Chapter 7

Nuclear power

Nuclear power is a relatively recent development in human history and its long-term future is still to be determined. It is an outgrowth of nuclear weapons development during World War II. It comes in two different technology types, nuclear fission and nuclear fusion. Both are discussed in detail below.

7.1 NUCLEAR FISSION

Nuclear fission power is an important energy option for the future, although highly controversial. It now accounts for 11% of the world's electricity. Sixteen countries depend on nuclear power for at least 25% of their electricity supply. See Figure 7.1 (42).

7.1.1 Fission fundamentals

I was first exposed to the basics of nuclear fission as an undergraduate engineering student, and at one point even considered changing my major to nuclear engineering. It is a 'technologically sweet' energy option from the point of view of

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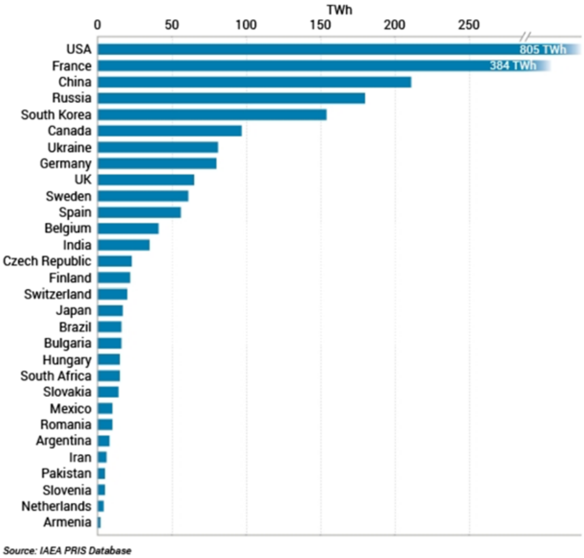

Figure 7.1 Nuclear generation by country 2016 (*Source:* International Atomic Energy Agency).

basic physics and offers the prospect of a very large source of electricity that does not release carbon into the atmosphere. The fundamental physics of nuclear fission are straightforward (see Figure 7.2).

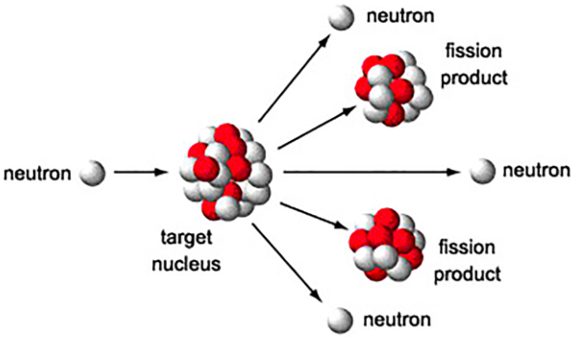

Figure 7.2 The fundamentals of nuclear fission (*Source:* Atomic Archive).

When a heavy (i.e., high atomic weight) nucleus (such as uranium or plutonium) is hit by a neutron it can split (fission) into lighter nuclei (fission products) and release additional neutrons. The mass of these fission products and released neutrons is less than the mass of the original target nucleus, and the lost mass is converted into energy according to the Einstein equation $e = mc^2$. This energy manifests as heat in a nuclear power reactor in which the target fuel, enclosed in fuel rods, is surrounded by water. The heated water turns into steam which is then converted to electricity in a turbine-generator. The fission products are radioactive, some with extremely long half-lives, and must be separated from human or other ecosphere contact.

7.1.2 Introduction to nuclear issues

I was reintroduced to the nuclear power issue in 1969 as a young physics professor at the University of Massachusetts. Given the strong feelings on all sides of the nuclear power debate, a few words on how I got into this issue may be helpful in understanding my personal views. I discussed this background in a 1982 speech at the University of Delaware (43), part of which I reproduce here.

> ‘Before I get into the substance of my talk, let me tell you a little about my background and my involvement with energy issues. I am trained as a low-temperature solid-state physicist, who was happily engaged in teaching and setting up and operating a new laboratory at the University of Massachusetts in 1969 when I first became involved with energy as a social issue. New England utilities, because of heavy dependence on imported oil, had early on looked to nuclear power as a response to this dependence. As a result, organized opposition to nuclear power also developed early in New England.
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> Thus it was in December 1969 that a colleague in the physics department asked me to attend an all-day seminar on the problems of nuclear power, which he could not attend because of a prior commitment. I did so, more out of respect for my colleague than curiosity, but that event surely has had its impact on my career. For the

first time I began to ask whether our nation's development of this power source may have left something to be desired. I also became painfully aware of how little I knew about commercial nuclear power, and decided to do something about it.

By talking with colleagues I was able to identify five other faculty members who were willing to meet once a week at lunch to discuss nuclear power issues and help to educate one another. This lasted about one year. During this period I found my interest in energy issues growing, and once-a-week discussions soon left me frustrated at my own pace of learning. Thus, I took the next step, which was to offer to teach an energy course to undergraduates, which I began to do in the fall of 1970. I know of no better way to learn something new than to teach a course where you have to keep ahead of your students. Shortly thereafter I was asked to serve as a science advisor to a newly founded New England citizens' group concerned about nuclear power, and I agreed. One thing led to another, and soon I was engaged in public debates on nuclear power with utility executives, scientists from Brookhaven National Laboratory, and the nuclear engineering department of MIT.

As my knowledge of nuclear power increased, and as I watched nuclear power become an important political issue at local, state and federal levels in the US and other countries, I came to several conclusions: I am not anti-nuclear, recognizing its carbon-free and large energy potential, but am sensitive to the concerns that many people have. These include high cost, routine releases of radioactivity from operating plants, shipping of nuclear wastes through populated areas, lack of long-term waste storage options, the remote but real possibility of accidents, and the potential for nuclear weapons proliferation. Alvin Weinberg, former Director of Oak Ridge National Laboratory, may have said it best in 1947 when he called nuclear power a 'Faustian bargain', defined by the Cultural Dictionary as follows: 'Faust, in the legend, traded his soul to the devil in exchange for knowledge. To 'strike a Faustian bargain' is to be willing to sacrifice anything to satisfy a limitless desire for knowledge or power.'

Clearly, there is a clash of values in our national debate on nuclear power. On the one hand we have advocates who, having looked at US dependence on imported fuels and at declining fossil fuel reserves, see little hope for energy independence and '… little long-range hope for the achievement of decent living standards everywhere …' without broadened use of nuclear power. They point to the unemployment that results when energy is scarce or very costly, and to the poor living conditions of a good part of the world, and ask how can we deny the benefits of nuclear electricity to these people. They also point to the risks of coal mining and coal burning, oil spills, the CO_2 problem from combustion of fossil fuels, and suggest that nuclear power, even with its risks, may be a reasonable choice in that context.

On the other hand, and exhibiting equal conviction and sincerity, are those who see viable alternatives to nuclear power, who question the feasibility and practicality of nuclear power for capital-poor nations without adequate roads, let alone power grids, who see any move toward a plutonium economy as a step down the road to nuclear war, who question the legacy a nuclear economy would leave for future generations, and who question the impact of human fallibility on the safe operation of the nuclear fuel cycle.

7.1.3 Issues

As a person committed to advancing our use of renewable energy, I have devoted most of my professional career to helping make that possible. Nevertheless, there are realities about how fast that can come about, and how to meet people's needs for electricity while that transition takes place. Nuclear power is a possible option for meeting that need, as well as a long-term, carbon-free energy source. The need for energy during the transition period is also an argument put forth for continued use of fossil fuels.

As for my personal views: while recognizing nuclear power's positive attributes, I have been distressed about how the nuclear industry has presented this technology to the public and often been resistant to acknowledging legitimate concerns associated with a nuclear economy. The cost issue is front and center with power utilities, especially now that natural gas costs are low due to fracking. It is my belief that a safe (i.e., non-meltdown) nuclear reactor can be built today – for example, a high-temperature gas reactor (HTGR) – unlike the early pressurized water reactors (PWRs) and boiling water reactors (BWRs) built at 3-Mile Island and Fukishima. Care and maintenance are critical, and human error and trying to cut costs have a tendency to get in the way. Nevertheless, the likelihood of a nuclear plant accident is arguably small, and if one rules out a meltdown, coal-burning plants may put more radioactivity into the environment than occasional radioactive gaseous releases.

The waste issue is a tough one, but one that has to be solved as we started off the nuclear era with tens of millions of gallons of high-level waste from weapons programs in WWII. Civilian wastes are adding to this total in an increasing number of countries around the world, and the long-term waste issue is being actively explored. I believe a solution will be found, probably in deep geologic storage, but at this point we don't know enough to be confident.

The weapons proliferation issue is the one that scares me the most, not just because of the growing knowledge of how to build a 'nuclear device' (i.e., a bomb), but also the potential availability of radioactive wastes that can be incorporated into a 'dirty bomb'. This latter possibility does not require great technical and manufacturing capabilities (it requires chemical explosive dispersal of radioactive materials) but can do immeasurable harm by creating uninhabitable radioactive zones. When I raised this issue with a representative of the US Nuclear Energy Institute his response was the US can handle such wastes safely, which may be true. But when I asked him about the many other countries that were adding nuclear power plants he went silent, illustrating the problem. Many countries will not have the means, technical and financial, to control these wastes as well as the US and a few other counties can, and the only answer I can come up with is internationalization of the waste disposal/recycling process. Another approach for future nuclear power plants may be to use a different fuel cycle that produces and consumes its own high-level waste. Modular reactors are also being discussed (100–300 MW units, as opposed to today's standard 1000 MW units) which in principle can be mass produced, be less capital intensive, and sealed without refueling for years to decades. Regardless, there will still be a waste problem that has to be addressed.

Assuming that the problems associated with nuclear fission power can be addressed successfully, which is still not clear, society will have some choices to make. Renewable energy is well on its way to entering the energy mainstream as a carbon-free, distributed, and large energy source, and one possibility is an energy future, post-fossil fuels, where nuclear power and renewable energy coexist. Other possibilities are a nuclear future or a renewables future. Given the complex issues presented by nuclear power my clear preference has been and continues to be a future energy system based largely on renewable energy in its many forms (see Chapter 8).

7.2 NUCLEAR FUSION

Nuclear fusion, the process that powers our Sun and other stars, is considered by many to be the 'holy grail' of energy supply. Why? The numbers tell the story.

7.2.1 Fusion fundamentals

The basic physics of fusion is well known and easily understood. When the nuclei of light elements (lighter than iron) are forced together, under extreme conditions of pressure and temperature, they will fuse – that is, form a heavier nucleus that is lighter than the combined mass of the two fusing nuclei. The mass that is lost is converted to energy according to $e = mc^2$ (see Figure 7.3).

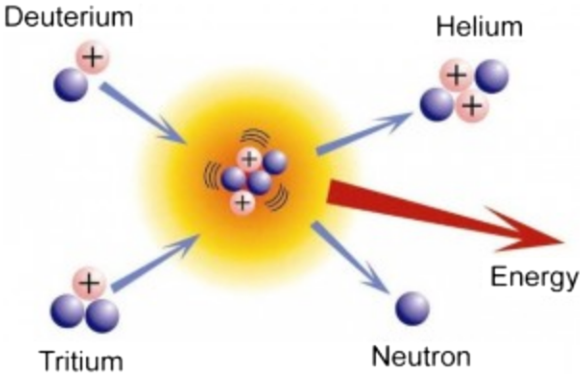

Figure 7.3 The D–T to helium fusion reaction (*Source:* Atomic Archive).

It turns out that so much energy is released in this process (a simple, back-of-the-envelope calculation is shown below) that, if the process can be harnessed on Earth, an unlimited source of energy is available. Fusion has other advantages as well as serious technological problems, which are discussed below. First, why are the numbers so intriguing?

While many fusion reactions are possible and take place in stars, most attention has been directed to the deuterium–tritium (D–T) fusion reaction that has the lowest energy threshold. Both deuterium ($_1H_2$) and tritium ($_1H_3$) are heavier isotopic forms of the common element hydrogen ($_1H_1$). Deuterium is readily available from seawater (most seawater is two parts ordinary hydrogen to one part oxygen; one out of every 6240 seawater molecules is two parts deuterium to one part oxygen). Tritium supplies do not occur in nature – it is radioactive and disappears quickly due to its short half-life – but can be bred from a common element, lithium, when exposed to neutrons:

$$^{6}_{3}\mathrm{Li} + ^{1}_{0}\mathrm{n} \rightarrow ^{4}_{2}\mathrm{He} + ^{3}_{1}\mathrm{H} + 4.8\mathrm{MeV}$$

D-T is also the reaction that largely powers our sun (although other fusion reactions do occur), routinely converting massive amounts of hydrogen into massive amounts of helium and releasing massive amounts of energy.

It has been doing this for more than four billion years, and is expected to continue doing this for about another five billion when its hydrogen supply will finally dwindle. At this latter point the fusion reactions in the core of the Sun will no longer be able to offset the gravitational forces acting on the Sun's very large mass and the Sun will explode as the Crab Nebula did in 1054. It will then expand and swallow up the Earth and its other planets.

7.2.2 Numbers

To understand the quantity of energy released: every cubic metre of seawater, on average, contains 30 grams of deuterium. As mentioned in Chapter 1, there are 300 million cubic miles of water on Earth, 97% in the oceans. Each deuterium nucleus (one proton + one neutron) weighs so little (3.3 millionths of a trillionth of a trillionth of a kilogram) that these 30 grams amount to close to a trillion trillion nuclei. Each time one of these nuclei is fused with a tritium nucleus (one proton + two neutrons) 17.6 MeV (millions of electron volts) of energy is released which can be captured as heat. Now MeV sounds like a lot of energy but it isn't – a Btu, a more common energy unit, is 6.6 thousand trillion MeV).

Now this is a lot of numbers, some very small and some very large, but taking them all together that cubic metre of seawater can lead to the production of about 7 million kWh of thermal energy, which if converted into electricity at 50% efficiency corresponds to 3.5 million kWh. If one were to convert the potential fusion energy in just over 1 million cubic metres of seawater (a small fraction of a cubic mile) one could supply the total annual US electricity production of 4 trillion kWh – and remember that our oceans contain several hundred million cubic miles of water. This is why some people get excited about fusion energy.

7.2.3 Barriers to fusion

Unfortunately, there are a few barriers to overcome, starting with how to get D and T, both positively charged nuclei, to fuse. The positive electrical charges repel one another (the so-called Coulomb Barrier) and you have to bring the distance between them to an incredibly small separation before the 'strong nuclear force' can come into play and allow creation of the new, heavier helium nucleus (two protons + two neutrons). It is this still mysterious force that holds protons and neutrons together in our various nuclei (the other three 'fundamental forces of nature' are the gravitational force, the weak nuclear force, and the electromagnetic force).

So how does one bring these two nuclei close enough together to allow fusion to occur? The answer in the Sun is extremely high temperatures and enormous gravitational pressure which we cannot reproduce on Earth. The pressures in the Sun, due to its large mass, are beyond our ability to achieve in any sustained way but the temperatures are not (temperature is a way of characterizing a particle's kinetic energy, or speed) and fusion research is focused on achieving extremely high temperatures (hundreds of millions of degrees or higher) at achievably high pressures. The fact that this is not easy to achieve is why fusion energy is always a few years away.

Two techniques are the focus of global fusion research activities – magnetic confinement (as in tokamaks and ITER) and inertial confinement (as in laser-powered or ion beam-powered fusion) (44). Several hundred million US dollars a year are being spent on these activities, mostly in international collaborations.

Fusion on Earth has been achieved but not in a controlled manner, and then only in very small amounts and for very short time periods with just one exception – the hydrogen bomb. This is an example of an uncontrolled fusion reaction (triggered by a fission atomic bomb) that releases a large amount of energy in a few millionths of a second. As the French physicist and Nobel laureate Pierre-Gilles de Gennes once said: ‘We say that we will put the Sun in a box. The idea is pretty. The problem is, we don’t know how to make the box.’

7.2.4 Pros and cons

The pros and cons of fusion energy can be summarized as follows:

Pros:

- virtually limitless fuel availability at low cost
- no chain reaction, as in nuclear fission, and so it is easy to stop the energy release
- fusion produces no greenhouse gases, and little nuclear waste compared to nuclear fission (the radioactive waste from fusion is from neutron activation of containment materials)

Cons:

- still unproven, at any scale, as a controlled reaction that can release more energy than required to initiate the fusion (‘ignition’)
- requires extremely high temperatures that are difficult to contain
- many serious materials problems arising from extreme neutron bombardment
- commercial power plants, if achievable, would be large and expensive to build
- at best, full scale power production is not expected until at least 2050.

7.2.5 Thoughts

Where do I come out on all this? I am not trained as a fusion physicist and so lack proximity to the efforts of so many for so long to achieve controlled nuclear fusion. Nevertheless, I support the long-term effort to see if ignition can be achieved (some scientists believe the ITER experiment is that critical point) and if the many engineering problems associated with commercial application of fusion can be successfully addressed. In my opinion the potential energy payoff is too big and important for the world to ignore. In fact I was once asked for my advice on whether the US Government should support fusion R&D by a member of the DOE transition team for President-elect Carter. I answered yes then and my answer hasn't changed.