Chapter 3: Rules, Evidence and Trust

The great enemy of the truth is very often not the lie – deliberate, contrived and dishonest – but the myth – persistent, persuasive and unrealistic. Too often we hold fast to the cliches of our forebears. We subject all facts to a prefabricated set of interpretations. We enjoy the comfort of opinion without the discomfort of thought.

John Fitzgerald Kennedy

Energy for civilisation
Natural rules of life 30
Energy and other needs 31
Solution without carbon dioxide emission 32
Sources of energy 33
Stored energy and its safety 33
Nuclear energy 34
Two soluble problems of power from nuclear fission 35
Widespread myths that should be contested 35
What happened at Fukushima Daiichi in 2011
Japan's preparation for the earthquake 36
Reactor shutdown and decay heat 37
Tsunami arrival 38
Reactor damage by tsunami 39
The chemical story 39
Radioactivity released into the air 40
Re-criticality suppressed 40
Radioactivity released into the water 41
Spent fuel ponds 41
Public trust in radiation
Ignorance and lack of plan 42
The fallacy of absolute safety and the loss of trust 42
Impact on public health 44
Protective suits that frighten or impress 45
Loss of life 46
Caution that harms people but protects authority
Psychological disaster at Fukushima 46
Symbols of hazard 48

Evacuation, clean up and compensation 48
Fear of artificial radiation 49
Questions about the danger of internal radioactivity 50
Radiation safety is inter-disciplinary 51
Fear of the radiation from a CT scan 52
Wastes, costs and conflicting interests
Comparison of waste products 53
Nuclear waste 54
The cost of nuclear energy 54
The scale of a nuclear reactor 56
Notes on Chapter 3 57

Energy for civilisation

Natural rules of life

Many questions are only as interesting as their answers. Such a question is: *What is the purpose of life?* We are not talking just about human life here, but all life, conscious and unconscious, down to the simplest cell. How does life in all its manifestations actually go about living? We may observe how it is intensely concerned with relationships and competition – personal friends and communal enemies, infections and antibodies, political parties and military campaigns. The Darwinian answer to the first question is *to survive* – and more certainly and prolifically than the competition.

But there are rules. Much as the individual may strive to survive personally, that is not the main aim of life in general. The first rule is that all individuals die – survival is only for their progeny. Any personal belief in the sanctity of life that we may harbour is not shared by nature. Frequently, countless individuals are sacrificed in the carelessly inefficient process of finding Darwin's fittest samples. Similar carnage occurs in the competition amongst cells in the microscopic world. Nature offers sanctuary to very few, and continuing life to none.

So the First Rule of Life is that it is limited. Death is certain and there are no exceptions.

Individuals arriving on planet Earth come with nothing except their genes, and when they die they leave behind everything they have built – money, status, personality, education. These may have been useful within their lifespan, but no more. That means the worth of these is far less than the genes left to posterity. So the Second Rule of Life is that you travel light – you bring nothing in when you are born and take nothing with you when you die.

There are no exceptions to this rule either.

Life as we know it is confined to the thin shell of the atmosphere at the surface of the Earth – so no wonder it is so easy to pollute. Expeditions from the surface of Earth have been few, limited in range and immensely energy intensive. Attempts to find life elsewhere in the universe have shown no success and, anyway, it is hard to see how life elsewhere could be of much benefit to us. So we should expect to be limited to a small, overpopulated and increasingly polluted planet, effectively alone in the universe. What do we need while we are here? Life needs energy, and energy has a rule: e*nergy is conserved*. You cannot make energy. That is a rule of physics. As with the two rules of life, there are no exceptions to the energy rule and its consequences are far reaching.

Energy and other needs

It is relatively easy to discuss past problems – we may speculate on those of the present day, but we are simply unaware of those of tomorrow. It is hard work seeing current events in perspective, so the best discussion of future problems we can offer is to start with those of today that currently seem to have no prospect of adequate solution. In 2015 that list includes:

- Climate Change. The scientific evidence is now widely accepted [[1]], although the effect of dynamic exchanges between the small mass of the atmosphere and the large mass of the oceans is still uncertain, quantitatively. Exceptional weather and melting ice sheets have influenced public views. Compared with even a year ago, noticeably fewer sceptical voices are now heard. And then there is the role of methane and its release in large quantities from a warming Arctic; the public do not seem to be generally aware of this yet.
- Socio-economic instability. Following the misinterpreted Arab Spring of 2011 instability has spread to a broad swathe of countries. Lawlessness seems to have be come endemic in some regions, and the world powers are less willing, financially and politically, to intervene. Perhaps that is because they have become less confident of their own stability than they were in the past. Fracture, if not collapse, of many regimes seems more likely than at any time in the past 50 years.
- Food, water and population. Malthus, an English cleric, famously wrote in 1798 that the world population must necessarily be limited by the means of subsistence, and would be suppressed by misery and vice. His predictions have been delayed in their effect, but their logic remains. Although today birthrates fall as societies develop, the demand for resources rises with an ageing and risk-averse middle

class. At the same time, societies with younger populations are unable to satisfy ambitions for food and jobs. The pressures of migration, exacerbated by changes in climate, are evident and likely to trigger increasing conflict. Meanwhile, clean water supplies remain critical, and extra food relies on aid that is inevitably limited.

- The threat of epidemic. The evidence from the Ebola outbreak of 2014 shows that the world is not well prepared and reacts slowly. If Ebola had been a more contagious disease the worldwide escalation would have been severe.

If we are not to find ourselves marooned on a shrinking ice-flow like a polar bear, so to speak, we need to find solutions to these problems.

Solution without carbon dioxide emission

Natural forces shape the future, but so too does human organisation, nationally and internationally. Is it possible that human society, using its collective intelligence and education, might achieve some acceptable degree of equilibrium, at least in the provision of energy?

Atmospheric oxygen and the combustible materials on Earth, including those that are buried as coal, oil and gas, together form an energy store, a kind of battery. Currently this store is being discharged at an ever increasing rate by human activity, directly and indirectly. Human life itself makes a small contribution by taking in food and oxygen, and releasing carbon dioxide, so too do animals, both wild and the domestic ones kept mostly as sources of food. Although discharges from volcanoes and forest fires may be natural, many other fires are man-made. So too are electricity generation, transport, heating and other industrial activity that use carbon energy. In earlier decades concern for the future of carbon energy was based on the limited supply of fuel, but that has changed. Now the main concern is the effect on the climate of the discharged carbon dioxide. Direct measurements of the concentrations of greenhouse gases like carbon dioxide, taken *anywhere* in the world, show how they are increasing every year, year on year. There are reasons, dependent on the physics of these gases, to suppose that these increasing concentrations should affect the Earth's climate [see Selected References on page 279, SR3 Chapters 2-4].

Mankind needs a supply of energy to be available at all times of day and night. Without it, conditions on Earth would not support a fraction of its population today and its loss would involve death on a worldwide scale. Yet the appetite for energy is too large for any available intermediate storage to make a significant difference. So, it is the source of the energy that matters, and this should not add significantly to pollution, or increase the likelihood of global disease, war, climate instability, water shortage or starvation. But does any available source meet these demanding requirements?

Sources of energy

The carbon fuels – oil, coal, gas and the various forms of biofuels – should all be ruled out because of the carbon dioxide they release. Radiation from the Sun gives solar energy, directly, but it also indirectly drives wind, wave and hydro power. The gravity and motion of the Earth relative to Sun and Moon is the energy source behind the tides. Another so-called renewable energy source is heat from the inside the Earth. This originates from the radioactive decay of elements scattered through the volume of the Earth. In fact the output of radioactive heat per kg within the Earth is about equal to the natural radioactive heat in the human body (see Chapter 7). In the Earth this heat provides, not only geothermal energy, but also the thermal power for the motion of the tectonic plates and thence earthquakes, tsunamis and volcanoes. Geothermal power is particularly accessible in places at the edges of tectonic plates, such as California, New Zealand and Yellowstone National Park.

Often included in a list of so-called renewable energy sources are biomass and biofuels. However this shows a strange lack of straight thinking. These sources burn the vegetable matter created by natural photosynthesis, thereby discharging the waste carbon dioxide straight back into the atmosphere. Nature works hard to grow trees and other vegetable matter to reduce the carbon dioxide in the atmosphere. This is something that man cannot do himself on a large scale, but the use of biofuels and biomass simply discards the benefits of this natural and successful carbon capture. Their combustion is an amazingly short-sighted development, no better than the use of coal, oil or gas. Furthermore, their production often displaces the growing of food on large areas of agricultural land, and, what is worse, in many parts of the world, forest is destroyed for the purpose.

Stored energy and its safety

Popular discussions of energy supply often conclude that the task would be simpler if we could store energy easily. This is not easy on the scale that would be required -- this is fortunate because, if it were easy, it would be dangerous. The problem is the need to control the extraction of the energy from such a storage, efficiently and safely. In the event of an accident any energy store is liable to discharge, releasing large amounts of energy unintentionally. The more easily and completely this energy can be released, the better is the store but the more potent and devastating is any potential accidental discharge. So energy storage appears as a safety hazard as well as a desirable element of an energy utility. The danger of large amounts of stored energy is exemplified by a hydroelectric dam, as discussed further in

Chapter 7. The important question is the quantity of stored energy that has to be released safely in the event of an emergency. A coal, oil or gas fired power station can be turned off quickly without releasing stored energy, provided that the fuel supply itself does not start to burn [2]. Interestingly, fusion power has remarkably low stored energy: when the reactor is turned off, energy production ceases immediately, but that is not available yet. A nuclear fission reactor is different – like a hydro-electric dam, it has a large stored energy and some of this continues to leak out in the days and months following turn off. This is the *decay heat* that has to be dispersed effectively somehow, and the accident at Fukushima Daiichi demonstrated how difficult this can be.

Nuclear energy

For any source of energy there are two important measures, energy density and intermittency. Energy density is the energy available per kg, and this is discussed further in Chapter 7. Some energy sources have such low densities that they cannot deliver the energy needed without an unreasonably large mass of fuel, or moving air or water, etc. Use of an energy source is made increasingly difficult if it is intermittent when the demand is continuous. Then some full scale backup supply or energy storage becomes important. Large scale sharing or averaging of many intermittent sources on a grid seems an attractive alternative but its success depends critically on the distance between sources and their pattern of intermittency. If the distance over which the supply has to be shared becomes large, the capital cost or the success of the sharing may fail. Thus wind, wave and solar power are only available for a fraction of the time, or in particular places, sometimes where fewer people live and work. Although coal, oil and gas discharge their waste carbon dioxide straight into the atmosphere, they do have a high energy density and are not intermittent unless political forces intervene – they can provide energy at any place and time. Geothermal power, like hydro power and tidal power, is effective where it is available, but that is the exception. Thermonuclear power, that is fusion power on Earth, will be very important when it becomes available, but a few decades of development for the materials and reactor construction are needed first. A pre-prototype reactor, ITER, is under construction in France and this will be followed by a full scale prototype. However, for the more distant future it does offer the real prospect of unlimited power using small quantities of ubiquitous fuel.

Nuclear fission has a high energy density – just how high may be illustrated by comparing it with a state-of-the-art lithium battery – the grounding of the Boeing Dreamliner in 2013was caused by difficulty with the energy retention of these batteries. Fully charged they store 0.2 kWh of energy per kg. That may be compared with the energy stored in 1 kg of thorium-232, that is 100 million times greater. Put more graphically, 100,000 tonnes of fully charged lithium batteries (the mass of the largest super tanker) hold the same energy as 1 kg of thorium-232. Even a nuclear physicist has to marvel at these figures.

As for intermittency, energy from a nuclear fission reactor is as effective as a fossil fuel plant. It can be available at all times and can be built anywhere, even in an earthquake zone. It does not have to wait for the wind, a sunny day or the tide to turn, and its environmental impact, underlying cost and accident record are second to none. Although improvements, like the use of thorium as a fuel, will become available within a few years, the equivalent uranium version is not new technology. It is available now, and has been for half a century.

Two soluble problems of power from nuclear fission

There are just two residual problems: firstly, a widespread public and political phobia attaching to anything described as nuclear or related to radiation; secondly, international regulatory authorities who, instead of working to dispell this radiation phobia, act to enhance it – and have persisted in doing so for 60 years. These problems could be easily overcome, if enough people set their minds to it. However, on the back of these two concerns an impression has been created that nuclear energy is inherently expensive and that its waste is a problem – neither of which would be true in an informed world.

A real understanding of nuclear technology and its effect on life is sparse among scientists, and in the wider population it is lacking altogether. In the following chapters we look at radiation and nuclear technology through the eyes of different disciplines. Although the use of nuclear energy is often described as complex or sophisticated, it is simple to grasp the basic facts sufficiently to appreciate its safety. The phobia continues to fuel stories in the press and popular literature and these have been self-sustaining.

There are new international moves [3] to question the policy of the various international and national safety authorities who have failed to correct dangerous misapprehensions about the safety of radiation. We need to understand the diverse reasons for the reluctance of these authorities to respond so far, but their steadfast adherence to the pseudo-science of LNT cannot continue to withstand the evidence for long.

Widespread myths that should be contested

Though admitted by few, the mass of the human race seeks out irrationality. As President Kennedy says in the quotation at the head of this chapter, although an unreasoned opinion can be comfortably embraced without effort or expense, confronting it takes time, study and even pain. Fortunately, there are people who want to make a difference and leave their mark. It is salutary to read of the experiences that Marie Curie went through to make sense of the mass of tangled observations which led her to the understanding of the atomic nucleus as it stands today. Her story gives an extraordinary example of what can be achieved under adverse conditions [[4], [5]]. Unfortunately, many in the affluent world effectively deny her painstaking work, preferring to imagine nuclear energy and its radiation to be part of a malign and irrational game of chance – until, that is, they are in the hands of clinicians using it to cure them of cancer or otherwise extend their lives.

With more study, every member of the public could understand more and forsake some of the answers that have been simply repeated and copied, over and over without questioning for the past 70 years. Why? Because those answers do not fit the medical and biological facts: the popular account of nuclear radiation and its effect on life given in the media is mistaken and the real effects are usually harmless and often beneficial, contrary to Hollywood dramas and stories.

So should mankind take the hard decisions of real life, or choose exciting make-believe stories that avoid having to study, just briefly, in the footsteps of Marie Curie? The real problems that threaten the future of mankind in the twenty-first century are not hidden. The need for food, water and a space to live have not changed, but with rising expectations and expanding populations, the requirement for education and real scientific understanding have become paramount. The total misapprehension of nuclear technology at all levels, even among many scientists, should be corrected because, when understood even at a simple level, the ability to contribute solutions to civilisation's larger problems can be appreciated.

What happened at Fukushima Daiichi in 2011

Japan's preparation for the earthquake

The Great East Japan Earthquake, also known as the 2011 Tohoku Earthquake, occurred at 05.46 UTC on 11 March 2011. Its magnitude was 9.0 on the Richter Scale and it generated an exceptionally large tsunami that hit the northeastern coast of Japan. Although this is thought to have been the largest earthquake to hit Japan in a thousand years, the Japanese have studied earthquakes extensively and their building codes dictate that buildings should withstand significant disruptive forces. In October 2011 when I visited the region some roads were still damaged by subsidence, but relatively few buildings appeared affected. A school building that I visited in Fukushima City had been damaged, but its replacement was already completed and ready for use. The preparedness of the buildings was matched by the disciplined and organised reaction of the people; they all knew that after such an earthquake they should expect aftershocks and should prepare immediately for a possible tsunami. Accordingly, as soon as the earthquake was detected, the population took to higher ground and other places of safety from the tsunami. Schools followed practised routines and moved quickly. Inevitably, hospitals and homes for the elderly were not able to react quite as fast.

Reactor shutdown and decay heat

Across Japan the earthquake itself triggered an immediate shut down of all nuclear power reactors that were working at the time. A shut down in the case of a nuclear fission reactor means that all neutrons are absorbed by the control rods, released to drop into the reactor. Consequently as soon as the reactors were shut down in Japan all energy production by nuclear fission ceased immediately, long before the tsunami arrived.

Neutrons are the go-between that enable the fission of one nucleus to cause the fission of more. If a fissile nucleus absorbs a neutron, it is likely itself to undergo fission almost immediately, thereby releasing further free neutrons. This nuclear chain reaction can only be mediated by neutrons; it can be stopped by the control rods, made of non-fissile nuclei which absorb neutrons particularly readily, but do not undergo fission, thereby breaking the chain.

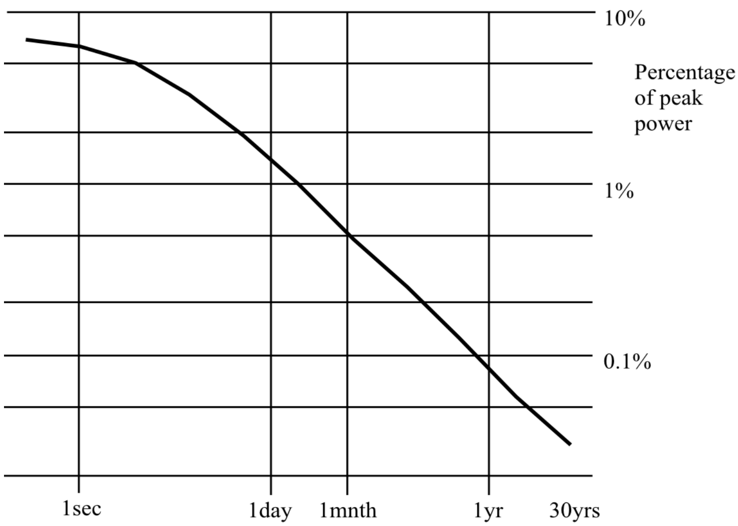

Illustration 12: A graph to show how the power of decay heat from a fission reactor falls with time after it is shut down . Note that both scales are logarithmic so that the low power after later times is shown as well as the higher power at early times.

However, although there is no more fission following reactor shut down, there is still some declining residual nuclear activity because many of the products of fission are still liable to decay. This releases energy known as decay heat as they change into more stable atoms. It is important to appreciate how quickly this decay heat declines initially. Immediately upon shut down it is 7% of the thermal power of the reactor, falling quite quickly to just over 1% after a day, as shown in Illustration 12 However, it falls more slowly as time goes on – after a year it is still 0.08%. Every reactor behaves similarly.

> You can calculate roughly what power such a reactor would produce by decay heat a day after shut-down. If before shut-down it was generating 1,000 MW of electric power with a thermal efficiency of 33%, the answer is just over 1,000 × 1% / 33% = 30 MW.
> A year later it would be down to 2.4 MW.

The reason for the shape of this curve of declining activity is that it is composed of the independent decay of many different nuclear isotopes, each with its own simple exponential decay and half-life. Initially the activity is dominated by the effect of the species with the shorter lifetimes, while later on, effectively, only the contributions from the longer-lived isotopes remain. At Fukushima Daiichi the concern was the decay heat produced in the early hours and days.

This energy has to be removed by the continued circulation of cooling water, otherwise the whole reactor will heat up rather quickly. But if the reactor was not shut down when the accident occurred, like the one at Chernobyl, the thermal energy production rate would be 2,000 to 3,000 MW, the same as the level of cooling needed in normal operation. In other words the shut down of each reactor at Fukushima reduced the scale of the initial energy available to a few percent of that at Chernobyl, and if that cooling had been maintained, there would have been no accident at all.

Tsunami arrival

The movement of the sea bed caused by an earthquake pushes and pulls the water like a hydraulic ram creating a wave on the surface of the ocean above. This wave moves at a speed of several hundred kilometres per hour depending on the depth of the ocean [6]. As it reaches shallower water this tsunami wave moves more slowly but its height increases. Then, like any wave reaching a normal holiday beach, it breaks – in fact, in a trough where the water is shallower the wave moves more slowly, but on a crest where the water is deeper the wave moves faster, until eventually the next crest catches up with the previous trough, causing the wave to break. In the case of a tsunami wave it can rise up and break in a particularly dramatic fashion.

So 50 minutes after the quake such a tsunami wave arrived at Fukushima

Daiichi. As the wave height increased it broke, carrying all before it as it rushed inland, smashing boats, houses, cars, shops, factories, power lines, roads and railways along the length of the coastline. Interestingly, the boats that survived were the ones that left port quickly before the tsunami wave arrived at the coast. Out at sea in deeper water the wave had not yet broken and was much smaller.

Reactor damage by tsunami

Thanks to their robust design none of the nuclear reactors in Japan was damaged by the earthquake although many were 40 years old. The Fukushima Daiichi nuclear plant suffered slight peripheral damage from the tsunami, because it had been constructed too low down and close to sea level. Specifically, its ancillary back-up diesel generators were sited in buildings on the seaward side, so that when the tsunami arrived, these were flooded and the main power lines to the plant were also destroyed, thereby leaving the plant without power, once the energy from the short-term battery back up was exhausted. After that three of the six reactors had no means to disperse the decay heat discussed above. In addition, there were water-filled tanks containing spent fuel elements that also needed to be cooled, because they too released decay heat, albeit very much more slowly being further down the curve shown in Illustration 12.

The chemical story

What actually then happened to the reactors and fuel ponds at the Fukushima Daiichi plant? The continuing output of heat from the reactors concerned could not be cooled initially and so the temperature of each reactor core rose, and continued to rise. Although nuclear activity itself is not affected by temperature at all, that is not true of chemical reactions. Each reactor was full of water, designed to moderate or slow down the energetic neutrons and carry away the reactor energy to the generating turbines when the reactor was working, and so also keep the reactor cool. With the reactor shut down, this flow of water is still needed to carry away the decay heat. Within the reactor core with its pressure vessel inside the containment vessel, the uranium fuel is sealed in tubes of zirconium, a metal whose only role is to keep the fuel and its fission products isolated from the water. When re-fuelling becomes necessary these tubes can be withdrawn cleanly, taking all the radioactivity with them, and be replaced or moved to a new position in the core. Zirconium is chosen because it plays no part in the nuclear reactions and is also chemically rather inert.

However, like most metals at sufficiently high temperatures zirconium reacts with water. This chemical reaction produces zirconium oxide and hydrogen gas. The metals sodium and potassium react in a similar way at room temperature, as shown in every school chemistry laboratory. Aluminium and iron effectively do the same when they corrode – so this stage of the story is not nuclear at all, but simply chemical. In the case of zirconium in water this reaction to form hydrogen begins if the temperature exceeds 1,200 C. So at Fukushima Daiichi the temperature rose and the zirconium corroded in the water, generating hydrogen gas. The story developed slightly differently in the three reactors, but the effect was qualitatively similar [7]. The pressure inside the containment vessel, already very high because of the temperature and the superheated steam, rose even further with the added hydrogen eventually reaching 8.5 atmospheres. The vessel was designed to withstand 5.3 atmospheres and so was in serious danger of rupture.

Radioactivity released into the air

So it became imperative to release the excess pressure – but something else had happened. The unused fuel and the radioactive actinides and fission products had spilled into the water from the damaged zirconium fuel elements. By releasing the pressure intentionally, steam and hydrogen escaped into the atmosphere but carried with them some volatile fission waste products, in particular the isotopes iodine-131 and caesium-137 [8]. (This radioactivity was not released into the environment by any explosion.) The total released activity of these isotopes was measured by several groups and is reported to be about 15% of that released at Chernobyl [9 ,10].

What happened next was really less significant although it seemed dramatic. As every science student knows, a mixture of hydrogen and oxygen can explode making water vapour. It is not clear what triggered the explosion but the hydrogen was very hot, so it would not take much. Anyway, the released hydrogen became mixed with the air outside the reactor and the resulting explosion was captured on video and transmitted round the world with the graphic description *explosion at crippled nuclear reactor*. Although true, this generated panic among those who did not understand that the explosion was not itself nuclear, was wholly outside the reactor and did not result in the release of any extra radioactivity at all – that had happened already when the hydrogen and steam were released. However, the panic, alarm and implosion of trust were real enough and were responsible for the dramatic setting of the major health scare and economic consequences of the Fukushima Daiichi accident.

Re-criticality suppressed

To stop the creation of further hydrogen and disintegration of the fuel rod assemblies the temperature within the reactors had to be reduced. Initially this was achieved by circulating seawater through the cores. At the same time, extra boron was added to the water, in the form of boracic acid.

Naturally occurring boron contains 20% boron-10 which is an exceptionally strong neutron absorber and so boracic acid acts like the control rods suppressing any possible neutron flux [11]. It has been confirmed that as a result there was no restart of nuclear fission, a process called *re-criticality*. This was in spite of the damaged fuel rods that melted and fell to the bottom of the 2.6 metre thick concrete containment vessel which they then eroded to a depth of 0.65 metre in reactor 1. In reactors 2 and 3 the depth was 0.12 and 0.20 metres respectively. This *meltdown,* so graphically described in Hollywood movies, was seized on by the media as a matter for horror, but it was less significant than the actual releases of radioactivity into the air and the cooling water. This meltdown should not be seen as a near-miss major incident. Criticality is hard to achieve in a carefully designed nuclear weapon with weapon-grade high purity fuel. There was no chance of an enhanced neutron flux, let alone an explosion in this case. If the melted fuel or corum, as it is called, had eaten its way through all layers of containment, the residual mess would not have compared with Chernobyl where a large fraction of the core contents was thrown into the upper atmosphere and the local environment, with remarkably small loss of life.

Radioactivity released into the water

As cooling was re-established, water passed through the reactor with its damaged fuel rods and came into direct contact with fission products, including iodine-131 and caesium-137, which are normally fully contained within the rods. These elements dissolve easily in water so that this became radioactive. In the immediate aftermath of the accident this radioactive cooling water was held in tanks awaiting proper filtration, but in the first few weeks there was inadequate storage capacity. That is why some of the less radioactive cooling water had to be released into the ocean to make room for that which was more highly contaminated. This was fully and properly announced, but the publicity went seriously awry, as discussed below. In addition, there have been some unintentional leaks and contamination of ground water; again, public perceptions have been misinformed. There were no direct health consequences of this released radiation or radioactivity, itself, for either the workers or the public. We come to the indirect social and psychological consequences later.

Spent fuel ponds

In addition to the cooling water for the reactors themselves, there was the water in the spent fuel ponds. This is intended to act as a radiation shield as well as a coolant; the ponds contained fuel that had been recently unloaded from a reactor undergoing maintenance, as well as long-term used fuel, destined for eventual reprocessing and storage. The fuel in the ponds contained no iodine-131 because nuclear fission had ceased much earlier –

that is many times its 8-day half life. Further, because it had not suffered the extreme heat of the recently shut-off cores, the spent fuel rods did not contaminate the water to the same extent. As it turned out, there was damage to the stored spent fuel rods in the ponds but the integrity of the ponds themselves was maintained and the water did not boil away, as some observers had speculated. Nevertheless, early in the accident concern for the spent fuel contributed to the political decision to attach severity 7 on the International Nuclear Event Scale (INES), the same as Chernobyl. This scale is discussed again in Chapter 6: it is not science-based and does not actually measure anything. It seems to be used by the authorities concerned to emphasise to the public the difficulties that they face. Unfortunately, the number looks like quantified science, but, by giving Fukushima parity with Chernobyl, the authorities succeeded in amplifying the problem of public concern, while improving neither trust nor understanding.

Public trust in radiation

Ignorance and lack of plan

Without power for lighting and adequate basic instrumentation, the operating crew at Fukushima Daiichi were in a technically difficult position, but they were also under great personal stress, as was Japanese society as a whole. This was because the planning, education and personal instruction that had proved so effective in reacting to the earthquake and tsunami had never been extended to the possibility of a nuclear accident. When it came to radiation and the release of radioactivity, there was complete ignorance, not only among the general population but at the highest levels of authority too. There was a general understanding that accidents were not possible because of the design and the regulations applied [12]. Disengagement from any personal responsibility or understanding of nuclear risks was not just national but international too. The buck was always to be passed upward with no really knowledgeable responsibility being taken at any level. Any aspect of life, not just a nuclear event, that encounters this level of ignorance and centralised reaction is a source for instability, especially when rapidly reported and amplified by modern 24-hour media. Inherent in this reaction was the perception that any understanding of nuclear safety requires a higher level of expertise.

The fallacy of absolute safety and the loss of trust

Among those on the ground in the Fukushima Prefecture, there seems to have been no one with any knowledge of the effect on public health of a nuclear accident and no one who had read the recent UN/WHO reports on Chernobyl and who had the necessary authority and confidence on which to base decisions. There were engineers who could speak of the reactors, but no one in authority to explain the medical implications for real people beyond the words of regulation. When the radioactivity was released, the public had no background knowledge on which to react to the news of the accident. In particular the scale of the danger was hidden from them, and so, for them, the natural reaction was to assume the worst.

The language of extremes carries no guidance or reassurance. In planning for the future, the possibility of a nuclear accident had been dismissed on the basis of assurances that it should not happen and that serious accidents can be prevented with sufficient safety measures. This is a mistake in principle because absolute safety is not possible. Every threshold can be exceeded, every protection overwhelmed, and nature is *always* capable of overwhelming man's best efforts – it can stage an accident by *force majeure*. Today, whenever this happens, the media adopt the story and quickly present themselves as being on the side of a mis-informed public, while repeating and amplifying their fears. In this respect the accident at Fukushima was worse than that at Chernobyl, where there was no free local press at the time of the accident. Following straight after the spectacular video of the tsunami, the news from Fukushima Daiichi with its video of the chemical explosions spread around the world, exciting the modern appetite for a sequel.

Obviously the tsunami was natural and could not be blamed on anyone, but the released radiation was man-made and therefore open to speculative political story-making. The media and their customers preferred accounts of reactors *spewing* radioactive material, generating for the audience horrific visions of dragon-like happenings, seemingly beyond the control of those in charge and the public imagination. By their repeated use in the daily press, the very meaning of the words *spewing* and *crippled* were changed in the language, as reporters exhausted their supply of other words to use.

These reports referred to levels of radiation as *high* without any attempt to explain what made a level high or otherwise. The consequence was a widespread haemorrhage of popular confidence in social and political structures in Japan and in science worldwide, with very few authorities prepared to staunch the flow in the early days when it mattered most [SR8]. Such a loss of trust is dangerous, as it threatens the cohesion of society itself, especially when it is based on a completely false assessment of the situation ramped up by 24-hour reporting.

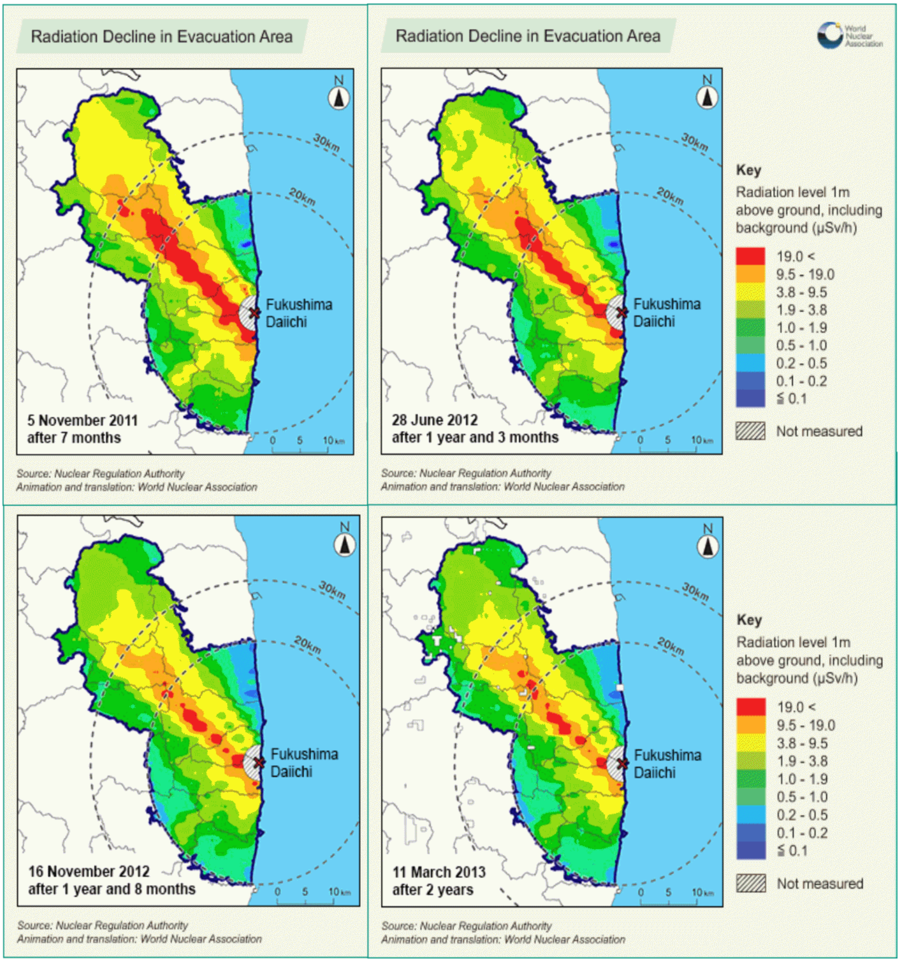

Illustration 13: Maps of the region around Fukushima Daiichi showing colour-coded radiation dose rate in the air 1 m. above ground in micro-Gy per hour. The red region is above 19 micro-Gy per hour or 21 mGy per month. The four maps are for different dates after the accident. The dashed circles are shown at 20km and 30km from the plant. [Reproduced by kind permission of WNA.]

Impact on public health

Most of the radioactivity was carried by the wind out to sea or inland to the north-west, in the general direction of the village of Iitate. The dashed circles shown on the maps, Illustration 13, at 20 and 30 km from the Fukushima Daiichi power plant itself, were used to define the evacuation zone. Later this was extended in the northwest sector because of the effect of the wind on the pattern of deposited radioactivity. To put the meaning of the coloured areas into simple perspective, anyone living permanently in the green zone would get an extra radiation dose rate equal to twice the natural rate in Colorado (6 mGy per year) where the cancer rate is less than the US average. The dose rate in the dark red regions (250 mGy per year) is a third of the safety threshold set by ICRP in 1934 (730 mGy per year) and, even by today's standards, carries no known risk of cancer. We look at this again in Chapter 9.

The area devastated by the tsunami was along the coastal strip and those areas where radioactivity was higher were mostly inland in the mountainous area beyond the reach of the tsunami. It has therefore been possible to separate the effects of the two accidents, although the situation became slightly more confused when some of those made homeless by the tsunami were accommodated in temporary accommodation in schools and halls inland, some in regions affected by higher radioactive contamination (see also evacuee account in Chapter 12).

The maps show where the radioactivity was carried by the wind, but the related fear spread around the world on the media. In addition to the official evacuation of Iitate and the 20 km zone, there was a larger and more significant voluntary exodus. School attendance by children from better-off families fell as a result. Unofficial news of voluntary evacuation encouraged people not to be left behind and at risk, as they saw it, and those who could flee most easily did so, even from Tokyo, some 150 km away. Many foreigners acted impulsively and caught a plane in search of absolute safety, receiving more radiation on the plane than if they had stayed put. Many foreign embassies set a poor example and encouraged evacuation – some moved their whole staff to cities elsewhere in Japan. Some officials, quite ignorant of what they were running away from, spoke darkly of a possible need to evacuate Tokyo. Most Japanese remained, bolstered by their proverbial stoicism, and the workers at the plant, treated by the world press as condemned men and women, stayed at their posts. History should find some way to record its thanks to them and their families for their bravery.

Protective suits that frighten or impress

Meanwhile, anxious to impress, officials, visiting dignitaries and press reporters eagerly donned impressive white protective suits and masks,. Such antics may make good television and improve the authoritative image of those who need to be seen doing something about the accident. But they do nothing for a Japanese child and her mother who see the school playground being dug up by workers dressed up in the name of an unseen and unexplained evil called *radioactivity* or *radiation*. This is made only worse when this supposed evil actually causes no harm whatever at the doses concerned. The harm comes from the fear that the image of dressed-up workers engenders, and from keeping children indoors rather than letting them out to play naturally. Unfortunately the majority of the population see their fear confirmed as established fact when workers and officials are dressed up in this way. An open-necked shirt with rolled-up sleeves, a firm hand shake and a cup of tea would be a better way to reassure.

Loss of life

There were two deaths at the nuclear plant in the first hours, but these were drownings caused by the tsunami itself. Some workers who got their feet wet in the basement flooded by radioactive water suffered beta burns to the skin on their legs, but this soon cleared up. Within a couple of weeks of the accident there were enough preliminary measurements to show that the released radioactivity was substantially less than at Chernobyl and it was clear that there were unlikely to be any casualties at all, even in the longer term [SR8]. Regrettably this was only acknowledged by the international authorities after a two-year delay during which considerable social and psychological damage continued. The Press Release by UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) reads:

> *31 May 2013 – Radiation leaked after Japan's Fukushima nuclear disaster in 2011 is unlikely to make the general public and the majority of workers sick, a United Nations scientific committee today said previewing a new report..... The committee added that no radiation-related deaths or acute effects have been observed among the nearly 25,000 workers at the accident site, nor it is likely that excess cases of thyroid cancer due to radiation exposure would be detectable.*[13]

Recent reports on the Chernobyl accident [14] confirm that there was no evidence for any other cancer types, even there. Given that the release of radioactivity at Fukushima is known to be substantially smaller than at Chernobyl, no cancers of any kind are likely at Fukushima. The same conclusion may be reached by comparing doses to Fukushima workers to survivors of Hiroshima and Nagasaki, and of the Goiania accident described in Chapter 6.

Caution that harms people but protects authority

Psychological disaster at Fukushima

Geraldine Thomas, Professor of Molecular Pathology at Imperial College London and Director of Chernobyl Tissue Bank, [15] has described the real damage:

> *All the scientific evidence suggests that no one is likely to suffer*

> *damage from the radiation from Fukushima itself, but concern over what it might do could cause significant psychological problems. It is therefore important to understand that the risk to health from radiation from Fukushima is negligible, and that undue concern over any possible effects could be much worse than the radiation itself.*

This fear has been caused in large measure by the inept international advice available via the various arms of the United Nations, specifically UNSCEAR and ICRP (International Commission for Radiological Protection). The advice to national governments is intended to manage popular fears by appeasement with an over-cautious safety policy. This is not based on the science of any actual risk, and it fails completely at a psychological and social level in the case of high profile accidents. It should be considered inhumane. The accident at Fukushima was not a radiation disaster, but many died as a result of it, not from radiation but from social stress. Nobody in Japan, or in the international community advising them, seems to have read and understood that the same mistake was made at Chernobyl, as most recently reviewed in a report by UNSCEAR on 28 February 2011, just 11 days before the Fukushima accident [[16]]. That report repeated that the severe disruption caused by the Chernobyl accident resulted in

> *major social and economic impact and great distress for the affected populations*.

As an article in Nature about the May 2013 report on Fukushima said [[17]]

> *A far greater health risk may come from the psychological stress created by the earthquake, tsunami and nuclear disaster. After Chernobyl, evacuees were more likely to experience post-traumatic stress disorder (PTSD) than the population as a whole, according to Evelyn Bromet, a psychiatric epidemiologist at the State University of New York, Stony Brook. The risk may be even greater at Fukushima. "I've never seen PTSD questionnaires like this," she says of a survey being conducted by Fukushima Medical University. People are "utterly fearful and deeply angry. There's nobody that they trust any more for information."*
>
> *Overall, the reports do lend credibility to the Japanese government's actions immediately after the accident. Shunichi Yamashita, a researcher at Fukushima Medical University who is heading one local health survey, hopes that the findings will help to reduce stress among victims of the accident. But they may not be enough to rebuild trust between the government and local residents.*

The conclusion that the reports lend credibility and offer hope are hardly appropriate, given that the danger and the required action was clear within a few days, as posted two years earlier [SR8].

Symbols of hazard

Authorities worldwide have used a symbol to encourage exceptional respect for radiation hazards. When it was first introduced, the tre-foil of radiation, Illustration 8*a* on page 9, may have been informative, but quickly it became a symbol that frightened people – like a swastika or a skull-and-crossed-bones. Its use as a practical danger signal became misused for purposes of intimidation and politics. It lost any educational benefit long ago and its use should be discontinued. To many people it is seen as some kind of symbolic curse – and a curse is not a reasonable instrument of safety. For instance, when used as a symbol attached to radioactive waste, it conveys, not information, but a message of great danger, usually where none exists.

A far greater hazard responsible for millions of deaths annually through dysentery and other water-borne diseases has no such symbol, probably because it is a Third World, more than a First World, problem. Illustration 8*b* on page 9 shows a candidate symbol drawn from the First World experience.

Evacuation, clean up and compensation

Illustration 14: An entry gate to the evacuation zone, photographed in December 2013.

At Fukushima the lack of trust, so evident on my first visit in October 2011, appeared to be equally strong in December 2013. I was introduced by an evacuee to his empty farmhouse and overgrown fields in the evacuated zone. I visited his cramped temporary accommodation where three generations were still living and enjoyed a meal at the café on the site. I learnt of his earlier alcohol problem and how by then he had a part time job as warden checking the empty houses and farms in the evacuated zone – which is how he was able to take me in through the locked barrier at the zone boundary (Illustration 14). I saw decontamination work in progress in the fields (Illustration 15) and monitoring stations with piles of sheeted contaminated top soil awaiting removal (Illustration 11 on page 12).

Illustration 15: Stripping fields of contaminated topsoil, photographed in December 2013.

Later I heard that the evacuee who showed me around had been able to buy himself a sizeable two-storey house outside the zone with the compensation money he had received. Compensation, and those who get it and those who do not, has upset the local housing market and is a source of grievance that has compounded distrust of the authorities for their handling of the evacuation and clean-up.

Fear of artificial radiation

In their attempt to find safety, people seek what they see as familiar and natural, perhaps because it is less likely to have been tampered with for some unknown purpose. But for community decisions, like sources of energy that affect everyone, such preferences should be justified by evidence. In connection with nuclear energy we should ask whether natural radioactivity in the environment is more benign than any possible artificial radioactivity released from a nuclear power plant.

Radioactivity is present everywhere in the natural world. Modern cosmology teaches that after the Big Bang, 13.8 billion years ago, the universe was dominated by radiation and the only elements present were hydrogen and a small amount of helium. All the other material that we see around us now, and from which we ourselves are made, is the nuclear waste from stellar explosions that happened later. Although nuclear activity has been notably quiet recently, at least in this part of our galaxy, that is certainly not true elsewhere in the universe, where nuclear action is widespread. We can see this in the amazing pictures of prodigious explosions and violent collisions that come from the Hubble and other powerful telescopes.

If that makes us think we have been lucky, we should not forget the radioactive decay heat that followed the formation of all our chemical elements as nuclear waste more than six billion years ago. Today the longest lasting but naturally unstable radioactive elements are still here – uranium, thorium and potassium-40 – decaying with their half-lives measured in billions of years. Natural and harmless, you might think, after such a long time. But the energy that they release is the source of the heat inside the Earth – it is decay heat, like the heat that caused the trouble at Fukushima. It is responsible for all geothermal heat sources in Iceland, Yellowstone National Park and elsewhere. It provides the heat and radioactivity for the *onsen*, the hot springs so important in Japanese culture, as well as the spas in Britain and the Baden in Germany that have been so popular since the time of the Romans. Today it is said that 75,000 patients worldwide seek radon therapy at these facilities [[18]]. More generally the radioactivity provides the energy that drives the movement of the Earth's tectonic plates – and so the volcanoes, earthquakes and tsunamis. In fact, this nuclear decay heat of the Earth, which is natural, killed 18,800 people in Japan in March 2011, while radiation emanating from the man-made reactors at Fukushima Daiichi killed not a single person. This shows how that which is man-made or artificial may be safer than what is found in nature, benefiting as it does from being designed and matched to the scale of human need. However, the distinction is only one of scale, since there is no real intrinsic difference between natural and artificial sources of radiation.

Questions about the danger of internal radioactivity

Domestically, the Japanese people are particularly concerned about cleanliness, so the possibility of radioactive contamination around the home causes much worry. But the thought of indelible contamination within your own body, beyond the reach of normal washing, is even more disturbing. So internal radioactivity and the cancer that such radiation might cause in years to come makes for deep concern. How can the Japanese people be sure that the internal radiation from the doses experienced at Fukushima is safe? Why is it unexpectedly harmless? Why have the Japanese people not been told anything about this? These questions are answered fully in Chapters 5 and 6, where we discuss how cancer therapy works and what happened in the town of Goiania in Brazil in 1987, when a redundant radiotherapy source was taken from a medical clinic.

Illustration 16: A new whole-body measuring unit photographed at the Minamisoma General Hospital, October 2011.

Comparison of the accidents at Goiania and Fukushima Daiichi tells us what we need to know about the chances of cancer caused by the radioactivity released in the power station accident. This comparison uses measurements taken in a very large survey of public internal contamination at Fukushima, discussed in Chapter 6. Many of those measurements were taken by the mobile whole-body radioactivity measurement unit. This is shown in Illustration 16 outside the General Hospital at Minamisoma, photographed when I visited there in October 2011.

Radiation safety is inter-disciplinary

The social and economic consequences of the Fukushima accident have been severe but avoidable, for the world, as for Japan. So why have both the Japanese and the international authorities been spooked by this accident, if the radiation has no serious medical effect on life? Firstly there is need to confirm that this really is generally true, and not some special case. Given the extreme energy of individual nuclear processes, how can it be that the effect of nuclear radiation on human health is modest – or even beneficial at low rates? This is a source of genuine surprise, even disbelief, to many physicists and engineers, who are familiar with these energies and the principles of their physical effect – though few are versed in the medicine and biology involved. This cross-disciplinary fault line is a part of the problem. It is one reason for the extreme caution applied to standards of radiation protection for the past 60 years. Marie Curie died in 1934 and the safety standards used then have been superseded by others, a thousand times more cautious in response to pressures from the public with the acquiescence of physical scientists. The wide divergence of these perspectives needs to be resolved with data and simple scientific understanding, as set out in later chapters.

Fear of the radiation from a CT scan

Ever since its discovery the penetrating powers of ionising radiation have been used to picture the inside of patients' bodies, initially as simple X-ray examinations and more recently as CT scans. These are now complementary to MRI (Magnetic Resonance Imaging) and ultrasound scans, neither of which uses ionising radiation at all. Together these methods have contributed to the early diagnosis of many conditions, including cancers, as part of the modern medical care that has increased life expectancy for so many. Fractured bones, dental cavities and foreign bodies can often be seen with quite small doses of ionising radiation, safely and effectively at modest expense. If the clinician requires better resolution or discrimination in the image, the radiation dose is increased. Over the years the method has been extended to make 3D anatomical pictures with a resolution of a fraction of a millimetre. Functional images, also in 3D, are given by PET (Positron Emission Tomography) and SPECT (Single Photon Emission Computed Tomography) scans in which a short-lived radioisotope is injected into the patient – these are both described as *nuclear medicine* and deliver a radiation dose similar to a CT scan.

Today many cancers are cured without the trauma of surgery, and the usual treatment combines chemotherapy with high-dose radiotherapy (HDRT), often simply called radiotherapy (RT). In many cases this has a good prognosis, although the radiation doses used are hundreds of times higher than used during a CT scan and may be given every day for a month or more.

The scares that appear in the popular press about the dangers of the low doses used in diagnostic CT scans, as opposed to therapy treatment, are without foundation, typically they are based on analyses of data that have been discredited in the medical literature [[19]]. In later chapters we look at the LNT hypothesis used in attempts to substantiate these scare-stories, why it is discredited, and the history that explains why it was ever taken seriously by scientists who had other motives (see Chapter 10). Here we note that patients receiving the much higher doses in a radiotherapy course, usually thank the clinical staff on completion of their treatment, and go home with a good chance of enjoying further years of life. Such are the benefits of modern medicine, and to refuse the much lower doses of a CT scan out of fear, makes little sense. The risk from an undiagnosed tumour, missed by not accepting a scan when symptoms suggested one, far outweighs the tiny risk from the scan itself. Of course the expense of a scan should not be accepted without reason, just as saying that a pedestrian crossing is safe to use should not be seen as an invitation to stop and sit down half way across the highway. Common sense should always be applied, but we all know that, and it applies to the safety of radiation.

Wastes, costs and conflicting interests

Comparison of waste products

For many people, concern about high-level nuclear waste tops their list of worries about nuclear energy, although with a little examination this can be seen as unreasonable. Like other technologies, nuclear power produces waste, and so strategies are needed to prevent safety being compromised or the environment being spoiled. Technologies and their wastes may be compared: whether the waste is toxic or contagious; whether the quantity is large; whether it can be reprocessed; whether the toxicity decays away in time; whether it is a gas or liquid that has been traditionally discharged into the environment; whether it is soluble and easily dispersed; whether it is solid and easily stored; whether it has other valuable uses.

For simplicity, let's compare three types of waste produced by human activity: combustion waste, personal biological waste and high-level nuclear waste [SR1].

Combustion waste consists of ash and carbon dioxide. In Illustration 9 on page 10 the canister on the left shows the mass released into the atmosphere every day for each person – the product of burning gas, oil and coal, including their contribution to transport, heating and electricity generation. The steady build-up of this carbon dioxide in the atmosphere is well established, even if the precise time scale of the consequences is less certain [SR3]. Anyway, the release of such pollutants from fossil fuel combustion is out of control and threatens life on Earth.

Biological waste is closer to home and its management is an individual and personal responsibility taught to children at an early age. Public discussion is unwelcome, but nature encourages everybody (and animals likewise) to control the release of waste into the environment by making it foul smelling – presumably as selected by evolution. Where the resources are available, the waste is washed away with water. However, where this fails and the waste reaches drinking water or the food chain, a closed biological loop results which, once infected, can lead to a biological chain reaction incubating disease. A recent well-publicised example was the cholera epidemic in Haiti, although in truth nearly a million children die every year from diarrhoeal disease spread by polluted water. Where the necessary investment is made, this waste problem is contained by recycling and engaging the process of natural decay. The effluent is passed through filter beds and the solids aerated to rot or decay naturally before being spread on arable or pasture land as a valuable natural fertiliser. In this way simple treatment of a dangerous waste product on a huge scale gives a valuable but safe product. This is accepted without comment in the press.

Nuclear waste

Nuclear waste is another waste like biological and combustion waste. However, unlike the latter two types, it has not caused any fatal accident. Specifically, there has been no radiation fatality from waste at any nuclear power plant. The quantity of waste is tiny by comparison, as illustrated by the canister on the right in Illustration 9 on page 10. This is directly related to the energy density of nuclear compared to carbon fuels – undiluted, a millionth of the fuel is needed to generate one kilowatt-hour of electrical energy, but that also leaves a millionth of the waste – the precise ratio depends on the choice of fossil fuel and whether the nuclear fuel is fully burnt (the size of the canister in Illustration 9 assumes that about 1% is burnt which is true in most current reactors). The waste is mainly solid and can be compactly stored; it is not discharged into the environment by default like carbon dioxide and biological waste. Like biological waste, it can be reprocessed, the valuable unused fuel recovered and reused, and other by-products used in the manufacture of all kinds of useful devices from smoke alarms to sources for sterilisation and vital medical scans.

The reusable fuel, uranium and transuranics including plutonium, have long life times, but the residual fission products decay naturally with half lives of 30 years or less. So these can be chemically separated and embedded in glass or concrete, and then buried. Within 300 years the activity falls by a factor of a thousand, and within 600 years by a million, becoming no more active than natural ores. The technology to vitrify the waste in this way is not new and has been employed for several decades. (If, instead, the unused fuel is *not* recovered or reused, the residual radioactivity lasts much longer – but that is a waste of valuable unused fuel.) Buried in a mine, waste can stay put securely for very much longer than 600 years, as demonstrated by the story of the waste left by the 2,000-million-year-old natural Oklo Reactor. However, we postpone a description of that story until Chapter 7. We also delay drawing conclusions about proliferation and plutonium until Chapter 12. Terrorists and rogue states are dangerous whatever means they use, but how hazardous is plutonium?

Nuclear waste has had a bad press, but that is nothing to do with safety. Compared to other wastes, it rates very well. What is the worst that can be said of high-level nuclear waste? That it does not smell? Actually that is not such a stupid question. The ability of life to detect radiation is important, and we study that in Chapter 5.

The cost of nuclear energy

What about the cost? the media exclaim, and people nod their heads in agreement. But think about it: where does the money go? It goes on safety, insurance, public enquiries, working practices that ensure safety – on a grand scale without equal! Well, if half the work force in the nuclear industry is engaged working on safety, waste and decommissioning, and, if those requirements were to be drastically scaled back without risk of any kind, the cost of nuclear energy should fall substantially. By 30%, at least. But there is no escaping the fact that the public clamour for even greater safety after Fukushima has increased costs yet further, even though the fears are groundless and the increased costs are not in the public interest. The ultimate problem is a regulatory regime that *demands* that nuclear plant designs are over-engineered in the name of safety. Behind that there is always a thirst for employment, a readiness by business to secure a contract to do a job, and a campaign by the press for increased safety.

In the Fukushima accident there was no loss of life at all due to radiation and, apart from the need to ensure that emergency generators are better sited, no major changes should have been required. Actually, the only substantial task should be one of education – the authorities should wake up to that, and the public should appreciate it. Education would address the real problem, be relatively cheap, and the cost of electricity should fall dramatically, not rise.

But the story has wider dimensions. Japan has no native supply of fossil fuel and its need for energy contributed to the causes of war in the twentieth century. This problem had appeared solved with its introduction of nuclear energy in the 1960s. However, currently (August 2015) all but one of its 50 nuclear power plants still remain shut down in response to public protest following the breakdown in public trust after the Fukushima accident. The impact on both the country's trade deficit and greenhouse gas emissions is severe. Japan imported fossil fuels for 88% of its electricity in 2013, compared with 62% in 2010. The additional fuel cost was ¥3.6 trillion ($35.2 billion). Japan reported a trade deficit of ¥11.5 trillion ($112 billion) for 2013, largely due, directly and indirectly, to additional fuel costs. This is much more than the 2012 trade deficit, and follows a ¥6.6 trillion ($65 billion) surplus in 2010. Electricity consumption has decreased since 2010 and tariffs for industrial users have increased by 28%. Emissions from electricity generation accounted for 486 million tonnes CO_2, 36.2% of the country's total in fiscal 2012, compared with 377 million tonnes, 30% of total in 2010 [[20]]. Although on 11 August 2015 the first Japanese reactor was restarted and others will follow, many have been permanently shut down because of the costs of compliance with unreasonable regulations. The situation is both needless and dire, but that is reflected to a considerable extent around the world where other nuclear programmes have been shut down, reduced or not started. This is less evident in countries where the authorities are not at the mercy of short term popular opinion. In a democracy having to conform to popular nuclear restrictions can reduce economic competitiveness. Authoritarian regimes need not be so encumbered, and this will give them a major competitive edge in future, both for electrical energy itself and for the ability to deliver new plants. Over the next century this will give them an economic advantage that many in the free world have denied themselves.

The scale of a nuclear reactor

As a rule, when costs increase unreasonably, something is wrong, either with the objective or the way that it has been set. Evidently the general apprehension about nuclear technology has driven absurd increases in costs. There are ways to reduce costs beyond simply addressing this apprehension. Current nuclear reactor designs are very large for two reasons, one social and one technical, but there are separate reasons why costs might be substantially reduced if they were smaller.

The scale of a nuclear plant is set in part by the level in society prepared to take responsibility for it. We may imagine a tiny plant supplying a village, a small plant for a town, and a large plant for a region. But if responsibility is not accepted locally it is referred upwards to a higher authority, although the idea that authority improves with such centralisation is questionable. Responsibility for the supply of electricity from nuclear energy has been passed up the line, all the way to the top with the involvement of international authorities. With some measure of dispersed responsibility, nuclear plants might be smaller, less expensive and have faster time scales for decision making and construction. Clearly, then, to reduce costs, much devolved responsibility should be considered. Nuclear energy is not a special case or category on its own. On what grounds would it be? That is precisely the kind of pleading that should be avoided.

A second reason for nuclear plants being large concerns how they work. Nuclear submarines are propelled by smaller nuclear reactors [[21]], but these use more highly enriched uranium than civilian electric utilities. The technical details concern the neutrons in the reactor; if the fissile uranium density is not high enough, too many neutrons may escape from the reactor core or get absorbed by fission products called poisons. By making the core larger the number escaping is reduced and the efficiency is increased, and that is what is done in a large traditional civil reactor. However, it is not clear that this is essential and new designs for small modular reactors (SMR) may be viable and cheaper. This is a matter of ongoing engineering debate.

SMRs would avoid the large *in situ* construction methods that have caused difficulties for new plants. An important scale is the experience of the builders. If nobody on site has ever built such a plant before, there will be setbacks, overruns and delays. If on the other hand there is personal experience from previous projects, and, in addition, much of the construction involves modules assembled off-site, the economies of repeated production will pay dividends in cost, reliability and safety. That is just economics, Henry Ford style. Production line methods for managing nuclear waste can reduce costs too. When competition and market forces, unfettered by heavy-handed regulations, can get to work, new designs will prove themselves and costs will fall. Proper safety regulation is essential as in other industries, but there is no reason to treat nuclear risks as special or different, provided the workforce is properly informed.

Notes on Chapter 3

1) Report of IPCC (2014) https://www.ipcc.ch/report/ar5/wg3/

2) The stories of *Centralia,* Pennsylvania, USA and *Morwell*, Victoria, Australia show what can go wrong.

3) Scientists for Accurate Radiation Information (SARI) (2015) http://www.radiationeffects.org

4) *Radiation and Modern Life* A book about Marie Curie by AE Waltar, Prometheus Books (2004)

5) D Ham *Marie Skodowska Curie* (2003) http://www.21stcenturysciencetech.com/articles/wint02-03/Marie_Curie.pdf

6) *Fundamental Physics for Probing and Imaging* An academic book by Wade Allison, OUP (2006)

7) *Facts and Lessons of the Fukushima Nuclear Accident*, A Kawano (TEPCO) American Nuclear Society, San Diego meeting, 12 Nov 2012

8) In addition there is caesium-134 and other radioactive isotopes of iodine. But these make no qualitative difference and we ignore them in this simplified account.

9) WNA on Chernobyl (2015) www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/

10) WNA on Fukushima (2015) www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident/

11) Boron used in the nuclear industry is enriched in boron-10. Since its atomic mass is 10% different to the majority boron-11, this is quite easily achieved by distillation, unlike for the isotopes of uranium that differ in mass by only 1%.

12) Unfortunately in 2015 the reassurance that nuclear accidents should be made so unlikely as to be impossible still seems to be a political requirement. Seeking this unrealistic goal is absurdly expensive.

13) UN news report on Fukushima (2013) http://www.un.org/apps/news/story.asp?NewsID=45058

14) *Health Effects of the Chernobyl Accident*, WHO (2006) http://whqlibdoc.who.int/publications/2006/9241594179_eng.pdf

15) *Health effects - facts not fiction,* Thomas GA (2013) http://www.jaif.or.jp/ja/annual/46th/46-s3_gerry-thomas_e.pdf

16) *New Report .... on Chernobyl*, UNSCEAR (28 Feb 2011) http://www.unis.unvienna.org/unis/en/pressrels/2011/unisinf398.html

17) Nature report on Fukushima (2012) http://www.nature.com/news/fukushima-s-doses-tallied-1.10686

18) Radon mine (2015) http://www.radonmine.com/why.php

19) *Regarding the Credibility of data* ....., Socol and Welch (2015) dx.DOI.org/10.1177/1533034614566923

20) WNA information on Japan (2015) http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan/

21) See *United States naval reactors* on Wikipedia.