Chapter 10 Action for Survival

The policy of being too cautious is the greatest risk of all.

Pandit Nehru, Prime Minister of India (1889–1964)

Relaxed regulations

Generally, in the early years of a fresh technology when less is understood, safety regulations should be restrictive in order to cover for the unknown to some extent. Then, as knowledge improves and the science becomes better understood, acceptable limits can be relaxed responsibly and with a clear conscience. With the relaxation can come greater levels of technical exploitation, and then improved prosperity and confidence. Unfortunately, this is not what often happens. The enactment of regulation is clumsy and often painfully slow, following disaster rather than preceding or preventing it. Then later, in a mistaken quest for absolute safety, legally inspired caution is used to generate ever tighter restriction under an ill-advised banner such as *you cannot be too safe*. Unfortunately, as knowledge builds, regulation is not rolled back as it should be, but often continues to tighten under the pressure of out-of-date information or the corporate tunnel vision of one or more pressure groups.

In the matter of radiation safety, in 60 years the regulation has tightened and the understanding has improved significantly such that the two are now far apart. In 1951 a limit was set by ICRP at 3 millisievert per *week* [27, p.35]. In 1957 this was tightened to 5 millisievert per *year* for the public and 50 millisievert for radiation workers. In 1990 these annual limits were reduced further to 1 millisievert and 20 millisievert, respectively. The limit for the public is 150 times tighter than in 1951. In addition, from 1955 the advice was given that

> *every effort should be made to reduce exposures to all types of ionising radiation to the lowest possible level.*

Various changes in the wording were made before this principle gained the acronym, ALARA, *as low as reasonably achievable*. Over the years, under public pressure and with improved measurement and other technical advances, the levels actually achieved through the ALARA principle have continued to fall. Generally, what may have started as advice and guidance has become frozen inflexibly into legislation and regulations.

In balancing the risks to man's survival, a totally fresh look at standards in radiation safety is needed. Consequential changes to safety laws and accepted working practice should be implemented with an eye to actual risk, not simply to placating supposed concern. There need to be upper limits on any single acute dose and on any chronic or repeated dose, accumulated within a repair time – conservatively suggested to be a month. Annual dose should not be used as a basis for regulation, and the use of collective dose, despite its administrative convenience, should be discontinued altogether. As set out in Chapter 7 suggested values for new limits, cautious but reflecting the known effect of repair and recovery times, are 100 millisievert for a single acute exposure and 100 millisievert per month for chronic or repeated doses. These values can be argued by factors of two, but in any event the limits should be several hundred times more relaxed than those currently applied. Interestingly, these proposed limits represent a relaxation by a modest factor of about six relative to the 1951 ICRP figures – a factor in line with what might be expected in view of the improved understanding of the mechanisms of radiobiology since 1951.

There remains the question of whether, *at some level*, there is still a small accumulation of irreparable reduced life expectancy as a result of radiation exposure. There seems to be little evidence for this at the present time – but we should put a limit on it. The clearest indication comes from the bone cancer data for the luminous dial painters showing a whole-of-life threshold

of 10,000 millisievert.[59] Use of 5,000 millisievert as a general whole-of-life limit is suggested. This is to be compared with the 30,000 millisievert dose routinely given to healthy tissue over just 2 or 3 weeks in a single course of radiotherapy – in that case the lifelong risks are small and difficult to measure (see p. 119). The suggested limit is six times smaller and is taken over a whole lifetime rather than a month, and so may be seen as conservative.

In the future, as yet more is understood about the biological response to radiation, in particular about adaptive effects, there may be scope for further relaxation of these suggested limits: an acute limit, a short-term (monthly) limit and a whole-of-life limit.

As argued by the report of the French National Academies [22], a relaxed radiation safety regime would have benefits in diagnostic imaging, where current limits too easily discourage patients from accepting procedures that would be in their best interest.

In radiotherapy the position is quite different. As new technical solutions to the targeting of radiotherapy emerge, the dose to the tumour can be increased while the dose to peripheral tissue and organs is maintained at existing levels or reduced. The result will be a substantially improved success rate for tumour treatment, independent of any change in radiation safety levels.

Sixty years ago, when radiation safety first became a public concern, the looming threat was nuclear war rather than climate change. Then, the effects of radiation in biology were poorly

[59] The threshold reported by Rowland [40] and discussed in Chapter 7 is quoted in milligray. The large component of alpha radiation implies that this limit represents a larger number of millisievert. Again our interpretation is conservative.

understood and there was little information.[60] All that has now changed, and there is every reason not to exercise extreme caution. Nature seems content to use safety factors of about 10, depending on the risks and resource costs, but what margins should be used when considering radiation levels in the handling of nuclear fuel and waste? And, how do costs depend on such margins? Safety factors of a thousand are not affordable.

This is not a case for any relaxation in the engineering design of stable nuclear reactors. The use of several layers of independent control systems with different technologies as back-up is implemented on all modern reactors. Care is used to ensure that these are physically segregated and cannot be overridden by inexperienced operators, as at Chernobyl. Better monitoring and instrumentation ensures that it is known from the reactor control room exactly what is happening at all points inside and outside the reactor, which was not the case in the Three Mile Island incident. Reactor operating conditions are chosen for which any small increase in temperature causes a reduction in power production, by design and without the intervention of any external control. The Chernobyl reactor did not have such inherent stability. It is a matter for judgement as to which individual older plants do not measure up to these standards and when they should be replaced. Often it is the quality and reliability of welded pressure vessels and pipework, and the ability to test them, that is the problem.

New power stations

In March 2008 there were 439 reactors in 30 countries providing 16% of the world's electricity. Only 34 new power reactors were under construction in 11 countries, notably China, India, Japan, Korea and Russia, while in the 1980s a new reactor was coming on stream every 17 days [51]. With the increase in activity in

[60] Consequently efforts were made to obtain better data by exposing military personnel to low levels of radiation from nuclear tests. These experiments have been reported by the press with horror, but were understandable if ill-advised in the circumstances.

China and India it is possible that there could be a new 1 GWe reactor every 5 days by 2015. Currently, few reactors are under construction or on order for the US or Western Europe. In Germany, Austria, Australia and New Zealand public policy excludes the construction of new nuclear power stations, and the few that exist are due to be phased out.

The design of most reactors under construction, such as those in Finland and France, is based on pressurised light water as moderator and coolant. This design, which was described in outline on page 145, includes two walls of safety containment vessel and four layers of independent control systems, each capable of shutting the reactor down in case of an accident. To contain the consequences of the heat released following an emergency shutdown and cooling failure, popularly described as a *core meltdown*, there is a special isolated cooling area within the safety vessel. The net result is that the reactor design is very safe. Comparison may be made with the Chernobyl reactor, which had no containment vessel at all, none of the inherent automatic safety features and no meltdown protection.

Six different new reactor designs called Generation Four [52] are under development [53]. They may be realised on a time scale of 2020–2030. New features would improve thermal efficiency, fuel burn-up and waste management. Some use helium or lead cooling to allow operating temperatures of 500 to 1,000ºC. Such a temperature would also facilitate direct production of hydrogen from water. On-site hydrogen production might provide efficient energy storage to cope with rapid fluctuations in demand. New ideas for closed fuel cycles, on-site reprocessing, actinide burn-up and the use of different fuels, could bring advantages to efficiency, cost, stability and control.

Another encouraging development is the Accelerator Driven Sub-critical Reactor (ADSR). This would use sub-critical fuel, that is not capable of sustaining a continuing chain reaction, such as natural thorium which is four times more plentiful than uranium. Fission is induced by neutrons generated within the reactor by an external proton accelerator [54]. Further neutrons

are generated in the fission process but these do not survive in sufficient numbers to keep the reactor going and so the fission activity dies away as soon as the accelerator is turned off. The control is fail-safe and the reactor operates, in effect, as an energy amplifier. Actinide isotopes that are created can be burnt up so that radioactive waste is reduced. The design of a suitable accelerator is under development – such an accelerator would also have an important application as a source for ion-beam radiotherapy [33].

The nuclear industry has changed. Today it is concerned with international competition, commercial development consortia, international standards, designs and scrutiny. In earlier days there were nationally based development programmes, some of which had their eye on defence-related objectives. Some states still harbour such ambitions for their nuclear development, but their identity is well established and their programmes are not related to substituting for fossil fuel energy.

Fuel and politics

In the first instance nuclear fission relies on uranium, which is approximately as common as tin or zinc in the Earth's crust, occurring in most rocks and also the sea. Its distribution in commercially extractable concentrations is shown in Figure 24. The reserves are price-sensitive, but there is little doubt that these are sufficient to last mankind for a century or more, well into the era of nuclear fusion power.[61]

This distribution is politically rather equitable, compared with oil and gas whose known reserves are concentrated in areas of the globe with considerable political and cultural instability – the Middle East, the states of Central Asia and parts of Africa and South America. The ambition of developed countries to secure oil supplies has shaped world politics for a hundred years. The

[61] Successful exploration continues. A recent new find of 103,000 tons in Namibia is reported (2009) to be recoverable by open pit working at $61 per kg.

control by Russia of a large fraction of the European supply of gas is a present source of tension. The geopolitical distribution of uranium ore is more neutral, and a major switch to nuclear power would have a welcome pacifying influence on world affairs.

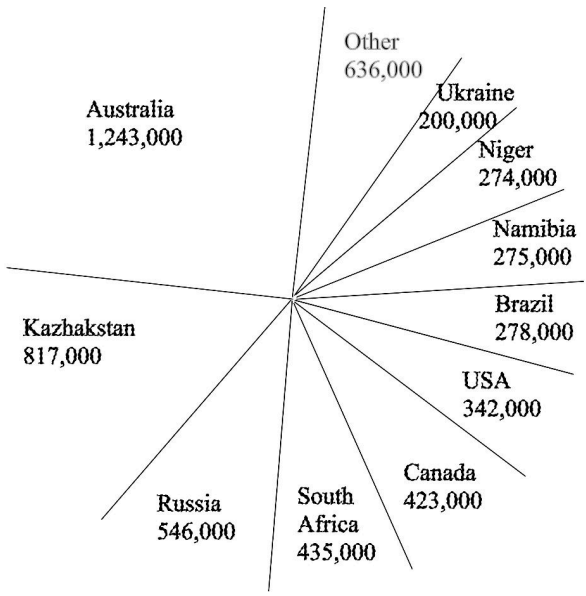

Figure 24 Worldwide distribution of identified uranium supplies (in tonnes of metal) recoverable at $130 per kg of uranium [55].

Another source of fission fuel is that provided by reprocessing. In addition, weapons-grade fuel may be degraded and used as a civil fuel source. Such a programme has been in operation by agreement between the USA and Russia since the end of the Cold War as part of the process of decommissioning nuclear weapons. Reprocessing plants were built initially to separate weapons-grade plutonium. As a result they have a sinister reputation and are closely monitored. But any separation activity releases the gas, krypton-53, into the atmosphere and this unique signature can be detected at distances of many kilometres [56]. The commercial use of reprocessing separates the re-useable actinides from the fission products, which has the environmental

bonus of removing the long-lived components from the spent-fuel waste. Such plants currently exist in the UK, France, India, Japan and Russia.

Waste strategy

In the public perception the risk associated with nuclear waste is seen as the major barrier to an expanded programme of civil nuclear power. This concern is misplaced and a block in the way of solving a serious problem for mankind.

If the actinides have been removed from the waste by reprocessing, the remaining fission products may then be buried. After 500 years their activity will have decayed by a factor 100,000. At that level it becomes harmless – standard vitrification and deep burial in stable geology are certain to last for very much longer than that. By contrast the heavy metal waste from a fossil fuel plant is often poorly packaged, buried in shallow sites and remains hazardous indefinitely.

Not to reprocess makes no sense, either commercially or environmentally. If the waste is buried without reprocessing, the actinides remain radioactive on geological timescales, even after the fission products have decayed away. Concerns have been expressed that such buried waste might leak away and show up in the water supply. The story of the two billion year old Oklo Reactor [6, 7] discussed on page 52 suggests that this is unlikely if the burial site is chosen with any care at all. The storage life achieved at Oklo was many thousand times longer than any timescale of concern to mankind.

But what would happen in the unlikely event that radioactivity *did* leak from such a waste depository and contaminate a deep aquifer? The ground water would become very slightly radioactive over a long period. But this happens all the time with the natural radioactivity in the Earth which nobody buried carefully. It is curious that today, in spite of the widespread public concern about nuclear radiation, tourists still flock to health spas that boast radioactive ground water and hot baths

heated by local radioactivity, that is geothermal energy. Their advertisements can be found on the Web. Here is one.

> *The Balneario de Fuente Amarga (Bitter Fountain) was established in 1867 and its waters declared for public use in 1871. It is located in the village of Tolox one hours drive inland from Marbella or Malaga at 360 meters above sea level at the entrance to the Sierra de la Nieves Natural Park and has clear air, a splendid warm climate, abundant water and green vegetation – a sheer delight in contrast to the pollution and stress of modern life.*
>
> *The therapeutic properties of the water are: natural essential metals, nitrogenous, curative radioactivity, and calcium. Therapies offered include: Asthma in children, chronic bronchitis, bronchial asthma, emphysema, conjunctivitis, allergies, kidney stones, diuretic cures.*
>
> *Therapy methods used include: drinking water, inhalations of natural gas, balsamic inhalations, natural gas aerosols, nasal douche, eye baths, mud spray treatments.*

And here is another.

> *Milk River Bath is mineral spa in the South West corner of Clarendon Parish, Jamaica. Owned by the Government of Jamaica since its opening in 1794, it now has about 6 public baths and a hotel with about 20 bedrooms. The waters are 9 times as radioactive as those at Bath, England, and three times those at Karlvoy Vary, Czech Republic.*
>
> *The 6 public baths are located in small private rooms off a seating area. The rooms are smartly tiled. Each can hold several people but the area for changing is really only suitable for one person at a time. The tepid water flows swiftly through the bath. The standard time for soaking is 15 minutes (for J$200 in 2006).*

An adaptive response to the low radiation levels at these spas just might confer a real benefit by stimulating the general response mechanisms to cell damage, although this is speculative. At

worst the radiation is just harmless and gives tourists a brief but welcome holiday away from their city homes.

If the actinides are removed from high level waste by reprocessing and then recycled as fuel, there is no need for large waste burial sites secure for longer than a few hundred years. Any deep dry mine should suffice as a depository. With Generation Four reactors or sub-critical reactors (ADSRs) the long-lived actinides can be burnt up to a considerable extent, so reducing the costly reprocessing of spent fuel as a separate stage.

Decommissioning

When a fission reactor reaches the end of its working life, it must be dismantled and the site cleared. If this is to be used for a replacement reactor, less stringent cleansing is justified, and decommissioning costs can be assessed on this basis. In fact it is very unusual to consider returning any heavy industrial site – refinery, steel plant or conventional power station – to agriculture or housing use.

The first step in decommissioning is to remove the fuel for reprocessing. This stage is much the same as happens during the operation of the working reactor, with the difference that the fuel is not then replaced. This takes about a year and removes 99% of the radioactive material.

The next stage takes longer. Any steel on the site containing cobalt that has been exposed to a neutron flux in the life of the reactor will have become contaminated by cobalt-60. This decays to nickel-60 with a half-life of 5.27 years and the emission of hard gamma rays.[62] As with all nuclear decays these cannot be simply *turned off* by any magic cleaning and the site remains hazardous. The most cost-effective procedure is to wait for 20 years, during which any activity drops to 5%, before dismantling and removing the last of the structural steel. By avoiding the use of cobalt steel as much as possible in new

[62] On page 137 it was stated that materials are very rarely made radioactive by radiation *except* by exposure to neutrons, as in this case.

reactors, the duration and cost of future decommissioning will be reduced. During this stage any material containing long-lived actinides is removed and buried as low or intermediate level waste.

In the final stage after 20 years any remaining fission products on the ground of the cleared site are left to decay. The caesium and strontium are the longest lived, with half-lives of 30 years. If left fallow for 150 years or more, the site would become effectively contamination free, but it is more sensible to re-use it earlier, for instance for suitable industrial storage. Early reactors were not built with decommissioning in mind, but new designs with less cobalt steel and the increased use of robotic handling will ease the task. Naturally, with a more relaxed tolerance of ionising radiation, the whole decommissioning process should become substantially quicker and cheaper – more like the decommissioning of a coal-fired power station for which no special provision is made.

No report has been found of any loss of life in the past 60 years due to radiation in the building, operation, fuel handling, waste disposal or decommissioning of a nuclear power reactor anywhere in Europe or the USA.

Proliferation and terrorism

Who is threatened and who would use nuclear weapons? No one side is trusted by the other in a war of fear – the same war of nerves and propaganda as was played out on the battlefields of ancient history. The difference is that in the modern version of this game of cards, no card is actually played – anyway, not in the past 60 years. Yet the war may still be won when the confidence of one side collapses, as happened at the end of the Cold War when the Soviet Union gave up the struggle. The radiation and the nuclear blast never actually came on stage – they remained virtual, a threat.

High purity uranium enrichment and the production of pure plutonium are indicative of weapon production. These are well

monitored by IAEA and this has prevented the proliferation of weapons in the past, at least in many cases. However, when weapons production is detected, political decisiveness is required to act on this information – but who should act? This seems to be a weak point. As a result, some nations have acquired a military nuclear capability and some have not – and the number who have rises slowly. Some nations behave responsibly in world affairs and have the stability needed to be custodians of weapon technology, and some do not. But technical and economic strength are not related to responsible behaviour. Narrow religious fundamentalism and local self-interest seem to drive the actions of nuclear and non-nuclear states alike. The possession of military might is no guarantee against harmful ideological or religious political control. It is clear that firm international control of enrichment and reprocessing plant needs to be enforced for the common good [57].

But the fear generated by the word *radiation* and the description *nuclear* in the minds of the public and press, can be exploited by governments and terrorists. For terrorists and small rogue states the task of building a viable bomb based on a nuclear explosive is difficult. However, any form of *dirty bomb* is a simple and credible threat, and this could be a conventional chemical explosive device that contaminates a local area by dispersing radioactive material. Or the threat might be to crash an airliner into a nuclear power plant. Such a strike on a modern plant would be quite ineffective, as the reactor containment vessel is massive and designed to withstand such exceptional stresses in any case. In the unlikely event that the vessel was breached, the worst that could happen is a spillage of radioactive fuel, but without the initial surge of heat that initiated the explosion at Chernobyl. As a result, any release of radioactivity would be local, and there would be no fallout without the exceptional heat to propel radioactivity high into the atmosphere. In short, a nuclear power station would be a very poor choice of target for an ambitious terrorist. But as a threat it would be very effective, unless a sizeable fraction of the population was sufficiently educated to see through the threat.

The message of the preceding chapters is that any threat or blackmail based on radioactive spillage ought to be treated as rather impotent, for, if carried through, the effects would be local and modest for all but a few. The only leverage of any threat would depend on the unbridled imagination of the public and press – and the possibility of ensuing popular panic. If people were better informed and reassured, the terrorists would have to change their minds and choose, instead, a genuinely more effective method, such as a 9/11 or a biochemical attack. So the best defence against a dirty nuclear bomb is public education with a more realistic radiation safety regime – in fact, a policy that simply devalues the currency of any such blackmail.

Fusion power

The long-term solution to the need for large scale energy supply is nuclear fusion power. This has been a prospect for many years but has now progressed to the point where it may be expected in a generation or two, well within the life of the latest fission power stations [45, 58].

The first task has been to realise the very high temperature required for long enough and with a density sufficient to ignite fusion. There are several ways to do this, but the current favourite is the toroidal tokamak. Ignition has now been demonstrated, but much more development is required to build a reliable power plant.

Fusion power will be safer and cleaner than fission power. Unlike in weaponry where fission is needed as a detonator for a fusion explosion, there is no role at all for nuclear fission in a fusion reactor. The principal waste product is helium, which is arguably the safest and most innocuous material on Earth. The reaction that produces the energy is between tritium and deuterium, that is

hydrogen-3 + hydrogen-2 → helium-4 + neutron.

The neutron which carries away most of the energy is then moderated by a lithium blanket surrounding the reactor before being absorbed by the reaction

neutron + lithium-6 → helium-4 + hydrogen-3.

Cooling circuits in the blanket deliver the energy to the turbines. Meanwhile the tritium is regenerated. The only input is lithium and deuterium [45].

Lithium is plentiful in the Earth's crust (50 parts per million). It has been calculated that the lithium in a used laptop battery and the deuterium in half a bath of water contain enough fuel to provide the energy requirements of a UK resident for 30 years. There is no long-lived radioactivity involved and the production of waste by-products is on a tiny scale. Tritium is very weakly radioactive with a 12-year half life, but there is no net production of it and the required inventory is small. In a fission reactor at any time there is enough unburnt fuel to power it for more than a year, and that is why control and stability are so important. But in a fusion reactor this is not so. Only a minute mass of fuel is loaded at any time and power production can be switched off at short notice by cutting the fuel supply, as in a petrol or diesel engine. There is no continuing energy release after shutdown, as there is in a fission reactor. There can be no widespread environmental consequences of an accident because the stored energy is less than in a fossil fuel plant. Like a fission reactor, a fusion power source is physically large with a high steady energy output, which could be linked to desalination or hydrogen production as well as electricity generation and local use of waste heat.

To realise such power plants, what is now required is further technical investment and development, largely in materials technology. This is the task for the International Thermonuclear Experimental Reactor (ITER) project that is now under construction in the South of France. No doubt there will be lessons to learn. Some of these may involve expensive setbacks, but they will not be dangerous on a global scale. No doubt there will be accidents – even some loss of life – on a local scale, as there is in any demanding human endeavour. But the record of the last 50 years in the nuclear industry suggests that when these

occur they will be due to familiar mechanical and chemical hazards like scaffolding, ladders, fire and electrical faults.

Costs and the economy

Can these substantial developments in nuclear and fusion power be afforded? The world needs economic stimulus in a period of recession, as much as it needs a scientifically viable approach to climate change. It seems likely that those countries and those businesses that can put these two together will prosper, although the current safety culture, planning laws and public perception of radiation obstruct this objective.

The current cost of nuclear power is amplified by radiation safety regulations and the voice of public concern. Every element of provision for public safety, worker protection and working practices raises costs. This is appropriate if those provisions are actually necessary. But if, as seems likely, many are not, the extra financial yoke that this places on the future of nuclear power may have serious avoidable consequences for civilisation.

The conditions in the waste reprocessing plant at Sellafield, UK serve as an example. In the storage hall where thousands of tons of recently vitrified waste are cooled awaiting burial in decades to come, the radiation level in the working area is less than 1 microsievert per hour, that is about 0.8 millisievert per month. This may be compared with the 30,000 millisievert per month received by the healthy tissue of a radiotherapy patient, and the figure of 100 millisievert per month suggested in Chapter7 as an appropriate safe limit – not that anyone would live for 24 hours a day, 7 days a week in such a hall. It is truly impressive that such safety levels are maintained, but this has been achieved at great cost and the money is not well spent.

With a major relaxation in the current value of radiation safety limits and improved public understanding, the competitive position of nuclear power would be transformed. The stability and control of any power plant should remain the prime consideration, but the cost implications of a relaxation on other parts of nuclear power plant construction, operation and

decommissioning would be significant. The handling, transport and security of fuel – as well as the cooling, storage, recycling and disposal of spent fuel – would still require measures of security and remote handling, but would be cheaper, faster and altogether less conservative.

The cost of decommissioning a plant at the end of its life should not be the major item that it is popularly supposed to be. The IAEA reported in 1990 that [59]

> *decommissioning was technologically feasible, the waste volumes were manageable, and that decommissioning costs had a very small impact on the electricity generation costs. On an annual basis, the funding required (costs) for decommissioning of a large commercial reactor would be 2%-5% of electricity generation costs.*

This report concerned the older plants that were not designed with decommissioning in mind. Since 1990 the working lives of many plants have been extended from 25 to 40, even to 60, years, and this spreads the capital cost. Modern plants with their improved design and working life of 60 years should have small decommissioning costs, even before the impact of reconsidered radiation limits. There is no justification for accounting the cost of decommissioning a nuclear plant any differently than a non-nuclear plant. The current tendency is to talk up the cost of decommissioning in the name of being responsible [60]. It is irresponsible to increase notional costs in the absence of related uncertainties.

The entire uranium and plutonium nuclear technology was designed and built from the basic physics upward in 3 or 4 years in the early 1940s. Today, internationally approved power station designs exist and, if mankind is serious in his reaction to climate change, such power stations could be constructed far more quickly than is supposed. The main causes of delay are planning and public safety concerns – with renewed public goodwill these could be accelerated substantially. Two other causes of delay are foundry capacity and manpower. There is a lack of capacity to

produce significant numbers of the large high quality stainless steel castings required – but recent reports suggest that this is being addressed. In the decades in which nuclear technology was out of fashion, the number of young people studying it declined. Today, in many countries the number of nuclear physicists and engineers is low and it will take time and effort to build up the required skills base and expertise. This will limit the rate at which new plants can be built and brought on stream. One real lesson that can be learnt from the Chernobyl accident is that the manpower required to operate, as well as to build, a nuclear power station must be properly trained and responsible. But this can be achieved. In 1940 there was no nuclear skills base at all, for the whole technology was new. Nevertheless, with determination the job was done in 4 or 5 years by importing and educating bright skilled people from other areas. Of course, any reckoning of the number of skilled physicists and engineers required should be reduced by reconsidering how many need to be engaged on aspects of safety.

Fresh water and food

There are further contributions that radiation and nuclear power can bring to help the environment.

As described in Chapter 2, to provide more fresh water from sea water on a large scale, desalination plants with abundant energy supplies are needed. Otherwise, major water shortages are expected in many parts of the world, as aquifers become exhausted and the climate changes. A nuclear power plant can provide this energy efficiently with sea water cooling and the desalination plant on the same site.

Most food produced never reaches the table. It is eaten by pests, or deteriorates and is thrown away. Its storage life can be extended by energy-consuming refrigeration, but an alternative method is sterilisation by ionising radiation. Food irradiation is recommended as completely safe by the World Health Organization [61] and is used in many countries. Extraordinarily, it is not permitted in most developed countries. Most western

consumers know nothing about it and so, if asked, would reject it simply on account of its association with radiation.

The sterilisation process uses very high doses of gamma rays from a cobalt-60 source, more than 50,000 gray, that is 5×10^7 millisievert. These gamma rays (1.3 MeV) are not energetic enough to excite any nuclei and it is not possible for them to make the food radioactive. However, it is sufficient to kill all microbes through the biological damage caused. The effect on the food itself is like pasteurisation, which causes cell death by heating – cooking is another similar process, that is trusted as normal and safe because it is familiar. Exceptionally, there are foods for which pasteurisation or irradiation have a slight effect on texture or flavour, and then irradiation is not considered suitable. Cooking is not suitable for all foods either, but that is a more extreme treatment. But some governments seem frightened to explain that food irradiation would be beneficial to their citizenry, and such lack of leadership itself gives cause for concern.

Such intense gamma ray sources have other important beneficial uses. In hospitals, exposures similar to those for food irradiation are used for the sterilisation of supplies, including dressings and surgical instruments. These powerful sources of ionising radiation are used also in industry for the non-destructive quality control of materials by detecting internal cracks and voids. As a result most materials do not break or fail, as was the case in earlier decades.

Education and understanding

There is a need to keep track of these intense sources. Accidents happen when they get misplaced, and this underlines the importance of long-term record keeping, improved public education about radiation, and increased availability of radiation monitors. These deserve attention at the same time as the suggested overall relaxation of radiation safety levels. More generally, the operation of a safe civil nuclear power programme in any society presupposes a certain level of political stability

and education. Otherwise, the required indigenous skills base and atmosphere of personal, as well as collective, responsibility are not likely to be maintained.

The links between safety, education and personal responsibility are crucial in every society, developed and developing. The political climate of the Cold War encouraged collective rather than individual scientific initiative and responsibility, as lamented by President Eisenhower in his prescient speech, delivered as he was leaving office in 1961. He was concerned for the voice of the alert individual citizen and, particularly, the freedom of universities.

> *In the councils of government, we must guard against the acquisition of unwarranted influence, whether sought or unsought, by the military-industrial complex. The potential for the disastrous rise of misplaced power exists and will persist....*
>
> *Only an alert and knowledgeable citizenry can compel the proper meshing of the huge industrial and military machinery of defense with our peaceful methods and goals, so that security and liberty may prosper together....*
>
> *In this revolution, research has become central; it also becomes more formalized, complex, and costly. A steadily increasing share is conducted for, by, or at the direction of, the Federal government. Today, the solitary inventor, tinkering in his shop, has been overshadowed by task forces of scientists in laboratories and testing fields. In the same fashion, the free university, historically the fountainhead of free ideas and scientific discovery, has experienced a revolution in the conduct of research. Partly because of the huge costs involved, a government contract becomes virtually a substitute for intellectual curiosity. For every old blackboard there are now hundreds of new electronic computers. The prospect of domination of the nation's scholars by Federal*

> *employment, project allocations, and the power of money is ever present and is gravely to be regarded. ...*
>
> *It is the task of statesmanship to mold, to balance, and to integrate these and other forces, new and old, within the principles of our democratic system – ever aiming toward the supreme goals of our free society.*
>
> Valedictory Speech (part), Dwight D. Eisenhower, 1961

The threats which he described did not disappear at the end of the Cold War. By then the collective machine that he identified had become increasingly international – and the safety industry was a part of that. But now the attitude to safety should change – it is imperative that it be recast to match the new threats to the world.

There is a further educational danger that has been added by the top-down centralised agenda that Eisenhower described. Organisation, especially of large-scale activities, is more manageable when separated into pieces. The temptation is to extend this from management to understanding, and to delegate fragments of a problem to experts. This may be efficient once the problem is structured correctly, but it means that few people, if any, get to appreciate and see the whole. Therefore, the most glaring errors can get glossed over and ignored. This, it would seem, is what has happened in the matter of the effects of radiation. In the recent past, education has been permitted to develop by encouraging such compartmentalisation. So the lesson needs to be learnt and the message needs to go out, that the benefits of specialisation are limited, and that learning in modules is often injurious to the achievement of a real understanding of the whole. The need is for generalists, both deep and broad, especially in the sciences. When expertise is used, it should be interrogated and spread around to inform the whole, not accepted blindly. Thinking by delegation – off-loading tasks of understanding to consultants – does not deliver the right answer. Learning ourselves from our own experiences, and from one another, is hard work, but we need to hand a broad scientific knowledge on to our children and grandchildren. The

alternative may be an environmental dark age from which there is no simple escape. Specifically, mankind must use his wits if he is to survive climate change. In the past he closed his mind to nuclear solutions, and this was a mistake because civil nuclear technology is the only possible approach that is sufficient to cut the main driver of escalating climate change. We need it to maintain the world economy while avoiding the discontent and unrest that could lead to dischord and war on a world scale.