects among residents living upwind and downwind from eight US closed reactors that were at least 113 km from other reactors in the years following closure. They found that the trends in infant deaths upwind from the closed reactors, or more than 64 km away from them, were no different from that for the national patterns. For downwind areas within 64 km of a closed reactor, however, they found that cancer incidence in children under five was reduced significantly in the years fol-

lowing closure. Other studies in Europe have found childhood leukaemia clusters near nuclear installations, although the exact cause is under dispute [12].

6.5.3 Nuclear Accidents and Reactor Safety

The above discussion only considered normal releases of radiation from nuclear power plants, but reactor failure can result in very large releases. Hirsch and colleagues [15] argued that once a reactor has been operating for about 20 years, the risk of serious accidents from embrittlement (and so the gradual weakening) of the reactor pressure vessel rises. Yet the lives of existing reactors are being extended beyond the four decades originally intended, because such an extension is far cheaper (and has fewer political problems) than constructing new reactors. Serious accidents can result in very large releases of radiation from nuclear reactors, as happened in Chernobyl. Fortunately, the interests of both local residents and utility owners of nuclear reactors overlap for serious accidents to plants—a widely publicised reactor failure, like TMI, can (and did) have a devastating effect on the fortunes of nuclear power. But such is not the case for the ‘routine emissions’ discussed above.

Charles Perrow [35] has analysed the safety of complex systems like nuclear power plants, from a social science viewpoint. He concluded that failures in ‘complex and tightly coupled’ engineered systems such as nuclear power plants were inevitable, examples of what he famously called ‘normal accidents’. These occur because:

[...] occasionally, though rarely, there are bound to be two or more failures that interact in such a way that no designer or no operator could anticipate, and if the system were also tightly coupled, the failures would cascade and bring the system down.

His proposed solution was to try to minimise the consequences of these inevitable failures by modularity, and by minimising the populations likely to be severely affected. Put simply, he proposed that people be barred from settling in, or alternatively, be relocated from, such high risk areas.

Normal reactor operation and releases during reactor accidents are not the only causes of radioactive releases from the nuclear fuel cycle. In the former USSR, in September 1957, a reprocessing plant for the nuclear weapons programme located in the southern Urals suffered a chemical explosion that lofted large amounts of radioactivity into the air, resulting in the contamination of many thousand km² of land [24]. (A month later, a plutonium production plant at Windscale in the UK, also suffered an accident with a smaller but still large release of radioactivity.) Yet if nuclear energy is to have a major energy role, reprocessing of spent fuel must be expanded many-fold.

A study of the Y-12 National Security Complex at Oak Ridge, Tennessee, in the US found that a large number of accidents at this huge nuclear weapons site had happened over the past decade or so, varying from uranium fires to waste drum explosions [9]. Yet the US has had long experience in dealing with the various parts of the nuclear fuel cycle. We must expect that countries with less tech-

nical sophistication and wealth will have many more accidents for a given nuclear power output. Michael Ramana [37] has quoted an old saying in the nuclear industry: ‘An accident anywhere is an accident everywhere.’ Nuclear power will not be well-served by a headlong expansion into countries presently without nuclear power.

6.5.4 Natural Hazards

Natural hazards can affect not only the operation of reactors, but also the integrity of mine tailings storage and high level waste storage. Earthquakes represent a particularly important hazard. In Japan in 2007, a 6.6 magnitude earthquake struck the Kaskiwakazi-Kariwa nuclear reactor cluster, the world’s largest nuclear power complex. The seven reactors were undamaged, but the earthquake led to their closure for several years [40]. They are finally scheduled for reopening in 2010. Many other populous countries that are earthquake prone, including Indonesia and the Philippines, are interested in nuclear power.

Safe operation of reactors can also be affected by fires, floods and even tsunamis. During the 2004 Indian Ocean tsunami, the site of a prototype fast breeder reactor under construction at Kalpakkam in India, was partly flooded [41]. Most of the world’s nuclear reactors are in danger of flooding, as they are usually located on rivers or coasts for access to cooling water. The danger is that the flood water could cause electrical short circuits or outright failures by flooding buildings that deal with plant safety. A power plant near New Orleans had to be closed because of risk from Hurricane Katrina.

Drought can also reduce the output from existing nuclear power if rivers are used to provide cooling water, as has happened in France in 2003. Since on-going climate change is likely to see more extreme weather events, as well as rising sea levels and storm surges, it is vital that future energy is generated by robust methods that are relatively impervious to any changes that might occur. Given the long life of reactors, existing plants are also at risk.

6.5.5 Nuclear Weapons Proliferation and Sabotage

The civilian nuclear energy programmes in the world today are, in large measure, an outcome of nuclear weapons development. The earliest reactors were military production reactors, optimised to produce plutonium. The spent fuel from these reactors was then reprocessed to extract this plutonium for bombs, such as the one dropped on Nagasaki, Japan, in 1945. An alternative route for nuclear fission bombs is to enrich natural uranium, carried out in giant enrichment plants. Weapons-grade uranium was used in the bomb dropped on Hiroshima, a few days before the Nagasaki bombing. Reactors, now optimised for electricity production, together with reprocessing of spent fuel and enrichment of natural uranium, are all

elements of civilian nuclear power production. An officially civilian nuclear power program can provide (and indeed sometimes has provided) an ideal cover for a military one.

Nuclear power installations such as power plants, cooling ponds, and storage areas for high level wastes are also at risk from deliberate acts of sabotage. After the events of 9/11, the risk of large airliners being deliberately piloted into such installations can no longer be ignored. An even earlier act of sabotage occurred in 1982, when the Superphenix reactor, then under construction in France, was the subject of a missile attack [43]. The consequences of such acts are yet another dimension we need to consider when we weigh up the various options for carbon mitigation. The concrete containment structure shown in Figure 6.3 would provide some protection, but as more passively safety features are implemented for LWRs, there are pressures to dispense with this expensive safety feature [27]. In any case, other sensitive installations such as cooling ponds, with high radioactive inventories, are not so protected.

We can give a rough estimate of how much plutonium fuel would be needed for the total reactor fleet, if breeder reactors produced all the world's current electricity output. In 2008, global gross electricity output was 20,202 TWh [2]. Assume 4.83 tonne of plutonium per GW capacity, as in the French Superphenix reactor (discussed below in Section 6.5.1.) With an 85 % capacity factor, roughly 13 thousand tonnes of plutonium is needed. Many thousands of tonnes more would need to be circulating in reprocessing and fuel fabrication plants, and in shipments from breeder reactors around the world to reprocessing plants. Since it only takes less than eight kilograms to make a Nagasaki-type nuclear weapon [51], diverting enough for a weapons program would be difficult to detect by international inspection. The chances of sub-national groups acquiring plutonium would also be much higher than today.

The dangers posed by the so-called 'plutonium economy' have not gone unnoticed; indeed it was the reason why the US decided against re-processing spent fuel in the 1970s. In unprocessed spent fuel, the plutonium is mixed in with intensively radioactive fission products, with much of the radiation coming from penetrating gamma rays. This radioactivity provides some protection against plutonium diversion [51]. One proposal is to have international reprocessing centres, where spent fuel would be reprocessed under international supervision. Where would these centres be located? Obviously the West would like them located in Western countries, but would this be acceptable to the rest of the world?

6.6 Nuclear Power: New Technology for the Long-term?

We have shown that among the challenges facing present thermal reactors are the prospect of future shortages of fissionable material, the need for safe and permanent disposal of high level nuclear wastes, and the risk of deliberate radioactive releases. The two new nuclear reactor types discussed here both aim to eliminate or at least reduce one or more of these risks.

6.6.1 Breeder Reactors

From the earliest days of nuclear power, it was realised that for nuclear power to have a long-term future, the development and deployment of breeder reactors was needed. If only thermal reactors were employed, uranium reserves were thought insufficient to fuel for long the grandiose nuclear programs that were envisaged. As we saw in the previous section, more recent reserve estimates, although adequate for centuries at present usage levels, would very soon be depleted if nuclear reactors were required to supply today's level of electric power, let alone total primary energy production.

Most of the world's thermal reactors use a 'once-through' fuel cycle in which the enriched uranium fuel rod assemblies are removed and replaced by new assemblies on a regular basis. The spent fuel is first placed in cooling ponds until its radioactivity has decreased. Although only a tiny fraction of the energy in the fuel is fissioned, it is then placed in temporary above-ground waste repositories prior to (it is promised) permanent burial underground. According to Price and Blaise [36], 'In this once through fuel cycle, about 99 % of the potential energy content in the nuclear fuel goes unused.'

In some countries, such as the UK, the spent fuel is reprocessed and reused in special nuclear reactors. Such reprocessing not only aims to make more efficient use of scarce uranium resources, but also to simplify the disposal of high-level nuclear waste. In the case of the UK, the plutonium generated by U-238 atoms capturing a neutron during reactor operation is chemically separated out from the spent fuel rods, and used to make 'mixed oxide' fuel. Given the very low conversion of nuclear fuels to usable energy during their stay in the reactor, it might be thought that the spent fuel could be reprocessed repeatedly until most of the fuel was consumed. But after several cycles the fuel would be 'poisoned' by the build-up of undesirable isotopes which lower reactor efficiency. At present any fuel which is reprocessed is only reprocessed once [36].

Although thermal reactors do produce some plutonium, this extra fissile material is not essential for their operation. But for fast reactors, the idea is not only to fuel them with plutonium, but also to have a blanket of U-238 to produce yet more plutonium. ('Fertile' materials like U-238, unlike the directly fissionable U-235, can only be readily fissioned by the capture of a neutron. Some of the U-238 atoms are thus converted to Pu-239 atoms by capturing the neutrons in excess of the one per fission needed to maintain the chain reaction.) Thermal reactors, as we have seen, use moderators to slow neutrons down, but fast reactors use high-energy neutrons, because they are more efficiently captured by U-238 nuclei, even if fast neutrons are not as good at fissioning U-235 nuclei. Reactors that have been designed to produce more plutonium fuel than they consume are called breeder reactors.

The Generation IV International Forum is an international consortium of nuclear energy countries formed with the aim of developing new reactor types. In 2001 they short-listed six reactor designs, the thinking being that probably only three of these would survive further screening and eventually become research prototypes [5]. Working demonstration models were not expected before 2030, or

even 2050 [7]. However, an August 2009 document on the World Nuclear Association website [58] listed seven reactor types, with no decision on which ones to develop further. The list included several fast reactor types, including the sodium-cooled fast reactor. Operating temperatures in several of the proposals are very high (up to 1,000 °C) necessitating the development of new materials. Higher operating temperatures and pressures, and higher burn-up of fuel in any fission reactor, thermal or fast, may help reduce costs, but they compromise safety [15].

Although breeder reactors are seen as Generation IV reactors, and so a future energy source, they are not new. A number of prototypes have been constructed, and a few are still operating, but only one commercial breeder reactor has been built: France's Superphenix, a sodium-cooled fast reactor. The decision to build the 1200 MW Superphenix was made in 1976, and the reactor was connected to the grid in early 1986. It then operated sporadically until 1996, when it was finally taken out of service after a life-time capacity factor of less than 7 % [43]. It is estimated that the reactor cost US\$ 9.5 billion (in 2008 values) to construct—the electricity generated was very expensive indeed.

In the US, several experimental breeder reactors were built, but the only commercial one was the Enrico Fermi plant near Detroit in Michigan. This plant was brought on line in August 1963, but was permanently shut down in 1972 after a major malfunction. Paradoxically, the cause of the accident appears to have been a last-minute modification to improve safety. Part of a small zirconium-clad metal pyramid, build on the containment floor to disperse any molten fuel from a reactor accident, came loose and blocked the sodium coolant flow. Japan and Russia have also had major accidents with their prototype breeder reactors, and in Germany, safety concerns have led to the closure of its prototype fast reactor in Kalkar. Today, only Japan and Russia, along with India and China, still have breeder reactor programs.

In India, a 500 MW prototype fast reactor is now under construction and is expected to be ready for operation in 2010. Two researchers, Kumar and Ramana [25] worry about its potential for serious accidents. As in all fast reactors, the core in normal operation is not in its most reactive configuration; distortion or melting of the fuel rods could greatly raise reactivity. Further, unlike water-cooled reactors such as the LWR, loss of the water coolant results in the reactivity increasing rather than decreasing. Quality control problems have also occurred during construction, and to save money, the containment structure is not designed to withstand reasonable worst case accidents.

There is, then, some operating experience for fast reactors. This experience indicates that they are much more expensive to build and operate than thermal reactors. Reprocessed fuel is much more expensive than the use of enriched natural uranium, which partly explains why it is little used. Because of the reactivity of the liquid sodium coolant, high power density, high operating temperatures, and negative reactivity, they are also inherently more difficult to operate safely than thermal reactors. Sodium leaks from the coolant pipes, and reactivity spikes have also occurred.

The need for multiple cycles of reprocessing to extract plutonium and other fissile material would increase the risk of plutonium diversion. Since a workable

nuclear weapon can be built with only a few kg of plutonium, the spread of fast reactors would increase the opportunity for new nuclear nations to develop nuclear weapons—and sub-national groups to acquire plutonium.

6.6.2 Fusion Reactors

The many drawbacks of fission reactors, whether thermal or fast reactors, are well known, because of their extensive operating experience. Fusion reactors, because they only exist as a possibility, do not suffer from actual adverse effects. Fusion reactors would develop energy by fusing together two light atoms, for example deuterium and tritium (D-T), two relatively rare isotopes of hydrogen. Fusion is what drives the Sun's prodigious energy output, and conditions similar to those in the Sun's core will be needed for successful fusion. One advantage of fusion over fission reactors is that the radioactive inventory is far smaller.

Smith and Ward [47] list the main three challenges for fusion power as:

- heating a large volume (perhaps 1,000-3,000 m³) of plasma to over one hundred million °C. The superhot plasma must be kept in a 'magnetic bottle', called a tokamak, to prevent it contacting the reactor walls and cooling
- proving that the materials chosen for the reactor walls are durable enough to survive the intense neutron flux and high temperatures
- ensuring that the inevitably complex system can operate continuously without frequent breakdowns.

The International Tokamak Experimental Reactor (ITER) was designed to help provide solutions to these problems, and site preparation work has started in Cadarache in southern France. But already, the cost of the project has doubled from the 2006 US\$ 7 billion estimate, and the estimated date for the first experiments capable of validating fusion has been pushed back from 2018 to 2025 [4]. These expected delays and cost inflation illustrate once more the contention of Hultman and Koomey [19] on over-optimism in nuclear costs and construction times.

Several researchers have made even more fundamental criticisms of fusion power. Echoing the earlier remark of Einstein, but perhaps with more evidence to support their view, Chauncey Starr and colleagues [48] pointed out that there is presently no interest from utility companies in hot fusion, and that this situation is 'not likely to change in the foreseeable future.' Only tax-payers money will be available for fusion development for many decades to come—private investors are not interested. Parkins [33] stressed that although commercial fission reactors followed fission bombs by only a few years, the fusion (hydrogen) bomb of the early 1950s has not, after more than half a century, been followed by commercial fusion power. He argued that the 'explanation has more to do with engineering than with physics.'

A fusion power plant will require a core volume roughly 150 times larger than a fission reactor of comparable power output. This in turn necessitates a very

large area (and volume) of surrounding blanket material to absorb the high energy neutrons released by the D-T reaction. Because of the neutron bombardment, the expensive blanket materials will become embrittled, and require regular replacement over the reactor lifetime [16, 33]. As a result of the radiation, dismantling, removal and replacement of the blanket will need to be done remotely. Parkins [33] and Hirsch [16] both concluded that the costs of fusion power would be far outside the competitive price range, whereas it needs to be much lower, given the financial risks involved.

6.7 An Uncertain Nuclear Future

Our discussion on nuclear power has illustrated a number of our central themes. One is the large uncertainty surrounding a number of issues important to nuclear power's future. We have little idea of the costs of new nuclear plants, even for thermal reactors, with over 400 units already in operation. Further, if nuclear power is to have a major role in future energy, the present dominant thermal reactors are a dead-end technology. Instead, breeder reactors, which in principle can utilise a much higher proportion of the energy potential of uranium, will be required in large numbers.

Thus the future will inevitably see designs that depart radically from existing ones, which reduces the value of the operating and design experience gained from the first half-century of nuclear power. In several of these proposed new designs, operating temperatures have been increased to as high as 1,000 °C, raising new questions about material performance and reactor safety. Even the innovative designs proposed for new thermal reactors can be very different from existing designs.

There is no consensus on the risks from low level radiation. The number of cancers that have been caused already by the radiation releases at Chernobyl are contested. Final health consequences are even more uncertain, because cancers can take several decades to develop after the radiation exposure, as the experience of Hiroshima survivors has shown. Nor is calculation of the dosage received by the population from a given release of various radioisotopes readily computed. It depends crucially on how the radioactive material is transported through the environment [12]. There have been cases of radioactive material being transported out of areas excluded to humans by bird and rabbit droppings.

A number of studies (eg [10, 29]) have pointed out that solving one problem in reactor technology often brings on several new ones. Increasing the burn-up of nuclear fuels does help promote economy and reduce both uranium throughput and waste production. A drawback is that it could have adverse effects on reactor safety, as it also increases the radioactivity and heat production of the wastes, making their handling and final disposal more difficult [10]. As is often the case in industry, attempts to lower costs can lead to compromises in safety. Some of the new designs for reactors have proposed to reduce costs by scaling down the robustness of the expensive containment building. Yet the strong reinforced con-

crete containment at TMI prevented a far more serious release of radioactivity from occurring [27].

It is instructive to compare the experience of nuclear power with other energy sources. It is true, as nuclear advocates claim, that coal is a very polluting fuel, even producing some radioactivity in addition to its large CO₂ releases. But the dangers posed by fossil fuel power generation are now well-known and uncontroversial. Diverting fuel from a fossil fuel-burning power plant is simple theft, not an international security issue. Nor does fossil fuel combustion leave waste that must be isolated from human contact for a period longer than modern humans have walked the Earth.

Although large hydro plants can, like nuclear power plants, take years to construct, such is not the case for important RE sources like wind or solar energy. Most wind farms and PV installations can generate energy and thus revenue within a year of the start of construction. Both these RE sources are modular, with much of the manufacture done in factories that continuously produce the units, enabling off-the-shelf purchase. A further difficulty for nuclear energy is the plethora of competing designs, with different coolants, operating temperatures and coolant pressures, moderators, and even input fuels, in addition to the range of design power outputs [38]. Manufacturing experience and operating experience will be thus spread thinly over a range of reactor types.

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