Nuclear is for Life

A Cultural Revolution

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For
George, Edward, Minnie,
Joss, Alice, Alfie
and
others of their generation
who inherit what we leave
About the author

Wade Allison is a Fellow of Keble College and an Emeritus Professor of Physics at the University of Oxford. There he studied and taught for 40 years, covering subjects such as electromagnetic radiation, particle and nuclear physics, and medical physics. His first book was an advanced student book: *Fundamental Physics for Probing and Imaging* (2006). Concerned that many otherwise educated people have significant misconceptions about radiation and nuclear energy he wrote his second book for a wider audience: *Radiation and Reason, the Impact of Science on a Culture of Fear* (2009). It attracted considerable attention around the world, especially following the accident at Fukushima Daiichi in 2011, after which it was published in Japanese and Chinese. Since then he has been to Japan several times to lecture and to visit teachers, community leaders, doctors and evacuees in the region affected by the accident. Incidentally, he has never had any connection with the nuclear industry.

Some reviews of *Radiation and Reason*

“Sensational.” Simon Jenkins, The Guardian

"I very much agree with the conclusions of this book, and am very pleased to see them presented in a style that makes them accessible to the general reader." Sir Eric Ash, FRS

"If Professor Allison's well-documented arguments are right – and if people can be persuaded to examine them! – his book gives us a little more hope of confronting the problems posed by both dwindling fossil fuel reserves and the release of their waste products into the atmosphere." Michael Frayn, playwright and author

“This is an important and useful book. Wade Allison's message is simple - we've got it wrong about nuclear power. We've over-reacted to the level of risk posed by low level radiation exposure, and because of that we make nuclear power ridiculously expensive. The arguments are very powerful.” Brian Clegg, Popular Science website

"Why I'm becoming a pro-nuke nut..... The other scholar challenging my nuclear views is Wade Allison....we must consider all alternatives available to us — including nuclear energy, which just a few months ago I fervently opposed.” John Horgan, Scientific American

“Even if you disagree with where Allison takes his arguments, a large part of the book is a good accessible review of the science of radiation and its biological effects. This in itself makes it a potentially valuable read for activists interested in nuclear and environmental issues.” Peace News
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Preface

This book expands on the message of *Radiation and Reason* (2009) following the Fukushima accident (2011). It is a broader study of the historical, cultural and scientific interactions of radiation with life; it asks why society takes such a cautious view of nuclear technology; it looks at the effects of nuclear accidents and other radiation exposures; it looks at the efficacy of safety, as provided by nature and as imposed by regulation; it explains how biological evolution prepared life to survive exposures to low and moderate levels of radiation; it asks if nuclear energy would be expensive, if normal levels of information, education, safety and design were applied.

These questions are not difficult, though far too few people are asking them. I suggest that the answers are important for everyone on the planet in view of atmospheric pollution and its effect on the climate. I shall be encouraging my grandchildren to read and look with fresh eyes at the amazing natural world that is our home. May they and their contemporaries understand better the beauty of what they see, and so look after it better than my generation has done.

Chapter 1 gives a short outline. The points it makes are supported by the evidence and discussion given in the body of the book. Chapters 2 and 3 discuss public confidence, trust in nuclear energy and the events at Fukushima. Chapter 4 tells how the use of energy has changed as life has evolved. Chapter 5 is about the science of radiation and how it affects life; including an explanation of the conventional LNT (Linear No-Threshold) model and why it is mistaken. More evidence of the effect of radiation on life from accidents and experiments is provided in Chapter 6. Chapters 7 and 8 cover the extraordinary natural protection of life afforded by the physical and biological sciences, each in their separate way. The task of outlining an evidence-based safety regime that takes proper account of nature is discussed in chapter 9, which then goes on to ideas of how this might be explained to the public who have been misinformed for so long. Chapter 10 is a historical account of the view that radiation is dangerous and why authorities still support this view in spite of the overwhelming evidence that it is mistaken. This historical account of the people involved, and why they behaved as they did, makes an interesting story that is more about human nature and less about science. Chapter 11 is a discussion of the relationship between trust in science, religious culture and natural philosophy. Chapter 12 summarises a number of conclusions.
The subject matter is far reaching and readers may wish to move from chapter to chapter, skipping sections that seem too obvious or demanding; to help in this some harder passages are shown enclosed in boxes. Some notes and references are given in square brackets and listed at the end of each chapter, but I do not imagine that readers will need to look at all of these. At the end of the book is a short list of recommended books, articles, videos and websites, referenced by labels [SR1] to [SR10]. There are also a glossary, lists of tables and illustrations and an index. Those illustrations that are quantitative are described as diagrams or graphs; others may be merely descriptive or sketches.

A study such as this is not possible without the help of many people. I have made many friends, some of whom I have never met but whose contributions have been essential and whose opinions I have come to respect. Mohan Doss, Rod Adams, Jerry Cuttler and other members of SARI, the international ad hoc group. Their knowledge and determination give great hope that one day radiation and nuclear energy will be accepted. James Hollow who read through drafts of *Radiation and Reason*, gave me unstinting assistance in Tokyo for this book too, also with help from Paul Eden. I also thank others who introduced me to useful contacts and information in Japan including David Wagner, Tateiwa san, Takamura san, Dr Oikawa, Dr Hashidume, Professor Tom Gill and Shoji Masahiko. I thank John Brenner, Ikeda sensei and Takayama san for their support, and also other members of SRI (Society for Radiation Information) in Japan for making me welcome on my recent visits. Those who have worked painstakingly through my writing and wielded a red pen with justice have my profound thanks: John Priestland, T.R., Clive Elsworth, Richard Crane, Richard Walker and, of course, my wife Kate who has also encouraged me and kept me going over the months and years. Thanks too to all members of my family who have seen less of me recently than they should. Thank you to Royston Robertson for drawing the cartoons, to Richard Crane and Michelle Young for building the website and to my son Tom for designing the cover, also to York Publishing Services who have been most helpful and held my hand during the publishing stage, as they did for *Radiation and Reason*. Inevitably and regrettably, when all is done, there are many omissions and no doubt some mistakes too, that should be laid at my door.

Wade Allison
Oxford
October 2015
Chapter 1: Many Misunderstandings

Gregory: Is there any other point to which you would wish to draw my attention?
Sherlock Holmes: To the curious incident of the dog in the night-time.
Gregory: The dog did nothing in the night-time.
Sherlock Holmes: That was the curious incident.

Silver Blaze (1892), Sir Arthur Conan Doyle

Summary

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Summary

The radiation disaster at the Fukushima Daiichi nuclear power station that occurred in March 2011 is curious. There was considerable escape of radioactivity and the incident was ranked in the most serious category possible. That there was not one health casualty from the radiation is a piece of evidence that calls for explanation.

We have got it wrong about the contribution that nuclear science can make to life. We should examine the hard evidence available not only from Fukushima but also from other accidents, clinical medicine and elsewhere in the light of current scientific knowledge. Critical to this conclusion is the way that living tissue responds to radiation (strictly, ionising radiation). This response evolved very early in the story of life on Earth, and without it life would not have survived. But its effectiveness is explicitly ignored in the formulation of current safety provisions, in spite of the paradoxically small loss of life in all nuclear accidents. In drawing up successful safety regulations to control conventional industrial and agricultural hazards, risks are considered calmly and in proportion. However for historical and cultural reasons, the same is not true for radiation hazards: these reasons are explored and clarified in later chapters.
For nearly a century our understanding of what nuclear technology has to offer has been obscured by ultra-cautious authorities hiding behind fragmented expertise. The broad picture, though muddied by history and assumed to be difficult, is not hard to appreciate in simple common sense terms. Most people are unaware of the large share of the physical world that is nuclear matter, and the amazing contribution that its use can make to prospects for a densely crowded Earth. Indeed, if nuclear energy is not the environmental threat that many suppose, it is the answer to several of the most serious problems faced by mankind: atmospheric pollution, and shortage of clean energy, clean water and food. In any democracy this matters because the electorate should understand the issues. Otherwise, irrational swings of mood or fashion affect decisions.

Our supremacy on Earth has depended on knowledge, confidence and teamwork through openness and mutual trust. However, in the case of nuclear technology these links have been broken and a massive cultural shift is needed to mend them. This is not a matter for top-down committees as much as explanation by individuals, engaging with simple evidence to build people's trust in science and society. Illuminated in this way, nuclear opportunities should become clear and no longer be a source of fear and obscurity.

Climate change

Carbon-based fuels are polluting the atmosphere. The concentrations of methane and carbon dioxide are rising fast every year and are now two to
four times higher than they have been for several hundred thousand years. Given the known properties of these greenhouse gases, it comes as no surprise that the polar ice caps are melting and the world temperature is rising. However, it might be a coincidence and not be caused by human activity at all. Yet, just as I should not expect proof that I am going to have a car accident before taking out insurance, so replacing carbon fuels as a matter of urgency is a sensible policy of mitigation. Replacement with the so-called renewables (hydro, geothermal, wind, tidal, waves and solar) is simply not sufficient, and biofuels and biomass release carbon into the atmosphere, almost as much as fossil fuels [see Chapter 3].

Fired by political self-confidence, German policy is to cease use of carbon and nuclear energies. Many other countries take a more scientific view and consider that switching to nuclear energy is the best that can be done to mitigate climate change. This policy has no technical drawback, but it has not been popularly welcomed because nuclear energy and its radiation are seen as frightening and dangerous. This causes people to close their ears and not want to know more. However, this fear of radiation has no scientific basis. The evidence needs to be explained clearly and understood widely, because radiation phobia is the only obstacle to the provision of cheap carbon-free energy [see Chapter 4, and also Chapter 2 of the book Radiation and Reason (2006), see Selected References on page 279, SR3].

The truth is that we have made a major cultural error by shunning nuclear technology. Big errors are the most persistent, and to get over them requires concerted action by individuals and governments. So why is that not happening? And how did we come to commit this error? To explain this, we will have to turn a few more pages and question some commonly held opinions [see Chapters 6, 9 and 10].

**Safety and medical care**

Does this mean that radiation is safe? And if so, how safe? How do we know that for sure? The short answer is yes: radiation is safe and it has been saving lives by diagnosing disease and curing cancer for over a century as pioneered by Marie Curie. A radiation dose used in a medical scan is far higher than encountered by the public in any nuclear accident, such as Chernobyl or Fukushima. *But how do you know?* you will say. To feel safe and confident about science, we should study and understand some parts ourselves and then talk to friends and contacts to build up trust in the whole. Without such a network of education and trust, in science as in other fields, mankind is doomed. In brief, if you want to be safe and confident, you need to find out what is going on.
In the case of radiation we should look at the numbers that describe radiation doses, and then ask more questions. During a course of radiotherapy treatment the patient's tumour dies from a daily dose 200 times higher than a typical diagnostic scan. In spite of receiving half this massive dose every day for five or six weeks, nearby organs almost always survive. But safety is always a compromise between engaging some risk to achieve a goal and doing nothing, such as staying in bed. So it is true that radiotherapy may have, perhaps, a 95% chance of curing an existing cancer, but a 5% chance of starting a new one. Only by looking at the evidence and understanding what radiation does, can real safety, and the feeling of confidence that goes with it, be achieved [see Chapter 3, and Illustration 2 described further in Chapter 9].
Illustration 3: The final confrontation with the Environmental Anti Fire Party in prehistoric times, perhaps.

Illustration 4: Picture. Shopping bag with simple sensible advice about UV radiation for families.
Hundreds of thousands of years ago, some say a million, man had the bright idea of bringing fire into the home. This was not at all safe, but the benefit to his standard of living with hot meals and warm accommodation quickly outweighed the risks. The choices of fire then and nuclear today are similar, except the risks are very much smaller for nuclear than for fire. In both cases education is key [see Chapter 2].

An example of the need for education about the physical world is protection against UV radiation in sunshine. Parents are given simple advice about how to teach their children to avoid sunburn and resulting skin cancer in later life. As an agent that can damage living cells, UV is much more intense but less damaging than X-rays [see Chapter 5]. But the net effect is similar: early cell death (sun burn) or later cancer (skin cancer). These cannot be compared quantitatively with the effects of nuclear radiation. However, although cancer from UV is common and cancer from nuclear radiation is extremely rare, public concern is the reverse.

At Fukushima there were no casualties from radiation ['] and the doses were so low that there will be none, even in the next 50 years, even among the workers at the plant [see the article SR8]. At Chernobyl radiation-related deaths were limited to 15 fatal cases of child thyroid cancer and 28 workers who fought the initial fire and died over the subsequent few weeks. At Fukushima many casualties were caused by forced evacuation and fear, not radiation. There were similar casualties at Chernobyl including several thousand unnecessary induced abortions performed far away, simply out of panic. Meanwhile the wildlife at Chernobyl today is thriving now that the humans have gone: this has been captured in several charming videos [see Chapters 2 and 3, and SR7].

Simple scientific pictures and the multiplication of some numbers show why nuclear energy is a million times more powerful than chemical energy. However, this energy source is so effectively hidden that its existence was not even suspected until the final years of the nineteenth century. But that still leaves open the question: What happens on the rare occasions that human tissue is actually exposed to nuclear radiation? [See Chapters 7 and 8.]

It appears odd that the extreme power of nuclear radiation should have so little effect on life, given that this is so very frail. We shall see that the answer is that the whole purpose of life has been to survive in the Earth environment, where ionising radiation and oxygen are the two most powerful physical agents to threaten living cells. Providing this protection is what life does – you could even argue that is all that it does, apart from an occasional battle with other cells and viruses. Each element of life's structure is designed to survive these two threats: eating, breathing, sexual reproduction, the partition of life into autonomous individual organisms and the structure of those
organisms as a myriad of autonomous reproducible cells. In some 3,000 million years of evolution it has perfected this protection, and a study of modern radiobiology reveals some of the mechanics of how cells cope with attacks by oxygen and radiation through strategies of repair, replacement, adaptation and stockpiling of resources. This leaves any protection offered by bureaucratic regulation way behind by comparison. People sometimes worry about the effect of the radiation dose they receive in medical treatment, as also they do about Chernobyl, Fukushima and other accidents. Instead, they should marvel at the extraordinary natural protection they receive, and then welcome the benefits that radiation has brought to modern medicine and health following the tradition introduced by Marie Curie [see Chapter 8].

Historical reasons for nuclear mistrust

The twentieth century was a turbulent time in history and perceptions were distorted by existential fears, even among eminent scientists. However, these can be seen more calmly now in a historical perspective [see Chapter 10]. During the Cold War, when there was great disquiet about radiation and the nuclear arms race, instead of educating the public, the authorities attempted to appease negative opinion by promising protection from radiation at wholly unnecessarily low levels. This approach was not successful, especially when accidents occurred in which public panic, not radiation risk to life, was the result. The authorities, themselves misinformed, failed to appreciate that safety and confidence are best established by education and trust, not rules
Illustration 6: Picture of banknotes. Independent thinkers like Marie Curie, Charles Darwin, Florence Nightingale and Adam Smith found the right answers without committees and achieved acceptance. In society today they symbolise trust, even on banknotes. We should follow their example when considering how to reach the public on matters like nuclear radiation.

Illustration 7: The legend of King Canute and his sycophantic followers who believed he could do anything, but did not think for themselves. So he had his throne placed on the seashore, and the commanded the tide to go back, which it failed to do, much to the surprise of his court. Science and nature do not obey regulations or the commands of authority. It is better that at least some people in society study and reach their own independent conclusions.
**Education, authority and confidence in society**

Like nuclear power, currency needs popular trust and support, and banks achieve this by enlisting pictures of famous figures, many of whom contributed much more to science than to banking. They were broad individual thinkers, not specialist experts or committee members, and we should follow the way in which they won public support. Certainly we should not believe everything we hear from uncritical popular chatter in the way the followers of King Canute did [see Chapter 9].

With proper education and training, the general population is well capable of acting rapidly and intelligently when faced with an accident. The immediate response of the Japanese people to the earthquake and tsunami of March 2011 is a good example of what can be achieved. In such a situation in Japan everyone knows what to do without asking authority. Because of their quick action, the death toll from the tsunami was much smaller than it would have been otherwise. With practice and study in school from an early age, confidence and trust are established, ready for when a real disaster occurs, as it did when the earthquake and tsunami hit. However, faced with an accident that was not a disaster, but about which they were totally ignorant – the nuclear accident – they could only look to authority, which gave no guidance, being as ill prepared as everyone else. Fanned by the world press a wave of distrust in authority and science then quickly followed [see Chapter 3].

**Waste, cost and vested interests**

![Illustration 8: Symbols of waste](image)

*a) A radiation hazard symbol for nuclear waste.  
b) A symbol of personal human waste.*

But which waste is linked to the greater danger – that is, kills more people annually?
In the popular press it is widely supposed that there is a problem with nuclear waste. If fully burnt, nuclear fuel produces about a million times more energy per kg than carbon fuels, and that means there is very little fuel and so very little waste. It is mostly solid and can be recycled to get closer to complete burn up. After a few years when it has cooled, the residue can be solidified in glass and concrete which can be buried for the few hundred years needed for its excess radioactivity to die away. Of course, if society wants to waste good money by making extraordinarily elaborate provision, there is no shortage of contractors who would be happy to step up to give the waste the Tutankhamen burial treatment, a large long-term deep and impregnable geological storage. At present nuclear energy is simply burdened by the prospect of what this would eventually cost and the provision that has to be made. This should not be the case.

But why pay so much? Unlike the waste from carbon fuel energy production or the personal waste of humans, there has been no known loss of life from civil nuclear waste. Discharge of human waste into the environment is the cause of a million deaths per year by disease; and the open discharge into the atmosphere of carbon dioxide and the other pollutants that accompany use of carbon fuels of any kind is no less harmful [see Chapters 3 and 9].

Nuclear energy is thought to be expensive, but where does the money go? Most of it goes, directly or indirectly, in salaries. So why does it take so many people so long to design, build and run a nuclear power station? Because it has to be safe! Indeed it does have to be stable in operation – which Chernobyl was not. But at least half of the man-hours, half of the workforce, is employed engaging with super-safe regulations, planning the...
decommissioning, checking workers in and out of secure areas for risks that have been grossly over-estimated. The consumer and tax payer have an interest in exposing this gross over-provision, but they do not understand.

Illustration 10: The interests of some parties are well served by the inflated costs of unscientific levels of nuclear safety, although neither the public nor the environment benefits at all

Part of the problem is suggested in Illustration 10. However, the cartoon does not refer to the nuclear industry itself whose ability to construct new plant has been priced and regulated out of the market without good reason. Countries less in thrall to regulators are able to invest for their future. They will become increasingly competitive and will come to dominate the market for the production of energy and the construction of plant. Decision makers in western countries should appreciate that the current regulatory strangulation is economically dangerous [see Chapter 12].

The task ahead

In the Cold War period people demanded safety from the threat of nuclear radiation, but were given regulations instead. This was delivered wrapped in pseudo-science and tied with legal knots. Blessed by committees of the United Nations and enshrined in national laws around the world, these restraints make it hard for the nuclear industry to make any progress towards construction of the new plant required. So legislators have urgent work to do, to release the nuclear industry from its straight-jacket.

On the professional side the pseudo-science, named LNT (Linear No-Threshold), has to be repudiated, just as the epicycles of Ptolemy were discarded to make way for the new understanding of planetary motion. Fortunately, the evidence against LNT is easier to understand than the
dynamics of the solar system. Simply put, LNT says that all radiation doses are harmful, however small, and that their effect is cumulative. The result is a policy for radiation safety (sometimes called Radiological Safety) that requires that all radiation exposures be kept As Low As Reasonably Achievable (ALARA), which in practice means within a small fraction of naturally occurring levels. This is unrelated to any risk, but comes from a political wish to say that the effects of radiation have been minimised.

LNT assumes that the damage to cells increases steadily with the radiation dose. This is a correct picture of the immediate impact of radiation, but the effect of subsequent biological reaction is to repair this damage within a few hours or days, unless the dose in that time is very high indeed [see Chapter 8]. The upshot is that the effect of radiation does not build up, and small or moderate doses have no lasting effect at all, like modest exposure to bright sunshine. Current regulations follow guidance given by the UNSCEAR committee (United Nations Scientific Committee for the Effects of Atomic Radiation) that denies the effect of this evolved biological reaction, although this was fully described by a unanimous and critical French joint report of the Académie des Sciences (Paris) and the Académie Nationale de Médecine in 2004 [see Chapters 4 and 8].

Safety regulations based on ALARA are not fit for purpose, and are dangerous to the economy, the environment and to life and limb. For example, they can frighten patients into refusing treatment that would benefit their health. In the Fukushima region they have discouraged Japanese parents from letting their children go outside in the fresh air to play. The increased mortality of needlessly evacuated old people there shows how these safety regulations can lead to death. The stacks of top-soil removed from fields, now denuded and infertile, show a sad pictorial example of the destruction
that unthinking fear can achieve [see Illustration 11 and Chapter 2].

Of course, the safety of radiation is important, but new regulations should be based on the threshold for radiation dose *rates* that can be shown to cause damage to health: there is no shortage of agreed data from the accidents that have occurred, and also from a century of experience of clinical medicine. The latter is particularly appropriate as the general public receive such treatment and are aware that it is beneficial, even though the dose rates are high by any standard.

A justifiable radiation safety threshold should be set as *high* as to do no harm, or As High As Relatively Safe (AHARS). A comparison between:

- the ALARA safety standard monthly dose;
- the dose per month experienced by the public in a radiation clinic;
- a suggested safe conservative monthly limit;

is made clearer, when represented by the areas of circles in Illustration 2 on page 4. The threshold, shown as the small green circle, is about the same as that set internationally in 1934, but is about 1,000 times the ALARA level, shown as the area of the small black dot that may only be visible on the expanded scale. That is the factor by which current regulations have typically exaggerated any genuine radiation risk. However, it is right that these ideas should be explored and checked in considerably more detail in the chapters that follow. In particular, possible values for thresholds and the evidence behind them are discussed in Chapter 9.

### Note on Chapter 1

1) In October 2015 a report circulated in the media referring to a Fukushima worker who contracted leukaemia. Such random cases are expected in any population and no causal link was suggested. However, under Japanese law because the worker had received a small dose of 5 mSv he was automatically entitled to compensation. This was misinterpreted by the media.
Chapter 2: Intelligence as an Aid to Survival

The most difficult subjects can be explained to the most slow witted man if he has not formed any idea of them already; but the simplest thing cannot be made clear to the most intelligent man if he is firmly persuaded that he knows already, without a shadow of doubt, what is laid before him.

Leo Tolstoy

It is difficult to get a man to understand something when his salary depends on his not understanding it.

Upton Sinclair

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Facing the problems of civilisation
Democracy and personal understanding

Can the planet support ten billion inhabitants? It almost certainly can, but severe conditions will be imposed by the environment, science, education and human behaviour.

The impact of mankind on the environment is among the world's most
pressing problems. It is time to ask questions: do we really understand nature? How can we use nature with minimal effect on its sustainability? Should we just carry on without re-examining earlier decisions and attitudes? There are facts that nobody can deny, even though some still question the causation of climate change:

- the atmosphere is tiny, equal in mass to a layer of water just ten metres thick around the world;
- the steadily increasing concentration of poly-atomic gases in the atmosphere;
- the definite, if erratic, rise in temperatures and melting of ice sheets;
- the increasing consumption of energy that is essential to any socially stable and expanding economy;
- a world population that increases with lengthening lifespans, unmatched by falling birthrates.

It may be late to take sufficient control, but it is never too late to take stock of the position and take action to reduce any serious consequences. Taking stock must allow the possibility that attitudes to major items in our armoury are misunderstood – that should include the historical view of the atomic nucleus and what flows from it. This book is not about climate change but it is such a stock taking.

Every child is taught from an early age that fire is dangerous. If the child fails to get the message, the chances are that the physical pain of a small accident will serve as a reminder, not easily forgotten. In the same way, each child is trained to cope safely with human waste – potty training comes high and early on the list of educational requirements. These are not options in human society, but young children learn easily. As they grow older, they become more selective about the information they absorb. This selection depends on what they have already learned and accepted, and on new evidence of which they become aware.

However, new evidence may conflict with what was previously understood and then be dismissed out of hand – that is the easy way out. Alternatively, the conflict must be examined – not a childish process, but one of ongoing self-education. A readiness to re-examine opinions like this is essential to any effective democracy because it allows views to flex as information changes. But such re-examination of opinions depends on sufficient numbers of the electorate being well informed, able to make up their own minds, and ready to change their opinion when evidence indicates. But, if views are long standing and get repeated uncritically, a democracy may be unable to change. Instead, it becomes locked into a semi-permanent misapprehension that leads
to ill-advised decisions. Stability is only established when real information is accepted and people are ready to learn afresh, but, as Tolstoy wrote in the paragraph posted at the head of this chapter, this presents a high educational challenge.

The task of this book is first to ask in straightforward terms why so many in society have an aversion to nuclear science; then to explain to them the balance of benefit and risk as it is known today. With the damage apparently inflicted on the environment by carbon combustion – coal, oil, gas, biofuels and biomass – the relevance of comparing nuclear energy to fire is clear.

Many people are reluctant to change their opinion even when faced with evidence that contradicts it. Such rejection of scientific evidence is too easy, especially when the reluctance is supported by a whole industry of experts – from local safety officers to international lawyers – who have jobs with careers and standing that depend on the status quo. The quotation by Upton Sinclair at the head of the chapter makes the point.

Unfortunately, these are the very authorities that the press and politicians tend to consult when they want advice and information. Such consultations are the norm, since few people are prepared to stand up and say that they themselves understand an issue sufficiently. In this way a pass the parcel culture of weak responsibility, stabilised by a fear of litigation, discourages personal judgement and leaves decisions in the hands of expert authorities who are least likely to recommend change. We shall go behind such interests to look at the evidence for what was previously claimed to be obvious and settled.

**Fear of traumatic change**

Deciding to change your opinion can bring an element of shock – an embarrassment that may be avoided by postponing the decision. Visualise a meeting on a very hot day at which a number of people are standing nervously around a swimming pool waiting for someone to dip his toe and announce to all that the water is acceptably warm. A dive into the water would be refreshing in the heat, but the immediate cold shock might be undignified in front of the others – so nobody jumps in. Everybody at the pool sweats uncomfortably, denying themselves the refreshment of the cool water. They remain prisoners of their indecision, unwilling to risk the cool splash of change.

It can take leadership to be the first publicly to express a change of view. Nevertheless, many of those previously active in campaigns against nuclear technology, including leaders of the Greenpeace movement, have actually switched their opinion of nuclear energy[^1], in particular Mark Lynas, Patrick Moore, Stephen Tindale, James Lovelock, Stewart Brand and others. These are the exceptions. But how is it then possible to go further and encourage
others to change their views, many of whom who are still deeply apprehensive of nuclear technology? Evidence is needed to account for how received opinion has developed since World War II, and an exposition is needed of the science and medicine involved.

**Learning from fable and science**

**Personal and public opinion**

What each of us, personally, knows of the world we inhabit is built on our accumulated experiences and observations, and these we extend by thinking and studying, based on our own learning. Together these form the basis of our personal opinions – meaning that we are able to check and verify them relatively easily. Ideally, this would be the basis of all that we acknowledge, but in a practicable world, we also need to listen to the opinion of others in order to engage with other questions and problems encountered in life. When we seek advice from another in this way, we try to choose someone with personal knowledge. Failing that we may have to follow a majority view. But this can be a bad move if everyone else does the same. We would all know what everyone else believes, but what passes for information is rootless, giving rise to unstable opinion and a potential for panic. To avoid this, a few people at least should actually understand a matter independently. This should not be seen as a recipe for a class of experts or high priests who then become motivated by their own group agenda when giving advice. Rather we should call for such expertise to be filtered through the education of new and younger minds so that ideas can be accepted or rejected by their unbiased studies.

Traditionally children are brought up with fairy tales that encourage them to keep their eyes and ears open and to acknowledge obvious truths. For example, they learn that old people lose their youthful looks but they must cope when their imagination raises a frightening question like *Is the apparent grandmother in reality a wicked wolf?* This book asks whether nuclear power is a similarly wicked wolf, which the popular imagination supposes with the help of the press. We should look at the evidence. This story is set, not in a dark and secret enemy research laboratory, nor in a frightening earth-bound forest, but in the huge natural universe – a universe that is largely benign, principally because we are creatures that have evolved to fit with it. Those who fitted less easily are the ones that already died out, according to Darwin. But the story continues – if we do not fit with our environment and look after it, we too may die out.

**Science before Earth began**

Before humans, before Earth, before the matter of which Earth is composed, radiation completely dominated everything in the universe. As the universe
cooled from its creation in the Big Bang 15.8 thousand million years ago, the
radiation subsided leaving clumps of matter to emerge as galaxies of stars.
With the exception of hydrogen, this matter was made of nuclear waste left
after an orgy of early-exploding stars that created all the chemical elements
we see around us today. Earth was formed some 4.5 thousand million years
ago, and not long after that the slow development of life began. Much later, a
mere million or so years ago, man appeared. Then, a few hundred years ago
man began to understand how he himself could engage the power of science,
culminating in his ability to work with radiation and generate energy from
nuclear matter.

Many speak as if nuclear energy and radiation were man-made, and perhaps
compare a decision to use it and its powerful influence to Adam and Eve
deciding to eat the forbidden fruit in the Garden of Eden. But man did not
make radiation or nuclear energy – it was nuclear radiation in the natural
world that was needed to make man, long before. Indeed it is the failure of so
many to eat the fruit of this knowledge that has lead to the sorry story of
Fukushima Daiichi – a tragedy of ignorance, a tangled web of
misunderstanding and undeserved distrust of which Shakespeare would have
been proud. The story deserves to be retold in a positive and properly
scientific light.

**Fire in the home**

Decisions about energy affect people's lives and many have strongly held
opinions. But those opinions, whether about conventional fuels or nuclear,
have to be confronted with evidence, and the right way forward has to be
argued out. We may imagine how mankind fared in earlier times when faced
by another question at least as momentous as a decision to adopt nuclear
energy and to phase out the burning of carbon fuels.

Perhaps many hundred thousand years ago there was consternation among
the more conservative environmentalists of the day when radical innovators
started building hearths and bringing fire into the home. Obviously, most
people were frightened – everyone knows the dangers that come when you
start *messing with fire* – and choosing to do so at home must have seemed
irresponsible. The readiness with which fire can catch and spread has been
the cause of countless fatal accidents – it is a thermal *chain reaction* that is
difficult to put out. Even today, in spite of regulation, instruction and ever-
ready emergency services, fire remains a threat with a substantial annual
death toll. When animals see or sense fire, experience tells them to run away,
and collectively they are apt to panic. Man usually does the same, but at some
point in the early Stone Age – nobody knows quite when – he made a
momentous stride for civilisation: overcoming his natural fear of fire he
stopped, used his brain and studied the problem. He realised that on balance
the benefits of fire outweigh its dangers, provided personal education and training is given to everybody, children included. It was a turning point that gave humans immediate supremacy over all other beings. Civilisation could not have developed without fire, and we would probably have remained animals with a limited population and a short and brutish life if we had heeded the advice of the environmentalists of those days pictured in Illustration 3 on page 5.

Initially, no doubt, few shared this enthusiasm, and we may imagine some noisy demonstrations with members of the Anti-Fire Party opposing the new technology because, as they said, everybody knew that fire was dangerous and they had tales of death and destruction to back their case. But in the end they were overruled, and the lure of hot cooked food and warm dry accommodation won the day. Perhaps it did not happen quite like that – perhaps the protesters, afflicted by poor health and inadequate diet, just died of cold and hunger, being uncompetitive with those who embraced the new technology. Anyway, every generation of children to this day has to learn respect for fire, often through the experience of a hot stove and a few tears.

In fact, the advance was not just the introduction of fire into the home but the power to think and act with confidence – to study and control the use of fire and other sources of energy in the environment. As man used his brain and learnt more, his confidence in his scientific studies grew, and cooperation and trust in society at large grew with it. But such trust is fragile and is easily lost or destroyed.

This process of learning has continued, and in the past century there have been two important discoveries suggesting that the decision to use fire liberally should be re-examined. Firstly, fire has consequences even more dangerous than previously understood, namely the effect of its emissions on the global environment [see Selected References on page 279, SR3 Chapter 2]; secondly, there is an alternative energy source to fire that does not have the same drawbacks, neither the tendency to spread and multiply nor the environmental impact. In addition it has more than a million times the energy density of carbon-based combustion.

This alternative is nuclear technology, first made known to the public in a sudden dreadful shock at the end of World War II with the bombing of Hiroshima and Nagasaki. This negative experience was reinforced by the political and military propaganda of the Cold War period. Notwithstanding this, the public has benefited from nuclear technology for over a century through its use firstly in clinical medicine to image the internal anatomy of the human body and its functioning, and subsequently to diagnose diseases and cure cancers without surgery. Today the question is whether nuclear technology is really as dangerous as the public has been encouraged to
believe. Fire is welcomed in spite of its obvious dangers. Should nuclear energy be rejected? Or should it be accepted as the least bad option to save the endangered climate? Or even, should it be welcomed because nuclear energy is safer than fire and only dangerous under quite exceptional conditions? Whether to use nuclear technology is the new Promethean question. It is a decision as important as the domestication of fire.

**Nuclear safety misjudged**

**The news from Fukushima Daiichi**

The accident at Fukushima has shown the answer rather clearly: nuclear power is safe to use. But this has not been appreciated. Furthermore, the relevant public education and training has not been given, and the guidance given by the authorities, both national and international, has been based on seriously mistaken science. As a result the costs of nuclear energy and its safety have been completely misrepresented.

Later chapters provide discussion and the evidence that nuclear power is safe. Based on this evidence, the authorities from the United Nations down should be urged to reconsider their advice, so that the wider public can make up their own minds. In democracies at least, politicians are likely to continue to appease the fear of radiation and make decisions that lead to a lack of economic competitiveness and environmental damage, locally and globally. However, once public opinion is better informed, leaders will see that there are votes in pursuing the course for the common good.

The press saw the accident of March 2011 as the start of a new era. For the first time since the man-made nuclear age began, the media were ready and present at the scene of a nuclear accident with their cameras running and ready to stream 24-hour news. They captured pictures of chemical explosions; they speculated about the significance of leaks of gases and water carrying radioactive waste material; making little comment on the deaths of more than 18,800 people from the tsunami, they preferred to keep media attention focussed exclusively on the big story – and they believed that was the nuclear one. Every day for weeks, then months and years, they described radiation escapes and radiation doses said to be high. But nothing happened – nobody was hurt by radiation or radioactivity. Unable to accept or appreciate that the script was not developing as they had expected, the journalists and reporters continued to rephrase the stories of high radiation readings and escaping radioactivity without being able to show why this mattered, except that it frightened people around the world who then bought their news stories.

On previous occasions when the press had reported from the scene for the first time, the consequences were far reaching. For instance, the open
reporting of the Vietnam War with its dramatic pictures and true accounts showed it to be genuinely shocking, and this contributed to turning public opinion against the war, at home in the United States and elsewhere. But never before Fukushima had the story been nuclear. Media interest in getting real nuclear pictures had never been satisfied in the 65 years since the bombing of Hiroshima and Nagasaki. The 1957 Windscale Fire was much smaller than Fukushima and not openly reported at the time; the Three Mile Island accident was contained and produced neither pictures nor casualties; Chernobyl was inaccessible, hidden behind the Soviet veil that crumbled shortly thereafter. So for the first few days at Fukushima, media reports felt able to indulge in nuclear superlatives, for the first time after many years of waiting. But apart from the fear maintained by the reports themselves, it was not like that. Lacking a ready script, the media started to scratch around for a story. Popular reports urged the public to blame the operating company, TEPCO (Tokyo Electric Power Company), and the Japanese government for lying, secrecy and bad management – they could hardly blame them for injury and manslaughter because there had been none. Few, it seemed, looked at what had really happened, or rather had not happened. Around the world the initial collective panic spread, unrestrained, in an atmosphere of global ignorance. Politicians and others drew up instant national policy reactions without fundamental reappraisal, and this was reflected too in official international reports, although these took many months, even years, to appear. But did anyone dare to ask the big question? Was anyone in danger from the radioactivity and its radiation?

All the nuclear power plants in Japan were shut down and put into stand-by. This resulted in electricity shortages and then massive economic and environmental costs, as substitute fossil fuel was imported and burnt. Over 100,000 people were evacuated from the region and many more left voluntarily. Food was condemned by regulation and more rejected by market forces, this in a relatively poor agricultural region where farming businesses were quite fragile anyway. Children were encouraged not to play outside, old people were moved from their sheltered accommodation, often with fatal results. The population showed all the symptoms of extreme social stress – bed-wetting, suicides, family break-up, alcohol dependence. No explanation was given to the local people of what was happening to them. Local discussion degenerated into arguments about blame and compensation. Inevitably those who moved away from the region were the more affluent, leaving an immobile residual population without the youth and ability needed for a viable community. At great expense, work began to remove topsoil, said to be significantly contaminated, from fields in the evacuated regions. But this policy was not thought through and had negative consequences:

- Topsoil removal was found to reduce the radioactivity of the fields by
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50% at most.

- Fields lost much of their fertility without their topsoil.
- The forests and steeper rocky regions above the fields could not be included in the work, but these covered a wide area, seen in the background in Illustration 11 on page 12.

It is difficult to see how this expensive work makes any sense. Later chapters will show why radioactivity in the region, as shown in Illustration 13 on page 44, is far from dangerous, so that a 50% reduction does not make a cost-effective difference. Teaching the local population about radiation and why they should genuinely have no worries would be a better investment, but obviously that would take longer. But for a start they would get some immediate hope and encouragement from viewing the professional videos showing wildlife thriving at Chernobyl today [SR7].

Around the world many other nations also panicked. Some withdrew their nationals from Tokyo, even from Japan, and introduced plans to shut down their nuclear plants and rely on renewables, which in practice increased their consumption of carbon. Eminent international bodies met and responded to popular demands for increased nuclear safety. Mandatory standards were raised, large numbers of people eagerly accepted new jobs in nuclear safety, and the quoted capital cost of nuclear power stations and the electricity they produce rose as a result. These funds and jobs became available as a result of the ballyhoo, but few analysed what had actually happened and whether it warranted such a reaction.

In later chapters we explore the worldwide cultural misunderstanding, with its roots going back 70 years, that lies behind this reaction to the accident, why it happened and what should now be done about it. Science policy blunders have been made before, but this one has wider consequences because it threatens both the world economy and, at the same time, the best prospect of stabilising the planet's environment for the benefit of all.

Matching evidence and expectations

What happened at Fukushima Daiichi was not what was expected. The supposed terrible tragedy seemed not to match the evidence. There are only two possibilities: either it was simply wrong to expect that such radiation would cause physical harm to the population; or the effects of the radiation will turn out to be much worse in the end than the results have so far suggested. These possibilities are investigated here.

For any experience that complies with common sense our expectations beforehand should match what happens. If this is so, our confidence builds. Otherwise we must admit that we have got something wrong and it is a
matter of back to the drawing board to understand how we were wrong. That is the scientific method. We could get mathematical at this point by expressing confidence as betting odds and work out what how expectations should change in the light of new information. Fortunately this can usually be avoided because the conclusion is plain to see. In particular, if the new information completely disagrees with the prior expectation, mathematics should not be used to hide the blatant inconsistency.

So we need to examine our expectations. If something is obviously at odds, we should not accept that some sophisticated statistical analysis or pronouncement from an eminent committee can avoid it. Such a situation is described in the story of the Emperor's New Clothes by Hans Christian Andersen. If the Emperor is wearing no clothes, then no pronouncement from his officially appointed international tailors carries any weight, and common sense is sufficient to see that. The radiation dangers experienced by the people of Fukushima are like the Emperor's clothes – they are not there! The situation must be reviewed and resolved.

Pseudo-sciences and wishful thinking

By examining other major nuclear accidents, particularly Chernobyl and the one at Goiania, it becomes clear that no incidence of late cancer or other mortality should be expected at Fukushima. So the predictions of disaster were simply wrong. We will need to examine where these came from. The story will go back many decades to the birth of a pseudo-science called the Linear No-Threshold Hypothesis (LNT). It is described as a pseudo-science because it is not based on observation but on a history of ideas, fears and human emotions, quite real in their own terms but not scientific. LNT joins other pseudo-sciences, such as alchemy and astrology, that seemed interesting in their day but were finally brought down by conflicting evidence. How do pseudo-sciences come to be accepted in spite of their erroneous basis? How did alchemy and astrology get their limited acceptance, and did LNT become accepted by authority following a similar route?

Science requires care and attention to detail if wrong turns are to be avoided. Navigation offers a practical example. A boat that sails from A to B on a map on a steady course will arrive happily if the voyage is less than a few hundred miles – that is called plane sailing, as it would seem no different if the Earth were a flat plane \(^2\). However if the voyage is longer, plane sailing does not offer the most direct route because of the curvature of the Earth: for this, the boat should steer on a great circle with a slowly changing course relative to the points of the compass. That may not be clear to the non scientist, but it shows how a proper understanding of the problem is needed if mistakes are not to be made. Likewise, on the safety of radiation, having found that we
were wrong, we should develop a deeper understanding so that we can make better decisions.

Astronomy impressed everyone in the ancient world, as it does also today. It began by describing events of exceptional regularity: the rising of stars, Sun and Moon; their links to tides and seasons; astronomical measurements for navigation with ever greater accuracy; the movement of the planets; finally the prediction of eclipses. The authorities of the ancient world were naturally in awe of the astronomer. No doubt they took the priest of this power into their confidence and asked his advice. The astronomer would be pressed on many urgent questions about which he was certain and others about which he was quite ignorant. But could he refuse the offer of research facilities and substantial grants? Perhaps he only had to guess whether the King would have a son. It is not surprising if at an incautious moment he accepted the research grant money on offer and agreed to use his astronomical powers to study the probability of the birth of a male heir. If he got the prediction wrong, the result might be fatal for him, but think of the grant and the studentships he said to himself. In this way the pseudo-science of astrology was born.

Predicting the weather was uphill work in ancient times, and it still is today. At that time, everyone's lives depended on what they could grow, given the weather, and what they could make with their tools of wood, stone and metal. The contribution of metalwork to the economic competitiveness of early civilisations was crucial, and the ability of their geologists and chemists to extract metal by heating and treating rocks was simply magic to the majority of the population. While they learnt how to produce base metals from raw minerals, everyone dreamt of producing precious silver and gold by extending the magic. Good research money was always on offer to any charlatan or fool unwise enough to offer to transmute base metals into gold. The pseudo-science of alchemy was driven by greed and ambition, and frustrated by true science. But that did not stop people indulging, and many legends recount the fate of those who used fair means and foul in their pursuit of riches in this way. Alchemy's credibility depends on gullibility and ignorance, but, like astrology, its faulty appeal is exposed by education.

Does LNT provide another example of such a pseudo-science, this time drawn from the mid twentieth century instead of the Middle Ages? LNT seemingly justifies a fear of radiation, or radiophobia. This fear may be genuine, but that does not mean that radiation is actually unsafe for low or moderate exposures, and of course fear should not be seen as a sufficient reason for proscriptive regulation. Those with a fear of the dark or of heights (like the author) may be really frightened, but such phobias are not built on science. It is dangerous and irresponsible to inflict on others the false rationalisation of such subjective phobias, however unbearable they may
seem personally. Forbidding anyone from going out in the dark or climbing ladders would be wrong, unless there were solid statistical accident data to justify it. Any such restriction would reduce productivity and competitiveness. More generally, our practical superiority over other animals depends on an ability to face any apparent dangers objectively.

**Fear of nuclear energy**

*A zeitgeist reconsidered*

Every age has its cultural spirit or zeitgeist. Some are beneficial while others are injurious. Religious ones may hold sway in a region, sometimes for many centuries. Secular ones can be geographical too, but seldom last so long. To adherents, the ideas may seem self evident, that is until they are found wanting and the false confidence they offer implodes. The persistence of some is stabilised for a time by hate or fear that suppresses study and open discussion. In this way deep examination is effectively prevented for everybody in society, except for a few technical priests. Ideas may appear to be isolated by education if people are made to feel that understanding is beyond them. Similarly the power of voodoo or the curse of a witch doctor may sustain a primitive belief by a collective intimidation that allows no questions.

In modern times, general improvements in education have prevented or suppressed many instances of false or malignant fashions. Among those that have persisted, few have exerted a widespread inhibiting influence as strong as radiation phobia – the reaction to matters invoking the words nuclear and radiation. In the wake of news of the nuclear bombs of 1945 came a prescribed litany of nuclear awe to which all assented, and still do. But in the twenty-first century the impact of carbon fuels on the environment has brought a fresh need to exorcise public fears of nuclear technology. A simple transparent appreciation of radiation is required to replace the rationalisation based on flawed science that has been used in the past to underscore radiation phobia.

The supply of energy and the ability to use it have been responsible for maintaining life on Earth from its beginning well over 3,000 million years ago. In the modern human era this has lead to large populations living under improving conditions. Until recent centuries change was dictated through natural selection, a gentle-sounding description of death, but which frequently occurred on a large scale. Today the ability of humans to study and plan provides a more welcome way to bring about change, although to be effective this depends on the education and understanding of decision makers – in a democracy, the electorate and the politicians answerable to them.
Popular opinion about energy is still heavily influenced by fear of nuclear energy. This threatens to restrict not only the supply of energy, but also stable economic growth, food and clean water for a population living in a fragile climate. The remarkable accident at Fukushima challenges this fear and calls for a re-examination of nuclear technology using a coherent modern scientific understanding of the physical, biological, medical, and social issues involved, expressed in a form understandable to a broad readership.

Trust in science is properly established by successful numerical prediction and measurement. Its explanation can be supported by pictorial diagrams and graphical descriptions that help make the truth intuitively obvious. The ability to draw or visualise a scientific result is as important to creating confidence for the scientist as it is for everybody else. So the following chapters use common sense, diagrams and pictures as well as a few numbers to help in reaching conclusions. Sometimes those numbers may be accurate and carry only a small uncertainty. Just as often the uncertainty may be quite large, but the conclusion will still be unavoidable if the alternative differs by a factor of hundreds or thousands. However, if all numerical comparisons are ignored, any discussions may degenerate into heated debate between parties unable to express their conclusions in clear numerical terms, as is often to be found in the media.

Notes on Chapter 2

1 Statements of environmental and other academic support for German nuclear power (2014) http://maxatomstrom.de/umweltschuetzer-und-wissenschaftler/

2 This is often described as plain sailing, a spelling that suggests a misunderstanding. The Oxford English Dictionary accepts both spellings.
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
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- Sources of energy
- Stored energy and its safety
- Nuclear energy
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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: energy 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 become 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 hence 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 2013 was 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 \[^{1, 5}\]. 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 forswear 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](image.png)

*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 $1,000 \times 1% / 33% = 30$ 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 \[\text{[11]}\]. 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.
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

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.]
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*
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, evacuues 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 8a 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 8b on page 9 shows a candidate symbol drawn from the First World experience.

Evacuation, clean up and compensation

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.
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.

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

2) The stories of *Centralia*, Pennsylvania, USA and *Morwell*, Victoria, Australia show what can go wrong.
5) D Ham *Marie Skodowska Curie* (2003) [http://www.21stcenturysciencetech.com/articles/wint02-03/Marie_Curie.pdf](http://www.21stcenturysciencetech.com/articles/wint02-03/Marie_Curie.pdf)
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.
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%. 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.
14) *Health effects - facts not fiction*, Thomas GA (2013) [http://www.jaif.or.jp/ia/annual/46th/46-s3_gerry-thomas_e.pdf](http://www.jaif.or.jp/ia/annual/46th/46-s3_gerry-thomas_e.pdf)
Chapter 3: Rules, Evidence and Trust


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


21) See United States naval reactors on Wikipedia.
Chapter 4: Energy to Support Life

Nuclear energy is incomparably greater than the molecular energy which we use to-day. The coal a man can get in a day can easily do 500 times as much work as the man himself. Nuclear energy is at least one million times more powerful still. If the hydrogen atoms in a pound of water could be prevailed upon to combine together and form helium, they would suffice to drive a 1,000 horse-power engine for a whole year.

Winston S Churchill, in the Strand Magazine (1931)

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**Escalating stages in the liberation of life**

**Energy for plants**

The surface of the Earth is warmed when the Sun shines on it, but as soon as night comes, the flow is reversed and the Earth cools by radiating its heat into space. The atmosphere blankets the surface, and the heat stored during the day in the rock helps to maintain the surface temperature. Whenever temperature falls, chemical changes slow or stop, including those that constitute the mechanisms of any form of life. When the Sun shines and it is warm, plant life can absorb energy by photosynthesis, so that it grows while also converting carbon dioxide in the atmosphere into oxygen. This is summed up in the following equation:

\[
\text{energy} + \text{carbon dioxide} + \text{water} \rightarrow \text{carbon/hydrogen (vegetable)} + \text{oxygen}.
\]

But at night this energy supply is cut off. In the winter the effect is even more pronounced and the plant may have to die back and wait for the warmth of spring.

**Energy for animals**

However, that is only the beginning of the story of life, because evolutionary biology has always striven to find new ways to compete more effectively. If it could take on board the products of photosynthesis by plants, that is food, and combine it with oxygen when required, it could effectively run photosynthesis in reverse and recreate the energy. Such a versatile energy store would act as a battery, storing the Sun's energy to maintain life during the night and in the winter:

\[
\text{vegetable matter} + \text{oxygen} \rightarrow \text{energy} + \text{carbon dioxide} + \text{water}.
\]

Within a few hundred million years and with plenty of room to experiment, that is what Darwinian evolution learnt to do. Forms of life using energy from food no longer needed to sit immobilised in the sun all day, but could move around – migrate by land, sea or air in search of the best source of vegetable food and the most pleasant climate. Life could now use its heat source, its energy battery, to keep its temperature optimised, night and day, throughout the year. This food-powered animal life acts as a biologically stabilised combustion engine – a pretty smart job compared to the ill-controlled combustion of vegetation that occasionally catches fire in the open environment. This sketch of metabolic life has omitted fish, birds and the many forms of parasitic life that hitch a lift at different levels. However, the story of how the energy flows is not upset by these additions.

Like plant life, animal life needs energy for growth and biological maintenance. By consuming food as fuel, animal life enjoys energy for transport and other motor skills that are denied to plants. Energy is also
available for competition between packs of animals of the same or different species. From sport and friendly competition to fighting and war, this is the essence of classical Darwinian selection, but today it is understood that this principle applies further — in fact, in the competition between life forms at every level. For instance between viruses and their hosts, each player evolves to find defences against attack by its adversaries. Imagine such a war game in which one adversary never changes strategy, but the other is alive to change and so evolves new strategies of defence and attack. The living player will always find a way to evade the attacks, however long that takes and however powerful the adversary; and he will find a way to attack his more powerful adversary successfully, too. Initially individuals may not win but in the end the selection of a winning strategy is guaranteed. This is the story that is explored in Chapter 8, with radiation cast as the powerful but changeless adversary, and living tissue in the role of the weaker, but artful, defending player that has learnt to survive.

**External energy for humans**

The advance that lifted mankind above the other animals was the Promethean step discussed in Chapter 2. In this the energy stored in plant growth could be harvested and used now, not just inside, but outside the body, still reversing photosynthesis, but in the process of combustion, *ie* fire. However the safety built into the oxidation of vegetation within the body is then no longer available. Mankind had to use his brain and introduce safety rules for himself.

This was a turning point and the beginning of safety through careful thought. From then on, safety was seen to be a matter not only for nature but also for conscious decision-making and discipline, handed down to later generations as an important ingredient of education. Initially this took the form of oft repeated cautionary tales told to children. In recent centuries these appeared in books that wove entertainment with instruction that was then more easily remembered.

Illustration 17 shows a page from an English translation of the well-known nineteenth century German children's book *Der Struwwelpeter*. While her mother is out of the house, the child, Harriet, disobeys her mother's instructions and plays with the matches, accidentally setting her clothes on fire. As the pictures relate, she is then burnt to death to the dismay of her pet cats, who are left weeping while only her shoes remain. With these dramatic details, children remember the dangers of fire and their parents' instructions.
Illustration 17: "Harriet and the Matches" from Der Struwwelpeter
A further change in mankind's engagement with energy came at the start of the historical era when he discovered that a vast store of the product of many millions of years of photosynthesis lay fossilised in the Earth, both in the form of coal, and also as oil and gas. There was an abundance of energy in this carbon battery – and we have been gorging ourselves on it ever since, while also increasing in population at an unsustainable rate. The most recent expression of this excess is the glee of politicians and industry at the prospect that even more gas can be accessed by fracking whilst ignoring the release of yet more carbon into the environment.

**Energy production that damages the environment**

Left to itself, nature usually metes out harsh treatment when such excess occurs in the animal kingdom – mass death through disease or starvation is normal, a horrific outcome to anyone with a belief in the sanctity of life. However, the sanctity of individual life has no role in evolution. Through the exhortations of religion, a belief in rights and the pressure of law, mankind has hoped that he might retro-fit the sanctity of life to nature as a principle – but that is an illusion. In good times he is inclined to forget that if he does not study and make the right decisions, nature – known as the Grim Reaper in earlier times – will take those decisions for him without regard to the fate of individuals.

If we are to stop exploiting the carbon battery, where might we find a source of energy to replace it? The question is as momentous as the one that we faced in prehistoric times when we adopted fire for our own use. The answer is nuclear, but society worldwide will have to address some misconceptions before it is likely to accept that.

The burning of coal, oil and gas release carbon dioxide into the atmosphere, and the combustion of waste, biofuels and biomass do the same. In fact, to make matters worse, because of the dioxide, the amount of carbon dioxide released is greater than the weight of carbon burnt by a factor $\frac{44}{12} = 3.7$. Our atmosphere is incredibly small and although it extends upwards from the Earth's surface for several miles, it is very thin, just one kg above each square centimetre, which means it does not take much to pollute it. Illustration 1 on page 2 shows how every year since the start of the Industrial Revolution, the concentration of carbon dioxide has risen far above values for the past 160,000 years. A basic description of why this increases the global temperature is given in Chapter 3 of *Radiation and Reason* [see Selected References on page 279, SR3]. Today, six years after that book was published the concentration has risen to 400 parts per million (ppm) and there is significant evidence that the average temperature, particularly in the Arctic, is rising. Table 1 shows how the concentrations of other greenhouse gases have also risen.
Table 1: Atmospheric concentration of the most significant greenhouse gases. IPCC data from http://cdiac.ornl.gov/pns/current_ghg.html

Methane is of particular concern because its greenhouse properties are more pronounced than those of carbon dioxide. Although it is oxidised in the atmosphere in 12 years on average, its concentration has risen by a factor of nearly three, and much of that increase has occurred in the past 50 years [see also Illustration 1 on page 2]. Significantly, there are large stores of methane under pressure in the cold of the Arctic in the form of methane hydrates on the seabed along the continental margins. These may become unstable as the ocean warms, which would result in the methane being released into the atmosphere. Methane is also stored in the soil under the Arctic permafrost, and warming increases the likelihood of a positive feedback in the climate system that releases this too \([^1]\). The most recent reports from 2013 and 2014 suggest that these mechanisms may be acting faster than previously supposed. There is evidence that methane is released in explosive events in Siberia and that its concentration is rising much faster in the Arctic than elsewhere \([^2, ^3, ^4]\).

The magnitude of the global warming effect is uncertain, but it will probably not be known precisely until it is too late. The uncertainty relates partly to the methane story, and partly to the role of the oceans and how fast they are acidified by absorbing atmospheric carbon dioxide. This book is not concerned with the Earth's climate directly, but it is the expectation of climate change that makes its message urgent, and the consensus of the Intergovernmental Panel on Climate Change (IPCC) supports that expectation \([^5]\). There is every reason to pursue nuclear energy to reduce any impact of anthropogenic climate change. This is an appropriate use of the Precautionary Principle: the extent of global warming is still uncertain and there is no down side to this policy of taking the precaution now \([^6]\). This may be seen as an effective mitigation policy, although it may well take more than a century for the atmosphere to begin to reach a new equilibrium, if there is one.
Energy without harm to the environment

If we are to avoid nature's solution by catastrophe, we will have to start some serious thinking about how life is lived and organised. This should go deeper than simply replacing all fossil fuels. We should study all the disciplines that enable us to live on a crowded planet, instead of lazily engaging in substitute understanding by simply accepting the consensus opinions offered by specialised committees. Generally these are not concerned to see how their different perspectives fit together as a consistent whole. It is unlikely that such consultant opinions played any part in the prehistoric decision to domesticate fire!

Today, a decision to opt for nuclear technology should be informed by evidence and education, and seen as much more clear-cut than the earlier decision in favour of fire. There is essentially no danger to a vast deployment of nuclear power to replace carbon fuels limited only by the speed with which the required education can be provided. But without the education, democratic mechanisms make starting such a major change difficult. If civilisation is not to be overwhelmed by climate change, the choice may lie between a loss of democracy for everybody and a new crash course in science for many.

We have used energy to cook food, improve diet and extend life expectancy through housing and better health. The wear and tear on the human body has been reduced by mechanised transport by water, rail, road and air. In the case of water and rail, there were many fatal accidents in the early days, but it was not until the second half of the nineteenth century that the democratic voice was raised in the name of safety. By the time that mechanised travel by road became possible, more safety was demanded in all aspects of life.

It was important that, rather than banning a new technology, the necessary education and training was provided, as earlier in the case of fire. Technology has always made some places dangerous, but we all learn not to go there, children included. Scare tactics similar to those used later for road traffic (and today for nuclear energy) were deployed by conservative groups to stop the introduction of railways as early as 1839, as shown in Illustration 18. In the case of road traffic, what actually happened in the nineteenth century is interesting. In the UK a series of restrictions was enacted culminating in the infamous Red Flag Act of 1865. This reduced the permitted pace of steam engines on the highway to walking pace, and required that a man should walk in front carrying a red flag. The *anti* lobby who pressed for legislation was concerned about accidents to pedestrians and frightening the horses, so they said.
Illustration 18: A poster of 1839. A NIMBY (Not In My Back Yard) scare about a new threat at the start of the railway era.
Later the development of the internal combustion engine and the need to compete with industries in France and Germany provided strong incentives to reconsider these restrictions. With hindsight we can see that modern prosperity with its reliance on road transport would hardly have been possible if the Act had not been repealed in 1896, even though safety concerns persist to this day. The public know that safety restrictions on their own would give insufficient protection in the event of a head-on smash. Drivers accept personal responsibility to maintain their vehicles to an agreed safety standard and stick to careful driving practices that prevent accidents.

Today, everybody accepts that as speeds are reduced, traffic accident rates fall. But there is no call for all road traffic to move at a speed *As Low As Reasonably Achievable* because that would take us back to the Red Flag Act. The case of road traffic is interesting – when it began, there was a powerful rail lobby anxious to protect their interests. Similarly today, there are large fossil-fuel interests who have no reason to object to nuclear technology being kept in check by stringent safety regulations – except, of course, in clinical use for their personal health when radiation doses, thousands of times higher, are welcomed by everybody.

If they had realised in time, the shipping companies with their luxurious ocean liners might have challenged the safety of air travel in a similar way. But they did not see the threat coming, and air travel was introduced gradually by the airlines. The romantic era of travel by sea with its ability to handle thousands of passengers must have seemed immune to a few aeroplanes with a handful of daring travellers. But, by the time the shipping companies realised that their business was threatened, it was too late.

**Externalising the power to think**

People have been much exercised by the uses and abuses of energy, but they have had less concern about the consequences of externalising their mental powers. In recent decades they have happily handed over many tasks in their amorous affair with the electronic computer. Do they feel less threatened by its power than by the power of the nucleus? Is this because society has not yet had an existential accident with computers? The protection against different forms of computer virus seem fundamentally weak when compared to the physical and biological protection against a nuclear accident. Perhaps the power of computers has seemed better hidden than nuclear power. But we may come to regret that, by spending time worrying about nuclear, we have neglected the safety of another power, our ability to think and solve problems, that once was exclusively ours, and that we increasingly sub-contract to silicon. Is this lack of vigilance just a matter of laziness, or an inability to imagine a disaster unless of a type that has already occurred?
Chapter 4: Energy to Support Life

Energy for excitement and risk
Need for fun and stimulation

The human reaction to real danger is not simply one of horror and dread. Quite the reverse: to make available the extra emotional energy to engage successfully in dangerous situations, evolution has provided a sense of excitement as a reaction to danger. It was important to the survival of early humans that this sense of excitement or courage should be a positive and enjoyable experience, without any deep rationalisation. Entertainment by excitement is a basic human need; it exercises the adrenalin reaction in readiness for a personal face-to-face encounter with real danger. Gladiatorial combats, mediaeval duels, back-street cock fighting, bull fights and boxing bouts, all these provided the ingredients of competition that excite an audience, and the greatest excitement comes in a contest between the most powerful, the champions. Safety, the protection from exposure to actual danger, has improved for almost all humanity in the past century, thanks to the application of science. Nevertheless the appetite for excitement is undiminished especially when it can be enjoyed vicariously from the reassuring safety of an armchair. Such is the nature of sport for much of the population.

Modern technology has provided the means to offer stimulating entertainment all day and every day – at its most exciting in the form of 24-hour news, for which the outcome is unknown in advance. Modern news media exist by sharing the excitement and thrill of speculation. Any suggestion that a duel has an entirely predictable outcome is a most unwelcome development for those whose business is selling stories that excite. The exciting high that news generates is not related to any desire to understand. The tsunami of the Great East Japan Earthquake of March 2011, the biggest of modern times, was shown lifting up cars, boats, ships and whole buildings, and carrying them far inland. The LPG store at Ichihara was shown destroyed and on fire. These dramatic pictures played to worldwide attention, as no other event could do, except the terrorist attack on the Twin Towers in 2001. From a bar stool with a drink amongst friends, or from a sofa with family at home, the excitement of an unfolding powerful physical on-screen event with undisclosed outcome trumps any human contest or even a historical epic, like that of Krakatoa in 1883, the largest explosion ever recorded on Earth. There is nothing logical about this reaction to danger, although it was necessary in primitive times as nature's way to make the task of coping with real danger seem both positive and welcome, when in the cool light of reality it is neither. Humans want to believe in dangers, especially if they do not affect them personally, simply to provide such excitement. This is why the world is reluctant to give up the story of Fukushima and accept that
in large part it is false.

**The effect of news**

Although an essential feature of nature, nuclear energy is frequently depicted as man-made. The accident at Chernobyl (1986) was unseen by the world, shrouded by the largest cover-up that the Soviet Union could mount in its dying days. Among earlier nuclear accidents, the Windscale fire (1957) was much smaller and largely covered up too. Three Mile Island (1977) produced no dramatic pictures for the media. The action was hidden from view, inside the reactor, the problem was contained and there was no disaster in the streets to cause excitement. But Fukushima Daiichi (2011) was different. Everyone saw the video of the reactors, apparently being overwhelmed by the wave and the explosions at the plant; the cameras pictured the abandoned streets after the evacuations and reported the panicked pronouncements of politicians, the emptying supermarket shelves, the planes filled with frightened foreigners running for home, and the men enveloped in protective suits and helmets arriving by bus. There was no shortage of fear, for the people themselves had seen the pictures; a fire-storm of reports about workers *struggling* and reactors *spewing* fed on one another, day after day. The workers certainly had a rough time, and at home their families were frightened for them; in many cases they had lost homes and relatives, missing presumed dead, in the tsunami. But soon things got even nastier for them, and their employers too, as a whirlwind of blame broke over the news reports. The supposition that in the event of an accident somebody must be at fault, and should be called to account, is an easy one to make, even when invalid. But the resources of nature available to create mayhem are unlimited and it is unreasonable to think that they cannot overwhelm any man-made defence, as the earthquake and tsunami of March 2011 did.

And something did not ring true in the extreme accounts of the nuclear accident at Fukushima Daïichi. Nature seemed to be reading from a different script. Was this a tragedy? *Hamlet* with no death? Nobody was reported to have died from radiation, but somebody should have asked why not, as the death toll remained firmly at zero. Pursuing the question and getting an answer is not difficult. In fact, technically, it is quite straightforward and simple to understand. However, the answer is unexpected to most people, for it calls into question assumptions that they have lived with all their lives. Learning new truths can be a positive experience, but it is hard to accept that what you previously thought to be true is in fact false. Here in these chapters there is sufficient explanation that the reader can decide for himself whether the tragedy that did not happen at Fukushima Daïichi was a lucky fluke or that nuclear radiation is not such a threat to life, even in an extreme case like this.
How much does this matter? Many of the problems facing mankind need energy, and surmounting misconceptions about radiation may be an important task in the early twenty-first century so we should ensure that we get a factual answer.

As for the media, they are in the business of engaging with personal excitement and encouraging the collective behaviour that leads from rumour to panic, and so selling copy. In the reporting of Fukushima they certainly succeeded in doing that. Evolution ensures that people should be alert for the
unexpected, although in their modern affluent lives this appears to happen
less often and this worries them. Today the threat of nuclear war still
speaks to the current state of the world, a voyeuristic, tourist filled
culture where catastrophe is viewed as entertainment by increasingly
desensitised masses. The iconic mushroom cloud ... serves as a
metaphor for larger societal issues such as global warming, nuclear
power, industrialisation and pollution. Issues that seemingly breed
adopted apathy, where individuals can do little but stand by and
watch.

Clay Lipsky [7]

Separating high from low risks in life

To help reach a more stable view, individuals should distinguish the
long odds on some of the risks that they worry about. For other risks
with short odds, they should react by working towards solutions, even
when the problem is global. In life everyone is a player – there are no
real parts for spectators, however excited.

In Illustration 19 many such risks are compared in terms of the average
lifetime risk for an individual. For a start, the lifetime risk of death, somehow
and at sometime, is 100%, and this is drawn as a large circle at the top with
black outline. Some risks of death are drawn as red circles with areas in
proportion; the ones in green are not risks of death but other probabilities
shown for comparison.

It is not possible to show all such risks in this way because some of the areas
would be far too small to see. So a small area of the upper circle is shown
magnified a thousand times. Within it some probabilities of death in the range
1 in a thousand to 1 in a million are shown magnified. These causes of death
in this second circle are unusual today and are compared with the chance for
three people at random being born on consecutive days in the year.

But the probability of some causes of death are less than one in a million and
their circles would not be visible, even on this expanded scale. So in the
lowest black circle of the diagram probabilities have been magnified a further
thousand times, making a magnification of a million. This is used to illustrate
that, for all the people in the world in 1945, the chance of dying from
radiation-induced cancer from the bombs at Hiroshima and Nagasaki was less
than the chance that two people at random having been born on February 29,
the leap day. The chance of being killed by radiation at a nuclear power plant
is 50 times smaller still. It is indeed hard to comprehend how small these
risks are compared to other serious hazards that beset us.

Personal experience can be used to put the significance of these numbers into
further perspective. Everybody knows someone who died of cancer or heart
disease. Perhaps you knew, personally, someone who died in childbirth. But it is unlikely that you knew someone who died in a plane accident or any of the accidents described by the smaller circles. Even the largest nuclear risk is seen to be minute compared with any of the conventional hazards shown. In fact it is partly because nuclear accidents are so very unusual and unfamiliar that they are newsworthy and carry extra dread – rationally, that is perverse.

**Energy as frightening**

Any source of energy able to replace carbon combustion has to be large and powerful to do the job – and such a powerful agent naturally overshadows any personal human effort. Such power may feel intimidating, but this primitive reaction is mistaken. It is not size and strength that determine whether an agent is dangerous; it is the relationship that we have with it, in particular whether it is understood and trusted. So we expect a flu virus to be more of a threat than an elephant, especially if we take the trouble to study the elephant and get to know it. In general people are likely to feel threatened by size and energy, whatever the technology, but it can be countered by sympathetic education if that leads to familiarity and confidence – like learning to drive a powerful car or watching others who are adept at doing so. Just imagine, if you had never been driven at speed in a car before, it would be an alarming experience.

**Safety in a natural disaster**

A mix of personal training and devolved individual judgement can be very effective in mitigating the effects of natural disasters too. The earthquake and tsunami that struck northeastern Japan on 11 March 2011 are an example. A long history of major earthquakes has ensured that Japanese building codes are rigorously enforced, and on this occasion the quake itself caused remarkably little damage. Everyone living in Japan has learnt about earthquakes and what they should do. Consequently they are calmer and more able to cope when one hits than would be the case in another country. The earthquake triggered well-practised actions by

Illustration 20: Photograph of Tsunami evacuation route instruction seen in the pavement [WWMA photo., Dec. 2013].
the population in anticipation of the tsunami and the after-shocks that followed. Such instructions of what to do are to be found everywhere in Japan – Illustration 20 shows a simple example seen in the street. At the time of the quake, there were 500,000 people in the region that was subsequently inundated [8, p. 41]. In the half-hour delay before the tsunami arrived almost everybody found their way to higher ground or another place of refuge. Schools were evacuated quickly following well-rehearsed plans. Inevitably many of those who got caught by the tsunami were the elderly who were unable to react so quickly. As of Sept 2012, 15,870 deaths were recorded with 2,184 still missing. It was an extraordinary accomplishment that 96% of those endangered by the unprecedented inundation were saved in such a short time. On previous occasions when a major tsunami had occurred in Japan, the death toll had often been higher, but experience had taught the importance of training and individual action. Such preparation is effective at giving confidence and in making relatively unusual phenomena more familiar to the population through practice and discussion.

Personal and national engagement with safety

However, when it came to the release of radioactivity the reaction was quite different: nobody knew what to do or what to expect. The danger was unfamiliar and its consequences unknown to almost the entire population. The necessary education and personal confidence were absent at all levels in society. In Japan and around the world, the collapse of confidence that ensued was in sharp contrast to the total absence of fatalities – or even serious casualties – due to the radioactivity itself. This near panic would not have happened if the population and the authorities had had a similar personally-informed awareness as they had when faced by the earthquake and tsunami.

What happened is seen by the Japanese people and their leaders as a failure of both Japanese institutions and individuals [9]. However, only the occurrence of the exceptional earthquake and tsunami were peculiar to Japan. The absence of personal confidence in radiation and all nuclear matters is an educational shortcoming that is equally serious in every country – a failure that springs from a distaste for learning about a matter that is thought unpleasant.

There is no man-made structure that cannot be overwhelmed by nature, and investing in an attempt to ensure 100% safety is a waste of resources, whether a sea wall against a tsunami or an ideal nuclear reactor. For the nuclear case it would be cheaper and more effective to invest in public education and some understanding of why nuclear technology is safe. That is what has been done so successfully over the years in Japan as protection against earthquakes and tsunamis. Regrettably, the Japanese people and their authorities have not seen how to apply this lesson to their nuclear experience.
They have joined in a blind worldwide technical rush to increase physical safety at nuclear power plants, either in anticipation of a popular loss of nerve or in the expectation that safety standards would be raised even higher.

Such work is very expensive, but does it reassure? Unfortunately, the sight of such large-scale protective measures being taken, in any context, only confirms in the public mind that there must have been a miscalculated danger in the first place. The conclusion is then reached that the public were previously inadequately protected, for which they blame the authorities. This raises the further thought – and then the rumour – that the danger might still not be adequately estimated, even after such new protection is made. The result is a lack of confidence that expands and feeds on itself. The miscalculation appears in the media with accusations of incompetence or cover-up, although that was never the cause of the problem. The real cause was a total inability to handle the public perception of what happens, or might happen in such an accident. But in Japan since 2011 there is nothing to suggest that these lessons have been understood.

Another accident similar to Fukushima is unlikely, but should one happen, there would again be no major health impact from the radiation. Any panic or significant economic impact would be caused by a failure of training and public information, unrelated to radiation safety – as in 2011. With the appropriate preparation and trust, there would be no serious consequences, as would have been true in 2011 if the Japanese authorities had only read the reports from Chernobyl and shared the information with the people in a programme of public education [10, 11]. This criticism is aimed not just at Japan but at every country that panicked. The lesson of Fukushima is universal and it has not been helpful that each nation has internalised its reaction, allowing it to become a matter for local political controversy and debate.

Education and democracy

In the usual way that history develops, the next major accident will be different from the last, so for any lessons learnt to be useful they should be seen in the broadest terms. If human life on Earth is to be sustainable for ten billion people or more with the benefits and aspirations needed for political stability, we will have to cooperate more than in the past. This will not work effectively unless individuals feel personally and democratically engaged. Future economic progress that provides stability and jobs for an increasing population depends on science and its applications, as it has since the start of the Industrial Revolution. Confidence and informed decision-making will not be forthcoming unless the science is adequately understood by sufficient of the population to engender trust. Without trust, democracy does not function effectively and society becomes unstable.
The present habit of authorities faced with scientific questions is to call upon experts to whom understanding is subcontracted – this is ineffective. It provides neither the right broad answers, nor does it build trust. Only personal understanding built on deep education and spread through the population, however thinly, can do that. Without such foundations decision-making is easily influenced by groups built around those who are simply frightened, do not understand the science or have lost confidence in the authorities. Over time such groups build up funds and staff with their own careers and mortgages. These then have a personal interest in fomenting distrust for as long as funds continue to roll in to the group.

A Babel of disciplines and conflicting interests

Education in different logical voices

The various disciplines involved in making decisions about energy and nuclear radiation are strangers to one another. They are all open to study, but in a traditional education young people are rarely brought up to establish any personal confidence in more than a few of them. This compartmentalised understanding then persists for the rest of their lives – and that is only for those few with an educational background of any relevance at all. This is an unfortunate omission in the structure of education, because these various disciplines are remarkably different and there is a need for people to understand how they relate to one another in the areas where they overlap. This is a call for an appreciation of the different perspectives of physical science, medicine, biology, social and economic science. Each may be coherent and logical in its own sphere, but reconciling them with common sense is important.

None of the disciplines is a no-go area to anyone ready to study and reach their own conclusions. Each field has its own intellectual ethos and reasons for it. But there are other more questionable pressures at work too – like the perceived need to defend jobs, career status and professional territory, to maintain budget allocations and to realise a return on previous investment.

Physical science and linearity

In the basic physical sciences the universe is portrayed as surprisingly simple. The descriptions that turn out to be correct are often symmetrical and seen to be more beautiful than the alternatives: being correct in physical science means being able to describe with a few fundamental principles and to predict, unfailingly and precisely. Admittedly there is no reason why physical science and mathematics should have such power, but as time goes on there are ever fewer situations in which they do not deliver.
Symmetry is an important paradigm in the account that physical science gives of the physical world. An inflated party balloon forms itself into a perfect sphere, and so too does a soap bubble. The material of the balloon and the film of a bubble are symmetrical and uniform. If that is not quite true, the difference in shape can be calculated from the extra rubber around the entrance pipe of the balloon or the weight of the drip of excess liquid hanging on the lowest point of the bubble. The near-perfect shape is delightful to child and scientist alike. In fact symmetry is a big subject and sometimes a curious one. Are left and right the same, only different? Similarly, forward and backward in time? What about different places or different times?

Uniqueness is another paradigm. In physical science a well-defined question usually has a single unique answer which is distinguished by its economy of expression – mathematical physicists see this as beautiful. A particular problem has just a single answer, but this is not true in biology, and in fact, uniqueness and symmetry play little part in most other disciplines. So the question is whether the same is true of every principle that is highly significant in physical science and mathematics. In particular, does linearity, an important (though not universal) principle in mathematical physics, apply in biology, in particular to the health effects of radiation?

We should explain what linearity means. For example, linearity usually applies to the way that waves behave, like the sound waves from each instrument in an orchestra. Although these are sent out into the concert hall all on top of one another, they seem to act quite separately, allowing the ear to distinguish the waves from each instrument, as if the others were not present. This is not a special ability of the ear – it applies to everything affected by the sound, unless the sound is actually distorted. When a number of causes and their respective effects add together in this way, the behaviour is linear, and then apparently complicated things become much simpler to calculate, easier to visualise and think about. It makes the physical world describable, like a structure of LEGO bricks, put together piece by piece.

But even in physical science, not everything is always so easy; there are many cases where linearity does not apply, for instance to the turbulent flow of liquids and gases where following the relationship between cause and effect is much harder. The atmosphere, and so the weather, involves such turbulent flow, and these non-linear aspects make predictions more difficult. So scientists welcome linearity when it applies. Indeed much of mathematical science is concerned with searching for ways to see behaviour in linear terms, either exactly or as a series of converging approximations which make calculations and predictions possible. But scientists need always to keep a sharp eye open for situations in which cause and effect are not related in this way. Pretending that something is linear when it is not is just wrong and can lead to dangerous misconceptions – as in the health effect of radiation doses.
**Linearity.** If a cause $X$ has an effect $x$ when applied to a system, and a cause $Y$ has an effect $y$, then what happens when causes $X$ and $Y$ are applied together, that is $X+Y$? If the effect is $x+y$, the effect is linear, and the responses to $X$ and $Y$ are independent. If the effect is anything else, the response is non-linear. Simple but very powerful, as it turns out.

Special case: If the response is linear, cause $X+X$ will give effect $x+x$; and $X+X+X$, will give effect $3x$; etc., and then the cause-effect relation is a straight line, as sketched in Illustration 21 on page 79. But it is a mistake to think that linearity is just about the dependence of an effect on its cause being described by a straight line rather than a curved one.

Suppose the occurrence of lung cancer is linearly related to its causes. If $X$ is smoking as a cause and $Y$ is radiation as a cause, then the cancer resulting from both together would be the cancer caused by smoking plus the cancer caused by radiation – that is $x+y$. But the analysis of lung cancer in populations exposed to smoking and radiation, in particular radon, the radioactive gas in the air, shows that this is not true. According to the data available, smoking on its own is about 25 times more carcinogenic than not smoking, and only in the case of smokers is there any evidence for extra carcinogenesis due to radon. So these causes of cancer are not independent, and so non-linear.

Conventional analyses of radon, smoking and lung cancer use the so-called Linear No-Threshold (LNT) model. This is a non-linear method called relative risk. The data do not show linearity and these analyses fail although they falsely conclude that radon is responsible for much lung cancer. This is discussed in more detail in Chapter 6.

Why does basic physical science so often enjoy the benefits of symmetry, uniqueness and linearity? The answer to this philosophical question is unknown. It is no answer to point out that, otherwise, the physical world would be more irrational and harder to describe. The world might indeed be inexplicable and unpredictable. In fact many in the world do not understand science and see exactly such an inexplicable world. Such people have to build confidence exclusively on a foundation of trust and belief, and that may be fragile and inflexible in the event of change. That is the reason to protect young children: their judgement and confidence lacks the stability that comes with education and experience. Without confidence the world can seem frightening. Engineering and technology are built upon the predictability of the world, and exploit it through mathematics and physical science whenever possible. Naturally, technology inherits this
logicality and simplicity, and to scientists and engineers the physical world often seems less dangerous and more predictable as a result. Therefore scientists should explain and share, as best they can, while respecting that others may doubt the confidence that physical science provides.

**Biology, medicine and the logic of evolution**

Although all of its components are simple and physical at an atomic level, life has not been designed using the principles of physical science in the way that the design of a car, bridge or electronic chip might be. It is not simple, symmetrical or unique, but is designed to survive and thrive within a certain range of conditions. Life is a product of evolution, and whenever conditions change the design gets modified too, otherwise it is liable to suffer a disadvantage. Actually, it does not get modified in the way that a computer gets updated by downloading a suitable patch: rather, it effectively modifies itself. As Darwin demonstrated, the design of each species and sub-species evolves locally to match the particular history of survival threats that it has recently experienced. This means that scientific logic, as understood in the biological and medical sciences, looks very different from that in the physical sciences. Each life form is a solution to a local problem and has no general reality at other times or places, unlike the prescriptions of physical science which apply at all times and in all places throughout the universe. The solution to a biological problem of survival, rather than being remarkable for its simplicity, as a physical science answer might be, is likely to be remarkable for its complexity.

These differences stand out strongly in a description of the effect of radiation on life. This happens in two stages: in the first, the radiation disrupts the atoms and molecules of which the living tissue is made. This is a matter for physical science and is typically linear – the initial damage is in proportion to the energy absorbed in the living tissue, as sketched in Illustration 21. The second stage is the story of how that tissue responds to the trail of broken molecules, if it is alive – this is a biological question concerned with the ability of cellular life to survive an attack. This is not at all linear, as will become clear in Chapter 8. In fact the assumption that the net effect of radiation is linear, just because the initial damage is linear, is the basic mistake responsible for the mishandling and misery of the Fukushima accident – and of Chernobyl before that. It is the crux of the message discussed in this book.
So the basis of the physical sciences and of the medical and biological sciences look sharply different for good reasons, but few scientists are familiar with both types of discipline. Consequently, physical scientists and engineers, though able to follow the physical behaviour of radiation, treat the behaviour of living tissue with great caution, it being quite unfamiliar. Most medical scientists are quite unfamiliar with quantum mechanics, where the fundamentals of nuclear physics are played out, though they are respectful of its powerful effects. In clinical medicine the priority is the well-being of the patient, and that comes before concern for the environment. Certainly clinicians are not eager to explain that the radiation dose to be used is tens or even thousands of times higher than any dose received in the environment – that might upset the patient and discourage them from accepting treatment that is clearly in their best interest. So many clinicians distance themselves from discussions of radiation doses in the environment, although they have been improving health and saving lives using moderate and high radiation doses ever since Marie Curie pioneered such work a century ago.

As a result the effect of radiation on life has been treated with unusual caution, even amongst scientists on both the physical and biological sides. This has suppressed the spread of a scientifically robust account, transparent and easy to understand for all concerned. Such an account should be written and explained. Instead, the story has appeared confused, for the political and historical reasons discussed in Chapters 9 and 10.

On the biological side, a unanimous joint report was published in 2004 by the French Académie Nationale de Médecine and Académie des Sciences [12] that...
set out a full academic case for a complete change in the regulation of radiation. However, this was written in professional language and never reached the public. As a result it has been effectively suppressed and not yet acted upon. Following the Fukushima accident, international professional opinion is pressing anew for public scientific and legal standards that accord with modern radiobiology [13].

**General public and common sense**

Most members of the public are nervous about nuclear power and radiation. They are aware that it involves a very powerful agent that they do not understand and so they suspend their common sense and confidence, thinking that they would not give them useful guidance. That is unfortunate. They are worried by the connection to nuclear weapons, but this is wrong – just as associating a log fire with the explosion of dynamite because both are chemical processes would be wrong.

Such misunderstandings have persisted for 70 years and public apprehension of nuclear technology has been exploited in international politics to apply diplomatic pressure to regimes in various ways. As the decades go by, the number of states which have sufficient resources to build a nuclear weapon but have not done so continues to rise. Weapons technology is far more demanding and expensive than civil nuclear power (access to which is internationally available), and the leaders of most countries have realised that it would be a waste of resources and valuable manpower to develop a weapon capability [SR4]. While super-powers attempt to dictate who may eat the forbidden fruit of nuclear technology, the public remain ignorant of the science and do not know whom to trust, particularly in those countries with a living memory of being on the front line, like Germany and Japan. In other countries, the public have recently understood that civil nuclear power may be a means to mitigate climate change and so they support the use of nuclear power as the least bad option. But others oppose it, remembering how much they were frightened by the threat of military and political nuclear forces at the time of the Cold War and seeing no reason to repeat that experience.

Universally, people are curious to know more and are ready to discuss the issues, preferably with someone whom they trust, even while disagreeing with them. They refer belief and disbelief in nuclear power, as if it were a religion. They seek someone to trust on the subject, while they learn to look at the evidence themselves and come up with their own judgement – at least that is the hope, and, anyway, the only sure way to build confidence. Education and trust are critical and it is noticeable how young people are more open, not having personally experienced the threat of the Cold War. But they should think it out again for themselves, and they need the opportunity for open discussion.
Parents take particular care over risks to children, and it is important and natural that they do so. However, authorities should not respond with radiation regulations that are more protective for children, unless it is shown that they are at greater risk. The question whether children are at more or less risk than adults from a given radiation dose is a biological and medical question, not a family one. If family concern, which is quite properly exercised by parents, becomes confused with the biological judgement, caution gets piled on top of caution, without limit. Such multiple caution has been responsible for children near Fukushima not being allowed outside to play in low radiation environments, when it would clearly have been in their interest to do so.

In some respects, children are more at risk than adults and in others, less. Around Chernobyl, some increase in thyroid cancer amongst children was caused by the ingestion of radioactive iodine, whilst adults were largely unaffected. On the other hand, the immune system that protects against precancerous cells is in general more vigorous in young people including children. It is older adults with their weak immune system in their declining years that are most susceptible to cancer. Cancer among young people is newsworthy because it is relatively unusual, but among the elderly it is not considered remarkable.

It does not seem appropriate that regulations should be pre-loaded with extra medical concern for children without clear evidence. Parents will show extra concern for their children anyway, as they should – but that is family care. Regulations that adopt a parental role can result in overly worried parents and overly protected children. In any case, public policy and regulations have to be built on trust which can only come with education. When this fails, as happened in Japan, children get kept in doors instead of going out to play.

**Committees that ensure caution**

Politicians have the task of matching energy with other elements of public policy to the satisfaction of the electorate and the requirements of industry. In this they may be watched over by a parliamentary committee whose numbers might include an economist and several lawyers but rarely anybody with the scientific confidence to reach their own independent judgement of the choices to be made [SR9]. They work with models of human behaviour and resources, shaped by inherited historical views and pressures from the electorate. Faced with a more challenging technical question they look elsewhere for authority and guidance from experts. If these are not available and the committee lacks confidence, an international body may be consulted.

Such a structure fails to make the required timely decisions in four respects.

- Emergency decisions may be needed in a day or two, but such
committees can take years to reach a conclusion [14, 15], even when useful and timely conclusions can be drawn in a few days from early data and some basic knowledge [SR8]. Curiously, nobody remarks on the unnecessary delay and its serious effects.

- The remit and membership of an international committee are focussed in one technical direction. They are prevented from responding to a broad crisis that stretches beyond the span of their terms of reference. For instance, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), established in 1955, is concerned with the effect of radiation itself. It is unable to respond to the social, psychological and educational consequences of the radiological regulations, as applied at Fukushima, for example. The economic and climatic effects of closing power stations and burning imported fossil fuel are beyond the committee's scope too. It was nobody's job to comment on the net response to Fukushima. That, not the effect of the radiation, was the human disaster.

- When a committee has to answer a question, the judgement of individuals, however able they may be, gets compromised by the need to reach a consensus. This averaging obstructs change, especially where members lack knowledge and confidence. The larger the committee, the greater this effect is, so a large international committee is very unlikely to recommend more than glacial change – the speed of decision is slow and each step change piecemeal. In the rare case that a committee chairman is able to overcome this tendency, then he himself would have been a better and faster source of opinion. The likelihood that such a committee would rethink a basic attitude, in this instance, towards nuclear radiation, seems regrettably small. So even with much goodwill, the guidance that politicians receive is heavily weighted to the status quo and can evolve only on a time scale of many years. Few people make this point but it can be otherwise, given leadership. The part played by Richard Feynman as a member of the Rogers Commission on the Challenger Disaster was an exceptional example [16]. The report was published five months after the accident in January 1986 with Feynman's contribution, a triumph of clear investigation in the tradition of Sherlock Holmes [17].

- Over time, a committee can become institutionalised with its own traditions and self-interest that reduce its readiness to consider change and make it slow to respond to any new challenge.

These shortcomings of expert committees act against the public interest, and
the large number concerned with radiation safety are no exception. But major change can only be expected when a sizeable fraction of the population sees that energy policy is headed in the wrong direction. The price of a successful democracy is that people should understand the decisions they make. Otherwise democracy is a loose cannon, with decisions based on random unexplored ideas. How long would it take to accomplish such an educational challenge? We have to press hard for it – there is no other way. Certainly, children and young people engage with the subject easily and discussion is very lively, though many of their teachers start with misconceptions that date from when they themselves were educated. The science is not difficult – the hard part is building trust and confidence, and, as with so many other aspects of human activity, that comes best through personal enthusiasm and face-to-face contact.

The public can show themselves to be brighter than media presentation suggests. The speed with which the ban on smoking was adopted and spread around the world gives room for hope. So too does the way in which the Japanese people have learnt to live with the dangers of earthquakes and tsunami. Given proper education and trust, they will respond, but so far this has not happened for nuclear radiation.

**Industry and its search for business**

The nuclear industry has an interest in presenting a justified view of the contribution that nuclear energy can make to future energy supplies. Unfortunately its voice is often seen by the public as compromised by an involvement in the technology that built nuclear weapons in the past, and by financial self-interest in the present. Weapon development for national defence programmes in the Cold War period was frequently hidden within projects advertised as energy production – and that has not been forgotten. Although today's power plants are designed, built, regulated and run by international, not national, concerns, most individuals in the industry feel that they have no voice and that the public at large sees their personal opinion as compromised, and so they keep silent on the main issue. In addition, although they are naturally the best informed on the physics and engineering hazards, they rarely have any knowledge at all of what modern radio-biology has to say about the health impact of ionising radiation.

Wider industrial interests, that is management and shareholders, are not concerned to question the basis of safety regulations. Their interest is to secure profitable long-term business for the investment they make, in spite of the changes to regulations and the financial restrictions imposed to fix concerns expressed by politicians and the press. To protect its financial future, industry is always ready to build or decommission whatever the market will pay for, even if the price is unacceptably high when eventually
charged to the consumer's utility bill, as it will be. The cynical politician, faced with groups of professionally organised demonstrators, may think that the impact on the consumer will be sufficiently far in the future.

Many environmentalists have engaged in some serious thinking, as expressed in books and films \(^{[18, SR6, 19]}\) and have now joined the call to expand nuclear power as soon as possible. The rump of anti-nuclear demonstrators are not well informed and prefer slogans to any discussion of medical or scientific facts \(^{[20]}\). The politicians should realise that the demonstrators are in retreat, their case being unsupported by sustainable evidence; and the media who like a debate to be two-sided should appreciate that pitching fear against science is not two-sided – it is irresponsible.

Overseeing and applying regulation of nuclear radiation safety is itself an extensive responsibility. Those who have built careers and status in this international business, with authority handed down from the United Nations, do not take kindly to studies that demonstrate this activity to be over-egged or quite unnecessary on its current scale. Naturally they resist vigorously any radical change that would upset the present structure, most of them preferring to stick with a religiously observed faith in a conservative view of safety. The cost of this safety provision is an unjustifiably heavy burden for which the consumer pays in one way or another. Those few in the safety business who have kept up to date with the science, not just the regulations, ought to be in a position to guide and contribute towards the re-education required.

**Historical view**

In retrospect, much of the development of nuclear technology was tainted by the spirit of the time. The political and military pressures of the Cold War period had a pronounced effect on the way nuclear energy was viewed and, unfortunately, that is still true today. Published papers in the best journals should be seen as trustworthy, although under exceptional conditions this may be compromised. In the period in which massive numbers of nuclear weapons were accumulated on both sides during the Cold War, some senior scientists yielded to the extreme pressure: a story that is told in Chapter 10. Their concern became the established view that nuclear radiation is injurious to health, although this is untrue. A broader historical account is given in the book by John Mueller [SR4].

**Other fauna and flora**

But there are others with whom we share the planet and whose interests should be respected. After the Chernobyl accident, it was generally supposed that with genetic changes, if not high death rates, plants and animals would be severely affected in the evacuated region around the remains of the reactor. They have been affected, but in a quite different way. They are
radioactive, but spared the human population, they seem to enjoy a new freedom \[21, SR7\]. The evacuated area around Chernobyl has become a *de facto* nature reserve with many species re-established and thriving. Evidently the wildlife is better off now, radioactive and without humans, than it was before the accident, not radioactive but hemmed in by humans. There are two lessons here: firstly that the human race has monopolised the planet at the expense of other forms of life; secondly, that the prevailing view that nuclear radiation as deadly is simply wrong. This is surprising: Chapters 5 and 6 provide more insight into the nature of radiation and further evidence of its effect on life; Chapters 7 and 8 explain the science that protects life from radiation.

**Notes on Chapter 4**

4) note deleted  
6) By the same criteria the application of the Precautionary Principle to nuclear technology is unjustified: nuclear technology is understood and mature, and the downside of not using nuclear endangers the environment and the capacity of the Earth to support its growing population.  
8) Lessons from the Disaster Y Funabashi et al, Japan Times (2011)  
13) Correspondence and articles posted by Scientist for Accurate Radiation Information (SARI) [http://www.radiationeffects.org](http://www.radiationeffects.org) See also Chapter 12.  
15) UNSCEAR report on Fukushima (2013)  

16) Rogers Commission on the Challenger Disaster (1986)  

17) Feynman's analysis of the Challenger Disaster (1986)  
http://science.ksc.nasa.gov/shuttle/missions/51-l/docs/rogers-commission/Appendix-F.txt

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19) Environmental and other academic support for German nuclear power (2014)  
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20) A video that challenges Helen Caldicott, McDowell (2014)  
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21) National Geographic on tourism at Chernobyl (2014)  
http://ngm.nationalgeographic.com/2014/10/nuclear-tourism/johnson-text
Chapter 5: Absorbed Radiation and Damage

Be less curious about people and more curious about ideas

Marie Curie

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**Sources of ionising radiation**

The discovery of radioactivity

When in 1896 Henri Becquerel discovered radioactivity by the radiation it emits, what did he actually observe? He had been looking for radiation emitted by crystals of different salts after exposure to sunlight – called fluorescence. He took a photographic plate, wrapped it in thick black paper and placed it underneath a pierced metal screen with the salts on top. On 26th February and the following days the sun did not shine so he abandoned the experiment and put the plate and salts away together in a dark drawer. On 1st March he developed the plate expecting to find no more than the faintest silhouette of the screen on the plate. What he found were very strong images of the screen, as he reported on the following day. Evidently the sunshine played no part so it could not be the result of fluorescence. Somehow the salts were emitting rays that had an effect on the photographic plate like X-rays, but normal X-rays need a source, an elaborate apparatus supplied with electrical energy. Since there was none he described the salts as the source of radioactivity. Whenever energy seems to appear or disappear without apparent cause, physical scientists get excited. Something quite new must be occurring, and indeed this was the case.

To anyone not already familiar with it, radiation may seem as mysterious today as it was to Becquerel all those years ago, but now we know that it is more a part of everyday experience than was realised. The word *radiation* covers any kind of energy on the move, often spreading out from a small region where it starts, that we call its source. It could be a sound wave from a musical instrument or someone speaking; or a radio wave transmitted by a mobile phone; or a water wave from a moving boat. These may seem relatively innocuous, but that depends on how big the various waves are. A tsunami wave whose source is the sudden movement of an area of ocean floor is just a water wave, but sufficiently large to be damaging, especially when it reaches the shore. Similarly, sound waves can be so energetic that they break when they reach human tissue – like water waves on a beach, dumping all their energy. Such sound waves at high frequency can be used to break kidney stones and to treat cancer tumours. So weak waves are harmless and strong waves of whatever the kind are damaging.

**Charged particle and electromagnetic radiation**

However, the radiation that Becquerel detected, often described as *ionising* or *nuclear*, is neither a sound wave nor a water wave. Three varieties of these waves are to be found in the environment, called alpha, beta and gamma. Alpha and beta are streams of charged particles: for alpha the particles are helium nuclei, helium is the gas used in party balloons to make them float
upwards; for beta the particles are fast electrons. The third variety, gamma, is an electromagnetic wave (EM) exactly like light, only more energetic. But that description is a bit sloppy, because for all radiation, including light, surprisingly, the stream of energy is built up in two ways: the number of bits of energy and the energy of each bit. For alpha, this is the number of helium nuclei and the energy each carries. Likewise for beta, there is the number of electrons and the energy of each electron based on its speed (its kinetic energy). Light and gamma radiation are similar; each bit is called a photon, or a quantum (after the Latin for how much). So there is the energy of each quantum and the total energy of these, added up. How the light behaves, including its colour, depends on the quantum energy. A quantum of red light is half the energy of a quantum of blue light, whereas a quantum of X-ray is more than a thousand times greater – and of gamma rays even more. The total energy gives the brightness. This is a little like the energy of a river that depends on how much water is flowing and also how fast it flows.

Radiation is called ionising if each individual photon or charged particle has enough energy on its own to break or ionise a molecule when it hits it. This does not depend on the total brightness, only on the energy of each photon or electron. Einstein's paper of 1905 gave this explanation using the quantum theory of light, for which he received the Nobel Prize in 1921. Note that this quantum theory is over a hundred years old and thoroughly established, despite often being described in popular media accounts as if it were mysterious and controversial.

**Radioactivity as a source of radiation**

The radiation that we just described, like X-rays or light rays, is delivered in an instant at the velocity of light and effectively travels in straight lines. It is transitory, passing through and only leaving a persistent effect if it dumps energy at some point. When it does so, it leaves damaged atoms and molecules, and these are what we need to study – it is this damage alone that can affect life. Radiation that passes through a body without dumping any energy is harmless.

The vague term radiation as used in popular media often confuses the radiation itself and radioactivity. Radioactivity refers to atoms liable to emit radiation, like those in Becquerel's salts. An unstable radioactive atom is almost indistinguishable from a regular quiescent one, except that it emits radiation just once at some random point in time – after that, it has lost its energy and cannot emit that radiation energy again. This randomness in time may appear to suggest that something is unknown. But this is a general feature of modern physics, known as quantum mechanics, that tells us very precisely the probability of decay per second, but not the time when an individual nucleus will decay. Each nucleus decays, emitting radiation in the
process and leaving behind a different daughter nucleus (this is often stable but in some cases may be radioactive in its own right). Because each unstable nucleus carries the extra energy to decay once, in a collection of atoms at a given time the number of nuclei available to decay includes only those that have not already decayed. In this way the number decaying falls progressively giving the famous exponential decay curve. The half life is the time for half of the atoms to decay, so after three half-lives only an eighth remain, and after ten half-lives only a thousandth remain (1/1024, to be precise), and so on.

**Carbon-14 – an example of radioactivity**

An example of radioactivity is radiocarbon, that is carbon-14. Most carbon atoms are carbon-12, and carbon-14 behaves identically in all but two respects. Firstly it has two extra neutrons in its nucleus so that it is heavier in the ratio 14:12, but this has little effect. Secondly it decays randomly at a steady rate, such that half the nuclei turn into nitrogen-14 in a period of 5,700 years.

Every year a tiny amount of fresh carbon-14 is produced by cosmic particles hitting the upper atmosphere, and this gets mixed in with normal non-radioactive carbon, so that every growing or living thing has about one carbon-14 atom for every $10^{12}$ carbon-12 atoms – but coal and oil do not, because having been buried for many millions of years all carbon-14 nuclei have decayed long ago. As soon as living things die, they stop eating or growing and their proportion of carbon-14 starts to fall. In fact, we can measure how old they are from how much carbon-14 remains, and this is how radiocarbon dating works. It was used to measure the age of the Turin Shroud that supposedly dated from the time of Christ, but was shown to be much younger (1275-1290 AD) \(^1\); then there is the record of the Ice Man frozen in an alpine glacier for 4,000 years \(^2\); carbon dating can also be used to spot fake vintage wines and whiskeys, if the contribution from nuclear testing, described in Chapter 10, is taken into account \(^3\).

If you are not measurably radioactive because of the carbon-14 you contain, any archaeologist can assure you that you have been dead for over 50,000 years. To that extent, it is healthy to be radioactive and certainly nothing to worry about. So we may calculate how radioactive each of us is.
Call it roughly 50 becquerel per kg – a becquerel (Bq) is a measure of radioactivity equal to one decay per second. So 50 decays per second for each kg of weight – that would be about 3,500 clicks per second on a counter, if that were able to detect every single emission of radiation in your body (taken as 70 kg). Actually the beta radiation from carbon-14 decay is an electron with very short range, so very few would reach the instrument and few clicks would be measured.

**Potassium-40 and tritium**

There is another source of radioactivity within everyone's body, potassium-40, which emits radiation with higher energy that goes further and is easier to detect. What this radioactivity is doing in your body is an older story that we will come back to later in this chapter. This adds another 61 Bq per kg making a total of about 7,400 Bq in an adult body, meaning 7,400 nuclear disintegrations per second. But this cannot be dangerous because it has been so since life began. The point is that radioactivity is just a latent source of radiation – radiation with delayed delivery spread out over a period of time. Is it more hazardous for being delayed, or less so? As we shall find in Chapter 6, it is actually less so.

Tritium is a radioactive isotope that has been in the news from Fukushima. It is an isotope of hydrogen with two neutrons that would normally be called hydrogen-3, but has acquired a special name of its own. However, until it decays, it behaves exactly like the other isotopes of hydrogen, including deuterium or hydrogen-2, except that it is heavier and so more sluggish in its normal reactions. Concern about tritium has formed part of the media story at Fukushima. As it happens, tritium is a product, both of the nuclear fission process itself and of hydrogen (in water) catching extra neutrons, although neither process can occur in a reactor that is turned off. How hazardous is a dose of tritium? (The measurement of doses in milligray (mGy) is described below on page 97.) The effect of a radiation dose rate in mGy per month to tissue depends rather little on the source of the radiation (except that alpha is somewhat more damaging than beta or gamma). As Table 2 on page 101 reveals, tritium emits beta radiation for which the energy in each decay is a **hundred times smaller** than for caesium-137 and **ten times smaller** than for carbon-14 [\(^4\)]. So it takes a hundred times as much activity of tritium as

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| The human body is more than 50% water and roughly half of the rest is carbon. The number of ordinary carbon atoms per kg in your body is 1,000(g in a kg)× 6×10\(^{23}\) (atoms in 12g of carbon)× 0.25/ 12 = 1.6×10\(^{25}\). Of these only 10\(^{-12}\) is carbon-14, so the number of carbon-14 is 1.6×10\(^{13}\). On average they decay in 5,700× 3.1×10\(^7\) (sec per year)/ ln2 = 2.5×10\(^{11}\) sec. So the number decaying per second per kg is 1.6×10\(^{13}\)/2.5×10\(^{11}\) = 64 decays per second per kg. = 64 Bq per kg. |

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caesium-137 (in Bq) to deliver the same radiation dose rate (in mGy per month). Since it is difficult to discern the health effect of caesium-137 (as will be shown in Chapter 6), it is even harder to discern the effect of tritium on health.

**Atomic analogues**

In many ways a proton or neutron bouncing back and forth inside a nucleus behaves in a similar way to an electron doing the same inside an atom, except that the numbers are rather different. Many of the everyday changes that happen around us – light and electronics, electrical and chemical changes, and so on, concern the behaviour of electrons and atoms. So familiarity with how atoms behave gives a window by which we can appreciate some of the actions in which nuclei get involved, but with greater energy.

When the nucleus of an atom decays, it emits ionising radiation, either as a charged particle or a photon. It is the difference in energy between the nucleus before and after that provides the energy for the photon or the particle. This is not an arcane process peculiar to nuclear physics; it is exactly parallel to what happens in a chemical reaction or light emission by electrons in the outer parts of atoms. Such emission of light is seen, for instance, in a flame or a street light. So the yellow light emitted by each atom in a sodium street lamp has a quantum energy – a photon energy – equal to the difference in energy between two states in a sodium atom. Simple experiments in a student laboratory show that atoms in the higher energy state decay to the more stable state with a half life of about $10^{-8}$ seconds. In a normal discharge lamp the electricity supply then provides enough energy to kick the atom back up into its unstable state so that the process repeats and the lamp keeps shining. In a filament lamp or flame it is the heat that re-supplies the energy to the atoms that emit the light. The characteristic colour of a sodium or neon advertising sign relates to the quantum energy; a mercury light involves several unstable states that then give a mixture of photon energies that appears whiter. In fact any material hot enough for its atoms to get kicked into higher states will emit photons in this way, and this is why hot bodies shine. The hotter they are, the more energetic the photons they emit, and the more photons they emit, too. So, while the dull embers of a dying fire are a pale red, the surface of the Sun, being much hotter, is much brighter and includes yellow and blue too, making a brilliant white with all the colours of the rainbow. The surface of some stars is even hotter still and they shine blue or even violet.

These are examples of the radiation spectrum, whose peak colour rises with temperature and whose overall brightness increases with the fourth power of the temperature. This was first explained by Max Planck in 1900 when he introduced the first revolutionary idea that grew in the 1920s into the
understanding of the physical world that today we call quantum mechanics or quantum theory.

**Calling it quantum theory may give the wrong impression to a general reader. In physical science the word *theory* does not describe some speculative idea, as it often does in everyday speech, but a quantitative understanding that may be used to make accurate mathematical calculations for what occurs. The account of atoms and light given by quantum theory has not changed since the late 1920s and its extension to nuclei was clear by the late 1930s – and the details had been filled in by the 1950s. There is nothing speculative about today's understanding of nuclear physics – and that includes the numerical value of quantities.**

This is a suitable point at which to mention how energies are measured. In the everyday world, energy is measured in joules (J), so that, for example, one watt (W) is a power (or energy rate) of one joule per second.

**However, these units are inconveniently large to describe the behaviour of a single atom or nucleus. Atomic energies (for each atom) are measured in electron-volts (eV), where 1 eV is the energy gained by an electron accelerated by 1 volt. Then 1 eV = 1.6×10^{-19} joules because that is the electric charge of an electron. So that a 60,000 volt gun in an X-ray tube produces electrons of 60,000 eV. Nuclear energies, being typically a million times greater than atomic energies, are measure in MeV, where 1 MeV = 1.6×10^{-13} joules. This is still tiny on our every-day scale, but enormous at the scale of a single atom.**

**The electromagnetic spectrum**

The photons and particles, the radiation emitted in nuclear decay, are indistinguishable in principle from those involved in the everyday physics of electrons in the outer part of atoms. The only identity tags that they carry are their energy and type. So the photons emitted in nuclear decay, sometimes called gamma rays, are absolutely identical to those emitted by electrons that have been accelerated from a heated cathode in an electron gun, such as used to produce radiation in a dental clinic and usually called X-rays. In clinical medicine, patients who express concern about radiation are occasionally told that the radiation used in Computed Tomography (CT) scans or in modern cancer therapy does not come from nuclei. This may indeed be true, but it is a bogus argument because there is no distinction based on the source. The descriptions *X-ray* and *gamma ray* are used more meaningfully to refer to photons of lower and higher energy with a conventional change of name at around about 100 keV, regardless of their origin.
Chapter 5: Absorbed Radiation and Damage

The spectrum of photons extends from gamma rays of the highest quantum energy and highest frequency (and wavelength much smaller than nuclear size) down to very low-frequency radio waves (and wavelength exceeding a km). This is shown schematically in Illustration 22. In the centre is the spectrum of light with its explicit rainbow in a narrow band. At wavelengths a bit longer (to the right) there is the infrared range; here, radiation is absorbed readily because it matches the natural rotation and vibration frequencies of molecules. At wavelengths just shorter than visible light is the ultraviolet range where materials absorb radiation strongly at the frequencies with which electrons vibrate in atoms. In between is the optical region, the light we can see; this is the fortunate range for which the energy emitted from the Sun's surface is maximum and also where many materials are transparent. It is no coincidence that this is the only range for which our eyes have evolved some sensitivity.

In the infrared to radio ranges, one photon by itself does not have enough energy to ionise a molecule, and in this range radiation is called non-ionising. Such radiation can only cause damage to atoms and molecules by heating them as a whole through the cumulative absorption of very many photons. However, if the total absorbed energy is high enough – as in a microwave oven – the material will start to get hot and then cook, if it is biological. Similarly, radiation from a mobile phone will warms tissue a little – not much, however, because most of the radiation passes straight through. Non-ionising radiation is harmless because the painful sensation of heat tells you to move out of the hottest sunshine, or take your feet away from the fire. If you cannot feel the heat it creates, it is quite safe. Public worry about the safety of non-ionising radiation only began recently when someone noticed
the word *radiation*!

**Linearity and its applicability**

**Initial radiation damage**

In the ionising region of the photon spectrum, that is on the left in Illustration 22, two significant changes are evident. Firstly, to the left of the UV absorption region, materials become increasingly transparent, meaning that radiation can penetrate deep into living tissue before being absorbed, and even pass right through and out the other side. This is the essential advantage that X-rays and gamma rays can offer to medicine, and that allows imaging and cancer therapy within the body without invasive surgery and its traumatic effects. The second difference is another consequence of quantum mechanics, noted by Einstein in his work on the photoelectric effect in 1905. The energy of the radiation when it is absorbed is not smoothly spread through the material, but is delivered as a series of distinct *events* (often called *collisions*), each such event being the absorption of a single photon. The initial damage at the site of an event depends on the energy of the single absorbed photon and whether it can ionise or break a molecule, not on the brightness of the total radiation flux. As a result, ionising radiation, including UV, can damage materials at lower energy fluxes than non-ionising radiation, and it does so without raising the temperature. This piecemeal action means that the effect of each photon is separate. The total damage to the material is proportional to the number of photons and quite independent of whether the photons all arrive at once as an acute dose or are spread out in time over an extended period of hours, months or even years. The total damage is also the same if the same radiation is spread out in space over a whole body or concentrated into a small spot: also, if spread over many people or all concentrated on one person.

This implies that the effect of radiation is linear because each photon acts independently. So the combined effect of a thousand photons is a thousand times the effect of just one. This is precisely the condition for linearity discussed in Chapter 4. It means that the immediate damage caused by radiation is linearly related to the total absorbed radiation energy, and there is no intensity of radiation so low that there is no such damage. And this conclusion is true for all materials, whether alive or dead.

**LNT model of long-term damage**

The assumption that this simple picture applies even to the resulting long-term radiation damage to living tissue is called the Linear No-Threshold (LNT) model. Looking at this model, why it is wrong and the evidence that confirms it is wrong, is a major objective of this book. Here is a brief
Summary of the justification for the LNT model:

The energy of radiation is deposited in an irradiated material as a series of essentially separate collisions. Therefore the net damage done to the structure of the material can be assessed by just adding up the energy of those separate collisions. Further, since there is no minimum total energy flux for a collision to occur, there is no threshold for damage and any radiation flux, however weak, incurs damage. (The contrary would be the case if, for example, damage only began when the temperature of the material was raised to some threshold.) In the cells of living tissue the significant damage is genetic damage to the structure of DNA. Such radiation-induced damage may be passed down to successive generations when the DNA is copied.

If this description were complete, a significant implication for society would then follow:

Nobody should countenance leaving such a genetic legacy. Therefore all ionising radiation exposure should be reduced to a level As Low As Reasonably Achievable (ALARA) and the use of any technology using ionising radiation, including nuclear energy, should be avoided wherever possible.

It might be asked:

How could such a picture based on the simple concept that was confirmed by Einstein with his Nobel Prize winning explanation of the photoelectric effect, actually be wrong?

Nevertheless, we shall show evidence that it is wrong, and pinpoint how this mistake occurred. This historical tale is recounted in Chapter 10.

**Failure of LNT model for live tissue**

The basic error is in thinking that any initial damage persists in the longer term, as indeed it would in dead or passive material – in other words, material not actively maintained by biological mechanisms. The LNT model ignores how biological life reacts to damage following a radiation dose. In this discussion we need to understand the effect of this biological reaction, how it works in principle, why it evolved and the evidence that confirms that its effectiveness is not the exception but the rule.

To make sense of the evidence, we shall need to quantify the energy of radiation doses, so that we can compare them for different practical situations. In traditional descriptions of radiation doses and their safety, the LNT model is already taken for granted. Since the evidence will show unequivocally that the LNT model is mistaken in its picture of biological radiation damage, we must take great care not to follow the LNT description
of radiation damage. This means that the next section matches only part of what is to be found in traditional radiation safety handbooks.

**Quantifying absorbed radiation**

**Radiation doses and radiation dose rates**

Radiation that passes straight through the body is harmless. It is only the energy that is stopped and absorbed that can do any damage, and that is what we need to discuss. Quantitative measurements allow comparison of doses in different situations. They enable meaning to be given to the scale of doses otherwise described simply as high or very high. Such comparisons bring some interesting surprises, for instance, the rate of energy in an ionising radiation exposure and the power from a simple light bulb, or between environmental and medical doses of radiation.

For the high doses used in cancer therapy, the precise dose delivered to the patient is important and mistakes of a few percent in the delivery can have consequences for the success of the treatment or even the survival of the patient. However, at lower doses the need is to note and understand the factors of ten involved – factors of two or three are not usually of practical importance for safety [5].

Energy is a well-defined quantity like mass, distance and time. An electricity meter charges you for measured energy in joules (J), with 1 Unit = 3.6 million J, so a joule is small in everyday terms. Actually the utility meter measures power, that is energy rate, in joules per second and then accumulates the total joules over time. One joule per second is called a watt (W, named after James Watt, the eighteenth century Scottish inventor). Radiation dose is a measure of the energy absorbed in each kg of tissue – so we have dose in joules per kg, and dose rate in watts per kg. A dose of one joule per kg is called a gray (Gy, named after Louis Harold Gray). Medical doses are often quoted in cGy (1 cGy = 1/100 Gy = 1 rad, an older unit); environmental doses are conveniently given in mGy (1/1000 Gy). These definitions and measurements are unaffected by whether LNT is assumed and that is why we use them here.

For radiation safety what is really of interest is how much harm the absorbed energy causes to living tissue. Can we use the absorbed energy as a surrogate for the biological damage? It will do if we assume that they are directly linked, won't it? As the evidence will show, it will not.

We may think of the scoring in a tennis championship as a parallel. Over the years, to identify the champion beyond reasonable doubt, a scoring scheme has evolved that works very effectively, more so than in many other sports,
perhaps. The result is exciting and competitive, but, notably, during a match all of the smaller points within a game are discarded. An LNT-like view of tennis might advocate selecting the champion by simply adding up all the points played and treating that as a surrogate for each player's ability. If that made for the most effective type of tournament, no doubt that would have been chosen years ago. But that did not happen, probably because it would miss the rise and fall of psychological tension that goes with the more structured scoring scheme. The evidence provides the answer, not an appeal to theoretical simplicity.

In the case of radiation, what kind of harm matters? Much of the damage to the contents of cells in irradiated tissue is of no lasting consequence, as most molecules are replaced regularly as part of the cell cycle. But damage to the DNA is different because it controls the copying process itself – it is the master record for the cell, coordinates its function and itself gets copied in the cell cycle, thereby potentially propagating damage to subsequent cell copies, even creating a flaw that could be passed to subsequent generations. However, this is a theoretical possibility that is only important if it happens – it is a matter for evidence to tell whether damage is actually propagated in this way.

The main question is how the biological damage is related to the energy absorbed. The LNT assumption is that damage is directly proportional to the dose. In the LNT model, after making some modest but poorly defined adjustments for the rate, tissue and type of radiation, the energy dose itself is taken as a surrogate for damage, but given the fresh name of sievert (Sv) instead of gray (Gy). But as will become evident in succeeding chapters, this is not a measure of the damage that we should expect for an active material like living tissue on the basis of modern biology. Nor does it match what is observed in the natural environment, a patient clinic, an animal laboratory experiment, or the casualties from an accident with radioactivity.

In the LNT model biological damage in sievert (or millisievert, mSv) is not measured but the result of applying assumptions. Without these the sievert is not meaningful. Within LNT the linear relation between Sv and Gy is assumed to be a simple numerical equality for beta, gamma and high-energy X-rays. Of radiation types frequently found in the environment only alpha is much different; it is assumed to deliver 20 times as much damage – that is each Gy of absorbed energy (per kg) gives 20 Sv of damage (per kg). Neutron and proton radiation have been assigned similar weighting factors too, but neither of these is often found outside a research laboratory or the core of a working reactor, so we ignore them here for simplicity.
Considerations that might complicate the simple relation between energy absorbed and final biological damage are ignored in the LNT model. In particular the possibility that patterns of deposited energy overlapping in space or time might influence the final outcome are excluded – incorrectly as evidence shows. In the LNT model a dose spread out chronically over the life of an individual is reckoned to be as damaging as a single acute dose of the same integrated energy received in days or hours within a small factor of about two. (In LNT this factor is called DDREF. If LNT does not apply, DDREF has no meaning.)

By a simple extension of linearity, the LNT model would imply a dose dispersed among many individuals is as damaging as the same total dose given to one individual. This would be administratively convenient, if true, because the total damage could be assessed simply from the dose added up for a population, an estimate called the collective dose.

The evidence will show that what reflects the biological damage more than the total absorbed energy is the rate at which energy is locally absorbed, that is the dose rate. This may be measured in mGy per month, for example. Obviously, reckoned in mGy per year the number would be 12 times larger, and in mGy per second, correspondingly much smaller. However, the use of an arbitrary period makes no sense. The important choice of time period is one to be made with data.

So what is the reason to choose a repair time of a month? This interval was discussed in Radiation and Reason, Chapter 7 [see Selected References on page 283, SR3]. Essentially it is the biological recovery time and so covers a range of values roughly spanning the typical cell cycle time and leading to a month as a conservative choice for safety purposes.

**Measurement of radioactivity in becquerel**

The dose rate that comes from a radioactive source depends on the activity of that source, and with some assumptions we can relate these two. Radioactivity is measured in becquerel – 1 Bq is one radioactive decay per second. This is a very low rate indeed, and the energy released by each decay is minute. Significant rates may be measured in thousands (kBq), millions (MBq) or even millions of millions (TBq) of decays per second. A technical point is that Bq refers to the total decay rate – to get the rate per kg the number of Bq needs to be divided by the weight in kg. But notice that Bq is already a decay rate per second, so it does not need to be divided by the exposure time. The energy dose in mGy is the other way around – it is defined as the dose per kg, but to get a dose rate it must still be divided by the dose delivery or exposure time. So an annual dose, reckoned in J per kg
(or Gy) received over a whole year, has to be divided by 31 million – the number of seconds in a year – to get the dose rate in Gy per second, the same as watts per kg. It is a matter for the evidence, not pre-conceptions, to decide whether it is the dose or the dose rate that is more significant, and it certainly makes a lot of difference: a difference that is frequently glossed over.

**Finding a dose rate from a measurement of radioactivity**

Sometimes the radiation dose received is caused by radioactivity within the body. In that case it is relatively simple to calculate the dose from the radioactivity, or vice versa, by assuming that all of the radiation emitted in the decay is absorbed. With this assumption the dose may be overestimated somewhat. For alpha all of the radiation is absorbed, but for beta about half the released energy escapes as invisible neutrino radiation, and for gamma a fair fraction may escape the body too.

When it decays, a nucleus releases a small amount of energy, call it \( E \). In principle, to get the dose from the decay rate, we add up the energy of all these decays. The number of decays is the rate in Bq multiplied by the number of seconds for which the dose is accumulated. To find the dose, we multiply this number of decays by \( E \) and divide by the weight in kg.

The energy \( E \) of each radioactive decay, expressed in joules, is a very small number, even for a nuclear decay. Nuclei differ but most of the energies fall within a modest range. Table 2 shows the energy for some of the more important decay energies: these are clustered around \( 1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J} \). (This number is simply a million times the electric charge of an electron.) So, assuming that all the energy is absorbed, the conversion from radioactivity (Bq) to dose rate (mGy/month) goes like this:

\[
\text{dose rate (mGy/month) = radioactivity(Bq) } \times \frac{E(\text{MeV}) \times 1.6 \times 10^{-13} (\text{J/MeV}) \times 2.6 \times 10^6 (\text{secs/month}) \times 10^3 (\text{mGy/Gy})}{70 (\text{mass of an adult in kg})}.
\]

As examples, we apply this calculation to the natural radioactivity in any human body, and then to the ingestion of contaminated water and food at Fukushima. Such calculations are not exact but they give answers, often correct to a factor two to four, and sufficient to show what is safe.
<table>
<thead>
<tr>
<th>Decay</th>
<th>Energy, MeV</th>
<th>Main decay type</th>
<th>Radioactive half life, sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium, H-3</td>
<td>0.018</td>
<td>beta</td>
<td>$3.9\times10^8$ or 12 yrs</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>0.16</td>
<td>beta</td>
<td>$1.8\times10^{11}$ or 58,000 yrs</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>1.32</td>
<td>beta, gamma</td>
<td>$4.1\times10^6$ or $1.3\times10^9$ yrs</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>1.17 + 1.33</td>
<td>beta, gamma</td>
<td>$1.6\times10^8$ or 5.3 yrs</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>0.54 + 2.28</td>
<td>beta</td>
<td>$8.8\times10^8$ or 28 yrs</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>0.97</td>
<td>beta</td>
<td>$6.9\times10^8$ or 8 yrs</td>
</tr>
<tr>
<td>Caesium-134</td>
<td>2.0</td>
<td>beta, gamma</td>
<td>$6.6\times10^7$ or 2.0 yrs</td>
</tr>
<tr>
<td>Caesium-137</td>
<td>1.18</td>
<td>beta</td>
<td>$9.5\times10^8$ or 30 yrs</td>
</tr>
<tr>
<td>Polonium-210</td>
<td>5.3</td>
<td>alpha</td>
<td>$1.2\times10^7$ or 0.39 yrs</td>
</tr>
<tr>
<td>Radon-222</td>
<td>5.5 + 6.0 + 7.7</td>
<td>alpha</td>
<td>$3.3\times10^5$ or 0.01 yrs</td>
</tr>
<tr>
<td>Radium-226</td>
<td>4.8</td>
<td>alpha</td>
<td>$5\times10^{10}$ or 1600 yrs</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>4.0</td>
<td>alpha</td>
<td>$4.5\times10^{17}$ or $1.4\times10^{10}$ yrs</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>4.27</td>
<td>alpha</td>
<td>$1.4\times10^{17}$ or $4.5\times10^9$ yrs</td>
</tr>
<tr>
<td>Plutonium-239</td>
<td>5.24</td>
<td>alpha</td>
<td>$7.7\times10^{11}$ or 25,000 yrs</td>
</tr>
</tbody>
</table>

*Table 2: Some frequently discussed radioactive isotopes. Where several energies are given, these are sequential decays to be added.*

In most cases of contamination, radioactivity gets distributed throughout the body and the radiation energy is then further spread out by the smudging effect of its range – the dose is not absorbed where the radioactivity was. This spreading is true for the important cases of potassium-40, caesium-137, tritium and carbon-14. Some radioactive elements accumulate in bone – strontium-90, radium-226, plutonium-239 and other metals – but that still gives rise to a widely spread distribution of absorbed energy. Radon is a gas and its radioactive decay products get caught in lung tissue. Iodine too is a special case because it is concentrated only by the thyroid gland and then decays with a half life of only a week, resulting in a concentrated acute dose.

As evidence will show later, it is the dose rate that matters to health, much more than the accumulated dose. The length of time for which the flow of radiation persists depends both on the half life of the radioactivity and on the rate at which the radioactivity is expelled from the body, sometimes called the biological half life [6]. If the biological half life is shorter, it will be more important than the radioactive half life given in Table 2. Such depletion is
important for both caesium isotopes shown in Table 2, which have a biological half life of about 100 days, but somewhat less for children who are thus at less risk than adults. This depletion does not apply to potassium-40 because it occurs naturally in the body and persists indefinitely.

If the radioactive source is outside the body altogether, the fraction absorbed is very much lower. Then, most radiation does not enter the body at all and exposure is easily reduced by simply moving away or reducing the time for which radiation is absorbed. Unless the source is very close, the radiation dose to the body falls with the inverse square of the distance. So, for instance, by moving three times further away from the source, the radiation dose is reduced by a factor of nine.

Illustration 23: A diagram of the average annual radiation dose to the UK population, total 1.4 mGy per year. Based on data for 2005.

### Natural internal dose

The natural internal radioactivity in the body is about 7,400 Bq. This is mostly due to potassium-40 and carbon-14, as used in radiocarbon dating. However, as shown in Table 2, the latter contributes a very small decay energy of less than 0.2 MeV, so that potassium-40 dominates the dose.

We calculate the annual dose that the natural activity of 4,300 Bq potassium-40 gives to a 70 kg man:

\[
4,300 \text{(Bq)} \times 3.1 \times 10^7 \text{(sec/year)} \times 1.32 \text{(MeV energy per decay)} \times 1.6 \times 10^{-13} \text{(J/MeV)} \times 1,000 \text{(mGy/Gy)} / 70 \text{(kg per adult)} = 0.4 \text{ mGy/yr.}
\]
This is an over-estimate because not all the beta-decay energy is absorbed (the neutrino escapes altogether). A better calculation would give an answer just less than 0.3 mGy/yr. This dose rate from internal activity is the same for everybody everywhere, and Illustration 23 shows that it accounts for about 18% of the average background dose rate of 1.4 mGy per year.

Note: the numbers in Illustration 23 look a little different from those normally quoted. That is because they are shown in mGy, instead of mSv. In mSv according to the LNT model, the contribution from radon is weighted by a factor of 20 as an alpha emitter. This factor has been removed, and so radon no longer dominates the average background and the quoted doses in mGy.

Other sources of natural background radiation

Other contributions to this average background shown in Illustration 17 are more variable. For example, the cosmic flux is partially shielded nearer to the equator by the Earth's magnetic field, but increases by about three times at the Earth's magnetic poles. It also rises with height by a factor of ten at 35,000 feet. This is caused by the primary cosmic flux from space generating secondary radiation showers at the top of the atmosphere that are absorbed by the denser atmosphere at lower altitudes.

Today a significant contribution to the average annual dose comes from medical procedures. Such doses have been rising yearly as more effective use is made of radiation for diagnostic imaging. This dose is a very long way indeed from being a genuine cause for concern – some two or three whole-body scans per week, every week, for 4 or 5 years would be needed before any negative health effect might become evident. But we return to this question in Chapters 8 and 9 because it is seen to be a source of popular concern.

Illustration 23 shows that a major contribution to the annual background radiation dose comes from gamma radiation and the ingestion of radon, both of which emanate from rock, water and soil, and are therefore dependent on the local geology which is very variable. Interestingly, some of the lowest annual doses are experienced by the crews of nuclear submarines, who are particularly well shielded by the ocean water from cosmic radiation and emissions from geological rocks. Some of the highest are experienced on high-altitude trans-polar flights, such as those taken by many who fled from Japan for Europe and the USA in March 2011. Indeed, on one occasion in 2013 on my way to Japan I omitted to turn off my own radiation monitor and it bleeped an alarm above 25,000 feet, albeit at an irrelevantly low radiation level. For some moments I thought my phone was ringing! Thankfully, nobody on the plane took any notice anyway.
Food regulations at Fukushima and Chernobyl

On 29 July 2011 the Japanese government published regulations that set the level of radioactive caesium in meat, above which it should be treated as contaminated, at 500 Bq per kg [7]. In April 2012 and April 2013, as a result of public concern, the level was tightened further to 100 Bq per kg [8]. What dose would someone receive if they regularly ate meat contaminated at this level?

The first government announcement stated that eating 1 kg of meat contaminated at 500 Bq per kg would give a dose to the whole body of 0.008 mSv, or more correctly 0.008 mGy. However we do not need to believe this – we can try a calculation ourselves.

Both caesium isotopes, caesium-137 and caesium-134, have a biological lifetime in the body of 100 days and we treat them together. Caesium has a chemistry like potassium and if ingested or inhaled, it becomes spread rather uniformly through the body like potassium. The period is 9 million seconds (100 days), so the dose over 100 days from eating 1 kg of meat (at 500 Bq per kilo) would be about:

\[
\frac{500 \text{ (Bq)} \times 9 \times 10^6 \text{ (seconds)} \times 1.18 \text{ (MeV)} \times 1.6 \times 10^{-13} \text{ (J/MeV)}}{1000 \text{ (mGy/Gy)} / 70 \text{ (kg adult weight)}} = 0.012 \text{ mGy per kg eaten.}
\]

This calculation has ignored that some gamma radiation and neutrino energy escapes from the body, and so is expected to be an over estimate. It is quite consistent with the figure of 0.008 mGy per kg given in the regulation [7]. Now we can ask a question, and then calculate the answer:

How much contaminated beef would a person need to eat in three months (100 days) to receive a dose equivalent to one medical diagnostic whole-body radiation scan, that is about 8 mGy?

The answer has to be 8 mGy divided by 0.008 mGy per kg, that is 1,000 kg = 1 tonne.

Obviously no one could eat so much meat in that time, and so ever receive such a dose under any circumstances. Consequently the regulation is ridiculous. Added to which, one such scan in three months is quite harmless – the threshold for any damage to health is at least 30 such scans in that time (on the basis of case made and evidence given in Chapter 9). Hence the Regulation of July 2011 has no rational basis, while those of April 2012 and April 2013 are even more illogical, as they relate to a personal consumption of five tonnes in three months!

After the Chernobyl accident there were similar concerns about levels of radioactive contamination of meat in Scandinavia. In June 1986 in Norway
the maximum activity permitted for food stuffs was set at 600 Bq per kg. The economic effect on the reindeer industry was so severe that in November 1986 this was relaxed to 6,000 Bq per kg [9]. In Sweden, 16 years later, on the 24 April 2002, the Swedish Radiation Protection Authority published an apology in the daily press [10]. They admitted that the intervention level had been set too low and that 78% of all reindeer meat had been destroyed unnecessarily, at great expense to the taxpayer and adversity to the industry. They lamented what had gone wrong, but still seemed unaware that the fault lay with the paternalistic application of ALARA-based principles to the safety of nuclear radiation. They were surprised that at the failure of their policy of setting a tight limit and telling the public that they should not worry. They did not understand that human nature is not set up to accept such a passive role.

**Water release at Fukushima**

The natural internal radioactivity of the body is 100 Bq per litre, that is close to the limits set for drinking water in Japan as reported in Sept 2011 [11]. This shows that the regulation is not related to any risk – it is said to be precautionary and describes a level of radioactivity that exists in nature anyway. It is intended to reassure and pacify public opinion – it does not depend on science. Worse, this appeasement is not effective and once trust is lost, the public remain disturbed, whatever limit is set.

On 4 April 2011 the Tokyo Electric Power Company (TEPCO), the company operating the Fukushima Daiichi plant, announced that it was releasing 11,500 tonnes of radioactive water into the sea [12]. It was forced to do this because it had built up an excess of contaminated cooling water, and it needed more storage capacity for water with greater contamination. It also said that the activity was about 100 times the regulation safety limit at 100 Bq per litre (at that time), but that it was quite safe. The apparent contradiction between these two statements stretched TEPCO’s credibility in the eyes of the public and the press.

A calculation is illuminating. The total activity to be released was $1.5 \times 10^{11}$ Bq, that is 13,000 Bq per litre, or 130 times the regulation limit for drinking water. We can calculate what dose would be received by someone who drank a litre of this water every day for three months. (To make a comparison we assume that the activity was mainly due to caesium since some weeks after the accident any contribution from iodine-131 with its 8-day half life was already much smaller and continuing to fall.) The total imbibed activity would therefore be 1.3 million Bq, and the dose would be

$$1.3 \times 10^6 \text{(Bq)} \times 9 \times 10^6 \text{(secs)} \times 1.18 \text{(MeV)} \times 1.6 \times 10^{-13} \text{(J/MeV)} \times 1,000 \text{(mGy/Gy)} / 70 \text{(kg adult weight)} = 32 \text{ mGy spread over 3 months.}$$
Even though nobody should be encouraged to drink this water, day after day, the radiation dose received by anyone who did so would be similar to that from one whole-body CT scan per month. We conclude that both statements made by TEPCO are true. What is false is the understanding that 100 Bq per litre is the limit of safety. Public policies may be factually correct, but, by quoting precautionary levels unrelated to any evidence of risk, such as 10 Bq per litre, they simply encourage a race to the bottom and a demand to ban any additional radiation at all \(^{[13]}\). To reassure the public, recent announcements about discharges to the ocean refer to activities that are a small fraction of drinking water guidelines \(^{[14]}\). Adherence to such standards costs money, but to what purpose?

Good safety is a matter of distinguishing clearly those situations that are safe, from those that are dangerous and should be given a wide berth. Saying that all discharges of radioactive water into the sea are hazardous is itself a dangerous statement. Consider a parallel in road safety: advising children to keep away from the edge of the roadway unless crossing should not be confused with warning them of the fatal consequences of remaining in the fast lane. Neither risk is a reason to close all highways, assuming that an elementary level of education is given. An equivalent simple provision for radiation is not given in any country.

On 2 April 2011 an unintended leak of a much smaller mass of water, 520 tonnes, was discovered with an activity of \(4.7 \times 10^{15}\) Bq and this was reported as successfully sealed off by 6 April. This was more dangerous, but the volume was small and became diluted to negligible levels in the ocean. Nobody was affected and there was no casualty unlike in other major accidents, such as the fire on the Piper Alpha oil rig in 1988 where 167 personnel were caught in the wrong place and died.

**Dose rates from external radioactive contamination**

The dose received is quite different if the radioactivity is external to the body. It is important to know the dose rate experienced by someone at a place where there is a nearby source of radioactivity. For instance, if the radioactivity on the ground was one million Bq of caesium in each square metre, how many mGy per month would someone receive who stood there? This question is too vague to give a clear answer, but we should try. Where does the radiation get absorbed? Half of the radiation emitted will go downwards and be absorbed in the ground. Some of that emitted upwards would be absorbed before it reaches anybody, too. It depends on whether the radioactivity is on top of the ground or lies below the surface – and that may not be known. If it is alpha radiation, it will all be absorbed in a few centimetres of air, so external sources of alpha activity are not a concern unless ingested in some way or absorbed through the skin.
For beta or gamma we can calculate the most pessimistic case in which all the radiation going upwards is absorbed by a human body with horizontal area, half a square metre. The dose that we calculate in this way will be an over-estimate, perhaps by as much as a factor of ten. If we knew more about the kind of activity and where it lay, below or on the ground, we could lower the estimated dose. Here is the calculation for the monthly dose, assuming that the recipient is exposed continuously 24/7 and without clothes – exceptionally pessimistic assumptions.

\[
10^6 \text{ (Bq per m}^2\text{)} \times 3 \times 10^6 \text{ (secs per month)} \times 0.25 \text{ (0.5 m}^2\text{, ½ up)} \\
\times 1.18 (E \text{ MeV, for caesium}) \times 1.6 \times 10^{-13} \text{ (J per MeV)} \times 1,000 \text{ (mGy per Gy)} / 70 \text{ (kg)} = 2.0 \text{ mGy per month.}
\]

This is equivalent to having two whole-body CT scans in a year and is a factor of 50 below the level of 100 mGy per month – the dose rate that is a scientifically justifiable safety threshold [see Chapters 1 and 9]. Any actual dose received by an individual is reduced further, unless the person lives on the spot with a million Bq per square metre. Wearing clothes or moving around will tend to reduce an external dose – unlike an internal source of radiation that remains present continuously until it decays, is excreted or exhaled. The highest-dose zones, shown in red on the maps of Fukushima, Illustration 13 on page 44, indicate where the dose rate is greater than 166 mGy per year (14 mGy per month) at a height of 1 metre. That is on the safe side of the limit suggested in Chapter 9 by a factor of approximately five.

But this is missing a rather important practical point. It is very difficult to measure the concentration of radioactivity on the ground. Radioactive atoms only differ from non-radioactive ones of the same chemical element by their decay and their mass. So the simplest practicable way to detect small quantities of radioisotopes is to measure the radiation that they emit. But the fraction of emitted radiation that reaches a detector will depend on whether the radioactivity is just on the surface, or buried a few millimetres below the surface; the latter will often be the case for open ground. Detection will also depend on the energy and type of radiation. Alpha radiation is absorbed by a few cm of air; beta radiation is not easily identified and can be much attenuated before it reaches the sensitive volume of a detector; only gamma radiation is detected and its source identified reasonably easily and efficiently. Although measurements are hard to make, exposure to external radiation is easily reduced by limiting exposure time, keeping at a distance from the source and using absorbing materials.

Just as a smoke alarm does not need to be precise to provide reassurance about fire, a radiation alarm can be quite crude and yet provide reliable safety. Simple devices that indicate a dose rate in mGy per hour usually count ionisation pulses in a crystal or gas and assume that these are due to gamma
rays of about 1 MeV. To do better, the energy of each pulse should be measured using a crystal like sodium iodide which can trap and measure the energy. Ultimately the radioisotope concerned would have to be separately identified, and the shielding effect of surrounding materials accounted for. But generally, for rough measurements in the environment with a hand-held instrument, this sort of detail is not available.

**Comparison of ionising and non-ionising radiation**

In the media, radiation fluxes are frequently described as *high* or *very high*, without any scale. Only if numbers are given, can any meaning be given to such descriptions. Below are a few examples of non-ionising and ionising radiation energy fluxes – the numbers are not precise, but sufficient to illustrate some differences, since these are large.

1. The energy consumption of the human body at rest, or the metabolic rate, is about 1-2 watt per kg, but this rises to about 6-10 watt per kg with mental or physical activity. Perspiration and convection in the human body are familiar ways in which the extra heat load is dispersed.

2. The safety limit for non-ionising radiation absorbed in live tissue is 4 watt per kg (set by US FDA). This limits the maximum radiofrequency power that is allowed for an MRI scanner or a mobile phone. If the power were higher, live tissue would start to feel hot.

3. A domestic microwave oven delivers about 800 watts, so the food absorbs about 800 watts per kg that heats and cooks it. This is 100 times the metabolic rate, so taking exercise or thinking hard does not release enough heat to cause self-cooking. This is indeed reassuring!

4. Sunshine has an energy flux above the metabolic rate which is why we feel significantly hotter in the sunshine. The *solar constant*, the flux of radiation reaching the Earth from the Sun, is 1,300 watts per square metre in total. Depending on conditions the flux of ultraviolet (UV) might be 30 watts per square metre, or about 0.1 watts per kg, averaged over a human body \([15]\).

5. Natural internal radioactivity in the body gives a dose rate 0.3 mGy per year, that is \(9 \times 10^{-12}\) watt per kg. The big reduction factor comes from the 31 million seconds in a year. The average total background ionising radiation is between 5 and 100 times larger, depending on location.

6. The absorbed energy dose rate from a PET scan (or from a CT scan notionally spread over an hour) is about 10 mGy per hour – this is 0.01 joules per kg per hour – and an absorbed energy rate of \(3 \times 10^{-6}\)
7. During a course of high-dose therapy the local healthy tissue receives an absorbed dose of 1,000 mGy, each day for 4-6 weeks – notionally spreading each daily treatment over an hour, that is $3 \times 10^{-4}$ watts per kg.

<table>
<thead>
<tr>
<th>Metabolic rate</th>
<th>Sunshine</th>
<th>Natural internal radiation</th>
<th>Average UK ionising radiation background</th>
<th>CT or PET scan</th>
<th>radiotherapy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>UV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$\sim 10$</td>
<td>$\sim 1/10$</td>
<td>$10^{-11}$</td>
<td>$5 \times 10^{-11}$</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$3 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Some approximate energy rates relative to the resting metabolic rate.

In Table 3 these absorbed energy fluxes are compared. Although the numbers are rough, the energy fluxes of sunshine and the metabolic rate are four orders of magnitude (factor of 10,000) greater than that of radiotherapy and, in turn, that is two orders of magnitude (factor of 100) above a diagnostic radiation scan; that in turn is another four or more orders of magnitude (factor of 10,000) above the average background ionisation energy flux, effectively the baseline for ALARA safety.

Expressed in another way based on the definition of a Gy, exposure to full sunlight gives a total energy flux of about 1,000,000 mGy per second. This indicates just how truly minute is a radiation flux that delivers 1,000 mGy per year.

So any description of a radiation flux as high should be seen in perspective; fluxes of ionising radiation are actually tiny. What happens is not a general macroscopic story, but a microscopic one, concerned only with the tiny fraction of atoms or molecules that get a hit – the rest are not affected in any way. We can find the approximate number of those that are affected quite easily. There are about $5 \times 10^{25}$ atoms in a kg and to ionise one of them takes a few eV, that is about $5 \times 10^{-19}$ joules. Then a CT scan of 10 mGy will ionise about $2 \times 10^{16}$ atoms per kg, that is about 2 out of 5,000 million atoms. That is indeed very few, about the same as two small grains in a whole 5-tonne truck load of sand. It does not imply that the damage may not be significant – an examination of medical data will show whether this tiny minority of damaged atoms or molecules is a threat to a living organism or not. Nevertheless, we see that the vast majority of molecules are not influenced at all by a typical flux of ionising radiation. What determines which atoms are affected? That is chance. It is the essential randomness of quantum mechanics at work!

It is hardly a surprise that it is not possible to feel ionising radiation from a CT scan or even radiotherapy, because the energy rate is only microwatts.
The molecules unlucky enough to get hit can feel it – but that is only 1 or 2 in 5,000 million. When the authorities announce to the press that very high radiation levels have been measured as a result of an accident, perhaps they should find out more precisely what that means and explain it to the people before allowing alarm and economic disruption to spread.

**Safety and sunshine**

We may ask what happens to this tiny minority of damaged molecules. The response to UV in sunshine is not a good example in some respects, but it is familiar and has some interesting things to say. Compared to X-rays or gamma rays, UV is exceptionally inefficient at ionising, but this is off-set by the extremely high flux of photons. Probably the majority of people are familiar with sunbathing and its effects; these are similar to those of nuclear radiation and in practice more serious. As most children learn from their parents, there are two kinds of damage:

- **cell death**, when layers of skin peel off that we know as sunburn and from which there is usually good recovery in a few days;

- **skin cancer** that may appear many years later and is often fatal, if not treated.

Compared to beta and gamma radiation, UV does not penetrate far through the skin, but is no less dangerous for that. There are 9,000 deaths from skin cancer each year in the United States \[^16\]. This is a rate of 30 per million, that may be compared with the death rate of 10 per million from fire \[^17\] and 103 per million from highway accidents \[^18\]. In all three cases public attitudes are reasonably informed, but could be improved. The authorities work to extend awareness, but at least there is no worldwide panic and no social or economic upheaval. In the recent past, however, in the case of nuclear radiation, the authorities have done nothing to inform the public, allowing apprehension to increase. Although the number of deaths from nuclear radiation is 10,000 times smaller than that from UV radiation, the population is not instructed and hangs on every word of ill-advised panic advice readily offered by the media. The result is highly destructive of trust in science and of mutual confidence in society as a whole.

In fact the immediate effects of high doses of radiation appear as skin burns, just as for excess UV. Such burns can be a side effect of a radiotherapy course and can be treated relatively quickly. Those people caught in some of the accidents to be described in Chapter 6, who received excessive radiation, also recovered. They include the crew aboard the *Lucky Dragon* fishing boat [Chapter 10], the 28 hospitalised patients at Goiania who underwent surgery [Chapter 6], and the two workers who got their feet wet in the Fukushima basement [Chapter 3].
The public view of the dangers of UV – in spite of the very real risks – is refreshingly different from that of nuclear radiation. People have learnt something about barrier creams and they know that the Vitamin D produced by sunshine prevents rickets. They have been warned of the danger of skin cancer caused by repeated over-exposure. Most are sensible and enjoy their summer vacations in the sun, gently engaging in natural acclimatisation in the first few days. This is the very kind of time-adaptive process that is important in the reaction of tissue to nuclear radiation, and crucial to the scheduling of radiotherapy treatment, but explicitly ignored by the current ALARA radiation safety regime.

Illustration 4 on page 5 shows an example of effective safety information: a plastic carrier bag given away by a local pharmacy which offers sensible advice to parents and their children on living with ultraviolet radiation. In spite of the high death rate from skin cancer, society is content to take normal medical advice and learn what to do – rather than rushing to consult a committee of the United Nations. If popular attitudes to UV radiation were to match those to nuclear radiation, travel firms might have a good trade in selling summer vacations deep underground with tours restricted to moonless nights to avoid the horrors of skin cancer. People have learned that the risks and benefits of UV should be balanced, and they should learn to do the same for other forms of radiation too. History is the only reason to single out nuclear radiation for special concern, but the historical story is flawed, as explained in Chapter 10.

**What happens to radiation in materials**

**Range and the hit probability**

The effect of radiation on materials, including live tissue, depends on the quantum energy of the radiation and its type – alpha, beta or gamma. There are other types of radiation, but these are seldom met outside a research laboratory and we can omit them without distorting the story. Nuclear photons are the same as the everyday variety emitted by atoms in street lamps, LEDs or red-hot materials. Beta rays and regular electrons are also the same – the different name only distinguishes their source; the same is true for alpha particles and helium-4 nuclei. In fact each type of radiation is the same in principle wherever it comes from – it has no memory of its emission, only an energy and a type. If it shines into a piece of material from the outside as an external source, or is produced as internal radiation from the radioactive decay of atoms already within the material, that makes essentially no difference to its effect either. What we need to know is where it is absorbed.

An important question is how far in material a quantum of radiation goes
before it is stopped or absorbed – this is called its *range*. Some radiation quanta or particles may pass clean through the material and out the other side, while others will *hit* atoms in the material, may stop, or be completely absorbed. Generally there is a considerable difference between types of radiation as to how this happens, but less difference between materials. Similar to the random timing of radioactive decay, the physics of whether a particle hits a particular atom in the material is random, with a probability determined by quantum mechanics. When an atom is hit by radiation in this way, the action is entirely confined to its electron cloud that lies outside the nucleus; the chance that the nucleus of the struck atom plays any significant part is far too small to matter. This has the crucial consequence for radiation safety: *radiation shining on a material does not make that material radioactive*. This may not hold true at the high energies found only in a research laboratory, or for a beam of neutrons. But neutrons are confined to the core of a working reactor and only those materials that have spent time there become radioactive from the effect of radiation.

Reactor fuel itself is not particularly active until it enters a working reactor and absorbs neutrons. Similarly the cobalt steel that was used in the structure of earlier reactors only becomes radioactive when regular cobalt-59 absorbs an extra neutron and becomes cobalt-60. In the same way, hydrogen in the water used to cool a working reactor core can absorb a neutron making deuterium, which is not radioactive, and that in turn can absorb another neutron to make tritium, which is mildly radioactive. None of these is made outside the reactor, or even inside when it is shut down.

When a photon hits an atom the result is quite different from when an alpha or beta particle does so. For a photon the whole of its energy is often absorbed and the photon ceases to exist – in its previous form at least. The random chance of a hit as gamma radiation passes deeper into material depends simply on the number of photons that have not *already* been absorbed, and this leads to an exponential distribution for the range of individual quanta. This is sketched in Illustration 24, reminiscent of the exponential distribution of radioactive decay, but in distance rather than time. The probability of collision is the same for each atom, and so the chance of a collision increases with the number of atoms, that is, with the thickness of material that the radiation traverses. In principle this is similar for any material, including living tissue. Incidentally, tissue behaves rather like water, since that is what it is largely composed of, and its average density is about the same.
Charged-particle radiation, including alpha and beta, has a rather different effect on materials. Quantum mechanics shows that compared with gamma radiation, there is a relatively large probability of a hit, but with a small energy deposition when such a hit occurs. After a hit the charged particle then continues on its way with an energy only marginally reduced. However, after thousands of such hits its energy finally runs out and it simply stops. The result is that a group of charged particles with the same energy have almost the same range, and the statistical fluctuations, which are the basis of the exponential distribution for photons, are almost absent. This gives a sharp spike for the range distribution as sketched in Illustration 24.

For a given initial energy, alpha radiation has a particularly short range compared with beta because the hit probability is very much higher, simply due to its low speed and higher charge \[^{[19]}\]. In fact alpha radiation is stopped completely by skin or a few centimetres of air.

A famous photograph of Queen Elizabeth II on a visit to the nuclear laboratory at Harwell early in her reign shows her receiving a bag of plutonium and being invited to feel its warmth \[^{[20]}\]. Her safety depended on the sharply-peaked distribution to the range shown in Illustration 24. If alpha particles had an exponential range distribution like photons some penetration of the bag would be expected. In fact she was then, and remains now, perfectly safe from the experience. Thanks to the unreasonably excessive caution of modern safety regulations, such a ceremony would not be allowed today. Now safety authorities are risk-averse and no longer act with science-based confidence.
The well-defined range of alpha radiation that protected Queen Elizabeth was deadly for Alexander Litvinenko \cite{21}. He was assassinated in London in 2006 by being given a pot of tea laced with between 100 million and 300 million Bq of polonium-210 which he ingested. Like plutonium-239, polonium-210 is an alpha emitter (see Table 2). Polonium was named by Marie Curie after her native Poland and she was awarded the Nobel Prize for its discovery in 1898. The range of the alpha radiation it emits when it decays is only 3.69 cm in air, so all the radiation was absorbed within Litvinenko’s body and he died of Acute Radiation Syndrome (ARS) after three weeks, on 23 November.

**Lack of discrimination in radiation damage**

What happens to the absorbed energy at the point where a hit by ionising radiation occurs? We have already seen that the nuclei of the material are really not involved: it is the electrons which form the outer structure of each atom and bind them into molecules that are affected by the impact. Whether the radiation is a charged particle or gamma, the mayhem that is left at the site of a collision consists of electrons, freed to wander off, and smashed pieces of molecule. These are often electrically charged, having lost or gained electrons in the melee. The energies typical of radiation, whether alpha, beta or gamma, are in the MeV range, considerably larger than the weak bonds of a small fraction of an eV that stabilise the state of molecules in their biological role. This is the reason that radiation damage is indiscriminate and much the same for any material. Atoms and molecules of all types are equally liable to be damaged and there are no special cases.

The immediate damage at each hit is localised, for instance on a single molecule, often with an electron expelled by the impact that then speeds off to stop further away. After the collision the broken molecule or ion will usually have considerable pent-up energy that is capable of creating further mayhem. Such a molecule is called a reactive oxidant species (ROS). With its energy it can ionise, break or excite other hitherto undamaged molecules, creating a trail that may reach nearby cells before it runs out of energy. This is an entirely chemical process, does not involve the nuclei and is independent of the radiation that started the process. The initial hit probability and everything that happens to the energy deposited in the material in the first fractions of a second are linear – its effects simply add up on top of one another. Any secondary electron or photon produced at the initial hit site with enough energy may be the source of further hits as a radiation track in its own right. With alpha and beta radiation such secondaries are less frequent, but with gamma radiation a secondary photon may carry energy some distance away to further sites until all energy is absorbed. None of this is affected by whether the material is living tissue or not.
Role of oxidants in damage to living tissue

In cellular tissue these secondary chemical effects caused by ROS radicals are especially significant for their effect on DNA. Simply put, living tissue is composed of many cells containing mostly water with various proteins that are the structure and functional workhorses of every biological cell. Also within each cell is a nucleus that contains the DNA responsible for creating and controlling the proteins. Only damage to the DNA is a matter of long-term concern. Provided that the DNA is not disrupted the other molecules that may be damaged by radiation are regenerated by the cell replacement cycle without lasting effect.

Since the effect of radiation is quite indiscriminate, it is water that suffers most from the initial hits, simply because it makes up more than half of the tissue mass. So, although DNA is occasionally damaged by direct hit, most damage is due to the secondary chemical effect of ROS fragments of water (H₂O) attacking DNA. These fragments include such dangerous reagents as hydroxyl (OH), hydrogen peroxide (H₂O₂), oxygen itself and their ions. It is reasonable to assume that this damage is linearly related to the energy absorbed because each physical process is independent and determined by quantum mechanics. Therefore, the combined initial effect can be found by adding up the independent contributions from each molecular hit – that is using the linearity principle.

It is often irrelevant that the damage was initialised by radiation. Other processes that produce these ROS cause damage to living cells in the same way. In particular, since the metabolic process of oxidising food provides the energy source for cells, accidental oxidation is a threat that biological cells have always had to live with. In each cell the mitochondria organelles burn the sugars and produce energy for the cell as a whole – these organelles must prevent any ROS produced in this oxidation from reaching the cell nucleus with its DNA. Inevitably some of these pollutants leak through and these are just as damaging to DNA as those from ionising radiation. In particular, ROS production increases with the extra energy production needed for normal muscular exercise and cognitive activity \[22\]. The ROS produced by an exposure to radiation over a period, a chronic dose, are a small addition to these natural processes and generally not distinguishable from them. However, a large acute radiation dose received in a short time is more damaging, as is excessive physical exertion.

High LET radiation

The damage to any material immediately after the absorption of ionising radiation consists of a distribution of these hits spread in space. Different types of radiation produce characteristic distributions: gamma rays produce a
sparse scatter of random hits; beta rays produce sparse hits lying along the paths followed by the energetic electrons; alpha rays give dense lines of hits lying along the track of each ray. This is called high LET radiation, with LET standing for Linear Energy Transfer, also known as dEdx in nuclear and particle physics [19]. The double charge and slow speed of alpha particles cause the high LET. On the other hand, the single charge and high speed of beta particles of a similar energy give low LET. Gamma rays give a wide distribution of hits so that they behave as low LET.

Living tissue is different from other materials because it reacts actively to the initial damage. This reaction takes place partly within individual cells and partly organically through the cooperative reaction of many cells. The hits from beta and gamma radiation are sufficiently far from one another that the subsequent biological response of repair and replacement at each hit can proceed independently without saturation. But at high LET the density of initial damage is so high locally that cells run out of the repair and replacement resources required. In particular the density of Double Strand Breaks (DSB) of DNA is enhanced. These are more difficult to repair, and the biological tissue suffers somewhat greater long-term stress than for the same absorbed energy at low LET.

In a truly linear theory there would be no such enhancement of the effect of high LET radiation. The acknowledged enhancement at high LET is accommodated in the LNT theory by assigning ad hoc weighting factors built into the calculation of damage in sievert. This arbitrary modification is applied in the LNT theory without explanation.

In a non-linear picture we may understand what happens. The local energy density of high LET is seen to impose a greater load on local repair and replacement mechanisms than the greater spatial uniformity of low LET. This argument suggests a spatial scale – if the repair services were available at any distance, there would be no dependence on LET. This spatial scale typically extends to groups of cells, signalling and cooperating together – or failing to do so when collectively overloaded. This range for repair in the spatial picture plays a role similar to the repair time in the time domain. Both are characteristic features of an active non-linear response, one localised in space and the other in time.

Detecting radiation

Natural detection in living tissue

Darwinian evolution has provided us with a level of natural sensitivity to
some sources of danger but not to others – for these we look to instruments or other strategies. We need to find out whether we are naturally sensitive and act accordingly. A familiar example is household gas: mixed with air it is explosive, but it is colourless and odourless. In a primitive evolutionary environment, having a sensitivity to natural gas would bring no advantage in the struggle to survive, and so evolution has made no such provision. In the modern world safety is ensured when the utility company adds a trace of another gas, t-butyl mercaptan, that does have a notably strong smell. This makes household gas routinely detectable to the nose, so providing a simple and effective addition to safety.

Similar methods help everybody to avoid the dangers of biological waste – in this case courtesy of nature rather than the utility company. Evolution has made human noses peculiarly sensitive to the gases given off by faeces and urine for just this purpose. You might even say that the smell is in the nose of the smeller, not in the polluted air that he breathes. What smells good, bad or indifferent has been tuned by evolution only to enhance human survival prospects. For example, dogs enjoy entirely different ranges of pleasant and unpleasant smells, much to the occasional disgust and social embarrassment of their owners. Vermin and lower biological agents have sensitivities, each tuned to their niche in the hierarchy.

There are many other examples of natural protection: our eyes are safe from the effect of steady bright light as is evident on the occasion of a solar eclipse. There is a natural temptation to look directly at the Sun, and health warnings are broadcast advising the public that this is dangerous. In practice, however, there are few such accidents because pain makes people quickly aware of excessive light in their eyes. Similarly, with non-ionising radiation at high-power levels, its heat is felt before it becomes dangerous.

But what about ionising radiation? May we get a heavy dose from its rays and not even know until it is too late? Why are humans not aware of ionising radiation, naturally? Is the failure to provide sensitivity to ionising radiation a rare oversight of Darwinian evolution? Would it not bring advantages? This is a proper question and the basis of genuine concern for many people. Let's look at the question. Biology would find the task challenging because the energy fluxes are in the microwatt range and any sensitivity would be liable to false alarms. As well as acquiring sensitivity to radiation we would like to be cured of the damage that it does to living tissue. Even though a simple electronic device is sufficient to say when and where ionising radiation is present, it would not provide for the repair of any damage caused. Evolution, it seems, has provided neither detection nor repair.

But in fact nature has been cleverer than this discussion has so far suggested. The natural detection of ionising radiation damage by living tissue has been
integrated with appropriate repair and replacement mechanisms. The messages of a radiation attack on life and the subsequent actions are quite subconscious and devolved down to the cellular level. If the body is attacked by ionising radiation – and this is happening all the time to some extent – the brain is not made conscious of it, and does not need to be, because the problems are detected and remedied at the cellular level, at the front end, you might say. We are mistaken if we ignore this biology while imagining that regulations control radiation safety [23].

There are three reasons for this brilliant integrated biological design:

- Life has evolved in many forms from single-cellular organisms through cabbages to primates – and recently humans. From the beginning, radiation and other sources of oxidation have been a source of danger that required detection and repair for all organisms, including those without a brain or even a central nervous system.

- If the central nervous system were made aware of the inter-cellular chemical signals that are triggered by a radiation attack, it would be overwhelmed by the high rate of false alarms caused by other oxidative processes. One may think of a domestic smoke alarm that is sited too close to the kitchen toaster – it causes frequent false alarms, until someone disables it. Such an alarm does not give an organism a selective advantage.

- Providing local repair and replacement mechanisms, integrated with local detection for all forms of oxidative attack, makes for devolved robustness and independence of different parts of a large organism with reduced lines of communication.

The result is that this superior devolved cellular safety system makes it simply unnecessary for humans to be alarmed by ionising radiation at low and moderate dose rates. That is as well since for the first 3,000 million years, there was no cognitive ability to respond to a radiation alarm.

Unfortunately official radiological protection policy ignores what nature has provided and tells the public that it should worry about such levels of radiation. Adding a cautious and extreme regulatory regime on top of the natural one is a mistake, similar to ignoring the old adage, Don't keep a dog and learn to bark yourself.

**Detection with man-made instruments**

But how about instruments that detect radiation? It is not difficult to build such a device and these may be simple or powerful, small or bulky. When Henri Becquerel discovered nuclear radiation he used a photographic plate. Our eyes are sensitive to colour only from red to violet, but a photographic
plate has a sensitivity to much of the spectrum, shown in Illustration 22, that extends from visible light onwards through ultraviolet to X-rays and beyond. A modern electronic camera can also be used to detect ionising radiation, although thicker detection materials have to be used if the radiation is not to pass through without giving a signal. An example of this is a clinical X-ray picture in which the radiation passes through the body with only the heavy calcium of the bones casting a shadow. A modern CT scanner uses X-rays in a similar way. If gamma rays with too high an energy are used instead of X-rays, even the bones do not show up much. The answer is to choose a photon energy which shows contrasting absorption in the patient but is captured efficiently in the detector material, whether photographic film, electronic semiconductor or heavy transparent crystal. The best material for this is one with the highest atomic number, in which the electron density is high and the electrons are tightly bound.

Modern detectors use exotic transparent crystals like bismuth germanate (BGO) and lead tungstate. Then, not only are photons detected efficiently, but the light-emitting cascades created within the crystal are tightly confined.

Beta radiation, like photons, is easily detected by an ionisation detector containing gas or a solid-state semiconductor. Alpha radiation is more difficult because it is absorbed so readily. Often it is stopped by air or the window of the instrument before it can be detected.

You may be thinking that you do not have access to such specialised and expensive technology, but that is untrue. For fire safety you probably have a domestic smoke detector. If not you can get one at a hardware store for about US $10. Inside is a radiation detector with a radioactive americium-241 source made from nuclear waste. If you open it up and take a look yourself, you will find the radiation symbol with details of the source. As a smoke detector it is fail-safe because any smoke in the air absorbs the ionisation from the radioactive source – the alarm triggers when it stops detecting radiation from the source. Without the source it could easily be redesigned as a cheap radiation alarm. Radiation is as easy to detect as burnt toast you might justifiably say. Why are most radiation detectors not so cheap to buy? If people wanted to buy them, they would be cheap – it is just a matter of the market. One could be incorporated into every mobile phone – indeed, I believe that such a phone is now available in Japan.

Professionals may say that is not good enough because it does not tell the type of radiation: alpha, beta or gamma. That is true, and most radiation detectors are quite unable to measure doses with any precision. But that misses the point, because all you should need to know for peace of mind is
whether there is an excess of radiation of any kind present. That is the same kind of simple question that you ask of your fire alarm. Provided that the alarm is raised promptly and efficiently, further investigations can then be made.

Notes on Chapter 5

2) South Tirol Museum of Archaeology http://www.iceman.it/en/node/247
4) In fact the beta decay energy of tritium is lower than that of any other known nucleus.
5) The high doses given in radiotherapy are an exception. There differences of a few percent may affect the success of the treatment.
6) Unlike radioactive decay biological excretion may not follow a simple exponential loss if several mechanisms are involved.
8) Japanese government regulation for caesium April 1, 2013: foods in general (100 Bq/kg), foods for babies (50 Bq/kg), milk (50 Bq/kg), drinking water (10 Bq/kg). Note that for foods in general the regulations are 1,250 Bq/kg in EU and 1,200 Bq/kg in USA, for milk and drinking water 1,000 Bq/kg in EU and 1,200 Bq/kg in USA
10) Sixteen years have passed since ...Swedish Radiation Protection Authority Swedish press, Dagens Nyheter (24 April 2002). (English trans.) http://www.radiationandreason.com/uploads/dagens_nyheter_C3D.pdf
14) On 2 Sept 2015 TEPCO reported that groundwater discharges to the ocean have been reduced to below 3 Bq/kg (caesium) and 1,500 Bq/kg (tritium). WHO drinking water guidelines are 10 Bq/kg (caesium) and 10,000 Bq/kg (tritium). Ignoring variations in conditions and the different effects of the UVA, UVB and UVC spectral ranges into which the ultraviolet spectrum is divided.
20) *Story of plutonium* Nuclear Engineering International (2005)
   http://www.neimagazine.com/opinion/opinionthe-drama-of-plutonium
23) Notably in 2015 the Nobel Committee gave the Prize in Chemistry for the elucidation of such DNA repair mechanisms.
Chapter 6: Effect of Large Radiation Doses

Brian: Look, you've got it all wrong! You don't need to follow me. You don't need to follow anybody! You've got to think for yourselves! You're all individuals!

Crowd: [in unison] Yes! We're all individuals!

Brian: You're all different!

Crowd: [in unison] Yes, we are all different!

Man in crowd: I'm not.....

Crowd: Shhh!

From Monty Python's Life of Brian

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Rise and fall of enthusiasm for science

Nobody knows who did it or when it happened. It may have been in Mesopotamia, or possibly early in the Greek era, that astronomers first successfully predicted a solar eclipse. As a demonstration of the power of mathematical science, it must have impressed the whole population. But respect for the word of science when established through awe and fear is not a sympathetic basis for understanding.

At a practical and political level it became apparent that making other useful predictions was not so easy, and physicists and astronomers had to accept defeat when they tried to extend their new-found powers to turning base metals into gold; similarly vain attempts in astrology caused the popularity ratings of science and scientists to wane. Scientific enthusiasm has always coexisted with a primitive awe and apprehension of natural phenomena; it has improved with education and successful prediction, but retreated under the influence of war, accident, pestilence, earthquakes, rumour, ignorance and the vagaries of the weather. So, while science slowly advanced, many natural phenomena became either deified or demonised by the public at large. For example, thunder and lightning remained a source of primitive fear that diminished only slowly as a deeper understanding of science percolated into society from the nineteenth century onwards. However, human prosperity has only really improved since confidence and a command of natural processes have become established.

Examining the strongest evidence

Members of the public are motivated by simple direct questions such as.

Is there a danger that could affect me, my family and friends?
They are less impressed by calculations and machinations they are unable to follow, and they are suspicious of regulations and restrictions which they see as a cover for higher prices, taxes, professional career building or political manoeuvring.

But ionising radiation has been in use for over 100 years in medicine, and for over 70 years in other spheres. So there is plenty of experience to draw on. Down-to-earth common sense answers can be given that do not rely on fancy mathematics or science. But it is not sensible to look at every source of evidence. It is better to concentrate only on the most significant; that means the most persuasive. Let's clarify this line of thought a little further.

The statistical significance of a result is poorly understood, with the result that weak conclusions get into the media and then have to be withdrawn, or worse, fail to be withdrawn. That commands no respect and should not happen. It was notable that prior to the report of the discovery of the Higgs Boson at CERN, there was an information blackout until the significance of the discovery could be confirmed at five standard deviations – a level of 1 in a million and representing confidence beyond reasonable doubt. Unfortunately, putative results in medical and biological sciences are seldom subjected to such strict tests and some conclusions are reported to be firmly established when at the level of only two standard deviations – in everyday language, that means 95% certain, or wrong 1 time in 20. Claims at such a weak level of confidence, a 5% chance of being mistaken, would lead to a rejection by referees for many scientific journals in other disciplines. Dubious results when picked up by the press become sources of confusion – what the press like to call matters for debate. But the press do not have the means to engage in such a debate. If the evidence is not strong enough to establish a firm result, all should agree to remain silent until further evidence becomes available. In the remainder of this chapter, we look at results that are widely accepted as beyond reasonable doubt.

**When radiation is fatal, sooner and later**

At a very high dose rate, radiation can kill not just cells or organs but whole organisms, and by examining data we can find out just how high the rate needs to be for this to happen. Radiation can be fatal in one of two ways. It can destroy the ability of a cell to service itself and engage in the cell cycle; this is called *cell death*. If too many cells are killed in this way the entire organism may be at risk from *Acute Radiation Syndrome* (ARS). This has nothing to do with cancer and takes place on the time scale of a typical cell cycle, that is within a few weeks at most. There is some difference between a dose given to the whole body and one applied only locally, but most organs fail due to the local dose when their own cells die independently of the fate of other organs. Some radiobiologists speak of cell death as a *deterministic*
process, but actually it is a biological reaction described by a probability like any other process – though that probability may be high for a large acute dose. Other historical descriptions: tissue reaction and early reaction, are descriptive and more helpful.

Most cells with damaged DNA are either repaired correctly by enzymes within hours or are repaired with errors such that they are not viable and fail to be reproduced in the cell cycle. However, a few of those that suffer DNA double strand breaks (DSB) are incorrectly repaired and yet survive. These mutations may persist in abnormal chromosomes whose behaviour is kept in check by the immune system. Failure of the immune system may result in runaway cell growth that hijacks the resources of the organism; this is the malignancy that we know as cancer. In its later stages such growth may go on to metastasise or spread through the blood stream to other locations and organs. With advancing age the immune system becomes less vigilant and errors may escape detection. The process is similar whether the error was initiated by radiation or another source of chemical oxidation. The probability that cancer develops is small and therefore apparently rather random, so it is sometimes called a stochastic process, although it does not involve any special kind of chance mechanism at a basic physical and chemical level. The description late reaction is less committal. We concentrate on cancer because data on late reaction for other diseases is usually less clear. The evidence shows that carcinogenic development is related more to the failure of the immune system than to the presence of an increased number of damaged chromosomes. The period in which the development of malignancy is kept in check by the immune system is called the latency.

Tumours develop at or near the site of the original radiative or oxidative attack – for example, smoking causes primary cancer of the lung and UV radiation causes primary skin cancer, rather than cancers elsewhere. This suggests that, although whole-body health is always an important factor, it is the local radiation dose rather than the whole-body dose that is important. This intuitive picture is supported by recent detailed clinical work reported by Tubiana and described in Chapter 8.

A malignant tumour develops at the expense of the host organism; it hijacks resources and physically invades the local tissue. The resulting disruption of the local blood vessels may be diagnosed with a functional imaging scan. If not removed or its cells killed, the tumour eventually metastasises, migrating through the bloodstream to establish further tumours elsewhere in the body. It may be removed surgically, or its cells treated by targeted radiation or chemical drugs. This may also be achieved with focussed ultrasound that destroys the cells of the tumour tissue by overheating – cooking, in fact. Even after it has spread, the progress of the cancer can still be reduced with radiation or chemotherapy. Such palliative treatment can extend life, even
though the cancer survives.

**High internal radioactivity, the accident at Goiania**

**The effect of intense internal radiation**

It is not a surprise that particular concern should be expressed about radioactivity inside the body. What data do we have and what can they tell us about any threat that this poses to the residents of Fukushima, now or in the years to come?

There is general agreement among international bodies that there is no significant evidence that radioactive caesium was responsible for any death at Chernobyl, either of identified individuals or of members within a group analysed statistically \[^1\]. However, it was responsible for several deaths in an accident with a caesium-137 source in the provincial town of Goiania, Brazil, in 1987 \[^2\], \[^3\], \[^4\]. But what was this very intense source doing there?

The radiation used to cure cancer by radiotherapy is no different from that present in a nuclear power plant, although the intensity used for therapy is far greater than that around a reactor except inside the vessel itself. The intensity of the therapy dose is designed to kill the cancer cells directly in its path by repeating the dose every day for 5 to 6 weeks. The radiation used in therapy may come from a radioactive source, either external or internal to the patient's body; alternatively it may come as a beam emitted by an accelerator in the therapy clinic shining onto the patient. The latter is preferred, simply because the radiation can be turned off by unplugging the accelerator and its beam can be steered in a particular direction. Although a gamma beam cannot be focussed or deliver energy at a specific range, a beam of charged ions used in the most modern radiotherapy can do both, so that the dose is confined very precisely to the tumour \[see Selected References on page 279, SR3\]. However, away from the world of modern technology a brief exposure to radiation from a powerful radioactive source is cheaper and simpler to provide. Well shielded sources have been used for over a century since pioneered by Marie Curie. As with the accelerator method, a powerful dose must be delivered in a short time.

**The accident, 13 September 1987**

The gamma source that had been used in the now-abandoned radiotherapy clinic at Goiania was caesium-137, which as a major constituent of radioactive waste, was readily available. Chemically, caesium is like sodium or potassium and relatively volatile. It is the most persistent contaminant of food and the environment after an accident such as at Fukushima and
Chernobyl. (In fact it is accompanied by another isotope, caesium-134, but we need not worry about that here.) The other contaminant, iodine-131, has a half life of 8 days, whereas caesium-137 has a radioactive half life of 30 years. But if caesium is inhaled or ingested into the body, it is expelled again with a biological half life of about 100 days because caesium, whether radioactive or not, is not a natural constituent of the body's biology.

Illustration 25: A map of Brazil showing the location of the provincial city of Goiania, just west of the capital Brazilia.

The shielded caesium-137 source that had been used to treat cancer at Goiania had an activity of 50.9 TBq. The $T$ of TBq stands for Tera, or a million times a million; that is a trillion. This activity is 500,000 million times the activity of a litre of water described by the Japanese regulations of 2012 as unsafe to drink at 100 Bq. But in use, the caesium-137 source was held securely in the shielded steel head which, when rotated to the ON position, would deliver 4,600 mGy per hour, suitable to treat a tumour.

By 1987 the source at Goiania was abandoned. It was removed together with its protective housing from the radiotherapy machine by some locals, hoping to make money by selling the steel of the unit for scrap. Having removed the head the gang took it home in a wheelbarrow and broke it open to reveal the source itself – 0.93 kg of caesium chloride powder. The two men were then exposed when they worked on the source and started to feel ill with
diarrhoea, vomiting, dizzy spells, and swollen hands. On 18 September they punctured the thin window with a screwdriver and the parts of the rotating source assembly were sold to the owners of the scrapyard next door. In their garage the source was seen to emit a pretty blue light, and over the next three days relations, friends and acquaintances visited to see the curiosity. On 21 September they extracted some powder, and distributed it to friends and visitors, some of whom daubed it on their skin. From 22 to 24 September two employees worked on the head to extract the lead. On 24 September fragments were taken into the house and handled during a meal, notably by a six year old girl, and then the source was sold to another scrapyard. By this time many people were ill and the remains of the source were taken to a local hospital, where the next day doctors were able to contact a medical physicist, who succeeded in raising the alarm after detecting the radiation with a borrowed detector designed for geological prospecting [^2].

<table>
<thead>
<tr>
<th>Whole-body internal radioactivity</th>
<th>Number of people</th>
<th>Radiation deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goiania [^2]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cs-137 more than 1,000 MBq</td>
<td>1</td>
<td>1 death, ARS</td>
</tr>
<tr>
<td>Cs-137 100 to 1,000 MBq</td>
<td>7</td>
<td>3 deaths, ARS</td>
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<tr>
<td>Cs-137 10 to 100 MBq</td>
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<td>Cs-137 1 to 10 MBq</td>
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<td></td>
</tr>
<tr>
<td>Cs-137 100,000 Bq to 1 MBq</td>
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<td></td>
</tr>
<tr>
<td>Cs-137 10,000 to 100,000 Bq</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Fukushima adults [^6]</td>
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<tr>
<td>Cs-137 12,000 Bq or less Aug 2012</td>
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</tr>
<tr>
<td>K-40 4,300 Bq</td>
<td></td>
<td>all humans</td>
</tr>
<tr>
<td>Fukushima children [^6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cs-137 all less than 1,400 Bq Nov 2011 - Feb 2012</td>
<td>1491</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Figures for whole body caesium-137 radioactivity at Goiania, compared to Fukushima (and to its natural look-alike, radioactive potassium-40, present in all life). Measured Fukushima limits should be increased by a factor 5 to 10 to account for the time lapse before measurement (given in the Table).

Casualties and internal radioactivity measurements

By 28 October eight people had contracted ARS, of whom four were dead. Altogether 249 people were directly affected by the radiation, externally or
internally. In 28 cases localised contamination and irradiation gave rise to deep burns on limbs and body, many requiring surgery. However, internal contamination gave the most significant exposures, with protracted or chronic doses persisting over a long period. Once caesium enters the blood stream, it is taken up throughout the body, particularly in muscle. The natural excretion period of caesium is about 100 days. The measured values of the whole-body internal activity for over 70 patients have been published by the IAEA [2, fig. 13 p. 55]. These are shown above in the unshaded bands of Table 4, arranged in order of decreasing activity.

Comparison to public measurements at Fukushima

The right-hand column of Table 4 shows that all fatalities had a whole-body internal activity exceeding 100 MBq, although half of those between 100 MBq and 1,000 MBq survived. Notably, in the 25 years since the accident, there has been no case of cancer in any band that could be attributed to radiation [5]. The shaded bands describe other data for chronic internal radiation, in particular those relating to the survey of adults and children in the affected Fukushima region [6] (see the mobile unit, Illustration 16 on page 51). Evidently, even the highest whole-body measurement of a member of the public recorded in the Fukushima region is at least 10,000 times smaller than the lowest internal dose that was fatal at Goiania, noting that none of those fatalities was due to cancer in any case. Also shown in Table 4 is the natural radioactivity due to potassium-40 present in all life. Potassium and caesium have very similar chemistry and therefore circulate around the body in the same way. However, irradiation by potassium-40 is chronic because it is included in all potassium in the environment – most famously in bananas [7]. This underlines how genuinely inconsequential small doses of radiation are – and even much larger ones too.

There are quite proper questions about the effect of internal radiation on pregnancy, but the data from Goiania offers some extraordinary answers too. One woman, already four months pregnant at the time of the accident, had an intake of 200,000 Bq and gave birth normally – both she and her child were radioactive, but this continued to decline by a factor two about every hundred days after the birth. Another woman who survived and had one of the highest internal intakes, 300 MBq, an activity as great as two of those who died of ARS, gave birth to a healthy child four years and three months after the accident [5, p. 47]. These data are very reassuring. Broadly they support for humans the conclusions found from experiments with mice [8] that pregnancies and foetuses are not as radiation-sensitive as is usually presumed.

The conclusion is that very large internal doses of caesium-137 had no direct carcinogenic effect over a 25-year period and that the possibility of cancer
from internal radiation by caesium at Fukushima is negligible. The number of people that were contaminated at Goiania is not high, but the internal activity that many of them received is very large. The woman who had the healthy child after four years had the same internal activity after the accident as she would have received if she had drunk three million litres of water with the contamination of 100 Bq per litre, condemned, without justification, as unsafe at Fukushima. At 10 Bq per litre, the upper permitted limit for drinking water as at April 2013, the volume of water would be thirty million litres, that is twelve 50-m Olympic swimming pools. For any reasonable person these data should close the book on whether there is any risk at Fukushima from caesium-137, even for foetuses, children and pregnant mothers. There are other sets of data in the scientific literature [9], but none that contradicts the conclusion that there is inadequate evidence for the carcinogenicity of caesium-137 in humans [10]. (For simplicity we have ignored the other isotope, caesium-134, that accompanies caesium-137, although there is no evidence for its carcinogenicity either.)

**Civil order and psychological effects**


> In one of the world’s worst radiological incidents, radioactive material stolen from a disused clinic in Goiania, Brazil, in 1987 caused the deaths of four people, while nearly 300 suffered radioactive contamination and more than 100,000 sought radiological screening. That incident involved the unintended release of radioactivity, but it remains the best real-world indicator of what could happen on a larger scale if terrorists were to detonate a dirty bomb in a large city or at a major public event.

This Goiania event may have been the world's worst such incident, but the number of fatalities was like a single family car hitting a tree and all four occupants being killed. Not an accident on a world scale. It was most unpleasant for the 249 others involved or for the 100,000 who rushed to receive a reassuring scan, but a general alarm would not have been justified. To be fair, though there was an information vacuum and many were frightened, there was no breakdown of law and order. Neither the Goiania accident nor a terrorist dirty bomb presents a global threat, and the Fukushima accident even less so, but the hysteria so quickly raised by today's 24-hour rolling media over such an incident could precipitate serious civil disorder. Regrettably, that may not be what Dr Amano intended to say. He appears to be talking up the seriousness of the accident itself, whereas it would be in the public interest for the IAEA to concentrate on providing proper education and information to the public in future, to reduce the fear
and uncertainty that can easily follow such an accident.

In 2011 a study reported that 42.5% of those who had been exposed at Goiania were suffering symptoms of depression, against 3% to 11% in the general Brazilian population [6]. The damaging effect of psychological stress in the community, so clearly seen at Chernobyl, and then repeated at Fukushima, was evident at Goiania too.

**Effect of the accident at Chernobyl**

**Places where time stood still**

At some places on Earth the human imagination is carried away by a single event frozen in time. A visit to Herculaneum or Pompeii, buried by volcanic ash in AD 79, recalls such a time and what was happening then, down to the smallest detail of everyday life, that would normally have been swept away by the onward march of later trivia. At Portsmouth in the UK the new museum of the *Mary Rose* houses another example, the flagship of King Henry VIII, that sank in a few minutes in 1546 but was recently raised with so many details of Tudor life preserved on board. In the same way a visit to Chernobyl and the town of Pripyat concerns what happened on a single date, 26 April 1986. It tells a unique story, one that should be preserved although its physical decay is already advanced. The environmentalist, Mark Lynas, recently suggested that it should be a World Heritage Site.

Frozen though these sites may be, the understanding of their message can mature, and so it has at Chernobyl. The site, deserted by human life at short notice and now overgrown, was reported as a waste land and dangerous for many years, but now in reality it is a wildlife park in all but name [SR7]. Flora and fauna are radioactive, but are no longer restricted by the disruptive intervention of man. The animals, birds and plants flourish freely along with the few human beings who stayed behind when others were evacuated [SR11].

**Scale of accidents**

At Chernobyl the water-cooled graphite-moderated nuclear fission reactor that exploded was designed and built by the Soviet Union [SR3 p. 73 & 141]. Unlike Western designs, including those at Three Mile Island and Fukushima, it had no spherical containment vessel, so any release of radioactivity was free to disperse into the atmosphere, and the control of temperature and rate of energy production was not stabilised by a fail-safe design. On the day of the accident the operators were ill-advisedly testing operating procedures with important safety systems disabled. They lost control and the temperature started to increase quickly. Soon the water, now steam, reacted with the
rapidly-heating graphite, creating hydrogen, whose pressure blew the top off the reactor. This hydrogen then exploded in the air and the whole mass of red hot graphite, now open to the sky, burned for days, sending much of the nuclear material upwards. A brave band of 237 workers fought the blaze, exposing themselves to the open reactor core, which was never shut down in the way that those at Fukushima Daiichi and all the others in Japan were. At Chernobyl the extreme heat of this open fire generated a rising column of gases, carrying all but the heaviest nuclear material into the upper atmosphere where it circulated around the globe. To put the comparison with Fukushima into perspective you might ask what happened to the cooling water. After all, that was the focus of attention at Fukushima. At Chernobyl none remained – it had reacted to form hydrogen or been vaporised. Cooling? There was none.

There is no doubt that Chernobyl was the worst civil nuclear accident, arguably the worst imaginable. The reactor had no containment vessel, unlike most reactors of that era and every one since. At the time the government of the Soviet Union was entering its dysfunctional phase prior to collapse, and information was not made available – in fact it was the detection of the radioactivity in Scandinavia that carried the news that there had been an accident at all. In response to Chernobyl, IAEA introduced the International Nuclear and Radiological Event Scale (INES) in 1989 to describe the severity of an accident, for a purpose that is unclear. Anyway, Chernobyl was retrospectively classified as 7, the maximum on the scale. Unfortunately, a position on this scale is determined by the administrative judgement of the authorities actually involved, rather than by an objective measurement like that used by seismologists in assessing the strength of an earthquake. In the case of Fukushima the Japanese authorities lost their nerve and gave it the maximum, 7, like Chernobyl. This was a basic mistake that simply escalated the public sense of panic. The Fukushima accident was never in the same class as Chernobyl. An unscientific index like INES simply excites instability in public opinion which is in the interest of nobody.

The question is sometimes asked, What should replace the INES scale? The answer is simple, Nothing. There is no such scale for fossil fuel accidents or the collapse of hydroelectric dams, although these involve the loss of large numbers of lives, which is very rarely the case for nuclear accidents. Scales of this sort fill no beneficial function. Why does anybody think that there is a need for a scale? Perhaps because they still see nuclear radiation as exceptional and needing extraordinary safety provision, but that is a political reaction, unsupported by objective scientific evidence. The worst recent accidents for a number of base-load energy sources are listed in Table 5. It shows that nuclear energy is far safer than other competing sources.
Chapter 6: Effect of Large Radiation Doses

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Date</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydro</td>
<td>Shimantan, China 1975</td>
<td></td>
<td>171,000</td>
</tr>
<tr>
<td>nuclear</td>
<td>Chernobyl, Ukraine 1986</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>oil</td>
<td>Jesse, Nigeria 1998</td>
<td></td>
<td>at least 300</td>
</tr>
<tr>
<td>natural gas</td>
<td>Chuandongbei, China 2003</td>
<td></td>
<td>243</td>
</tr>
<tr>
<td>coal mine</td>
<td>Soma, Turkey 2014</td>
<td></td>
<td>301</td>
</tr>
</tbody>
</table>

Table 5: Recent high-mortality accidents for base-load energy sources [12].

Press reactions to such a calm assessment of the Fukushima accident have included, *But there was a triple meltdown!!* Except in horror movies where the science is adjusted to make the story exciting, a nuclear meltdown is much preferable to a nuclear reactor that blows up, as happened at Chernobyl. Even there, the effect of the radiation itself on people's lives was very limited compared with accidents from other energy sources (see Table 5).

**Effect on local mental health**

At Chernobyl the local authorities were slow to act until the international alarm forced them to acknowledge what had happened. Chernobyl is in a poor area of Ukraine largely dependent on agriculture. So, unaware of the accident, the country people continued to eat locally produced food, absorbing radioactive fallout from vegetables and dairy products as they did so. Then, suddenly and without notice, many of them were herded into buses and evacuated to unfamiliar accommodation quite unsuited to their way of life. Unemployed and ignorant of what had happened to them, the evacuees and their families developed all the usual signs of severe social stress – suicide, alcoholism, family break-up, increased smoking and hopelessness.

**Mortality from radiation**

Accounts of accidents record the details of injuries, lists of fatalities and social consequences, even though these may not be known precisely. Also important is the number of cases that would have happened anyway without an accident. Exposure to radiation can result in eye damage and beta-burns to the skin, similar to sunburn, although recovery from such conditions is usually complete. However, at the time of the Chernobyl accident and for many years thereafter, there was wild speculation that the number of deaths that it would cause would be high – tens and hundreds of thousands – and the reasons for this expectation were cultural and historical, as discussed on Chapter 10. But after a lapse of 25 years it is now possible to set the record straight and give generally agreed scientific estimates of the number of
deaths, and to understand the effect of the radiation in terms of modern biology.

What do such numbers mean and how are they found? There are three types.

- First, there are the deaths of identifiable individuals who would otherwise have lived. We do not need fancy mathematical statistics to get the answer for them; we know who they are, individually by name.

- Second, there may be a group that as a whole shows a significantly larger number of deaths than would have been the case without an accident, but for which it is not possible to distinguish the individual casualties from those cases that would have occurred anyway. To be confident that the radiation accident was a cause, two large groups need to be compared which are similar, except that one was irradiated by the accident and the other was not. Estimates of the number of extra deaths and its uncertainty involve a statistical calculation. The conclusion may be quite firm or it may be decidedly weak.

- Finally, there are those who might have died from the accident but for whom no clear statistical evidence is available. This is a don't-know situation and the evidence does not exist; it is dangerous just to speculate in the absence of evidence. But in the early years after Chernobyl it was possible to argue that one should wait and see. After 25 years this is no longer reasonable and the conclusions of no evidence are looking final.

**Death from Acute Radiation Syndrome**

At Chernobyl there was one group of individually identifiable victims. These were the 28 men who died after fighting the fire at the reactor in the first few days. Death was from ARS, not cancer, and the mortality among the 237 firefighters in each dose range is shown in Illustration 26. The graph shows that for those who received less than 4,000 mGy, labelled point A, the mortality was only 1 in 195. At higher doses the mortality rises steeply and reaches near 100%, point C, at around 7,000 mGy, point B. Evidently there is a threshold in the region of 3,000 to 4,000 mGy and the data for rats described by the smooth curve show a similar effect. All those who died of ARS did so within a few weeks and the others recovered.
A significant question is what happened subsequently to those of the 237 fire fighters who survived early death by ARS. In 25 years in any such group some would die anyway. The questions are whether more of them died than expected, and whether the complaints that they died from have any connection to radiation. The numbers are relatively small and so fluctuations are expected. Nevertheless, the World Health Organisation has not reported any significant signs or correlations among these closely monitored survivors, suggesting extra cases of leukaemia, for instance \[^{13}\].

### Cases of child thyroid cancer

There was one small group of extra deaths that were identified, though only statistically. The incidence of thyroid cancer in the regions of Ukraine, Belarus and Russia near to Chernobyl showed an increase of about 6,000 among children \[^{14},^{15}\]. Some of these were unrelated to radiation (and so would have occurred in any event) and others were detected prematurely because they were screened intensively. Some may have been caused by the ingestion of radioactive iodine-131 from vegetables and milk contaminated by fallout. Iodine, whether radioactive or not, is concentrated into the thyroid gland, especially in growing children. The uptake of iodine depends on the supply of iodine in the local diet which may be poor, as it is in Ukraine, or rich, as it is in Japan, where iodine-rich sea weed is eaten regularly. Any radioactive iodine is diluted by the presence of regular iodine, whether from normal diet or taken as a supplement. Radioactive atoms decay with a half-life of eight days and then become harmless. So children born since the

Illustration 26: A graph of data showing for different radiation doses the mortality of the 237 early fire fighters from ARS (crosses labelled by number of deaths/total for each dose range). The curve is from similar data for rats.
accident cannot be affected, and indeed they do show that the cancer rate has returned to its normal low level. Thyroid cancer can be treated making use of the same high efficiency with which iodine is concentrated by the thyroid. In a course of therapy the patient is injected with much more radioactive iodine that then kills the tumour cells. In spite of the increased reported incidence, most cases were successfully treated and, as a result, the number who have died from the radiation is not 6,000 but 15.

The intensive screening process caught some cases that would not have developed and these cases were not caused by radiation. The extent of these false diagnoses is debated. But if normal potassium iodide tablets had been taken, as they were in many places in Japan, the number of real cases at Chernobyl would certainly have been reduced. Given that the release of iodine-131 at Fukushima was much smaller than at Chernobyl, no real increase in the incidence of child thyroid cancer beyond that which would have occurred without the accident is expected, and certainly no death.

There continues to be no evidence for any other fatality at Chernobyl caused by radiation. In particular, in agreement with findings for the survivors of Hiroshima and Nagasaki after 50 years, there is no evidence for any increased incidence of deformity or inherited genetic effect.\[16\]

**Loss of life caused by fear**

Fear of the radioactivity released in the Chernobyl accident spread far beyond the evacuation zone and those labelled as sufferers. Concern about any possible risk to later generations was reflected in increased abortion rates in the following months in many countries, even those quite far away. In Greece, for instance, this was evident as a sharp dip in recorded birth statistics, indicating that there were 2,000 extra abortions there.\[17\] These statistics indicate drastic personal action taken in response to the threat of radiation, when in reality there was no danger at all.

As described in *Radiation and Reason* [SR3], social stress and fear of radiation is now considered by the World Health Organisation (WHO) to have been responsible for many deaths, although reliable numbers are not available. The rural population near Chernobyl had little education or experience of life in nearby towns and their disorientation was caused by their hurried and unexplained evacuation. Officially labelled as *victims of radiation*, a description beyond their knowledge and disconnected from their sensory experience. They suffered from the threat of unknown disease, the scramble for compensation and life in an unfamiliar place. These led inevitably to general stress, dependency and hopelessness.

In 1986 the Cold War was not yet over and for a number of years the international community continued to be so transfixed by the much-hyped
Chapter 6: Effect of Large Radiation Doses

dangers of radiation and radioactivity that they overlooked this suffering, which was the most serious health outcome. It was not until 2006 that the truth was fully acknowledged in international reports, the latest draft from UNSCEAR being published less than two weeks before the Fukushima accident [18].

**Mistakes at Chernobyl repeated at Fukushima**

These reports on Chernobyl by WHO, IAEA and UNSCEAR remained unheeded by the authorities in Japan when the accident at Fukushima occurred, and the mistakes of Chernobyl were repeated there. Why did the authorities in Japan not have a plan of action? Why did they act seemingly unaware of these reports? Their reaction is not uniquely Japanese, and it is probable that the national authority in any other country would have reacted similarly had such an accident occurred there. Instead of thinking for themselves as they do when faced with an earthquake or tsunami, the Japanese authorities turned for advice to the US Nuclear Regulatory Commission (NRC). Why?

Advice is sought from higher authority for any threat that is not understood or trusted, in Japan as elsewhere. Unfortunately the Japanese government lacked both understanding and trust, and so consulted the US NRC. This was unfortunate because it was headed at the time by Gregory Jaczko, who held long-standing anti-nuclear views. Clearly he had not read and understood the UN reports either, and the Japanese government seems to have received inept and dangerous advice. Jaczko was replaced as head of the US NRC a year later.

The Japanese people would seem to have been victims of their deferential attitude to the US, an unfortunate outcome given the indigenous expertise in Japan. Much of the finest scientific work on the beneficial effects of radiation at low dose rates comes from Japan, but there is a culture of compartmentalised responsibility, an unwillingness to make public comment on any matter unless required to do so. But Japan is not alone in this and other cultures suffer from the same paralysis of opinion. What distinguishes Japan is its geology, and that is what caused the damage and loss of life, not its use of nuclear energy.

**Chronic and protracted doses, radiotherapy**

**Dose rates, time scales and whole-of-life doses**

The permanent damage inflicted by a radiation dose spread out over a period of time is quite different from that inflicted in an acute dose, a single dose all at once. Even when the total dose, that is the energy deposited in joules per
kg, is the same, the extension in time alters the effect on the organism in two ways. Firstly, although in a short period the resources needed by cells to replace or repair temporary damage get rapidly used up, a dose delivered over a longer period allows time for further resources to become available. Secondly, it allows the cell (or cells) to adapt their readiness for any further incident in the light of experience.

Here is an analogy. If an acute dose is like a sprint, a chronic dose is like a long-distance run, and the adaptation is like the improvement over time that a history of regular exercise builds up. Adaptation is least in response to an acute dose, such as the flash of gamma rays and neutrons experienced by the inhabitants of Hiroshima and Nagasaki. So the effect of acute and chronic doses are different. A steady chronic dose rate is measured in mGy per day, for example, while a single acute dose is measured in mGy, full stop.

Traffic accidents provide another analogy. These are related principally to the speed at which vehicles travel, and less to the distance they cover. If distance were related to accidents, the police might hand out tickets to motorists travelling more than 15,000 miles, for example. But since distance is less important than speed, and accidents do not accumulate with distance provided the speed is kept low, the highway police only give tickets for the rate of distance (that is the speed) over 70 miles per hour, say. Slower speeds do not accumulate accidents, or speeding tickets.

Similarly, the evidence for the damage due to a radiation dose suggests that it depends primarily on dose rate, not accumulated dose. The difference between an acute and a chronic dose may be as obvious as the difference between miles and miles per hour, but, nevertheless, they are frequently confused.

As argued in Radiation and Reason [SR3], there are reasons to give chronic dose rates a daily or monthly time-scale, for that is the scale of the biological repair and replacement processes, some linked to the cell cycle. To be conservative we consider chronic dose rates in mGy per month. Only for irreparable damage would mGy per life be appropriate, and only by examining data can it be discovered whether this is applicable to any extent. What is the effect of a chronic radiation dose rate? Where does evidence to answer this question come from? The biological response to a radiation dose is the subject of Chapter 8, but it is good scientific practice to let the evidence speak for itself before interpreting it in one way or another.

**Experimental data on mice, dogs and humans**

We start with the effect of beta and gamma radiation \[^{19}\]. (The effect of alpha radiation is somewhat different and will be described at the end of this chapter.) Large-scale radiation experiments on humans, even under controlled
Chapter 6: Effect of Large Radiation Doses

conditions, are frowned upon because they are thought to be dangerous. Instead we have to rely, either on experiments with animals, or on the best human information that is available, by chance or accident. In controlled experiments on animals their number can be large depending on the resources available. Observations may be compared in detail with a control group which is identical in all respects, except that its members did not receive the radiation dose. Results from a relevant experiment were published as early as 1915 and 1920, and are described in Chapter 8. Today genetic variation can be removed as a possible source of confounding by employing a single genetic strain of mice for both the irradiated and the control group. However, mice differ from humans, and dogs are different again. Conclusions found in mice or dog experiments cannot be related directly to humans, most obviously because their life spans and metabolic rates are different. So results can only be indicative, although, for acute experiments at least, the agreement may be fair.

But it is in the effect of chronic doses that such experiments are most useful, for instance to show the different sensitivity of adults and juveniles or foetuses. Some authorities suggest that sensitivity to radiation decreases with age, but others point out that youth is less sensitive, thanks to a more effective immune system. When tested in experiments on mice these questions can be answered quickly and also combined with post-mortem examination. The short lifespan of mice limits the useful information that such data can give for any prolonged exposure. A better choice is the study of beagles with a natural lifespan of 12 to 15 years. In such studies with various lifelong dose-rates, lifespans and causes of death can be compared with those of a control group who were not irradiated. These data do show significant effects from chronic radiation, but only at high dose rates together with high lifelong doses. The details will be seen in Chapter 8. It is still relevant to ensure that the most significant human data tell a consistent story.

Cancer caused by radiotherapy for an earlier cancer

The task is to track down evidence for human cancer – carcinogenesis, if you prefer the long name – due to chronic or protracted radiation. This turns out to be surprisingly difficult, in large part because chronic radiation simply does not cause cancer at low and intermediate dose rates as readily as might be expected. What happens at high dose rates, such as used in the medical treatment of cancer? This radiotherapy is given as a course lasting six weeks or so; each day a fraction of the radiation dose is given. This protracted dose is better seen as a chronic rather than as an acute dose, because a day is long enough for the irradiated tissue and its cells to react to the radiation, as confirmed in laboratory test-tube experiments. In practice this fractionation of the treatment turns out to be essential to its success [20].
The point is that, although this very large dose, given every day, may kill the cells of the tumour as intended, it may also itself be a source of new carcinogenesis in the healthy tissue close by. Examined in this way, data on the vast clinical experience of radiotherapy can come close to answering the question of a threshold,

What is the lowest chronic radiation dose rate that is found to give rise to cancer?

There are many details that make a quantitative conclusion difficult. Nevertheless, members of the public undergoing a course of treatment receive up to 1,000 mGy per day to healthy tissue which then recovers. This amounts to a very large total dose over a period of a month or so, and they thank the radiologists for this treatment that is given to kill their cancer, or at least provide palliative relief. As we shall see in Chapters 8 and 9, the chance that the radiation causes a new primary cancer is something like 5%. If it were much higher, the clinicians would scale back the daily dose; if it were much lower, they would increase the dose to be more certain of curing the initial cancer.

Indeed, everybody knows a friend or relative who has experienced such a course of radiotherapy treatment with this sequence of high doses. These data do not come from experiments in a concrete bunker hidden away at a secret research laboratory that might be thought unfriendly or untrustworthy. On the contrary, the public have every reason to accept and acknowledge such information. They should realise where it comes from. A discussion of the doses used is openly available on the website of the Royal College of Radiologists [20].

Living with artificial radioactivity

Are there no data for humans exposed to a constant radiation dose-rate lasting many years? Sources of such data are unusual, even for moderate rates, but they do exist and there is one in particular. In 1982 a development of 1,700 apartments was built for 10,000 residents in Taiwan. The structural steel used was contaminated by cobalt-60 – it must have included scrap structural steel from a fission reactor. This isotope is formed when natural cobalt-59 in structural steel absorbs an extra neutron. Such neutrons do not exist in the wild, because left on their own all neutrons decay with a half-life of 10 minutes. The only place where cobalt-59 might meet a free neutron is inside the vessel of a working fission reactor. Anyway, what were the consequences of the accident?

Cobalt-60 has a half-life of 5.3 years and decays with the emission of a 1.3 MeV gamma; such radiation is very penetrating. In the Taiwan apartments it irradiated the occupants continuously over a period up to 20 years without their knowledge. By the time this was discovered 1,100 people had received
an annual dose of more than 15 mGy; 900 had received between 5 and 15 mGy annually. The residents were quite unaware of their exposure and there seems to be general agreement that the data show no evidence for excess cancer or any other ill effect \[21\]. The data have been examined for beneficial effects of low dose rate radiation, but 15 mGy per year is too low a dose rate for any significant conclusion to be drawn. Data for larger chronic dose rates would be needed to show firm evidence of an effect although claims are made.

**Living with natural radioactivity**

A source of chronic radiation that is occasionally much larger than 15 mGy per year is the ever-present natural background radiation that varies considerably, depending in particular on the local geology and height above sea level (discussed in Chapter 5). The geological dependence comes from local variations in naturally-occurring potassium, uranium and thorium ores. Alpha radiation is absorbed within the minerals, but the gamma escapes to contribute to the environmental background. Radon, the naturally occurring radioactive gas, contributes by escaping too.

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Radon-222 was discovered by the German chemist, Frederick Dorner, in 1900. It is a noble gas with complete electron shells and little interest in chemical combination – in fact it is the heaviest in the sequence of such gases that starts from helium and runs through argon to xenon, and finally radon. It is produced in the alpha decay of radium-226 which is a member of the decay sequence that starts from uranium-238. The concentration of uranium in the Earth's crust is very variable, and so that of radium is too. Radium-226 has a long half life, but is relatively soluble in water. So when it decays to radon-222, it may already be dissolved; this is significant for the half life of radon-222 is only 3.8 days. (If still in the rock, it would escape into the air much less frequently.) Each atom of radon has a mass 222, eight times heavier than a nitrogen molecule in air, and so the gas naturally accumulates at low level, particularly in mines, cellars and caves.

Exposure to radon may depend on location within a house, how the house is built and the way it is occupied and ventilated. As a gas and alpha-emitter, radon is expected to cause lung cancer. The picture is one in which radon is inhaled from the surrounding air and some atoms decay before it is exhaled again. The products of decay are not gases, and these products themselves decay in a number of sequential alpha and beta emissions that add further dose to the lungs (see Table 2 in Chapter 5).

Because radon is a colourless and odourless gas present in the home, it can
haunt the imagination of the *worried well*, just as effectively as any tale of *germs round the bend*. Many home owners are persuaded to pay for radon remediation, and a radon survey may be recommended by their agent when they sell their property \(^{22}\). Such attention to domestic radon has become a profitable industry in affluent countries, bolstered by regulations not amenable to public scrutiny. The concentration of radon in the air is measured in Bq per cubic metre. The *Action Level* recommended in the UK is 200 Bq m\(^{-3}\) with a *Target Level* set at 100 Bq m\(^{-3}\). These may look reasonable numbers, but the actual radon concentration at this Target Level is truly minute. Even if radon did have an odour or was coloured, it would not be detectable because its proportion at this level is only 1 part in \(6 \times 10^{17}\).

We can calculate the radon concentration for an activity of 1 Bq per m\(^3\):

\[
\text{We can calculate the radon concentration for an activity of 1 Bq per m}^3 \\
= 474,000 \text{ (secs, mean life radon-222)} / 2.68 \times 10^{25} \text{ (total molecules per m}^3) \\
= 1.768 \times 10^{-20} \text{ radon molecules per air molecule.}
\]

At the Target Level the concentration is 100 times larger than that. That is less than 2 parts in \(10^{18}\), a million times a million times a million - that is not very much!

What radiation dose is received by inhaling air containing 1 Bq m\(^{-3}\) radon? Estimates vary within a factor ten. The ICRP says that it gives 0.017 mSv per year \(^{23}\ p 16\). UNSCEAR says it is equivalent to 9 nSv per hour, or 0.079 mSv per year \(^{24}\). Being conservative and taking the UNSCEAR value, the dose to someone living 24/7 in an environment at the Action Level would be 16 mSv per year, less than 2 CT scans. That should be of no consequence, but what do the data say is the effect on the lungs of this modest dose rate?

There is no shortage of academic studies that cast doubt on any link between domestic radon and lung cancer \(^{25, 26, 27, 28}\) and, equally, a number of studies \(^{29, 30, 31}\) that, by relying on a curious derivative of the LNT model, keep the radon safety industry and the radon mitigation services in business. So should householders worry about domestic radon? The basic question is whether there is a significant measured correlation between the radon environment and the incidence of lung cancer. The published answers to this question are quite unsatisfactory and such a correlation is not established. One may draw the conclusion that spreading concern about natural concentrations of radon deceives the public and that any related remedial work is wasteful, unnecessary and should be discontinued. There are technical but critical points to summarise and we put them in a box so that readers can skip over them if they wish.
This is a brief summary of comments on the case made by those who report a correlation between domestic radon and lung cancer:

1. The effect of radon must be small because the initial local national analyses reported no statistically significant influence. The large continent-wide meta-analyses \([^{29}, 30, 31}\) make identical heavily loaded assumptions in order to show that environmental radon causes lung cancer, a result that they claim to be significant. Because of these contested assumptions the three claims are not independent.

2. The claimed linearity would mean that each cause and its effect is separate from every other cause and its effect. The science behind this was discussed in Chapters 4 and 5, and also in Radiation and Reason, Chapter 7. In other words, if the dependence of the cancer risk \((R)\) on radon concentration \((r)\) and smoking \((s)\) were linear, \(R\) would be

\[
R = A*s + B*r + C
\]

with \(A, B\) and \(C\) being constants. \(C\) is a background. But the data say that this is not true for the carcinogenic effect of radon and of smoking.

3. The authors of \([^{29}, 30, 31}\) use a non-linear formula for \(R\) of the form (with \(C, D\) and \(E\) constants)

\[
R = (C + D*s) * (1 + E*r).
\]

Significantly in their formula the dependence of \(R\) on radon \(r\) also involves smoking \(s\) which makes it non-linear. They call this the Relative Risk model. In fact, since smoking increases \(R\) by a factor 25 according to them, their analysis forces a radon dependence which is 25 times larger for smokers than non-smokers. They offer no justification for this blatantly non-linear assumption, except to mis-represent it as being linear.

4. All available data in the literature on cancer induced by radon have been re-analysed recently by Fornalski and Dobrzynski \([^{27}\] using a full range of possible hypotheses. These include constant risk, linear risk and relative risk as applied by the 3 meta-analyses (so called LNT). If this model is forced, their analysis agrees with the results found by the proponents.

However, having compared the likelihood of the different models quantitatively all 28 sets of available data, Fornalski and Dobrzynski conclude \([^{27}\]

*a Bayesian analysis shows that the radon data published in 28 analyzed studies bear no evidence of the dependence of lung .....*
In summary, find that betting odds of 90-to-1 in favour of no dependence of lung cancer on radon against the standard safety story. An example of a study that did not assume the relative risk model is the analysis of cancer data on non-smoking women in former East Germany \[26\]. In the south east region the radon concentration is high, but the data (up to 1,000 Bq per m\(^3\)) show no indication of any increase in cancer, in disagreement with the general meta-analyses.

Meanwhile there is an extensive tourist industry based on spas that boast of hot radioactive waters that are claimed to provide therapeutic benefits \[32\]. They may well do so, and at the very least are popular with customers. The water is warmed by geothermal heat, that is fired by the radioactivity that makes the centre of the Earth hot and provides the energy for all volcanic activity and earthquakes. Not surprisingly many such facilities lie at the boundaries of tectonic plates, including Iceland, California and Japan. These therapeutic centres have a strong tradition in Germany which like Japan is a notably radio-phobic country.

The conclusion should be drawn that this radioactivity, either in background radiation or in health spas, certainly does no major harm, although it is not intense enough to show the threshold at which damage to health begins. We should continue our search for evidence of the effect of more intense chronic radiation. And cancel that expensive contract for radon remediation on the house too.

---

**Effect of intense chronic alpha radiation**

**The life of Marie Curie**

For Marie Curie, working with alpha decay was an integral part of disentangling the elements produced in the natural radioactive decay of thorium and uranium. This was a matter of chemistry, as well as physics, and it was through their chemistry that she was able to identify them. Clearly, she was exposed to beta and gamma as well as alpha radiation throughout her career, but nobody has even guessed what dose she must have received. One may speculate that she adapted to radiation as she lived to 66, not far short of...
the average life span at that time, showing that her life was not drastically foreshortened by her radiation work. Her husband, with whom she shared her first Nobel Prize, died at age 46 in a horse-drawn road traffic accident in Paris, vividly showing how life depends on chance, but her achievements did not.

Because alpha radiation has a very short range, the dose that it gives is confined to a region very close to the source, and that makes the dose harder to measure than that from beta or gamma radiation, both of which spread out. Alpha radiation is high LET, so it is intense (in joules per kg) and gives more biological damage per joule than beta or gamma radiation by a weighting factor. This factor is the cause of some mumbo-jumbo in the LNT model, as described briefly in Chapter 5. For alpha radiation the factor is taken to be 20. We ignore this and look for a threshold in mGy per month. Any threshold found for permanent damage by alpha radiation is then an extremely conservative estimate of any threshold for low-LET radiation. This is the strategy we follow.

The Radium Dial Painters and litigation

Practical radiation safety, like safety in other activities, is largely a matter of education, training and overcoming ignorance. A historical instance is the story of the Radium Dial Painters. These were mostly young girls who were employed to paint the faces of watches and instruments with luminous paint early in the twentieth century. The paint contained radium whose radioactive decay provided the energy for it to glow in the dark. Painting the fine lines, numerals and dots was exacting work, and the best workers licked their brushes to keep a fine point. The industry intensified in the First World War, but it was not until 1926 that it was shown that the technique of licking caused bone cancer and the practice was stopped \(^{[33]}\). This action was immediately effective as will be apparent from Illustration 27.

Radium has a chemistry like calcium, and once in the body, it finds its way to tooth and bone where it stays for a long time. Radium-226, the isotope concerned, has a half life of 1,200 years, so providing a chronic source of alpha radiation for the remainder of the person's life. The radiation has a very short range and the damage it causes is to the bone. Bone cancer has various forms, but is relatively unusual and no statistical expertise is needed to appreciate its effect. Illustration 27 is a plot where each symbol represents the death of a worker, with the distance across the plot showing the date at which she started in the industry and the distance up the plot showing her whole-body radioactivity count rate in becquerel (on a logarithmic scale). There are two kinds of symbol: '+' for those who died of bone cancer and 'o' for all of the others. Note that there is no case of death from bone cancer among those who started after 1926 (the vertical line) and none either with a whole-body
count rate below 3.7 MBq (the horizontal line). In total numbers there were 1,339 painters with count rates below 3.7 Mbq (and no cancers); out of 191 painters with more than 3.7 MBq, there were 46 deaths from bone cancer.

Illustration 27: Data for the deaths of Radium Dial painters and whether they died from bone cancers (+) and otherwise (o), according to radioactivity intake and year of entry. Horizontal dashed line is activity threshold for bone cancer 3.7 MBq.

The plot shows a clear threshold for cancer at about 3.7 MBq, whole-body alpha radioactivity. Another message was also clear: there is a need for safety standards and for the public education that should go with them. With these in place from 1926, safety was assured.

However the incident had mixed consequences and casts a long shadow down the history of radiation safety $[^{34}]$. The new safety regime was introduced following denial by management and litigation by workers. This
engendered a spirit of fear and distrust of nuclear radiation for the first time. In fact the law is a totally unsuitable instrument that turns science into a set of instructions to be obeyed, instead of guidance to be understood. In the history of radiation the case of the Radium Girls has resulted in safety advisors putting the need for education second to the need for precautionary measures, even where these are unnecessary. For many organisations since that time, safety has become more a matter of protecting those responsible from litigation, than protecting employees from injury. On the employee side, unknown science became distrusted by default, whereas collaboration and education should have been demanded instead.

On the positive side the incident demonstrates evidence for the existence of a threshold. No statistical gesticulations are needed to see the result, although the processes of litigation ensured that for many years the data in Illustration 27 were not freely available. The threshold in whole-body radioactivity of 3.7 MBq was established in 1941 by US National Bureau of Standards [35]. A practical threshold for a lifelong chronic dose was established by Robley Evans at 10 Gy [33], that is in the region of 1,000 mGy per year [36].

How does this observed threshold for radium compare with the non-observance of cancer at Goiania below 100 MBq for caesium-137? The energy of each radium decay is six times that of caesium (see Table 2 in Chapter 5). So the Dial Painter threshold would be compatible with a cancer threshold of 20 MBq or higher for a whole-of-life caesium-137 exposure. At Goiania no cancers were seen for 100 day exposure to 100 MBq and more. We may not conclude very much except that the data are not in obvious conflict. This seems a rather empty statement, but it matters, because in both cases the exposures are very large relative to the usual safety prescription. In Chapter 9 we will pick these numbers up again, checking them against other sources to arrive at a sensible and consistent conservative safety bound for chronic radiation of all types.

**Safety of plutonium as a new element**

The nuclear bomb dropped on Nagasaki in 1945 used plutonium-239, rather than uranium-235, the nuclear explosive used at Hiroshima. Plutonium is an artificial element that only existed in microgram quantities until mass produced by the first nuclear reactors after December 1942. Plutonium-239 decays by alpha emission with a half life of 24,100 years, and its rate of fission is smaller than its alpha rate by a factor of $4.4 \times 10^{-12}$. So in effect it does not fission at all, except when artificially stimulated by neutrons. This shows that plutonium-239 is a rather innocuous material, in spite of the character given to it in horror movies. In fact, the reason it acquired a dubious reputation in the early days was rather circumstantial.

After the unpleasant surprise of the carcinogenic effect of radium, as exposed
by the Dial Painters, the safety environment for any new unknown alpha emitters was precautionary and suspicious. Nobody wanted to get caught out twice, especially given the possibility of being faced by a clutch of ambitious but un-scientific lawyers.

To set up a sound safety regime for the new element would have required a supply of plutonium and sufficient time in which to conduct tests: for even with animals such experiments take time. But the quantity of plutonium needed and the time scale on which it had to be manufactured and machined, always with the necessary safety in place, was extraordinary. To make a critical mass (several kgs by 1945) the quantities had to be scaled up 1,000 million-fold from the microgramme quantities initially available in 1942 when safety procedures had first to be considered. Such a scale-up for an unknown material would alarm any responsible safety authority!

Nevertheless, safe working practices had to be decided, rapidly and in secret. Experiments with animals were rushed and did not always give consistent results. The uncertainty made some experiments with humans essential. These were carried out necessarily in secret, and without the knowledge of those treated; this deception added to the public distrust, when in later years it was revealed what had been done.

The uncertain conclusions of the tests, the secrecy, the pressure and the obvious lack of confidence at that time led, all too easily, to extra-cautious safety regulations, the antithesis of Marie Curie's advice, *Nothing in life is to be feared. It is to be understood.* Unfortunately, however, the legacy of distrust has never been reversed, and the reputation of plutonium has never been rewritten, as it should have been. Hollywood and the media have been happy to maintain its reputation as *the most dangerous element on Earth,* an accolade better deserved by oxygen.

It was established that plutonium is not retained in the body as effectively as radium and, although both elements are found in bones and teeth, plutonium does not penetrate into bone to the same extent as radium. Under the manufacturing conditions of the Manhattan Project, inhalation of plutonium dust caused most concern at the time. But the medical records of all those Los Alamos workers with lung activity greater then 52 Bq showed no negative effect that could be attributed to plutonium when analysed 42 years later in 1991. Lung activities in 1987 (or at death) ranged to 3,180 Bq with a median value of 500 Bq. The highest activity is compared with the threshold found for the Radium Dial Painters in Table 6.
Table 6: A comparison of human cases involving high internal activities of various different alpha emitters.

Evidently, even the highest level of plutonium activity is substantially less than the threshold for cancer among the Radium Dial Painters. Such a comparison would be ill-advised if the difference were small, but that is not the case. The worst fears of those charged with the safety of plutonium workers in the 1940s were not realised in practice. Nevertheless the reputation of plutonium as the most dangerous substance known to man has never been corrected in the popular mind.

**Extreme experiences, Litvinenko and McCluskey**

Malicious intent is dangerous, whatever technology is used. The poisoning of the Russian agent, Alexander Litvinenko, in London in November 2006 would have been no less fatal if he had been assassinated by Lucrezia Borgia (1480-1519) with arsenic, administered in a glass of wine. The massive dose of polonium-210 that he was given in a cup of tea, once ingested, could not be treated, although as an alpha emitter the radiation was not dangerous to others. He died after three weeks.

Single cases should be seen only as qualitatively interesting, but the story of Harold McCluskey is at least a happier one. At the Hanford Plutonium Finishing Plant in 1976 he was working through a glove box behind a lead-glass screen. When there was an explosion he received an intake of at least 37 MBq of Americium-241, 500 times the occupational limit. Americium-241 is an alpha emitter used in a small quantity in domestic smoke alarms; it is a component of nuclear waste. McCluskey survived for another 11 years after the accident, eventually dying from coronary artery disease. A post mortem examination is reported to have revealed no signs of cancer in his body.
activity was a factor ten greater than the threshold seen for the Radium Dial Painters, although an examination of Illustration 27 suggests that painters who had an activity similar to his had a 50% chance of dying of cancer. He was fortunate. He died aged 75, continuing to the end to be a vocal supporter of nuclear power.

**Uranium – natural, enriched and depleted**

Like plutonium, uranium is a typical alpha emitter and it does not fission or release much energy. It only comes into its own and starts fissioning when stimulated by free neutrons – and they are not around except inside a working reactor, or a detonating weapon. Consequently it is remarkably safe and easy to handle. Its most obvious property is its density, 19.1 times that of water, and that, with its hardness and high melting point, is the reason for its use in conventional armaments.

Natural uranium is 99.3% uranium-238 (with a half-life of 14.1 billion years) and 0.7% uranium-235 (with a half-life of 0.7 billion years) with trace amounts of uranium-234. Uranium, enriched as a reactor fuel, has a few percent of uranium-235, but handling it is not hazardous. Only when quantities begin to approach the critical conditions of geometry and enrichment does the neutron flux begin to multiply. Otherwise, uranium is a fairly safe material.

Depleted uranium is even safer, the percentage of uranium-235 having been lowered – hence the description *depleted*. Its lack of risk is the subject of two reports by the Royal Society [40, 41].

**Notes on Chapter 6**

2) *The Radiological Accident in Goiania*, IAEA (1988)
5) NJ Valverde (2013) private communication
7) *The banana equivalent dose* Wikipedia
   http://en.wikipedia.org/wiki/Banana_equivalent_dose

9) These may be seen at [http://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+7389](http://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+7389)


11) [http://www.washingtonpost.com/opinions/time-to-better-secure-radioactive-materials/2012/03/23/gIQAn5deaS_story.html](http://www.washingtonpost.com/opinions/time-to-better-secure-radioactive-materials/2012/03/23/gIQAn5deaS_story.html)


16) The international safety authorities have expressed concern at the use of the English prefix *in*- which sometimes, but not always, means *not*, as in *inexpensive*. They therefore drop the *in*- from *inflammable* and from *inheritable* too. This text is not an international safety manual and adheres to traditional English usage.


19) Called *Low LET* radiation its effect is sparse and spread out. Alpha radiation is called *High LET* and is locally concentrated at the microscopic scale.


22) Advice given to house owners by Public Health England [http://www.ukradon.org/information/housesales](http://www.ukradon.org/information/housesales)


26) Becker K *Health Effects of High radon Environments in Central Europe: Another Test for the LNT Hypothesis?* (2003)  
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2651614/  
27) *Pooled Bayesian Analysis of Twenty Eight Studies on radon Induced Lung Cancers.* Fornalski and Dobrzynski, Health Physics 10; 265-273 (2011)  
http://journals.lww.com/health-physics/Abstract/2011/09000/Pooled_Bayesian_Analysis_of_Twenty_Eight_Studies.6.aspx

28) *Radon risk and Cancer* C P Connell, Forensic Technologies Inc  
http://forensic-applications.com/radon/reviews.html

http://www.bmj.com/cgi/content/full/330/7485/223

http://www.jstor.org/pss/3581380

http://www.jstor.org/stable/20486020

32) *Radon risk in spas?* G Koteles  
http://www.omfi.hu/cejoem/Volume13/Vol13No1/CE07_1-01.html


34) http://en.wikipedia.org/wiki/Radium#Luminescent_paint

35) The factor of 37 appears frequently because 37 Bq = 1 nCi. The Curie (Ci) is an older unit of radioactivity.

36) According to LNT using the prescribed weighting factor $w=20$ for alpha radiation, the dose 10 Gy would be 200 Sv, that is 200,000 mSv.


38) *A 42-y Medical Follow-up of Manhattan Project Plutonium Workers* Health Physics Voelz GL et al. (1991)  


Chapter 7: Protected by Physical Science

In the beginning the universe was created. This has made a lot of people very angry and has been widely regarded as a bad move.

Douglas Adams (1952 – 2001)

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Nucleus at the centre of the atom

Physical science and quantum mechanics

Unlike biological science, which relates to life on Earth, physical science applies everywhere in the universe and at all times. We know this because when new instruments allow us to look in more remote places or reconstruct what happened at earlier times, science finds that the same laws at work as apply here and now. Of course it is the ambition of every young red-blooded scientist to find conditions where predictions based on current knowledge fail. Science aims not to defend its current ideas against attack, as its detractors sometimes suppose, but to mount such attacks itself. A lack of success in this object represents a triumph for the state of the science. The way in which the laws of physics are used to make predictions is what scientists call theory, a description that can give rise to some popular misunderstanding. There is nothing iffy about theory. At the end of the nineteenth century, classical physics, the theory that had been built up on the foundations laid by Galileo and Newton, was found to give wrong predictions, but in the early decades of the twentieth century the laws of quantum mechanics were established, culminating in the work of Paul Dirac, one of the most brilliant physicists of all time [1]. Today quantum theory or quantum mechanics – we use the descriptions interchangeably – appears quite secure in spite of its counter-intuitive results. Some of these are important, even for a brief understanding of the atom and its nucleus.

Here is an everyday example of the strange ways of quantum mechanics. When an electric current passes along a wire, electrons (which are particles of ordinary matter) travel through solid copper with only the smallest hindrance. This is incomprehensible to common sense and to classical physics too, but is quite normal in quantum mechanics. It is not really weird because it happens every time we turn on an electric light! It is the real world and we should take it on board.

In the 1920s some of the more wacky consequences of quantum theory were thought to be quite beyond the reach of actual experiment, but the scientific papers of the day described what should happen in these experiments if you ever could do them – they were called Gedanken or thought experiments. Physicists in those days were wrong to think that these would be forever impossible to do, and recently such experiments have been carried out and have shown that the theory was correct in its predictions. So there is every reason to be confident in the current theory of the physical world, which means that it can be used productively for the benefit of society, knowing that it is unlikely to fail. In practical applications, it is normal to use a common sense or classical picture of physical science (even though it is technically wrong), referring to quantum theory only where it has something important
and significantly different to say – and that is the case for the simplified
descriptions in this book, usually classical, but sometimes quantum. So what
are the elements of physical science and how do they behave?

**The cast – proton, neutron and electron**

The theory is like a play with a cast of characters and a script or plot for how
they interact or relate as the story develops. Here is a simplified summary –
correct but omitting some characters that do not come into our story of
everyday energy and the environment. (These extra characters are well
known and have been studied carefully at laboratories like CERN, Geneva.)
The cast consists of a colossal number of particles, of which there are only
three different kinds: the proton, the neutron and the electron. Every electron
has the same negative electric charge, rotates on its axis (spin), has a mass of
$9.1 \times 10^{-31}$ kg, and behaves as a point in space. It is a principle of quantum
mechanics that all electrons are completely indistinguishable from one
another. The proton and neutron have positive and neutral electric charge
respectively, also rotate, but are some 2,000 times heavier than the electron.
The script tells us that, electrically, the electrons and protons attract one
another, but that electrons mutually push one another apart with an inverse
square law; and any number of protons do likewise. Neutrons, being neutral,
are uninfluenced by the electric charge of electrons and protons. But there is
another force called the **strong force** that acts between neutrons and protons
when they are very close $[\text{[2]}]$. If protons and neutrons are further than a few
times $10^{15}$ metres apart, the strong force is absent – this distance is 100,000
times smaller than an atom. Just as the neutron is oblivious of the electric
force, so the electron is oblivious of the strong force. So essentially, electrons
and neutrons never collide – it is as if they can pass right through one
another.

**Atomic structure of matter**

So how do these simple ingredients with their mutual attractions and
repulsions determine the structure of matter, that is, the aggregation of very
large numbers of electrons, protons and neutrons? There will be much more
to say about energy in the next section, but here we just need the principle
that the most stable structure should be the arrangement of lowest energy.
That is the structure that you get when these electrons, protons and neutrons
just fall in on top of one another, so to speak. The result is many neutral
atoms, each composed of a roughly equal number of electrons and protons
with some neutrons. Within each atom the neutrons and protons fall inwards
to form the very dense nucleus at the centre of each atom. To understand the
details we need to look at how the arrangement of lowest energy comes
about.
The energy concerned will be made up of simple kinetic energy, \( \frac{1}{2}MV^2 \) for a mass \( M \) with speed \( V \), and the potential energy due to the forces described. The strong force dominates, so, first of all, the protons and neutrons cling together under their mutual attraction. This ceases to be effective for very large numbers of protons and neutrons when the cumulative mutual electrical repulsion between the protons, with its longer range, becomes larger than the strong attractive but short range force \(^3\). This limited composite of protons and neutrons is the nucleus; all nuclei are about the same size within a factor 5, that is a few times \( 10^{-15} \) metres across. The most stable has about 26 protons and a few more neutrons, but those with up to 90 protons and 150 neutrons are also more or less stable. This is the story behind the nuclear binding energy curve shown in Illustration 28, where the heaviest and lightest are the least favoured, energetically. So energy can be released in two different ways: firstly, if a nucleus with the very largest value of \( A \), the number of protons plus neutrons, could split into smaller ones – this is called nuclear fission; secondly, if a pair with the very smallest number \( A \) can be combined in some way – this is called nuclear fusion.

That such changes are quite extraordinarily difficult to achieve is closely related to the inherent natural safety of nuclear energy. The effectiveness of this security completely overshadows any regulation that might be imposed by any human safety authority. To see how this happens we need to look further at the structure of matter on a wider scale.

Because of their large positive charge there is a very strong mutual repulsion
between nuclei, and consequently they are pushed to positions at a maximum distance apart. What sets the scale of this separation and, therefore, the average density of all normal matter? This is where the electrons play an essential part. To minimise the overall electrical energy their number equals the number of protons. So each nucleus is surrounded by enough electrons to balance the number of its protons, roughly speaking. Indeed the outermost electron should balance the combined charge of the nucleus and all the other electrons further in. This is a single question: how does an electron behave when orbiting around a net equal and opposite charge.

We need quantum mechanics to understand nature's solution to this question. It is a matter of the balance between two effects, the electrical one that pulls the electron and nucleus together and another force that pushes them apart – this is where the quantum wave nature of the electron comes in. You cannot put a wave into a region that is smaller than its wavelength – putting it graphically, the region needs to be at least one wiggle in size, as sketched in Illustration 29. Since the work of Louis de Broglie in 1923, it has been known that the momentum of a particle (its mass times velocity) when multiplied by its wavelength is a constant, known as Planck's constant – and this is precisely true for all particles at all times. Consequently, it takes kinetic energy, the energy of motion, to keep a particle in a small region, and the smaller the region the more energy it requires. By balancing this energy against the electrical attraction between an electron and a nucleus, the size and energy of an atom is set. We can calculate this ourselves, as given in the boxed discussion below. If you prefer, you can skip this and just pick up that the size of every atom is roughly $10^{-10}$ metres across.

**Roughly, what is the energy of a mass $M$ held in a box of size $X$?**

In Newton's mechanics any mass $M$ with speed $V$ has kinetic energy $E = \frac{1}{2}MV^2$, and also a momentum $P = MV$. This means that $E = \frac{P^2}{2M}$.

In quantum mechanics information about the momentum $P$ is given by a wave with wavelength $\lambda = \frac{h}{P}$ where $h$ is Planck's constant, $6.6 \times 10^{-34}$ J s.

If the wave describes the position of $M$, it cannot be kept in a region $X$ smaller than about half a wavelength, as sketched in Illustration 29.

So $h/P \approx 2X$ and $P \approx h/2X$, where the wavy equal sign means we have ignored that space is 3D but the result is still approximately correct. *continued on overleaf.*
Using this result we can replace $P$ in the formula $E = P^2/2M$ to get $E \approx \hbar^2/8MX^2$.

This is what we wanted to find, a formula for $E$ given the values of $M$ and $X$. Now we can put in some numbers and find some answers:

**What is the size of an atom, roughly?**

For an electron ($M = 9.1 \times 10^{-31}$ kg) in orbit round a nucleus, this kinetic energy should about match the electrical potential energy $e^2/4\pi\varepsilon_0X$ in standard SI units which means $X \approx 4\pi\varepsilon_0\hbar^2/(8Me^2)$

So putting in the numbers, the size of the atom is calculated to be about $X = 3 \times 10^{-10}$ m across. Actual measured sizes are 2 to 3 times smaller.

**What is the energy of an electron in an atom, roughly?**

Putting in numbers for an electron in an atom of size $X \approx 3 \times 10^{-10}$ m gives kinetic energy $E \approx 7 \times 10^{-19}$ J, that is 4 eV.

The measured energy of the hydrogen atom, as an example, is 13.8 eV.

These calculations are over-simplified, which is why the answers come out slightly wrong. Using quantum mechanics to calculate the actual wave shape in three dimensions, highly accurate energies are derived. Although the answers then depend on the details, the broad principles are already here. As a study of chemistry relates, these finer details depend on the way in which neighbouring atoms share electrons to form molecules, and a study of condensed matter physics describes how these molecules or atoms configure themselves in a 3D-crystal, or in a liquid or gas. However, within a factor ten, all atoms are of similar size, and the energies of their outer electrons are similar too.

Notice that if you skipped the calculation in the box, you will have to trust the result. The only alternatives are to turn your back on the whole business or to study it yourself. In general these are the three options: trust, ignore and study. But only the trust and study options lead to better prospects for life.

**Nuclear sizes and energies**

What happens if a similar argument is applied to the protons and neutrons inside an atomic nucleus? The nuclear size was measured to be some $10^{-15}$ metres in the early twentieth century by means of Rutherford Scattering experiments. The energy of protons and neutrons inside comes out at about 20 MeV by the same argument as used for the energy of an electron confined to an atom.
So there is a factor of a million between the energy of an electron in an atom and the energy of a proton or neutron in a nucleus, as described by simple quantum mechanics. Chemical energy, for instance the energy released by burning carbon fuels, comes from the electrons when atoms are rearranged in molecules. In a similar way, nuclear energy comes from rearranging protons and neutrons in nuclei. So this factor is the basic reason why nuclear energy is about a million times more powerful than carbon fuel combustion. These simple calculations have extraordinary consequences.

### Energy in physical science

#### Conservation of energy

Energy is a crucial quantity in basic physical science, and hardly less important in everyday life. One of the underlying laws of science is that energy is conserved, so energy cannot be made and can only be transformed from one form to another or moved from one place to another – that is why conservation is important. So whenever reference is made to saving energy or generating energy, that can only mean retaining it in a usable form, or transforming it from a stored to a more readily accessible form.

That is rather an important point. It means that a search for a way to store energy is just a search for another energy source – a source and a store are similar. The science that describes what you can do in principle when you move energy around is called thermodynamics, but we need only its simplest idea here, that energy is conserved. As a consequence, energy stores are potentially just as dangerous as energy sources. Consider the energy stored by a hydroelectric dam. A crack, whether initiated by an earthquake or a design failure, may be a precursor to the release of a wall of water on those who live downstream. To avoid this it is necessary to be able to release the energy stored in the full dam as fast as possible, but without causing loss of life. So the problem of dispersing stored energy in the event of an accident is not peculiar to a nuclear reactor with a rapidly rising temperature, like the ones at Fukushima Daiichi. If a sufficiently large energy store were developed to accumulate energy from wind or solar, it would have a similar problem in the event of an accident – even if the principle of making such a

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What is the energy of a proton (or neutron) in a nucleus, roughly?

Using the same formula $E \approx \frac{\hbar^2}{8\pi^2 M X^2}$ that we used for an electron in an atom, we put in the values for a proton mass ($M = 1.7 \times 10^{-27}$ kg) and a nucleus of size $X \approx 3 \times 10^{-15}$ metres (eg for carbon-12).

The calculation gives a value $E \approx 3 \times 10^{12}$ J, that is 20 MeV.

Actual observed proton and neutron nuclear energies are a few MeV.
store sufficiently large could be solved. At present there is no such solution, so the problem of its safety has not arisen yet.

A brief discussion of energy should help us to compare different sources.

**Kinetic energy – the energy of motion**

Material in motion carries energy in a form called kinetic energy. Examples are the movement of wind and water, or the rotation of a turbine. It is notable that the energy of a moving mass increases with the square of its speed, so, as road safety demonstrations are always keen to point out, a car moving at 40 miles per hour has four times the energy that it has if moving at 20 miles per hour. This energy also increases with the mass of the moving object. Thinking about the energy of wind, the mass of air reaching the blades of a wind turbine each second increases with the wind speed. Therefore, the energy per second available from a perfect wind turbine increases with the \textit{cube} of the speed. So there is a thousand times as much energy available from a turbine in a wind at 50 miles per hour as at 5 miles per hour. That is a significant problem for a wind farm that is intended to provide a steady supply of electricity in variable wind conditions. In high-wind conditions this energy is liable to damage the turbine, even to destroy it – and therefore much of the cost of a wind turbine goes into ensuring that it is strong enough to withstand the highest wind conditions. This can be done but it is expensive. Wind energy is a poor resource because the mass is low, the wind speed is not great and is highly variable.

Tidal currents are more predictable and water has a higher density than air, but the speeds are very low even in the best isolated locations. Wave power has higher speeds than tidal but all of the unpredictability of wind. The destructive power of wave energy is legendary, and defence against exceptional storms is difficult and expensive.

**Thermal energy**

Higher energy is available when larger masses move at higher speeds, like the speed of sound. The molecules in a gas move around randomly at such speeds, which is how they are able to transmit the pressure waves of sound so fast. These moving molecules in a hot gas or liquid are therefore a good energy source in principle – and this is what we know as thermal or heat energy. As this way of introducing it suggests, heat is a very powerful source compared to wind, although there are problems because the motion is random in direction. The Second Law of Thermodynamics sets the maximum efficiency with which such random thermal energy can be converted into a more useful form like a rotating turbine or an electric current. This efficiency is seldom good. In a typical oil, gas, coal or nuclear power station this efficiency may be as low as 30%. That means twice as much energy is going
to the cooling tower or heating the river as is coming out in the form of electrical energy.

| We omit the details here, but this maximum efficiency is given by the quantity (1-\(T_1/T_2\)) where \(T_1\) is the absolute temperature of the exhaust and \(T_2\) is the absolute temperature of the hot source. \(T_1\) is never much less than ambient temperature, 293 K, so that there is great advantage in having \(T_2\) as high as possible, whether in a diesel car engine or a nuclear power station. |

This is the reason that a fossil fuel plant may generate three times as much carbon dioxide as you might expect. For instance, power plants may be described as 3,000 MWh (meaning thermal power) or 1,000 MWe (meaning electrical power). That difference is large and matters. It means that 2,000 MW of energy has to be discarded and this applies to carbon-burning plants as much as to nuclear ones. There are processes that can make good use of discarded heat, such as greenhouses and local combined heat and power (CHP) schemes.

Here is a rough comparison between wind energy and thermal energy. (This refers to the energy per kg and so does Table 7. As already pointed out, in terms of the energy per second, light winds come out even worse in the comparison because the mass of air, the number of kgs hitting the turbine, falls as the wind speed drops.)

| The energy of mass \(M\) moving at speed \(V\) is \(\frac{1}{2}MV^2\). So air moving at 60 miles an hour, that is 22 ms\(^{-1}\), carries 240 Joules of energy per kg, as wind. |
| The random motion of the molecules of the same kg at room temperature is 770 miles an hour, that is 345 ms\(^{-1}\), that is 59,500 Joules as heat energy. |
| So the energy of wind in each kg, even blowing at 60 mph, is smaller than its thermal energy by a factor 200. |

### Directional energy

There are other forms of directional energy such as gravitational energy that can be converted to electrical energy more efficiently than thermal energy. Lifting a mass upwards by a distance increases its potential energy and dropping it turns this extra energy into directional kinetic energy. If a frictional brake is applied, the energy ends up as thermal energy and the brake will get hot. Note how kinetic energy can be turned back into gravitational energy quite easily, but once the energy becomes thermal, it cannot efficiently revert to potential energy again – this is the influence of the Second Law of Thermodynamics. Hydro-power is the important example; the efficiency means that energy can be stored; that is surplus energy can be used
to pump water up into a reservoir, and then reconverted back into electricity at a later time, although the number of sites where this can be done on a grand scale taking advantage of natural land formation is limited. Consequently such storage is insufficient to support a whole national energy policy. The cost is quite high and safety is a concern, as always for energy storage. Directional chemical energy storage – battery storage in fact – is another important solution that is useful, but has limited capacity.

**Energy density**

A useful measure when discussing energy is *energy density* [see Selected References on page 279, SR1]. Imagine a waterfall, as an example. You might get the same flow of energy from a very high waterfall with a trickle of water passing over it, as you do from a large flow of water passing over a low waterfall. Nevertheless, the high waterfall provides a more powerful source of energy that could push back the flow of a low waterfall, as it were. We can describe this by looking at the *energy per kg* instead of the total energy. This energy density is called the potential. Sources of high energy density are much to be preferred; they are compact, require less mass of fuel and generate less waste. Table 7 shows the vast difference between the energy density of different sources, even neglecting the poor efficiency factor of $\frac{1}{3}$ for coal and nuclear, both being non directional.

<table>
<thead>
<tr>
<th>Source</th>
<th>5 mph wind</th>
<th>60 mph wind</th>
<th>100m high waterfall</th>
<th>Fossil (coal)</th>
<th>5% enriched uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid battery</td>
<td>0.15 million</td>
<td>1.7</td>
<td>240</td>
<td>1000</td>
<td>24 million</td>
</tr>
<tr>
<td>60 mph wind</td>
<td>240</td>
<td>1000</td>
<td>24 million</td>
<td>4 million</td>
<td>million</td>
</tr>
<tr>
<td>100m high waterfall</td>
<td>1000</td>
<td></td>
<td></td>
<td>24 million</td>
<td></td>
</tr>
<tr>
<td>Fossil (coal)</td>
<td>24 million</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% enriched uranium</td>
<td>4 million</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 7: Energy density for various sources (measured in joules per kg). Note that the energy density of wind is 144 times larger per kg at 60 mph than at 5 mph, but the energy per second is another factor 12 times higher because more kgs hit the turbine in a second at 60 mph.*

All forms of energy contribute to the energy $E$ in the equation $E = Mc^2$, where $M$ is the mass change. In spite of what you may find in popular accounts, this famous equation has no special relationship to nuclear energy. For example, the water at the top of a waterfall has slightly more mass than the same water at the bottom when stationary although the difference is tiny. Because nuclear energies are large, the mass change is measurable when some $E$ is extracted. The exchange rate, $c^2$, is an impressive $9 \times 10^{16}$ joules per kg. This is how much energy you would get if *all* the mass were turned into energy, but the entries in Table 7 are much smaller. Comparison between the columns shows what really matters. In particular, the number for uranium is larger than that for coal by the same factor as 1 hour of work on one hand, and a lifetime at 60 hours a week on the other $[^4]$. When it comes to the
amount of waste produced per unit of energy, the mass of waste produced by nuclear is smaller than that produced by coal by 167,000. This factor is deduced by taking the numbers from the Table, 4 million million divided by 24 million. If the part-used nuclear fuel is recycled, the situation is even more beneficial.

Here is a slightly different comparison. A modern Li-ion battery stores as much as 0.2 kWh of energy in 1 kg of lithium. How does that compare with the nuclear fission energy stored in 1 kg of thorium, for example? In the nuclear fission of a nucleus the energy released is about 200 MeV – that is 1/1000 of the total \( M c^2 \) of the atom. So there are \( 9 \times 10^{13} \) joules of fission energy per kg of thorium. That is \( 2.5 \times 10^7 \) kWh per kg, or 100 million times the energy capacity of the Li-ion battery. That number means there is no contest between a chemical battery and nuclear energy as a source of electricity. A battery can just about serve as short-term portable storage, but it needs to be recharged frequently from a base load power plant.

**Natural apprehension**

It is natural that without sufficient reassurance large energies cause concern. Standing at the base of a major hydroelectric dam would generate an unpleasant frisson of fear for most people. Tanks of volatile inflammable fossil fuel and stores of chemical explosives are no better. Once ignited, fossil fuels fires are liable to spread without control, especially when the fire escapes into the environment. Mankind has had to face up to living with this risk for many millennia. A question is whether the assurance of safety that cannot be given convincingly for fire can be given for nuclear energy. Since the energy density is very much higher, the assurance needs to be that much more complete.

Surprisingly, this assurance is provided from three separate and independent sources. Firstly, it comes in principle from physical science, as described in the remainder of this chapter. Secondly, it comes in principle from biological science, as described in the next chapter. Finally, it comes in practice from the experience of seventy years of deployment of nuclear energy with a safety record that is better than offered by any other energy source.

**Nuclei inviolate**

**Isolation by the coulomb barrier**

Although nuclear energy is immensely powerful on paper, it is far safer than expected. Each nucleus lives an isolated celibate life with its nuclear energy securely locked and the nucleus of one atom never meets the nucleus of another. In fact, on Earth only one nucleus in a million has changed at all
since the Earth was formed more than 4,500 million years ago, and then only by decay. The laws of physics that describe the unconditional electrical repulsion between like charges ensures that the nucleus is prevented from doing anything at all. Apart from being carried about passively at the centre of its atom, the only activity possible for some nuclei is rotation – and for more than half of them even that is excluded. (Interestingly, this rotation is the basis of MRI, more fully described as nuclear magnetic resonance (NMR) imaging – the adjective nuclear is usually omitted from the name out of a misguided sensitivity to popular nuclear phobia.) Each nucleus is individually packaged in its own enveloping electronic atomic cloud, 100,000 times its size, and held in position by an intense electrical force. This packaging is extraordinary. It is no wonder that none is ever damaged! One can only marvel at the degree to which nuclei are isolated from one another.

When Rutherford analysed the first experimental data in which two nuclei (helium and gold) were fired at one another, he was able to show that because they could bounce off one another at 180 degrees without penetrating one another, all of their electric charge must be concentrated in a nucleus of tiny dimensions. The inverse square law means that the electric force increases by a factor of $10^{10}$ in moving close to the nucleus. This electric defence is called the Coulomb barrier – Coulomb was the pioneer in the unravelling of the physics of electricity who first described the force between electric charges.

So even the most energetic nuclei can only bounce off one another and do not have enough energy to penetrate the barrier. In their isolation they are prevented from releasing their energy under almost any circumstances. Only at the centre of the Sun at a temperature of some 15 million degrees does a nucleus get enough energy to meet and react with another, and even there, only once every few billion years. In the entire life of the Sun such an encounter will happen just once for each hydrogen atom. That is when it reacts with another to form helium, releasing the energy that gives us sunshine and the mainspring of energy for life here on Earth – the details are more complicated, but the idea is that simple.

**Nuclei protected from alpha, beta and gamma radiation**

This isolation of each nucleus from every other is entirely electrical in origin. But can radiation penetrate this barrier and so react with the nucleus? Alpha particles and other beams of positively charged particles are repelled by the positively charged nucleus and cannot reach it at normal energies. This does not apply to negative and neutral particles, but let's look at each of the candidates: first, energetic electrons and photons – we come back to beams of neutrons and what they might do on page 172.

In the environment, electron and photon radiation (beta and gamma) may
have an energy up to about 2 MeV. Within the target nucleus the neutrons and protons are tightly bound, and a certain minimum energy is required to dislodge one. This is analogous to the photoelectric effect in an atom, where a certain minimum energy is required to dislodge an electron, as mentioned in Chapter 5. In the nuclear case the minimum energy varies between about 5 and 7 MeV – similar to the energy of nuclear quantum waves worked out roughly in the box on page 161. As in the photoelectric effect nothing substantial can happen unless the energy given by the electron or photon to the nucleus is greater than this value. So in the environment, alpha, beta and gamma radiation can do no more than just bounce off a nucleus. Only in a research laboratory can radiation be given enough extra quantum energy to tweak a target nucleus enough to make a material radioactive.

This is a crucially important result for nuclear safety. It says that nuclear radiation – that is alpha, beta or gamma – can never make another nucleus radioactive. That means that radioactivity never spreads from material to material: it never catches and increases in the way that fire does. Radioactivity may be carried from place to place, but each individual radioactive nucleus can decay just once, so as time goes by, the radiation emitted must die away. This gives nuclear a degree of safety and proliferation resistance that is qualitatively superior to any fossil fuel hazard. Following the Fukushima accident nobody seems to have told the families in Japan about this. They looked on radioactive material as if it was contaminated by a virus, Ebola for instance. They were frightened of catching its effect, when there was no reason to be. The difference is simple and it should have been explained to them that radioactivity is not contagious. That was negligent.

**Radioactive power in nature**

**Components of background radiation**

The nuclear security provided by the Coulomb barrier is so good that it was not until the last years of the nineteenth century that the existence of nuclear energy was stumbled upon. Nobody guessed the presence of this buried treasure. Its impenetrable bulwark has provided protection from the accidental release of this latent energy, ever since it was breached in the extreme conditions of element-forming nuclear explosions that preceded the formation of the Earth. Everything on Earth today, except hydrogen, is actually nuclear waste from that epoch. Since then, thanks to the Coulomb barrier, activity cooled off rapidly. Most of the unstable nuclei that were left decayed to stable forms, leaving the particular atoms that we find around us today. Although that was a long time ago there are a few exceptional isotopes with such long lifetimes that they are still present and decaying today, notably uranium-235, uranium-238, thorium-232 and potassium-40. These
are the sources of the radioactivity that we call *natural*. In reality there is no comfort at all to be attached to this *not-made-by-man* label. Such make-believe descriptions owe more to man's desire for security than to any objective science. These primordial radioactive isotopes are scattered everywhere at low concentrations. Potassium-40, naturally present in all life, gives most of the internal radiation dose that the human body gives itself, that is 0.24 mGy per year, discussed in Chapter 5. The radioactive nuclei present in rocks, soil and water give much of the external dose to the human body (about 1.2 mGy per year, including gamma rays and radon gas); the rest comes in the form of medical doses and cosmic rays from space. These rays produce showers of secondary particles in collisions at the top of the atmosphere, and some of these reach ground level.

This so-called natural radiation amounts to about 1.0 mGy per year, but varies a lot according to location. The composition of the local rock and the radon that it releases is responsible for the wide variation of tens of mGy per year in places such as Brazil, Cornwall, the Czech Republic, India and Colorado. Reported doses depend on conditions, for instance whether buried in the sand, unventilated in a cellar, or taken in the fresh air. Spas which offer health benefits from radon in their waters are common in these regions, as well as in Japan, Jamaica and Germany.

Closer proximity to the Earth's magnetic polar regions and greater altitude increase exposure to cosmic rays because these are less deflected by the Earth's magnetic field and absorbed by the atmosphere, respectively.

**Radiation history of the Earth**

After the Earth formed and started to cool, life evolved to be tolerant of the slowly declining flux of ionising radiation, for if it had not, it would not have survived. In early times the flux of radiation came, as it does today, both from local radioactive decay within the rock, soil and water of the Earth and from radiation reaching the Earth's surface from space. Knowledge of the half-lives of radioactive isotopes, some still in the Earth's crust today, and a few others that decayed away in the past 4,500 million years, comes from laboratory experiments. This enables us to know the activity of the Earth's crust after the first 1,000 million years, and the dominant change was the gradual decay of uranium-235 (lifetime 700 million years). The lifetimes of the other major isotopes, potassium-40 (1,250 million years), thorium-232 (14,100 million years), and uranium-238 (4,500 million years) are sufficiently long that their activity has not changed much. Neptunium-237 (2 million years) would have died away quite early. It is simple to work out what the activity was 2,000 million years ago. The answer is that it was just over twice what it is now. That is not a larger difference than the variation from one place to another in radiation from rocks today. The big difference
between then and now would have been in the energy available to drive the movement of the tectonic plate; this would have been greater by the same factor two. Earth's volcanic activity must have been that much greater. Even today, shifts in the Earth's crust have a greater impact on the safety of life than radiation itself, as was evident in Japan in March 2011.

Today the flux of radiation from space, when filtered by the atmosphere, is the source of only about 10% of the typical natural dose. The composition of the atmosphere varied in the past and changes in the ozone layer affect the flux of UV reaching the surface. In the past it is likely that external events including stellar outbursts, within and beyond the galaxy, altered the flux of cosmic rays. These are also influenced by the Earth's magnetic field, and data show that has changed frequently in the past.

While there were times when the atmosphere was thicker with extra CO\textsubscript{2} and water vapour than today, it is probable that there were other times when the atmosphere was a less effective radiation shield. Whatever those variations, it is likely that they were more significant to the viability of life than changes in the flux of radiation from rocks. Indeed, we are faced by such atmospheric changes today and the importance of these will continue to dominate the flux of radiation.

**Power for plate tectonics**

The main sources of natural radioactivity are listed in Table 8 with their abundances in the Earth's crust.

<table>
<thead>
<tr>
<th>Element</th>
<th>Potassium-40</th>
<th>Thorium-232</th>
<th>Uranium-235</th>
<th>Uranium-238</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half life</td>
<td>$1.27 \times 10^9$ yr</td>
<td>$14.1 \times 10^9$ yr</td>
<td>$0.5 \times 10^9$ yr</td>
<td>$4.5 \times 10^9$ yr</td>
</tr>
<tr>
<td>Absolute element abundance</td>
<td>20,900 ppm</td>
<td>9.6 ppm</td>
<td>2.7 ppm</td>
<td>2.7 ppm</td>
</tr>
<tr>
<td>Relative isotopic abundance</td>
<td>0.01%</td>
<td>100.00%</td>
<td>0.70%</td>
<td>99.30%</td>
</tr>
</tbody>
</table>

*Table 8: The main naturally occurring primordial radioactive isotopes (ppm means parts per million).*

The energy that their decay releases is sufficient to maintain the Earth's high internal temperature, and this generates the slow radial convective circulation of the Earth's mantle. As a result sections of the Earth's crust that float on top of the mantle are moved about. These sections are the tectonic plates whose collision and relative motion are responsible for all volcanic and seismic activity. So the Japanese earthquake and tsunami of 11 March 2011 were
caused by the Earth's own natural radioactive decay heat, vastly more damaging than the effects of the man-made decay heat released by the Fukushima reactors.

If we look upwards, our view of the universe is almost unobstructed, but if we look down our ability to see what is happening a few hundred metres into the Earth is almost non-existent. We do know that the temperature in a deep mine is elevated and this increase continues towards the centre of the Earth. The gradient in temperature means that heat is continuously flowing outwards, by convection and conduction, and has been since the Earth was formed. The current heat loss is measured as about 44 TW (terawatt), corresponding to the Earth cooling by about 2 degrees every million years (if the heat were not replaced). Such a calculation, first carried out by Lord Kelvin in 1862 without any knowledge of the contribution of radioactivity, suggested that the Earth should have cooled much more than it has in its 4.5 billion year life.

One large-scale manifestation of the movement of plates on the Earth's surface is the Ring of Fire [5], a line of volcanoes, trenches and earthquake locations that stretches in a huge arc around the Pacific Ocean from New Zealand, crossing the Equator between the islands of Indonesia, north to Japan, across to Canada, along the San Andreas Fault in California and southwards along the Chilean coast of South America.

**Darwin and the 1835 Chilean Earthquake**

Charles Darwin on his voyage aboard HMS Beagle observed the Great Chilean Earthquake and Tsunami of 1835 that destroyed Concepción and Talcahuano [6, page164-166]. In his journal for 20 February he wrote:

*This day has been memorable in the annals of Valdivia, for the most severe earthquake experienced by the oldest inhabitant. I happened to be on shore, and was lying down in the wood to rest myself. It came on suddenly, and lasted two minutes, but the time appeared much longer. A bad earthquake at once destroys our oldest associations: the earth, the very emblem of solidity, has moved beneath our feet like a thin crust over a fluid;— one second of time*
has created in the mind a strange idea of insecurity, which hours of reflection would not have produced.

And on 4 March he saw the effect of the tsunami created by the earthquake:

*We entered the harbour of Concepcion. While the ship was beating up to the anchorage, I landed on the island of Quiriquina. The mayor−domo of the estate quickly rode down to tell me the terrible news of the great earthquake of the 20th: "That not a house in Concepcion or Talcahuano (the port) was standing; that seventy villages were destroyed; and that a great wave had almost washed away the ruins of Talcahuano." Of this latter statement I soon saw abundant proofs − the whole coast being strewed over with timber and furniture as if a thousand ships had been wrecked. Besides chairs, tables, book−shelves, etc., in great numbers, there were several roofs of cottages, which had been transported almost whole.*

His scientific observations are impressive and show profound physical intuition:

*The effect of the vibration on the hard primary slate, which composes the foundation of the island, was still more curious: the superficial parts of some narrow ridges were as completely shivered as if they had been blasted by gunpowder. This effect, which was rendered conspicuous by the fresh fractures and displaced soil, must be confined to near the surface, for otherwise there would not exist a block of solid rock throughout Chile; nor is this improbable, as it is known that the surface of a vibrating body is affected differently from the central part. It is, perhaps, owing to this same reason that earthquakes do not cause quite such terrific havoc within deep mines as would be expected.*

But his remarks on the social effects are notable too:

*It was, however, exceedingly interesting to observe, how much more active and cheerful all appeared than could have been expected. It was remarked with much truth, that from the destruction being universal, no one individual was humbled more than another, or could suspect his friends of coldness − that most grievous result of the loss of wealth.*

**Social reaction to a natural disaster**

Though the public may be accepting of natural disaster at the time, looting and dissension often follow. In 1906 the San Francisco Earthquake was followed by a serious fire. While no one could blame the authorities for the quake itself, much dissent surrounded the question of responsibility for the fire [*page 301*]. Five months after the quake the British Consul General of the time wrote of the insurance debacles, about the strikes and riots that he
felt were gripping the city, about the fractious and disputatious mood of the place, and of how even the local press was abandoning its eternal optimism and beginning to ask questions about the city's long-term future.

Such a loss of trust in society seems to be the most serious avoidable consequence of a natural disaster. Since nothing can be done about the disaster itself, the distrust is focussed onto a secondary consequence, a human accident around which blame and litigation can continue to rage for many years after. In the case of San Francisco it was the fire, and at Fukushima the release of nuclear radiation. Though precedent says that such human reaction may be expected, the distrust may not be justified by the evidence at all, and twenty-four-hour media enable such distrust to spread around the world, more than in the past. This makes it all the more important that responsible people appreciate this social phenomenon.

The public loss of confidence in nuclear power following Fukushima is the case in point. The public should understand that from a physical point of view, nuclear power is extraordinarily safe at the point of production – in fact so safe that only with considerable large-scale investment and great technical expertise is it possible to realise any nuclear energy at all. Any man-made regulation of nuclear material is a pale shadow of the security with which physical nature has surrounded this energy source. In his day, Darwin's conclusions about nature were obstructed by the prevailing religious way of thinking – today, realistic attitudes towards nature are obstructed by the popular zeitgeist of radiation phobia.

**Physical security of nuclear energy**

**The neutron, unique key to the nuclear energy lock**

In spite of its extraordinary physical security it is just possible to unlock nuclear energy. The key is the neutron whose existence was unknown until 1932 because it too decays (with a half-life of a few minutes) and so does not exist freely in the wild at all. The only place that free neutrons are to be found is inside a working nuclear reactor, and fleetingly in an exploding nuclear weapon. When a nuclear fission reactor is shut down, as was the case for all the reactors in Japan immediately following the earthquake, the neutrons are all absorbed and nuclear fission is halted immediately. The only further energy release is by nuclear decay, that is the decay heat.

The neutron is the brother of the proton from which it differs only in having no electric charge. Oblivious of the electric Coulomb barrier, a neutron can pass freely into a nucleus.

Sometimes it just bounces off the nucleus, which may sound rather
unimportant, but it is the way that neutrons in a working reactor transfer their energy to the moderator, often water or graphite. This energy is then carried to the steam turbines to generate electricity.

Sometimes the neutron reacts with a nucleus to make a new isotope which will usually be radioactive. This is the only way that new radioactivity is created. Examples that have been mentioned already are the production of plutonium, americium, cobalt-60 and tritium. When a reactor is shut down, materials of neutron-absorbing elements like cadmium and boron are dropped into the reactor core.

Sometimes a neutron hitting a nucleus can cause it to split in two, to fission. In fact this is truly exceptional. Although the nucleus of iron (A = 56) is more stable than any heavier nucleus (see Illustration 29 on page 158) fission is inhibited by the Coulomb barrier. Without stimulation fission is suppressed \([9]\), but a neutron can provide the required extra fillip to an exceptionally heavy nucleus with an odd number of neutrons, such as uranium-233, uranium-235, and plutonium-239. Fast neutrons can cause heavy nuclei with an even number of neutrons to fission too \([10]\). Only if this key is inserted into this lock – a neutron is the key and these relatively rare isotopes are the lock – can nuclear energy be released by fission. No greater safety is imaginable, I maintain.

**Inherent physical safety**

Fire can catch and spread to make an enlarged conflagration; so can disease, which multiplies and spreads by infection. As described on page 166, radioactivity cannot do this: it can be transported from one place to another, but not increase. In fact it can only diminish with its own particular half life. Each radioactive nucleus emits radiation just once as it changes to a lower energy nucleus – and that is it – finish (unless the daughter nucleus happens to be radioactive in its own right).

The rate of decay is unaffected by temperature, pressure, chemical agents – in fact it was this property that impressed Marie and Pierre Curie most of all, and made them realise that the radiation was coming from somewhere deeper inside the atom than had ever been studied before. Their observation has other more practical consequences that are seldom appreciated by those outside the field. Because nuclear decay is unaffected at all by any other influence, it does not matter if the radioactive material melts or boils. A nuclear meltdown, an idea so central to many nuclear horror films, has no effect whatever on nuclear decay. It might spill or disperse the radioactivity into the environment, but it does not increase the amount of radioactivity or the rate at which it decays. The popular reaction to nuclear accidents would be more restrained if this was explained, even though it might spoil the shock-horror impact of many fictional stories – and the mistaken descriptions
by the press of actual incidents too. The decay of radioactivity is unlike the persistence of chemical poisons, such as arsenic or lead, that remain hazardous indefinitely. There were sad stories in the Japanese press in the months following the Fukushima accident of people being ostracised on the basis that they had been irradiated and might infect others. The same happened to the Hibakusha, the survivors of Hiroshima and Nagasaki.

In their apprehension people worry that ionising radiation might cause a particular disease or type of damage. But as explained in Chapter 5 radiation is quite indiscriminate. It is not tuned to damage any particular molecule and its energy is much larger than the energy that keeps ordinary molecules together. The damage is purely molecular and electronic, and the nuclei of the material take no active part in the impact of the radiation and the damage it causes.

Waste from an ancient reactor

The nuclear reactor built by Enrico Fermi in Chicago in 1942 is often described as the world's first, but, interestingly, that is untrue by a wide margin. In the 1970s the remains of a uranium reactor that operated more than 2,000 million years ago were discovered at Oklo in Gabon, West Africa. It was a natural reactor that ran by itself, and when its fuel ran low the nuclear waste that it had created stayed put where it lay. The fascinating story is told in a Scientific American Report [11].

In uranium ore the concentration of uranium-235 in the majority uranium-238 is 0.720%. But when a rich deposit of uranium was discovered by French geologists at Oklo, it was found that the concentration was only 0.717%. Further detective work proved what had happened. Uranium-235 decays by alpha emission with a half life of 700,000 years, so 2,000 million years ago the concentration of uranium-235 must have been about 3%, much higher than today and about the same as the enriched fuel used in many of today's reactors. The other crucial ingredient for such a nuclear reactor is water, and at Oklo all those years ago as the seasons came and went, the water table rose and fell, regulating the reactor. The rare isotopes in the waste left behind have enabled scientists to reconstruct what happened.

There is an important message in this discovery: it is wrong to suppose that radioactive waste is just released into the environment like carbon dioxide from combustion: the evidence shows that it may stay where it lies for half the age of the Earth. Worries about nuclear waste leached by ground water should be seen in proportion. There is little danger of it leaving even a therapeutic spa for our successors.
Notes on Chapter 7

1) *The Strangest Man* A biography of Paul Dirac by Graham Farmelo, Faber (2009).

2) The strong and electric forces determine the structure of matter. In addition there are gravity and the *Weak Force* (related to the electric force).

3) They are also pushed apart at short range by the Fermi degeneracy pressure, a quantum effect that comes from the lack of distinction between protons (or between neutrons). It also applies to electrons and is related to the Pauli Exclusion Principle.

4) This is the point that the Churchill quotation at the head of Chapter 4 is trying to make. It seems that he was quite well briefed in 1931!


6) *Voyage of the Beagle* Charles Darwin,


8) A rare exception: a tiny number of free neutrons per year are released at the top of the atmosphere by cosmic radiation, just enough to make the few atoms of carbon-14 whose concentration, about 1 part in $10^{12}$, is measured in the process of radiocarbon dating used in archaeology.

9) Only 1 in 2 million uranium-238 nuclei decays by fission, even though its half life is 4,500 million years. So without neutron stimulation the fission decay rate is $10^{-16}$ per year.


# Chapter 8: Protected by Natural Evolution

*Take no thought for your life, what ye shall eat, or what ye shall drink; nor yet for your body, what ye shall put on. Is not the life more than meat, and the body than raiment? ... Consider the lilies of the field, how they grow; they toil not, neither do they spin: And yet I say unto you, That even Solomon in all his glory was not arrayed like one of these.*

St Matthew's Gospel, Chapter 6

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Reaction of nature to radiation

Game changing

It can take a long time for the appropriate reaction to a sudden unexpected event to become clear. Immediate conclusions reached in a state of shock can be inept and injurious. So it was with the reaction to the terrorist attack on the Twin Towers in New York in 2001. It was immediately assumed by the US administration that this was a game-changing event, and that the rules and guidance for the conduct of society, provided by justice and diplomacy and built up over past centuries, no longer applied. More than a decade later – a decade that saw imprisonment without trial, unrestrained state-sponsored surveillance and wars that could not be won – it is widely agreed that the initial flash judgement was misguided.

The detonation of the two nuclear bombs on Japan in 1945 had a similarly profound and unbalancing effect. Suddenly the rules of life seemed to have changed and the spirit behind the bombs appeared all-powerful. So, when it came to matters of safety, whatever physics and physicists seemed to say was treated with priority. The power of nuclear energy was seen to be alarming and extra caution was readily added to match public concern, with which those scientists not knowledgeable in nuclear physics could only agree. Only clinical medicine continued, fearlessly and undeterred, to follow the legacy of Marie Curie in the use of moderate and high levels of radiation for real health benefits for many millions of people.

Natural and responsive biological protection

The effect of making health decisions based exclusively on energy needs, as described by physical rather than biological science, may be illustrated with a story.

A physicist and a biologist enter for a marathon to be held in three month's time. The physicist argues that he will need to store up as much energy as he can and so stays in bed to ensure that his bodily reserves peak on the day. The biologist applies more common sense knowing that life is generally adaptive in its response to stress. Each day he runs for exercise, going a little further every time and building up to the marathon distance. When the day of the race comes, the biologist runs a good race but the physicist collapses well short of the half way mark and is taken off to hospital.
The message is so obvious, but does it apply to the stress caused by radiation? Unfortunately the authorities' view of its safety is to follow the physicist and minimise the dose by staying in bed, or rather the equivalent. A common sense view would look at the biology more than the physics – but the biology has been largely ignored for the past 70 years.

Natural biological radiation protection is as significant as that provided by the constraints of physical science, described in the previous chapter. The two are complementary and the combination is outstandingly effective. Only under exceptional circumstances is there any justification at all for adding a third level of protection, such as regulation. The biological response ensures that most current safety prescriptions should be redundant – such as those put in place by authorities with an eye on the public political reaction to the bombs of 1945 and the Cold War propaganda that followed. Unfortunately, few physicists have any appreciation of the role of biology, and many biologists are in awe of the physics expressed in a mathematical logic that they are not able to follow because their education never prepared them. Meanwhile, popular opinion, guided by politicians and the media who have little or no understanding of either discipline, remains confused and easily frightened. So for many decades nuclear power has been seen as mysterious and unsafe, and therefore to be avoided whenever possible. In reality its safety is outstanding and second to none.

**Biology designed for survival**

The business of life is survival, and life searches for the best design for the prevailing conditions by trial and error. In principle, life might have existed as a single vast organism, for instance as envisaged by the astronomer Fred Hoyle in his novel, *The Black Cloud* [1] – but that would make it very vulnerable. Biology found that survival is best assured when its chances are divided statistically into a large number of similar elements, so that if some happen to fail, there will be others that succeed. If some are unlucky, there will be lucky ones too. In life this design feature is realised on two distinct scales – the scale of individuals and the scale of cells. Society, or life as a whole, is made of modules – individuals – and each individual is made of cells that are also modular. A child playing with LEGO bricks quickly learns the versatility and potential for strength that such a modularity brings. Unlike the design of nature realised in physical science, biological realisations in nature are not simple, unique or universal. They come in many forms – the vast array of different animals, plants, fungi, fishes, insects, viruses and bacteria, each competing for viability in the given local environment.

The expression of life as multiple individuals allows each to survive on its own, and also to cooperate and work together in herds, packs or families. They may also compete or fight one another with the benefit of internally
selecting the strongest and fittest within the group. This improves the chances for the herd as a whole by culling the oldest and weakest, and maximising resources for the survivors. However, mutual help and communication between individuals, especially within family groups, can also improve the survival prospects for the herd as a whole.

On a microscopic scale and within each individual, the design of life repeats the statistical strategy by building individuals from many cells. These cover different functions, but, as with individuals, a spread of risk is achieved by having large numbers of them that are more or less interchangeable. The provision of master copies of the DNA, the individual's unique genetic barcode, within every cell makes for resilience in the face of external attack. It also acts as a personal identification system that minimises incidents of friendly fire between cells. The affiliation of cells is policed by the immune system which attacks any seen as foreign. Communication between cells within an individual by chemical messaging is as highly developed as it is between individuals in a group by speech, written and electronic means.

On each scale the design is honed to maximise survival, and everything gets reproduced and replaced: cells are copied and die in the cell cycle; individuals reproduce, sexually or asexually, and die. If a cell is attacked and does not survive, there are replacements that do. If an individual dies, there are others to take its place, because life aims for the survival of the species, not the survival of the individual. The sanctity of life, the survival of the individual, is not part of the scheme, and nature endures losses of individual lives on a massive scale, which is salutary for us to remember as we face a challenging future. Until now there has always been another distinct civilisation to take over when one fails. But with globalisation the strategy of survival for human society through plural diversity appears to have reached its limit.

**Active response to an attack**

When life is attacked, either at the cellular or individual scale, it does not simply rely on its passive design but has active responses as well. At a social level, there are all the familiar defence mechanisms of individuals, separately or jointly, including concerted military action. At the cellular level the proteins and other working molecules of biochemical life when damaged can be replaced by reference to the DNA as master record. When the DNA itself is damaged it can usually be repaired without introducing an error. This is relatively straightforward in the case of a Single Strand Break (SSB) because the famous double stranded helical structure of DNA means that the other strand remains attached and error-free correction is normal. If both strands are severed, a Double Strand Break (DSB), correction is still possible and recent work has shown how this is done \[^{13}\]. Most errors that might be
introduced into the DNA during the DSB repair process would prevent it being copied in the cell cycle, so the mutation does not propagate. Furthermore, a cell with damaged DNA may be selectively killed, a process called apoptosis. The choice between repair and replacement as the best way to remove the damage is determined by making the optimum use of the resources available. Nevertheless, if the mutation does get copied successfully, the immune system continues to scan for any cell that shows signs of not belonging. This is a major problem in transplant surgery; such foreign cells are liable to be rejected unless the immune system has been suppressed.

**What happens when biological protection fails**

The protection system has two failure modes, described in Chapter 6:

First there is a short term functional breakdown of organs caused by having too few operational cells; typically there may be insufficient resources to maintain both the repair of damaged cells and the cell cycle that produces new ones by copying. Such widespread cell death first affects systems with rapid cell cycle activity, notably the central nervous system and the gut. This condition is Acute Radiation Syndrome (ARS) which may be fatal within a few weeks. Otherwise, recovery is usually complete once the cell cycle has been re-established.

Then there is longer-term failure through undiagnosed repair errors that can give rise to uncontrolled growth of cells, injurious to the health of the organism as a whole. Such growth, unchecked by the immune system, is what we know as cancer. If not treated, this can develop and spread elsewhere in the organism, hijacking resources and leading eventually to death.

Cancer induced by radiation is not generally distinguishable from cancer initiated by other oxidative agents. Such agents occur naturally in the absence of radiation when reactive oxidant species (ROS) leak from the mitochondria that provide energy to cells for muscular activity, nervous communication and the process of thinking.

We may imagine analogous failures in an army of men. The first such failure mode is when the army is defeated through a loss of men and resources in battle. The army is united, but the defeat is quick and decisive. The second mode is through an insidious loss of morale, desertion or mutiny with men turning on one another. As an illustration, these may be likened to death by ARS and by cancer, respectively.

Historically, it was found that an exposure to radiation above a certain threshold gave rise to a reddening and inflammation of the exposed tissue where excessive cell death caused a loss of function in a few days. This is like familiar sunburn, although the radiation and damage penetrate deeper.
This *early reaction* is still sometimes referred to as *tissue reaction* today. Then there is *late reaction*, an alternative name for radiation-induced disease like skin cancer.

Other names for the two reactions, *deterministic* and *stochastic*, suggest, deceptively, that there is more than one kind of causality at work; the data simply show outcomes with high and low probabilities, respectively. For example, among those who received high whole-body doses of internal Cs-137 in the Goiania accident, half of those with more than 100 million Bq died of ARS, including one person with 1,000 million Bq and a dose of 4,000 mGy. But another who did not die of ARS survived until 1994 before dying of alcoholic liver failure, not directly related to radiation, in spite of an accumulated dose of 7,000 mGy. In biology the effect of a dose varies from patient to patient, and the label *deterministic* appears inappropriate.

**Stabilisation and adaptation**

Examples of stability and its characteristics

Illustration 30: A sketch graph showing a typical stabilised response (or failure rate) to a stress, as found in electronics, management and engineering, and characteristic overload threshold.

Illustration 30 shows an example of a curve that might describe the stabilised response to a stress. It could apply in many different contexts, like the management of a company, for example. Any small stress should have no
noticeable effect on the company, provided everybody concerned knows what to do and takes action accordingly. However, there is a threshold beyond which there are not enough staff, or not enough money, for example, to cope. Or, perhaps, there are not enough phone lines, or warehouse capacity. There is no need to be precise about the meaning of failure – in each context it is usually clear. Anyway, this is where the curve rises to the right of the threshold, and for a stress or loading that exceeds the threshold, the failure rate rises relatively sharply.

An electronic amplifier stabilised by feedback behaves in a similar way; there is only so much current available to provide the correcting signal, so that above a certain threshold the feedback is no longer effective. We could look at many more examples, but all have similar features, and there is no reason to suppose that the response of living tissue to the stress of different radiation doses is any different. If there is, why should that be? There is nothing different about radiation, it is just another stress. Contributions to the response come from the initial effect and then the correction and repair effects, that together reduce or eliminate on-going damage.

In each example there is a time element to the story. The stress that matters accumulates in a short time window needed for repair or feedback to act. For the biological impact of radiation, as in the management or electronic examples, what happens outside this recovery period is less important. As always, empirical evidence should be the arbiter of whether this picture is qualitatively correct or not. We need to look at further details but it is significant that the mortality curve for Chernobyl workers (Illustration 26 on page 136) has the same generic shape as Illustration 30 and is not a straight line.

**Adaptation, when the response learns**

But the generic feedback or repair description shown by a stress-response curve like Illustration 30 is seldom a complete description of what happens. As a result of a stress failure or a near-miss, the shape of the curve may adapt or change. In this way the curve itself may depend on the history of recent stresses. For the example of a company, recent experience may persuade the management to hire more staff, increase financial provision, install more phone lines, or acquire more warehousing, so that next time there is an unusual stress there will be less chance of a failure. In terms of Illustration 30, that means the curve would be shifted to the right and the threshold raised. Such dynamic adaptation increases the likelihood that the company survives. That is what good management does.

Indeed survival is central to the function of biology too, and it would be surprising if such adaptation played no part in its strategy. Adaptation is what
is happening in any fitness regime. Exercise, taken each day below the threshold of real harm, encourages the body to improve cellular repair resources and blood flow. Provided exercise is not excessive and damage is not done, the improvement means that the threshold at which damage occurs is actually increased each day. Then the exercise taken each day can be extended without harm – there is a limit, but it is very much higher than the limited exercise that can safely be taken by someone who lives a sedentary lifestyle. As explained in Chapter 5 oxidative stress plays a crucial part in physical and mental activity, and the adaptive benefit of exercise and cognitive activity is effective in overcoming oxidative attack.

We should expect that radiation too would stimulate the cellular repair and replacement mechanisms, so that following a radiation exposure, cells would increase their inventory of antioxidants, DNA repair enzymes and other defences against oxidative damage. Indeed there is evidence that they do, and they add to resources for immunity, too. On this basis we expect that the damage threshold would increase for subsequent radiation exposures. Do real data suggest such adaptation to radiation actually occurs? We shall see that they do [2, 3, 4].

**Chemical nature of initial radiation damage**

Exposure to radiation and muscular activity seem very different, but that is not true of the damage they inflict. Some damage to DNA caused by radiation is a direct collision of the radiation with the DNA molecule itself, but since the DNA forms a small fraction of total body weight, and half of that is water, most of the broken molecules left by radiation are fragments of water, such as H, OH, O and H$_2$O$_2$, in electrically charged and uncharged states. These hot radicals, the ROS mentioned in Chapter 5, are also made by a cell's mitochondria, its power source. In fact it is estimated that in a single cell, $10^9$ ROS per day are produced by normal metabolic activity – that is just over 11,000 per second [5]. Is that reasonable? In the box on the next page we calculate how well the biology is designed.

All ROS are highly destructive, and every cell has to keep a supply of antioxidants whose business is to mop up and quench the ROS before they use their high activity to break and ionise further, otherwise undamaged, DNA. In recent years it has been popular to take antioxidants to enhance the suppression of early pre-cancer conditions. However, this is found to be ineffective, probably because it is the concentration of oxidants that triggers inter-cellular chemical messages. By taking extra antioxidants such messages about oxidative attack are suppressed and other cellular defence mechanisms are stood down.
We can do a rough calculation to check that these numbers are reasonable:
If the mass of a cell is about $10^{-9}$ g, that is $10^{-12}$ kg, then this leakage rate is $1.1 \times 10^{16}$ ROS per kg per second.
If one ROS carries an energy of about 10 eV, that is $1.6 \times 10^{-18}$ J, so all these ROS comprise a power loss of 0.0018 watt per kg.
A resting human produces about 2 watts/kg. So for every 2 watts generated, the energy lost by leakage of ROS is 0.002 watts, roughly.
So biology has evolved a power source with an inefficiency of 1 part per 1,000. That seems reasonable. Much worse would waste energy. Much better would suggest a waste of resource and over-design.

The message to take away is that the ROS from a radiation dose and from normal metabolic activity are chemically rather similar for many purposes, including carcinogenesis, the tendency to initiate cancer. What is important for control of ROS is their uniformity in space and time – short acute bursts in time and high concentrations in space are not easily quenched.

**War games of evolution**

However, it is not only the response to a threat that may change and adapt, but the threats themselves. Consider first the political world of individuals and nations. (We will come back to the microscopic world of cellular life later.) In that case responses to military threats are frequently explored and evolved by engaging in war games, to find ways to out-wit the other side. An actual engagement might go either way, depending who is the stronger or cleverer. But if one side sticks to a never-changing strategy, then eventually the other side should find a way to win, whatever their relative strengths.

And so it is in the microscopic world too. In the battle between cells and viruses there are no certain outright winners – both sides are constantly changing strategy by mutation and immunological adaptation. The battle goes on. Sometimes the virus wins and there is an epidemic. Sometimes the immune system with its antibodies wins, often with active help from health programmes too.

But in the battle between physical ionising radiation and life, the situation is quite different. The effect of the radiation is set and fixed by physical science – it never changes. But living organisms and their cells are free to evolve and find a defence against radiation that is more or less complete. This is true in spite of the overwhelming fire power on the radiation side and the extraordinary frailty of life on the other. Biology has had over 3,000 million years to come up with its defence strategy against the seemingly all-powerful ionising radiation.
This is the point that mankind has failed to realise. In formulating our attitude to radiation, we have been too readily impressed by the imbalance of fire power without noticing the overwhelming effect of the strategic design of life.

Energy, mitochondria and keeping fit

Keeping fit encourages the body to maintain adequate resources ready to repair its working cells. Regular exercise is a simple way in which to raise the norm of what the cells of an organism expect and are prepared for. At the microscopic level the damage to be repaired is due to the oxidative processes that we have been discussing. Energy is provided to cells by the mitochondria, which burn nutrients taken from the blood stream using oxygen carried by the red blood cells, and make the energy available to the rest of the cell by means of molecules of adenosine tri-phosphate (ATP). This process or metabolism produces about one watt of energy per kg of body weight, enough to keep the body warm and provide the basic physical and mental energy it needs, and where extra energy is required it provides more. In so doing oxidative agents (ROS) may leak from the mitochondria and inflict damage on the DNA in the cell nucleus that is indistinguishable from the damage caused by the ROS released in the radiolysis of water – that is the break-up of H$_2$O by radiation.

However the energy per second absorbed from any ionising radiation is remarkably small compared to one watt per kg, the power of metabolism when resting. A patient receiving a course of radiotherapy gets a high radiation dose each day: the energy deposited in healthy tissue is 1,000 mGy per day, that is one joule per day per kg. That means that in one second the metabolic process delivers as much energy as the patient receives in a whole day in radiotherapy treatment. The ratio, the number of seconds in a day, is a factor of 86,400, so it is no wonder that ionising radiation does not make the patient feel hot – it is extremely weak. Natural background radiation at an average 1 mGy per year is even weaker, less than the metabolic rate by a factor of one billion. It is the leakage of ROS from the mitochondria that is responsible for most of the natural oxidation of DNA. Adaptation, as a response to moderate physical or mental exercise, stimulates and strengthens protection against ROS and their effects. Radiation is no different because the ROS and their effects are very similar, especially at low LET. This is probably why low-dose radiotherapy, usually as whole-body or half-body, can be effective at stimulating the body's resistance to cancer. It may be why treatment in health spas that offer radioactive waters brings welcome relief, even in an era when fear of radiation dominates the lives of many people. Somehow people have allowed themselves to imagine that radiation health from natural and artificial sources are quite unrelated. For instance, the
radiation in the onsen in Japan, and the Baden in Germany, is the same as the radiation that comes from the radioactivity released at Fukushima Daiichi. In fact both are harmless at the levels encountered, but cultural perceptions have prevented people seeing the connection.

**Evidence for adaptation to radiation**

The effectiveness of regular stimulation by moderate doses of radiation applies to the immune system as well as to the inventory of antioxidants and DNA repair enzymes. As early as 1915 and 1920 the results of simple but clear experiments on mice were reported by Murphy and published in the Proceedings of the National Academy of Science [6, 7]. The experiments were carried out on two groups of mice. Those in the first were given a single small exposure to X-rays and a week later were injected with transplantable cancer. Those in the second were treated in the same way but without the exposure to X-rays. The experiment was repeated three times. In each case the cancer infection rate for the group given the X-rays was a factor three smaller than for those given no X-rays, as shown in Table 9.

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<td>Infection rate in mice after X-rays</td>
<td>25.0%</td>
<td>29.0%</td>
<td>28.6%</td>
<td>27.5%</td>
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<tr>
<td>Infection rate in mice without X-rays</td>
<td>77.8%</td>
<td>87.5%</td>
<td>60.0%</td>
<td>75.1%</td>
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*Table 9: Effect of X-rays on infected mice observed by Murphy (1915).*

The experimenters found a similar stimulation by five minutes of exposure to dry heat at 55-60°C in place of the X-rays. Evidently the increased lymphocyte count responsible for the improved immunity could be stimulated in different ways. The beneficial effect was not immediate and did not persist; they found that one week was optimal. Further, if the X-ray dose was increased even more, there was a negative effect on the lymphocyte count.

**Hormesis – the by-product of adaptation**

A recent general review traces the history of the beneficial effects of low doses of radiation back to the original discovery of X-rays [8]. As an illustration of this positive view we sketch a possible dose-benefit curve, Illustration 31, where the damage threshold is at point B and there is benefit in region A. To emphasise the benefit instead of the damage, this diagram is shown upside down compared to Illustration 30. There is a popular saying *You can have too much of a good thing.* So it is with the health effect of most agents – the right amount may be healthy, even essential, but too much is harmful, whether it is a drink of water or a dose of aspirin.
The principle also applies to physical exercise; some is much better than none, but an excess causes injury. This idea was described five centuries ago by Paracelsus, the physician and botanist (1493-1541), who wrote, *Omnia sunt venena, nihil est sine veneno. Solo dosis facit venenum*, which translates *Everything is poisonous, nothing is without poison, but it's only the dose that makes it poisonous.*

With exercise or regular stimulation the point $B$ moves to the right – each day the damage threshold increases a little. That is, it adapts. So studying curves misses the point – response is a live parameter, not easily tamed by mathematics or simple diagrams. The benefit of adaptation may only last for a certain time and may need to be stimulated again. As an example, the efficacy of regular exercise for general health is well known $[9]$, although fitness does not last very long. So it is back to the gym.

But what about the body's response to radiation? That is not likely to be a simple matter of studying straight lines or even curves, either – radiation response seems likely to be a matter for flexible pragmatism rather than cautionary dogma. Because the initial effect on cells of exercise and radiation includes the chemical action that increases production of ROS, these two elicit the same protective and adaptive responses. Thus a history of past exercise and past radiation are both effective at stimulating adaptation. Doses of ionising radiation at low rates suppress cancer incidence to below what would have occurred from background oxidation in the absence of radiation, just as exercise does.

*Illustration 31: A sketch graph of a health-exercise curve indicating some benefit for modest exercise but damage for an excess.*
In summary, because of adaptation to past history, a response curve like Illustration 30 tells only part of the story. For a dose below damage threshold, beneficial adaptation does not just reduce the incidence of any cancer that might have been caused by radiation, but it reduces the incidence of cancers from other causes too. This effect is called *hormesis*, although it is of secondary importance as far as safety is concerned. The primary question concerns the dose rate at the threshold of damage, point $B$, the *No Adverse Effect Level* (NOAEL), as Jerry Cuttler has called it. In summary, the point $B$ moves as the organism adapts.

Illustration 32: Data showing the mortality and lifespan of dogs:
(1) lifelong chronic whole-body 3 mGy daily doses of radiation; (2) similar dogs given no dose. Data from Fritz et al [12].

**Effect of chronic radiation doses on dogs**

We are interested to find the damage threshold for a lifetime dose received as a steady chronic dose rate. To date the most thorough experiments to answer this question have used dogs. For a single acute radiation dose the mortality of Chernobyl workers, shown in Chapter 6, was similar to that for a large numbers of rats. But rodents are not suitable for whole-of-life studies of
chronic doses because they have much shorter lives than humans. But dogs live longer than rodents and a fair fraction of a human lifetime.

Lifespan and mortality data for dogs, given a chronic 3 mGy daily gamma radiation dose throughout life, are shown in Illustration 32 \[^{10}\]. This also shows similar data for dogs who received no dose. Each plotted symbol represents the death of a dog (some are omitted to improve clarity where they coincide);

- the horizontal position of the symbol on the plot gives the age in days at death (and, on the upper scale, for the irradiated dogs, the corresponding accumulated lifetime dose at death);
- the vertical position gives the mortality of that group of dogs at that time;
- the choice of symbol shows whether the dog died of a fatal tumour (F) or another disease (O).

The data show that the mortality of the 92 dogs who received 3 mGy per day is not significantly different from the un-irradiated dogs until they have received a lifetime dose of somewhere between 6,000 and 9,000 mGy. So for dogs, this is an estimate of the threshold we want, and, interestingly, the symbols do not suggest that fatal cancers predominate. Such data do not exist for humans, but the numbers are indicative for this high chronic dose rate. We will need more such indications before we can suggest convincing safety thresholds for dose rate and for whole-of-life dose in humans. This we do in Chapter 9.

There is another but more sensitive way to look for changes that may give rise to cancer, perhaps many years later. Instead of examining data on mortality or morbidity we can look instead at the actual genetic changes induced by the radiation. There is an important study of this kind on genetically identical mice \[^{11, 12}\]. The mice were irradiated chronically for 5 weeks at a rate of 3 mGy per day, and compared with mice a) that were not treated at all, and b) that had received the same radiation but as a single acute dose (100 mGy). The authors found no genetic effect at all for the treatment of the chronically treated mice. The acutely treated mice showed genetic effects linked to DSB only, showing that the SSB had been repaired successfully. Evidently both the SSB and the DSB were correctly repaired for the mice receiving the chronic dose, confirming that for mice a chronic dose of 90 mGy per month for 5 weeks is harmless. This genetic observation is more sensitive than a test for cancer as it is looking before the immune system deteriorates later in life.

Furthermore, recent research on mice has successfully explained and shown
how DSBs are repaired \[^{13}\]. This is a field in which understanding is progressing rapidly. As far as safety regulations are concerned, the important point is that for a chronic dose delivered at 90 mGy per month, there is no detectable genetic damage after five weeks – and if there is no genetic damage there can be no link to subsequent cancer. It is true that this conclusion is for mice, not humans. But we can say that the risk of cancer for mice is reduced by at least a factor of 50, if the dose is given chronically, instead of acutely. ICRP guidance acknowledges no more than a factor 2 relaxation of risk for a dose delivered chronically. In the LNT model this factor is called the Dose and Dose Rate Effectiveness Factor (DDREF) \[^{14}\].

**Low-level radiation protection by regulation**

From the dawn of cellular life, biology has had to cope with attack by oxygen and by radiation. Step by step it has evolved methods of protection that are extraordinarily effective, as the accident at Fukushima and other similar evidence have shown. None of these methods calls on the sensory system or the brain of a living organism to do anything at all – for most of the evolutionary span the organisms that needed protection had no such sensory system anyway.

But now something has gone seriously wrong. What has happened? In the middle of the twentieth century the international community suddenly engaged with the problem of protecting life from radiation. Initially, that is in 1934, safety levels were chosen based on limited data and modest understanding of radiobiology. Nevertheless they were quite close to those that science would justify today. In the meantime, in the names of conservatism and precaution it was decided to use the LNT and ALARA philosophy, ignoring completely the understanding of modern radiobiology, in particular the evolved protective provision that has been in place since life began.

Illustration 5 on page 7 is a comment on the relative efficacy of the regulatory safety system and the natural evolved one. The latter has been honed to do the job of providing actual and immediate protection; the former offers only bureaucratic regulation, but no active protection at all. It is time to stop denying nature and trusting solely in regulation.

**Medical treatment with ionising radiation**

**Life out of warranty**

Evolution has delivered life designed to survive so effectively that we may wonder why there is any need for humans to study their own survival any further. It is true that often the best medical treatment is to not intervene and
let natural protection apply its remedy. But this ignores the fact that evolution has worked to ensure the survival of species, not individuals. If mankind wants individuals to survive, medical intervention will sometimes be necessary. Evolution has little interest in the life of individuals beyond the reproductive and parenting age. After that individual life is *out of warranty*, as it were. Only through education, the useful ongoing transfer of knowledge from older to younger individuals, is there any evolutionary advantage in the extension of life into old age. So medical treatment adds to what nature can do.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.9</td>
<td>0.5</td>
<td>-0.4</td>
<td>9.6</td>
<td>6.3</td>
<td>-3.3</td>
<td>21</td>
<td>25</td>
<td>+4</td>
</tr>
<tr>
<td>Japan</td>
<td>0.6</td>
<td>0.3</td>
<td>-0.3</td>
<td>8.1</td>
<td>6.5</td>
<td>-1.6</td>
<td>23</td>
<td>26</td>
<td>+3</td>
</tr>
<tr>
<td>Russia</td>
<td>2.7</td>
<td>1.1</td>
<td>-1.6</td>
<td>21.8</td>
<td>24.1</td>
<td>+2.3</td>
<td>18</td>
<td>17</td>
<td>-1</td>
</tr>
<tr>
<td>USA</td>
<td>1.2</td>
<td>0.7</td>
<td>-0.5</td>
<td>13.2</td>
<td>10.5</td>
<td>-2.7</td>
<td>21</td>
<td>23</td>
<td>+2</td>
</tr>
<tr>
<td>Germany</td>
<td>0.9</td>
<td>0.4</td>
<td>-0.5</td>
<td>11.8</td>
<td>7.4</td>
<td>-4.4</td>
<td>20</td>
<td>24</td>
<td>+4</td>
</tr>
<tr>
<td>UK</td>
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<td>0.5</td>
<td>-0.5</td>
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<td>7.4</td>
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<td>20</td>
<td>24</td>
<td>+4</td>
</tr>
<tr>
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<td>1.5</td>
<td>-3.9</td>
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<td>9.7</td>
<td>-5.3</td>
<td>18</td>
<td>19</td>
<td>+1</td>
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<tr>
<td>India</td>
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<td>5.9</td>
<td>-7.0</td>
<td>27.4</td>
<td>20.5</td>
<td>-6.9</td>
<td>15</td>
<td>17</td>
<td>+2</td>
</tr>
</tbody>
</table>

*Table 10: Some changes in mortality and life expectancy in recent years.*

Mortality and life expectancy have improved dramatically in recent decades for rich and poor alike, as shown by the numbers in Table 10. Control of disease, advances in clinical medicine, improved standards of living and better availability of food and clean water are responsible.

### Diagnostic imaging including CT scans

For most of its evolutionary development, life had a very basic nervous system, if any. As a result the powerful brain that man has today remains poorly informed about those processes that are active in his own body and evolved long ago to be able to work unsupervised. Undoubtedly, given the power of the brain, life could have evolved a broadband diagnostic network that allowed each individual a much higher degree of self diagnosis. On the other hand, perhaps, giving such power to the *worried well* to fret over their potential ailments does not help their survival by selection. When a patient
presents himself to his physician, he has little to say because his brain often has only vague ideas about his complaint. The physician needs more diagnostic information than the patient can give. Apart from what he can learn from a superficial examination and the patient's own account, he needs scientific aids to probe the body using the penetration of sound waves, radiowaves or ionising radiation \cite{18}. These have been developed to image both the anatomy and how it is working – a functional image. The physician can select a method from the simple and readily available, to the finest and most sensitive, from a low technology X-ray photography, through ultrasound and MRI scans, to CT and radionuclide scans. All but the simplest are in 3-dimensions, and today these can be combined to produce composite images. They are described in accessible terms in *Radiation and Reason* [see Selected References on page 279, SR3]. These advanced techniques are becoming more and more widely available in spite of the high cost and expertise required. The reason is that physicians find them effective and so money is made available to pay for them. It is a good example of what public confidence in science can achieve when the benefits are properly appreciated.

On the public side, patients are reassured to see the pictures, even though some worry whether the methods themselves are dangerous in some way – although they are not, and we shall see why. The radiation involved in MRI is in the radio range and non-ionising. This has not caused the same concern about safety as methods using ionising radiation – CT scans and isotope scans. In fact, the power used in an MRI scan is far higher than used in a scan based on ionising radiation. As discussed in Chapter 5, the former is measured in watts per kg – it can only heat tissue and its safety limit is set by comparing with the regular metabolic heating rate, a few watts per kg. The power of an ionisation scan is measured in microwatts per kg, a million times smaller. As explained in Chapter 5, its safety is not related to heating, but to its effect on a minute number of individual molecules.

The number of MRI and CT units has grown very rapidly in recent years. The extent of current provision can be judged from the data shown in Table 11.

The US authorities have reported that the mean annual radiation dose from CT scans has risen to about 3 mGy per member of the US population, comparable with the mean natural background and three times the suggested limit for artificial sources of 1 mGy per year. There are two points to note. Firstly, there can be no difference between the effect of doses from natural sources and from medical or other artificial sources. Secondly, there is no evidence that doses hundreds of times larger than these figures have any negative health effects whatever. Many concerns would be laid to rest by comparisons with information for much higher doses or by simple statistical scrutiny. (Mistaken claims in the fields of biology and public safety often arise from a naive use of statistics. For instance, they treat as established any
result with 95% confidence level, without accounting that 1 in 20 such conclusions is false. Such methods cause misunderstandings and publicity disasters that do not occur in fields with more discipline in their use of statistics.)

<table>
<thead>
<tr>
<th></th>
<th>MRI units</th>
<th>MRI examinations per million per year</th>
<th>CT units</th>
<th>CT examinations per million per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>OECD</td>
<td>12</td>
<td>47</td>
<td>23</td>
<td>132</td>
</tr>
<tr>
<td>Australia</td>
<td>23</td>
<td>39</td>
<td>39</td>
<td>94</td>
</tr>
<tr>
<td>Germany</td>
<td>10</td>
<td>17</td>
<td>17</td>
<td>49</td>
</tr>
<tr>
<td>Ireland</td>
<td></td>
<td>16</td>
<td>15</td>
<td>69</td>
</tr>
<tr>
<td>Japan</td>
<td>43</td>
<td></td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>6</td>
<td>39</td>
<td>7</td>
<td>73</td>
</tr>
<tr>
<td>USA</td>
<td>26</td>
<td>91</td>
<td>34</td>
<td>228</td>
</tr>
</tbody>
</table>

Table 11: Scanner units and examinations per year per million population for 2009 or nearest year. [19].

**Isotope imaging**

The radiation of a CT scan is transitory. It passes through the body in a flash. What is left are the broken molecules, as already described, but the radiation itself has gone. The case of isotope imaging is different. The radioactive isotope is injected into the patient's body and radiation is emitted as the isotope decays. In this way the radiation is spread out by the delay of the decay process. There are two technologies, Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET). The half life of commonly used isotopes are: two hours for fluorine-18 in a PET scan, or six hours for technetium-99 in a SPECT scan. The way these methods work is described in *Radiation and Reason* [SR3]. The story of the Goiania accident, told in Chapter 6 of this book, is a graphic demonstration that delay does not worsen the effect of a radiation dose; in fact, by spreading out the initial damage, the repair and replacement mechanisms are enabled to reduce long-term damage far more effectively.

The PET method of imaging gives better images at lower doses than SPECT, but is more expensive. One problem is that, because it decays so quickly, fluorine-18 has to be brought within a couple of hours or so from the
accelerator where it is made. On the other hand, technetium-99 comes from the decay of molybdenum-99 that is produced in nuclear fission, with a useful half life of a week, which eases the logistics of supply. Readers worried about nuclear waste should note that molybdenum-99 is just one of a number of valuable components of fission waste. Although PET gives better images, its higher cost means that its use is spreading more slowly and 80% of isotope imaging uses SPECT [20]. There are some 30 million examinations per year, including 6-7 million in Europe, 15 million in North America and 6-8 million in Asia/Pacific.

Cancer as a class of diseases has proved particularly difficult to diagnose and to treat. As other diseases have been controlled or their incidence reduced, cancer has become a more prominent cause of death. Ionising radiation, far from being a significant cause of cancer, is a major tool in its diagnosis, and most effective in its cure. Just as diagnosis is often more effective when methods are used in combination, for instance PET plus MRI, so cancer therapy often combines radiation therapy with surgery, or more often with chemotherapy. Improved success with therapy has come with the use of real-time imaging to target the tumour and then monitor the progress of its demise.

**Radiotherapy – the use of radiation to cure cancers**

Human society is regrettably coy about talking of things thought to be unpleasant. The hope is that someone else will deal with them, unseen by sensitive society. For example, sewage must be reprocessed and recirculated in a densely populated environment. It is a luxury to be able to ignore it, but in a world facing climate change there may be more unpleasant matters that we will have to attend to. An important early task is to identify all those matters we prefer to ignore. The list is likely to include death and cancer, and many people would add nuclear radiation too. In each case we are stronger and better prepared if we study them. For instance, being hesitant about cancer is responsible for many tumours that are diagnosed too late.

Radiotherapy is used in the treatment of cancer care not only with the aim of achieving complete remission, but also in palliative care to reduce pain and slow the advance of a cancer that may already have spread or metastasised. A diagnosis of cancer is a shock to the patient, but in fact the prognosis for many cancers today is usually good, and a majority of those receiving therapy go home to further productive years of life. At the end of their treatment they shake the hands of their clinician and nurses, warmly and with thanks. This is in spite of the fact that during the 4-6 week treatment they will have received a radiation dose to large parts of their healthy body that may be more than 1,000 times that from a CT scan or from the radiation experienced at Fukushima, incorrectly thought by many to be dangerous.
The radiation used in normal high-dose radiotherapy (RT or HDRT) comes either from a radioactive source or from a beam of electrons from an accelerator. The latter is essentially an X-ray gun, as used in a dentist's surgery but at higher power. Ideally the radiation shines onto the tumour and kills its cells. The difficulty is that the gamma radiation cannot be focussed – at best it travels in straight lines, at worst it is scattered and wanders about, some getting absorbed by the healthy tissue in front of the tumour (unless the tumour is on the surface) and some behind. It is this poor delivery of the radiation dose that gives rise to the friendly fire or collateral damage inflicted on nearby healthy tissue during the treatment of the tumour itself.

There are various ways in which the delivery can be optimised:

- By the use of gamma rays with energy well above 1 MeV to reduce scattering and absorption for deep penetration;
- By using a number of different beam angles to deliver doses that overlap at the tumour but spread out around to reduce the dose to healthy tissue;
- By carefully mapping the delivered dose in 3-dimensions linked to automatic collimators that shape the beam profile, a computerised process called treatment planning;
- By brachytherapy, the use of low-energy gamma or beta radioactive sources of short range, temporarily implanted in or near the tumour, instead of an external radiation beam. Iodine radioisotopes are used to treat thyroid cancer, one of the most successful kinds of cancer treatment – even though at Chernobyl exposure to such isotopes may have caused the cancer in the first place. The efficiency with which any iodine in the body becomes concentrated in the thyroid, and nowhere else, is responsible for both effects. The iodine has only to be injected into the bloodstream and does not need to be surgically implanted. Brachytherapy is also used to treat non-malignant thyroid disorders. Iridium-192 implants are used especially in the head and breast. They are produced in wire form and are introduced through a catheter into the target area. After administering the correct dose, the implant wire is removed to shielded storage. Brachytherapy is designed to give less overall radiation to the body in cases when radiation can be localised to the target tumour, and it is used in particular in the treatment of prostate cancer.
- Unlike gamma rays, energetic beams of charged ions can be focussed and targeted to stop at the depth of the tumour and deliver most of their energy there. Such ion beam therapy is not yet available in every clinic, but is the best for the treatment of deep cancers. In such
therapy, the dose can be delivered to the tumour more efficiently. Then the peripheral dose can be reduced while the tumour dose is increased, thereby improving the prognosis for successful treatment.

In the early days of radiotherapy, before WWI, the dose had to be given over a period because of the limited power of X-ray machines – and patients did well. As the equipment improved, it became possible to deliver the whole dose in one or two sessions, but it was found that patients did not survive. Today the dose is given in daily fractions spread over a period of 4-6 weeks \[^{21}\]. Each day the tumour cells get slightly too much radiation and die progressively. Each day the healthy cells get about half as much radiation and just manage to recover by the mechanisms of replacement, repair and adaptation – in simple common sense terms, they get used to the radiation, and this helps them to survive the extended chronic dose rate of 1,000 mGy per day, far in excess of 0.08 mGy per month (1 mGy per year), the ALARA limit recommended for public exposure in the environment by the ICRP \[^{14}\].

Unless ion beam therapy is used, the dose that can be given to the tumour is limited to about 2,000 mGy per day, by the effect on healthy tissue within 5-10 cms. In a century of experience oncologists have learned that any tissue that receives much more than 1,000 mGy per day is likely to fail as a result of cell death; they have also learned that if the peripheral dose is reduced much below 1,000 mGy per day, the chance that the tumour receives a sufficient dose for successful treatment falls significantly. As described by the Royal College of Radiologists best practice is rooted in such compromise and empirical guidance rather than in regulation \[^{21}\].

In spite of scare stories in the press, the medical use of radiation continues to expand. The World Health Organisation (WHO) reports that the number of X-ray examinations worldwide is more than 3.600 billion annually \[^{22}\]. Currently 37 million nuclear medicine procedures are carried out and 7.5 million radiotherapy treatments are given. These numbers were posted in 2014 but the use of radiation in medicine continues to increase as the benefit to patients gains further recognition and more equipment becomes available. A directory of radiotherapy centres (DIRAC) has been available since 1955 and is now maintained by IAEA. Some data are summarised by geographical zone in Table 12.
### Table 12: Geographical distribution of radiotherapy centres and units with radiation from electron accelerators and from radioactive sources, external and internal \([23]\).

<table>
<thead>
<tr>
<th>Sub continent</th>
<th>centres</th>
<th>treatment planning stations</th>
<th>therapy units</th>
<th>acceler-</th>
<th>external radioactive source</th>
<th>internal (brachy-therapy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>2,787</td>
<td>326</td>
<td></td>
<td>4,083</td>
<td>158</td>
<td>885</td>
</tr>
<tr>
<td>Western Europe</td>
<td>1,039</td>
<td>1,587</td>
<td></td>
<td>2,552</td>
<td>107</td>
<td>427</td>
</tr>
<tr>
<td>Eastern Asia</td>
<td>1,934</td>
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<td></td>
<td>2,048</td>
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<tr>
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<td></td>
<td>225</td>
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<td>185</td>
</tr>
<tr>
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<td></td>
<td>126</td>
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</tr>
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<td></td>
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<tr>
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<td>330</td>
<td></td>
<td>560</td>
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<tr>
<td>Middle East</td>
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<td>225</td>
<td></td>
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<tr>
<td>South East Asia</td>
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<td>111</td>
<td></td>
<td>176</td>
<td>90</td>
<td>46</td>
</tr>
<tr>
<td>East Europe &amp; North Asia</td>
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<td>567</td>
<td></td>
<td>487</td>
<td>506</td>
<td>277</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>7,646</td>
<td>5,846</td>
<td></td>
<td>21,462</td>
<td>2,347</td>
<td>2,395</td>
</tr>
</tbody>
</table>

Apparently resources are unevenly distributed. Less developed countries have few electron accelerator therapy units as these are expensive and require more highly trained staff. But units are available that use intense gammas from external radioactive sources, usually cobalt-60 or caesium-137 – the accident at Goiania described in Chapter 6 involved such a source. Ion beam therapy requires a more powerful accelerator, but is already available in some countries and in future it will doubtless become the preferred treatment for all deep cancers.

Radiation dose rates in excess of 40,000 mGy per month have been in use for over a century and accepted by the public to cure cancer in the tradition of
Marie Curie [21]. This treatment would be more accurately described as High Dose Radiotherapy (HDRT). It is aimed at the offending tumour with the intention of killing the cancerous cells, while sparing the surrounding healthy tissue as far as possible.

There is a further way in which ionising radiation has been used to combat cancer, and that is called Low Dose Radiotherapy (LDRT). In this case low doses are given over a period of time to the whole body, or sometimes half the body. The dose, perhaps 50 mGy per month, is chosen to stimulate the adaptive reactions described in this chapter. The effect is to harness the body's natural defences against cancer, particularly the immune system. Success in the use of LDRT has been reported in Japan and elsewhere [24, 25, 26]. Members of the public have some general familiarity with such radiation therapy at a low level through the popularity and benefits of spas, worldwide. However, LDRT has yet to be as widely accepted as it may be in the future.

**New second cancers years after radiotherapy**

![Illustration 33: Plot of data from Tubiana et al showing how incidence of a second new cancer depends on total dose absorbed (if any) in treatment of the first cancer.](image)

In the previous section it was stated that when planning a course of HDRT radiologists give a tumour as much radiation as the healthy tissue around it can withstand. That means that radiotherapy patients sometimes suffer from
peripheral skin burns, and also that the radiation that kills the tumour cells may accidentally cause a new primary cancer in the previously healthy tissue. The chance is said to be about 5%, and the cancer can usually be spotted and treated early. It is important that authoritative data from an international group confirm this description.

This has been provided in a recent paper by Tubiana and his clinical team in UK and France [27]. Five thousand survivors of childhood cancer who had received radiotherapy treatment were studied, and their subsequent health followed for an average of 29 years. The number who developed a new second primary cancer was 369, or 7.4%. The study asked a very interesting question about these second cancers:

What was the total absorbed radiation dose from the first treatment at the site where the second cancer later developed?

They were able to infer the answer from a reconstruction of the original treatment plan. They then plotted the number of second cancers per kg against this dose – the result is shown in Illustration 33. Along the bottom on a log scale is the total dose in Gy (the daily dose added up for the whole treatment) at the site where the second cancer turned up. On the left is the cancer incidence for places far removed from the radiotherapy beams. From this plot it is possible to draw the following conclusions:

- there is no evidence of any new primary cancer caused by a radiation dose less than about 5 Gy, that is 5,000 mGy;
- for doses in the range 5 to 40 Gy the risk of a second cancer increases progressively at higher dose – this is evidence for a late response to a very high protracted dose;
- there is evidence of a beneficial suppression of cancer incidence for radiation doses around 0.5 Gy, that is 500 mGy.

**Cancer induced by CT scans**

Another study, also of children, has claimed that there are health risks for CT scan doses that are 100 times lower than the threshold shown by the radiotherapy work of Tubiana et al. Its authors, Pearce et al [28], conclude:

Use of CT scans in children to deliver cumulative doses of about 50 mGy might almost triple the risk of leukaemia.

Many technical objections that cast severe doubt on this claim have been published [29], but, unfortunately, when the label children is attached to a study, the media are ready to accept any story, in spite of technical objections. The use of the word might in the Pearce claim is characteristic of publications seemingly designed to influence by suspicion rather than to convey any firm
scientific conclusion.

There is a fashion to cast doubt on the efficacy of radiation medicine and to question the goodwill of the medical fraternity. This seems to be driven by a wish to enhance fears of radiation, in line with the media reaction to the Fukushima accident. A casualty is a general and unsubstantiated erosion of trust that is itself dangerous.

But within clinical medicine the dangers are elsewhere, as observed recently by Bill Sacks, a retired radiologist:

The craze that emerged 10 [or more] years ago for whole-body screening with CT of asymptomatic patients resulted in a lot of harm to patients and a little benefit. The harm, however, was not from radiation, but rather from incidental findings which were exceedingly common, with follow-up including such things as thoracotomies for lung findings that needed biopsy but turned out to be benign, with all the pain and suffering that such surgery occasioned, plus out-of-pocket expenses. The number of false positives when you go hunting without reason is always large. The small benefit was thought at that time to consist of the much smaller number of patients in whom incidental unsuspected cancers were found at early stages that were treatable. ... the whole-body screening CTs did more harm than good, except for the owners of the imaging centers, who usually were also the ones to do the follow-up imaging for “incidentalomas.”

So asymptomatic patients should be worrying about subsequent procedures, not radiation.

Symptomatic patients should not worry about radiation either. For them a radiation scan may resolve doubts about a diagnosis. In such situations there are several risks, some small, some large. In a recent paper Zanzonico and Stabin [30] reported a study of the net benefit of diagnostic radiation scans for several medical treatments. They showed that PET scans save the lives of more than 2,000 suspected lung cancer patients a year in USA, at the expense of a theoretical loss of 60 lives by CT-induced cancer as calculated pessimistically using the false LNT mortality (5% per person per Gy [14]).

Similarly, they found that over 30,000 lives of coronary artery disease patients are saved by CT scans for a dose to which the LNT attaches less than 3,000 deaths by CT-induced cancer – although there is no clear evidence for any of these LNT risks. Thus the net benefit of a scan is quite clear whenever there is the slightest symptomatic concern.

It is remarkable that the public and press worry about trivial risks from radiation scans when the benefits are so evident [31]. The safety of radiation should be a minor consideration in any decision to have frequent
asymptomatic scans.

Opposition to CT scans on grounds of safety seldom mentions radiotherapy with its higher doses. Perhaps that is just ignorance; perhaps it is because details of the treatment of those who are more seriously sick, are seen as personal and less suitable for attention-grabbing publicity. Yet people should know that for a radiotherapy dose, a thousand times higher than CT, the benefit of radiation treatment is overwhelming.

Here are some numbers. Over a month of a radiotherapy treatment the tumour gets more than 40,000mGy and the peripheral healthy tissue as much as 20,000mGy – that is five times the fatal dose experienced by some Chernobyl workers. Evidently, the success of radiotherapy with its fractionated treatment is witness to the biological repair mechanisms. And everyone knows a friend or relative who has experienced this, if they have not done so themselves. So, put simply, radiotherapy treatment of deep cancers would not be effective if LNT were applicable, and every member of the public has the evidence close at hand.

**Biological safety of radiation**

**French National Academy Report**

Current radiation safety regulations are based on LNT and ALARA, in part because, in professional memory, they always have been. For most of those with responsibility in the field, it is simply their job to follow them[^32] – they may differ somewhat from nation to nation, but by small factors compared with what the scientific data indicate. There has not been any great pressure to update them to match the science, because they are seen to be safe – in respect of litigation, rather than actual danger. As long as safety levels are set with an eye on a court of law, the answers are likely to be highly distorted. But, with job and budget security in mind, few are interested in upsetting the apple cart. Truth can wait – it must be someone else's problem.

However, there are two groups of professionals who have reasons not to be easily impressed by this *laissez faire* position: the environmentalists and the medical profession, at least those familiar with the science. The environmentalists have serious questions to ask about a new worldwide expanded use of nuclear power to replace carbon – there is no other solution that is up to the job of providing liberal energy on the scale required. Some environmentalists who were previously opposed to nuclear power on political grounds have now understood the technological benefits and safeguards – we met some of them in Chapter 2. Some radiographers, oncologists and radiobiologists know the science and are alarmed that their patients have been affected by a popular wave of radiophobia that discourages them from
accepting radiation treatment that would be beneficial to their health. The views of the international committees that firmly resist change are heavily influenced by American concerns – there, threats of litigation seem to be more important than science and the environment. But an initiative has come from the French, a unanimous Joint Report of the Académie des Sciences (Paris) and the Académie Nationale de Médecine, published in 2005 entitled *Dose-effect relationships and estimation of the carcinogenic effects of low doses of ionizing radiation*[^33]. The Report is a technical review of biological evidence that repeatedly contradicts LNT and supports the existence of response thresholds. A conclusion directly relevant to the application of nuclear power is expressed in typically dry terms:

*Decision makers confronted with problems of radioactive waste or risk of contamination, should re-examine the methodology used for the evaluation of risks associated with very low doses and with doses delivered at a very low dose rate.*

Unfortunately, neither the public nor such decision makers read these reports.

**The treatment of pregnant women and children**

Many a popular article about the safety of radiation includes a reference to the sensitivity of children. The assumption is made that they are more sensitive than adults, and pregnant mothers and foetuses more sensitive still. Few medical accounts challenge this, but little evidence is offered either. It is usually seen as obvious in any popular discussion. But is it true?

Without getting into details, there is reason to expect that children and foetuses should be different from adults. Their cells divide more frequently because they are growing and developing, rather than simply being maintained as in an adult. However, immune protection slows with age, and it is immune failure, not increased mutations, that increases the likelihood of cancer.

The mutation model of cancer cannot explain the following three observed features of cancers:

- When the immune system is suppressed, as in organ-transplant patients or HIV patients, cancer rates more than double. Hence there is little credibility in the prediction of a small percentage increase in cancer from LDR based on this model.
- When people exercise vigorously and regularly – even 5 minutes of vigorous exercise results in DNA damage[^34, 35] – their cancer rates go down considerably for many types of cancers.
- Everyone has mutations in their bodies that are potentially cancerous but no more than half are diagnosed with cancer in their lifetime[^36].
New research shows how the immune system controls cells transformed by low levels of radiation \[^{37}\].

Less than 1% of all cancers are found in young children aged 0-14 years. Predominantly cancer is a disease of the old, not the young, and headline accounts of individual cases of child cancer, with the concern that they naturally raise, should not be seen to override this general observation. This has been checked in particular cases, for instance in careful work based on large populations, to confirm that there is no evidence for an excess of radiation-induced leukaemia cases among children living near nuclear power plants \[^{38}\]. In any event the size of possible doses is much smaller than variations in the natural background radiation.

The results were recently published of an experiment designed to test the effect of radiation on pregnancy and early development of mice \[^{39},^{40}\]. These were divided into two groups, two weeks before mating. Throughout the experiment, which lasted for up to 20 weeks from birth, the groups were given to drink either natural water or water containing 20,000 Bq of caesium-137 per litre. This activity in water is 2,000 times the regulation limit for human consumption imposed in Japan since April 2013. A human drinking a litre of such water per day, every day, would reach a steady whole-body activity of 2.9 MBq \[^{41}\], which is 30 times less than the smallest whole-body activity that caused any loss of life at Goiania. The mice experiment observed no significant differences in the pregnancies, blood counts and other markers indicative of bone marrow function between the two groups. The number of mice is not made clear, but these results are not inconsistent with the two successful human pregnancies at Goiania and they do not suggest that a chronic dose of caesium at this level is above any threshold that affects foetuses or children (or adults).

Thyroid cancer in children is a special case because any iodine, whether regular or radioactive, that enters the body gets concentrated in the thyroid gland if the food supply was previously deficient – as was the case at Chernobyl, but not at Fukushima. The short lifetime of radioactive iodine means that the radiation dose is acute and confined to a small volume. These are the conditions in which biological protection is most easily overloaded. The same is not true for any of the longer-living caesium, strontium or other environmentally significant radioisotopes that get widely spread through the human body.

Whether regulations should treat children and pregnant women as a category distinct from adults is a question separate from whether they are affected differently by radiation. Should they be permitted radiation scans and therapy under the same criteria as adults? That parents and husbands should take special care of them – and exercise that care when giving permission for
treatment – is not the issue. Natural affection and bonding ensure that they would do that in any event, whatever any safety regulation might say. But should special care be taken of children and pregnant women at a legal level, as well as a family level, when in fact there is no scientific or medical evidence for a general increase in sensitivity to radiation? It seems unwise to double count by stacking caution on top of itself, rather than to provide family education and advice – as is given for sunshine and UV. There appears to be no logical case for treating pregnant mothers and children any differently from adults as far as regulation of exposure to radiation is concerned. Unfortunately nobody seems ready to say this in public – another omission that is a result of radiophobia. This is a case of confusing personal and family care, where sentiment should have free rein, with societal and legal responsibility, which should be rooted in objective evidence.

Social and mental health

Illustration 34: Data showing the mortality of residents in care homes for the elderly that were evacuated in Japan[^44].

If the physiological effects of radiation accidents have been exaggerated by a wide margin, that cannot be said of social and mental health. Feelings of ignorance in the event of an accident cause personal distress that can turn into panic, especially if large numbers of people find themselves in the same situation. If no one is ready to explain what is happening, some feeling of mutual support is given by blaming some individuals or authorities, right or wrong. This is a relief mechanism which gives the impression we are doing something. Without it distress can result in mental or social illnesses of
various kinds.

The elderly and less articulate are least able to take it out on someone else, and so are worst affected. Social and mental stress may be expressed in many diverse ways and it is not easy to find firm quantitative estimates, but social workers are in little doubt about the symptoms that they encounter. At Chernobyl the result was alcoholism, family break-up and states of hopelessness \(^{42}\). At Goiania the number affected was smaller, but the stress was expressed in cases of alcoholism and high rates of depression compared with the national average \(^{43}\).

At Fukushima there were early deaths among the elderly, bed wetting among children, and a general witch hunt of those in authority who were thought to be responsible. As mentioned above, this acted as a stress-relief mechanism, but built up collectively, with encouragement from the media, into ugly demonstrations and pressure groups which are not easily reassured by factual explanations they do not wish to take on board. Elderly residents in care homes are a particularly vulnerable group. At Fukushima, those who were evacuated at short notice suffered disruption to their normal level of care in addition to feelings of fear. Both contributed to the high mortality recorded for residents at the time of the accident \(^{44}\). This is shown clearly in Illustration 34 as an increase in mortality from an average of 10-20% to 65% in the period of March 2011.

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7) *The Effect of Physics Agents on the Resistance of Mice* James B Murphy, Rockefeller Inst, PNAS (1920) [http://www.pnas.org/content/6/1/35.full.pdf+html](http://www.pnas.org/content/6/1/35.full.pdf+html)
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22) http://www.who.int/ionizing_radiation/about/med_exposure/en/ [June 2014]

23) http://www-naweb.iaea.org/nahu/dirac/default.asp


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Calculated from 20,000 Bq/litre and mean retention time of 100 days / ln2.


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Chapter 9: Society, Trust and Safety

\[Ah,~this~is~obviously~some~strange~usage~of~the~word~'safe'~that~I\]
\[wasn't~previously~aware~of.\]

Douglas Adams, \textit{Arthur Dent} in \textit{The Hitchhiker's Guide to the Galaxy}

### Establishing public trust
- Earning trust and telling the truth
- Popular culture and the Precautionary Principle
- Innovation, leadership and confidence in science
- Communicating truth and confidence to others
- Recent leaders in the science of radiation
- Confidence to change an opinion
- Rights, duties and the survival of the fittest
- Losing trust by offering appeasement
- Money and safety – two social inventions of limited worth

### Major health consequences of radiation accidents
- Cancer from Hiroshima and Nagasaki
- Inherited abnormalities caused by radiation
- Civil nuclear safety and radiological protection

### Radiation doses As High As Relatively Safe
- Acute, chronic and lifelong thresholds of risk
- Radiation dose rates compared using a picture
- Largest lifelong dose that is safe
- Origin of currently recommended safety limits
- Conscious thought and adaptation
- Public attitudes towards nuclear technology

### Notes on Chapter 9

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**Establishing public trust**

Earning trust and telling the truth

To the extent that people distrust one another, society fails and large populations become unstable; instability is a euphemism – in reality it brings a likelihood of war, famine and a dramatic fall in world population. Improvements in living standards need individuals to develop new ideas, and that requires imagination and creative intelligence shared with others. The
use of imagination alone too often brings apprehension of others and misunderstandings of the natural world. It creates fear of the unknown or ill health that needs to be challenged by evidence and study.

In earlier centuries the public could be persuaded to support national policy through spectacular displays of military colour and fleets of ships decked with outsized flags. But with increased education the public take more persuasion. What they are told needs to foster trust in the authorities, but in times of war, to deceive the enemy, the whole truth is not told. To continue such deception is to live on borrowed time – sooner or later the truth will come out. In the meantime an increasingly tangled web of deception is woven. Hence the advice: *Truth To Tell: Tell It Early, Tell It All, Tell It Yourself.* [1]

Since World War II the matter of ionising radiation safety has become further and further removed from objective truth. In 1934, the year that Marie Curie died, radiation protection recommendations were based on avoiding burns, called *tissue reactions*, and the longer term effects known from the discovery of bone cancers among the Radium Dial Painters in 1926. The recommendations were based on a damage threshold set at 0.2 Roentgens per day; in modern units that is 640 mGy per year of gamma rays. In 1951 the safety threshold recommended by the International Commission for Radiological Protection (ICRP) was lowered to 0.3 Roentgens per week, which is 140 mGy per year. In 1955 the ICRP recommended that the use of a damage threshold be discontinued and that the LNT model be used to assess proportional risk all the way to zero dose. From high dose data it was judged that the slope of the LNT straight line corresponded to an increased mortality risk of 5% for each 1,000 mGy of whole-body dose (assumed to be gamma rays or other low LET radiation) [2]. The vital question is why this change was made.

Two reasons are apparent:

- epidemiological evidence of excess cancer malignancies among radiologists, and also among industrial and defence workers;
- indications of excess leukaemia cases in the survivors of the atomic bombings at Hiroshima and Nagasaki, whose probability of occurrence, not the severity, was assumed to be proportional to the size of the dose.

Today neither of these reasons look tenable. As discussed in *Radiation and Reason* [see Selected References on page 279, SR3], the dominant effect amongst groups of radiation workers and ex-workers below the age of 85 is that they have a mortality which is consistently 15-20% lower than other comparable groups [3]. This is true in different countries. Whether there is an undetected selection effect, the so-called Healthy Worker Effect (HWE), or a
hormetic effect, cannot be determined from these data. However, claims for small increases in cancer rates of a few percent depending on lifelong accumulated dose have been made \[^3\]. The doses involved are no larger than background variations that show no such effect; the claims are of questionable statistical significance; they cannot be taken seriously while the much larger HWE remains unexplained and uncontrolled.

The incidence of leukaemia at Hiroshima and Nagasaki was also discussed in *Radiation and Reason*, [SR3]. Among 86,955 survivors there were 296 cases between 1950 and 2000, while data on those not irradiated suggest that there would have been 203 cases in the absence of radiation. There was no evidence of radiation-induced cases for doses below 200 mSv.

But starting in the 1950s there were other forces that began to influence cultural attitudes to radiation, and Chapter 10 follows how these distorted the views of both scientists and politicians from that time.

### Popular culture and the Precautionary Principle

General education has provided little appreciation of ionising radiation and nuclear technology. Few people go out of their way to study or attend public lectures on the subject out of interest. Most prefer to avoid matters that they think promise no excitement or stimulation. They are content that practical matters are handled by consulting expert opinion, although that does not build a sense of trust in the way that personal knowledge and experience would. Dismissing this ignorance as a consequence of globalisation is no solution. A few decades ago, most people could tinker with their car, and, if it ceased to work, get it going again – but not today. Globalisation has removed individual responsibility for many aspects of life, but some matters like the effect of nuclear energy need to be talked through holistically – and this is harder if the technology is obscure to almost everybody. People should have direct or indirect contact with someone who understands and can answer questions. That is essential to social cohesion and the stability of public opinion.

Popular opinion is impressed by what science achieves. People notice that science frequently consolidates its findings into principles or laws, and these are accepted as analogous to legal laws. Then any conclusion drawn from a generalisation that has been blessed with the title of *principle* or *law* assumes an extra legitimacy in the public mind and is seen to need no further questioning.

One may think of the popular *Law of Averages* or the *Law of Unintended Consequences*, neither of which deserves such lofty status. Exactly how such a title is conferred is unclear – but its indiscriminate use is not scientific. A significant example is the *Precautionary Principle* that appeared in the 1980s
and has been used intensively in the safety industry ever since, frequently with the effect of obstructing innovation or buttressing restrictive practices.

The *pre* prefix added to *caution*, the regular common sense word, implies a sensible policy of additional safety during the introduction of a new technology, for which measurement and monitoring procedures are primitive and understanding is still uncertain. However, application of this idea incurs extra costs and is time consuming; it leads directly to lower productivity and uncompetitive practices in industrial applications; as soon as understanding and information allow, it should be superseded. Its application to nuclear technology with its advanced measuring and monitoring instrumentation, and a century of understanding, has long been entirely inappropriate. It is being used as a cover for public fear and to disguise the ignorance of those supporting it.

The public believe that understanding radiation is beyond them, but for safety at least, that is incorrect. Although they have never been told the real story of nuclear radiation in accessible every-day terms, it is high time that they were – at school, in public lectures and in the media. Future prospects for world economic prosperity and a sustainable environment depend critically on explanatory education and improved public trust in science. This is essential if the known benefits of nuclear technology – power, clean water, food preservation, advances in healthcare – are to be widely accepted and realised. These are needed if man is to survive on planet Earth in large numbers with good health and a fair standard of living.

Dangers from choice of lifestyle are often discounted relative to those seen to be caused by the irresponsibility of others. Significant external threats to family life may centre on economic stability and social competitiveness, but worries that impact individuals, such as cancer and death, though far more threatening, are personal and do not contribute to collective fear and panic. In crowds overreaction can be reduced if enough individuals show leadership, but others need to trust them. Otherwise, rumour, amplified by uninformed imagination and repetition in personal and public media, becomes unstable with the result that public confidence implodes and the mutual trust that is essential to an effective society is seriously damaged. A similar example is public attitudes to *genetically modified* (GM) crops, particularly in Europe. Reporting on nanotechnology has had some ill-informed moments too.

As population density increases, the necessity of mutual understanding increases too, and there is no question of going back to the way things once were. More than ever before, it is essential that trains run on time, utilities are delivered reliably, vehicle drivers are trained and disciplined and telephone and internet services are up and running. For the future there is the need to find new opportunities for economic expansion which put yet more emphasis
on education and building confidence in the applications of scientific understanding.

In the past two centuries such opportunities have come from applications of engineering and medicine, based largely on exploiting the outer (or electronic) part of atoms – that is chemistry, electrical power, electronics, lasers and the science of materials. But the inner (or nuclear) part of atoms has only been exploited for health in the footsteps of Marie Curie a century ago. The use of radiation and nuclear technology in other contexts has been largely avoided, primarily because of the phobia felt by public and political authorities. In an era that includes climate change that is a restriction we can no longer afford.

**Innovation, leadership and confidence in science**

Science is for participants, not spectators. It should be experienced personally in the real world through study, experiment, prediction and imagination. Everybody on Earth is involved to an extent, and denying this reduces the possible scope of life. Such active experience of science has lifted man above the plants and animals and made him master of his destiny by understanding how to solve the problems that threaten survival, not just at the level of tribe or group but at the individual level too. Rules, customs, laws and habits which ensure the continued existence of a group are cumbersome and apt to change slowly – as anyone who has served on a committee is aware. An individual who is able to deploy rational thought and apply it scientifically to overcome the challenges he encounters, improves the life-chances for all in the group through to an ability to change rapidly and innovate that is excluded by the inertia of committee-land.

If everybody followed the guidance of the official consensus, many advances in the history of mankind would not have occurred. So a balance is needed between innovation and obedience to authority. How has this balance worked for the wider good in the past? Who successfully combined innovation with authority?

Science is not alone in searching for such figureheads. Think of the banks – the issuers of bank notes denominated in the local currency – they are concerned to impart as much gravitas and respectability as they can muster for their notes, new and used. Whom do they select? Past monarchs and other heads of state, especially those with reputations immutably assured by history, but also great scientists and thinkers. In Illustration 6 on page 8 are four such figures, two men and two women: some have much to say about the science with which we are concerned; the others have authority and wisdom that is no less relevant.

It was the breadth of their lives, as well as their incisive technical ideas, that
was the key to their success. Certainly none set out as an expert in their field, since that did not exist prior to their contribution, and some of them would have been obstructed from carrying out their work by modern regulations. Many of their applications for research grants would have been rejected by the peer review mechanism and, in fact, they had to overcome substantial obstacles to get their ideas established.

Adam Smith (1723-1790), economist and philosopher, has appeared on the Bank of England twenty-pound note since 2007. He is said to have disliked Oxford and committees, and he lived in Scotland.

Charles Darwin (1809-1882), naturalist, biologist, geologist, and student of divinity, has appeared on the Bank of England ten-pound note since 2000. He had a remarkable eye for geology which seems to have inspired his view of the evolution of life, a synthesis in tune with the writings of the environmentalist, James Lovelock, today – or the other way around, perhaps.


\[
\text{How very little can be done under the spirit of fear.}
\]

Marie Curie (1867-1934), physicist, chemist and pioneer radiologist, was born Marie Sklodowska in Poland. Her portrait appeared on the Polish 20,000 zloty note in 1989 and then on the French 500 franc note in 1998.

\section*{Communicating truth and confidence to others}

Thinkers like Adam Smith and Charles Darwin achieved new goals by concentrating on fresh data interpreted with common sense and imagination. Florence Nightingale is generally remembered for her pioneering work in nursing at the time of the Crimean War in 1855. However, the method that she used to promote nursing was quite revolutionary. Prior to her work, political and military authorities had concentrated their attention on the supply of fresh troops and munitions for the battle front and paid little heed to the fate of the wounded. In her work she collected data on mortality rates among casualties and analysed them to show how much more effective the war effort would be if greater care were taken to nurse wounded soldiers. To do this she used new graphical techniques to bring life to her data and arguments when trying to make her point to those less gifted in numeracy. She herself, being a distinguished early statistician, ensured that lay people and politicians understood the implications of the data. An example of her use of coloured charts is shown in Illustration 35. Her method and success provide us with an important example because we try to follow the example of her graphics when trying to bring to life the safety of radiation (Illustration 2 on page 4) and when talking of waste (Illustration 9 on page 10).
Recent leaders in the science of radiation

The mission to set the record straight on the relative safety of ionising radiation is not new. A number of distinguished scientists, oncologists and engineers who died in recent years made major contributions during their lives to the public understanding of the effect of low doses of radiation:

Maurice Tubiana (1920-2013), a French medical physicist and oncologist. A leading author of the highly significant 2004 French National Academies report [4], Tubiana championed the safety of nuclear power and wrote the book Arretons d’avoir peur! [Stop being frightened!] He was given a military funeral in the Hotel des Invalides in Paris.


Theodore Rockwell (1922-2013), a nuclear engineer, particularly in submarine propulsion. A tireless campaigner for facts in support of nuclear power.

Myron Pollycove MD (1921-2013), a radiobiologist whose clinical work and writings contributed to our understanding of the effect of low-dose radiation.
Don Luckey (1919-2014), a biochemist who surprised the world in 1982 with the message that low-level radiation is good for health and followed it with the first Symposium on Radiation Hormesis in 1985.

Bernard LH Cohen (1924-2012), a physicist who staunchly opposed the LNT model and wrote six books on nuclear physics and nuclear power.

Lauriston Taylor (1902-2004), a physicist. Charter member of ICRP 1928. Founder and chairman for 48 years of NCRP. In a 1980 lecture he made several statements that are still relevant today:

*Today [1980] we know about all we need to know for adequate protection against ionizing radiation. Therefore, I find myself charged to ask: why is there a radiation problem and where does it lie?*

*No one has been identifiably injured by radiation while working within the first numerical standards (0.2 roentgen/day) set by the NCRP and then the ICRP in 1934.*

*An equally mischievous use of the numbers game is that of calculating the number of people who will die as a result of having been subjected to diagnostic X-ray procedures. An example of such calculations are those based on a literal application of the linear non-threshold dose-effect relationship, treating the concept as a fact rather than a theory. ... These are deeply immoral uses of our scientific knowledge.*

**Confidence to change an opinion**

What is really necessary is to persuade the public that radiation is more or less harmless at a level that anyone is ever likely to encounter – so they should be content to embrace it. The public has a pre-existing view – they believe that they already *know* that radiation is dangerous. The words of Tolstoy quoted in Chapter 2 are worth repeating here:

*The most difficult subjects can be explained to the most slow witted man if he has not formed any idea of them already; but the simplest thing cannot be made clear to the most intelligent man if he is firmly persuaded that he knows already, without a shadow of doubt, what is laid before him.*

So the message that tells them that radiation is not dangerous is ignored or treated as unwelcome. Telling people that they have no need to worry is seldom effective.

However, there is an important group of people who have completely changed their minds. That is very difficult to do, especially for those who
have been publicly active in their opposition to nuclear technology. Five of them – Stewart Brand, Mark Lynas, Gwyneth Cravens, Richard Rhodes and Michael Schellenberger – have made a documentary, *Pandora’s Promise* [SR6], directed by Robert Stone, in which they explain why they now support nuclear energy. More important than the outstanding reviews that it has received is the example that the film gives of people, not scientists, who have looked at the evidence and stood up for what they now believe. There are others too; a new website offering nuclear generated electricity in Germany [6] went live in December 2014 with the support of former activists, founder members of Greenpeace and other environmentalists, including Patrick Moore, Stephen Tindale, James Lovelock and Stewart Brand.

But most people have busy lives, so difficult and confusing questions, such as whether to use nuclear energy, have to take second place to matters of money, children and employment. And the specialists around the world have their professional standing and reputations to worry about, too. They are anxious to be seen to support their own consensus and do not want to appear to change tack – unless everybody else does too. So they have a considerable inertia.

And the political authorities? Well, they have to face up to difficult questions and ensure that they have the electorate behind them when they do, because woe betide them if the lights go out on their watch. So what are they to do? They must synchronise any change of opinion:

- They need to try to appreciate the balance of the discussion themselves.
- They need to get the backing of the international experts – they can hardly hold out against those who are sanctioned by the UN.
- They need to get the objective facts properly covered for the benefit of schools, colleges and evening classes – and the teachers who cover these.
- They must ensure that the necessary changes in policy are accepted and supported by a majority of the public.

How such a change should be managed was described in an invited talk at the 1992 World Economic Forum, Davos, by E Schein of MIT School of Management [7]. To introduce a real change of paradigm, as needed here, the existing order has to be seen as increasingly threatening and the new order has to be introduced in a positive and rewarding light. The current world order based on the combustion of carbon (hitherto seen as comfortable and welcoming) needs to be re-presented in its threatening colours of imminent and unavoidable climate change. The new order has to reconfirm the headline that with reworked regulations nuclear-generated electricity should indeed be almost *too cheap to meter*. This raises an interesting question: *which*
commodities should not be too cheap to meter? We might suggest that water should replace electricity as a suitable utility to be more universally and aggressively metered – but that is another issue.

Using reason to change minds requires hard work and discipline. Evidently the senior environmentalists who have adopted a new view have been able to do this, but most members of the community at large have not. There is an interesting parallel in the therapy treatment of stroke patients that requires similar application. Following an attack, functional MR images show how the existing mental functions of the damaged region of the brain have to be transferred to a different, but undamaged, healthy region. This then needs to be programmed for its new role, and the patient has to work very hard at mental and physical exercises, with the help of therapists, for this to happen successfully. It would seem that embarking on a complete change of opinion on an emotive subject such as nuclear energy is a similar process. It is not just a matter of transferring knowledge – it has to be assimilated and accepted.

Making such a transition successfully may be eased by varying the medium in which the case is made. Humour, music, plays, novels, video and poetry could contribute towards establishing a change of culture. In the days of the Cold War an important impression made this way helped to influence a couple of generations of young people, who marched and demonstrated against everything that nuclear energy stood for. To replace that fear and mass dread with a cultural rehabilitation of radiation and a whole new attitude to nuclear technology, will require a new culture that appeals to the identity of another generation – although their loyalty will, hopefully, still be to the environment and world peace, like their grandparents 50 years before.

But time is important. Humans may have a long lifespan, but in 50 years much experience gets lost. Basic knowledge may be recorded, but more subtle skills and the confidence that goes with using them are easily lost. The experience of building railways in the UK, like the skills of ancient Greece and Rome, were all but lost in a few generations. Much of the practical experience of building nuclear power plants has already been lost and must be imported – an expensive thing to do. The rebirth of a nuclear age should not be long delayed, and educational programmes should aim to transplant still-living experience into fresh minds before it is lost.

Rights, duties and the survival of the fittest

The survival of the fittest, the rough melee of evolutionary biology, makes no reference to rights. Rights are additions that we have to give up occasionally to survive, and safety is one of them. Indeed there is a tradition of honouring those who do put aside their own safety for the sake of others on the battlefields of war.
But not every such choice is faced on a battlefield. There are other much more prosaic situations where there is a duty to step out of line and expose personal judgement in front of others. That may require a similar mix of bravery and self-confidence to that needed to enter no man's land and rescue a fellow soldier under fire. Here is an example with a stark message. Over many decades the infamous personality, Jimmy Savile, inveigled himself into many people's confidence in UK hospitals and outside in the wider community, and then sexually abused patients, staff and visitors, while enjoying special open access at all times. Many suffered, many more knew, but nobody spoke out sufficiently to question the authorities who claimed they knew nothing about it. Nobody was prepared to put aside their own psychological safety to save others. Duty?

Hans Christian Andersen's tale, *The Emperor's New Clothes*, is told to children who find it very funny, but also appreciate its seriousness. The vain emperor and his entourage of sycophantic courtiers stick to the official line that he is wearing a magnificent new suit of clothes, when in fact he is wearing nothing at all. Nobody dares to say what all can see – except a small boy from the street who shouts out the truth. The story is a harmless rendition of the Jimmy Savile story – but nobody spoke out in the Savile case! There was silence, and many innocent people suffered for many years in consequence.

Duty includes saying it *how it is* when everybody else appears ready to deny it. Doing so may risk unpopularity and isolation, but what is obvious should not be denied. If on re-examination and re-testing no flaw comes to light, it remains undeniable.

It is interesting to read Charles Darwin's thoughts about many of the geological rocks and fossils he found in his journey round South America in HMS Beagle in the 1830s [8]. It was obvious to him that these were immensely old, having started below sea level and been pushed up, heated, weathered and broken. To him the Earth was not just old, but very much alive, and the biblical account of the Earth, as young and dead, was entirely mistaken.

**Losing trust by offering appeasement**

Equally mistaken is the account of risks to life from ionising radiation, described by the LNT model and adopted by the current safety regulations: these imply that all radiation doses be kept as low as possible (ALARA), the basis for safety legislation around the world. Attempting to build public trust by appeasing worries about safety on this basis makes several assumptions that are untrue or damaging to society:

- It assumes that ionising radiation and radioactivity are extremely hazardous to life. As we have seen that is not the case and we have
Chapter 9: Society, Trust and Safety

the evidence and explanations to hand.

- It assumes that society at large is too stupid and ill educated to understand the simple scientific situation. This is a denial of democracy and a council of despair – or a case for maintaining a scientific under-class, forever stupid and uninformed, while matters are overseen by a hegemony of safety experts. We must hope that young people will demand to be educated and have the truth explained – hopefully some of them are reading this book.

- It assumes that the general public has no experience of significant radiation doses, let alone the very high doses received beneficially in therapy and the much more moderate doses in scans. Society would benefit from a more open explanation of such treatment by the medical profession.

- The current safety regime assumes that the accident at Fukushima indicated a need for greater safety in the design and operation of nuclear plants. This is untrue. The claim suggests appeasing the media clamour for further safety, which is a waste of resources. New designs should be developed, and should be selected in due course on economic as well as safety grounds. They should burn the existing stockpile of partially used fuel, and be able to burn thorium fuel too, but safety should not be the single priority – it certainly is not in the carbon fuel industries. Most existing reactor designs were seen as acceptably safe before the Fukushima accident, and should be seen as equally safe now.

There are vested interests who have reason not to support any liberalisation of nuclear energy and a reduction in radiophobia: those in the media who have preached against it and taken a stand for many years; those in the safety industry for whom the status quo offers stability of career and reputation; others with long-term commitments to pressure groups, such as Greenpeace. There are more who have thrown in their lot, investment or career, based implicitly on ALARA. Few of these would welcome change, but the young people of tomorrow whose future is at stake have no such baggage.

If the public feel that they can trust neither the science nor the authorities, confidence is eroded and few people feel able to exercise their own judgement. Democracy only works when voters study the actual evidence, not just what others say about it. The voice of science itself is not democratic – that is, its truth is not influenced by any kind of vote. Nor indeed does it bow to authority or any court of law. Nature is the popular face of science, and independent of any green agenda, nature will do what science determines – and intelligent authorities know that.

Illustration 7 on page 8 may bring a smile. It tells the story of King Canute, a
wise Scandinavian and English king who reigned a thousand years ago. He was pestered by his courtiers who thought only of winning his favour, and that anything he commanded would be done. To show them this was not true, he ordered his throne to be taken to the water's edge on the beach as the tide was coming in. Then he commanded the tide to go out, but his sycophantic followers were surprised to see the tide disobeyed and the water continued to rise, lapping around the king and his throne. Man cannot stop nature, and there is no design of nuclear power station that cannot be overwhelmed, if not in one way, then in another. It is nobody's fault that accidents like that at Fukushima Daiichi happen. Nature has the last word, as King Canute himself understood.

There is no tradition that scientists take an Oath of Duty, but perhaps there should be. Physicians traditionally take the Hippocratic Oath to place the health and safety of their patients first. In a similar vein, research scientists should implicitly agree to put truth about nature in first place. Then they might appreciate how nature provides better protection than reliance on regulation. Law, obediently followed and backed by the possibility of redress, is no substitute for active and knowledgeable accident prevention in the first place. A similar observation is that taking out insurance is inferior to good care, and that a successful insurance claim never returns what has actually been lost.

Money and safety – two social inventions of limited worth

Insurance and legal redress come down to money. Like money, safety is a social rather than a physical measure: both relate to contracts involving trust and confidence within society, but both are flawed. Money is not itself beneficial – that only happens when it is given away in exchange for something desirable. All money must be surrendered at death anyway. Similarly, all safety provisions must fail in the end, since death is a given for us all.

At best, money and safety provide choices. The value of money is flexibility in the range of goods for which it can be exchanged. But if many people hoard it or nobody wants it, it enables no contracts and ceases to have any dynamic value for society. Any such reduction of contracts puts a sharp brake on social and economic activity of all kinds. An obsession with safety has a similar effect by reducing human activity or squandering it on unproductive investment. For example, to be safe and avoid the many small risks of the day, to save money even, you might decide to stay in bed, thereby cutting productivity and contributing to a decline in the economy. Safety comes at a price.

But, if instead of a risk-averse attitude towards safety, the population at large
is more inclined to take a calculated gamble, ideally by examining the science and reckoning the chance of success or failure, the economy would be stimulated. The social cost of an occasional failure would be more than balanced by the economic uplift.

So, today, how far are we from some sensible compromise or equilibrium? Attitudes to money are poor, but perhaps not completely distorted. However, the view of nuclear safety is so totally unbalanced that to some groups in society, any risk at all is unacceptable, while no one else dares offend this extreme sensitivity. The politics of this situation is stabilised by scientific ignorance, but the economic consequences are dire and will continue to be so. When combined with the growing use of carbon fuels, the environmental consequences are seen to threaten the existence of human civilisation and other forms of life.

The way in which we use safety today is equivalent to a policy of financial liquidity in which we are so frightened that we hand all our money to the government for safe keeping. Such a regime would have no liquidity at all, no risk takers and no prospect of prosperity. That is not hard to see.

**Major health consequences of radiation accidents**

**Cancer from Hiroshima and Nagasaki**

There would be no particular excuse for anybody to be frightened of radiation if WWII had not ended with two nuclear bombs being dropped on the cities of Hiroshima and Nagasaki in August 1945. The principal effects of a nuclear weapon are a blast, a fireball and a prompt pulse of radiation. At Hiroshima and Nagasaki these killed at least a quarter of the population of 429,000. In 1950 when reliable records were compiled, only 283,000 survivors could be traced, and their medical health has been followed ever since [9]. Knowing where the bomb detonated, where the individual was and what material there was to shield them from the radiation, enabled individual radiation doses to be calculated for 86,955 of these survivors. These doses were checked against the personal radiation history of individual survivors as recorded by chromosome abnormalities and unpaired electron densities (ESR) in their teeth. The average whole body dose of survivors was 160 mGy from the acute X-ray and neutron fluxes. Most of those who died within days were killed by the blast and the fire, but some succumbed to Acute Radiation Syndrome in a few weeks. Although a few died of cancer before 1950 the majority of such cases would be expected later, in the period 1950-2000 for which data are available. Similar data for inhabitants who lived beyond the reach of the radiation have also been analysed for comparison. This is important because the normal cancer mortality rate in the absence of an artificial radiation dose is not small, and any comparison should be made...
with groups of inhabitants who are otherwise the same.

Of those survivors with a reconstructed dose, 10,127 died of solid cancers between 1950 and 2000, compared to 9,647 expected based on data for those not irradiated; for leukaemia the numbers are 296 and 203. Together these numbers mean that 93% of cancers would have happened anyway and 7% were caused by the radiation. For the 67,794 survivors with doses less than 100 mGy, the numbers are 7,657 and 7,595, and for leukaemia 161 and 157. For this group of survivors the numbers of extra deaths (62 solid cancers and 4 leukaemia) are smaller than the standard random errors calculated by Poisson statistics (90 and 13), and so are not significant measurements. But in this group of 67,794 people the risk is only about 1 in 1,000, anyway. For comparison, the lifetime chance of dying in a road accident varies between 3 and 6 in 1,000. So, for all practical purposes there is a threshold of risk from a dose of acute radiation at about 100 mGy. What happens at lower doses is too small to measure – even among the survivors from the bombing of two major cities whose health is followed for 50 years. Perhaps it is best summed up this way:

Suppose you were unlucky enough to be in Hiroshima or Nagasaki when the bombs were dropped, and you survived until 1950. If you received less than 100 mGy (like 78% of the other survivors), then the chance that you died of cancer between 1950 and 2000 from the radiation would be less than 20% of the chance of dying from a traffic accident in the same period of time.

The dose at Hiroshima and Nagasaki was an acute radiation pulse with little protracted or chronic contribution from residual radioactivity. This is the worst case – the same total radiation dose suffered as a chronic dose due to radioactivity spread over days, months or years would be substantially less dangerous, thanks to biological repair, replacement and adaptation.

Inherited abnormalities caused by radiation

But cancer is not the only worry that people have had about radiation since 1945. Having learned that radiation has the power to modify DNA, there has been concern that radiation might modify the design of human life itself, as inherited by each generation and passed down to later ones. It is clearly possible, but does it happen? At the time of the Cold War, imagining the implications of this possibility increased the nuclear threat – and was, therefore, an effective political weapon. It fuelled decades of horror fiction – stories of two headed monsters, and pets with extra legs, made exciting entertainment and stimulated the imagination. Unfortunately it took a few years before the scientific consensus emerged that there is no such evidence, based on the survivors of Hiroshima and Nagasaki, on data from Chernobyl, or any other source. It does not happen, in humans anyway, but in the 1950s
and 1960s before this conclusion was reached, asking the question had major consequences, as we report here in Chapter 10. But in 2007 the ICRP cautiously reduced their risk coefficient for inherited damage to some 20 to 40 times smaller than that for cancers \[10\]. That inherited genetic damage has never been seen in higher life forms is thanks to the immune system, but that does not mean it can never occur. In principle, any of us could be hit on the head by a meteorite tomorrow, but that is not going to happen either.

Civil nuclear safety and radiological protection

In the context of a nuclear power plant and far away from the blast and fire caused by the explosion of a nuclear weapon, the idea of safety covers two quite separate concerns: the control of the reactor and the protection of people, the latter usually described as radiological protection.

Shutting down a reactor by absorbing all free neutrons stops all further nuclear fission, but leaves unquenched the 7% of its power output that comes from radioactive decay, the decay heat. At Fukushima the consequences of being unable to remove this decay heat resulted in the destruction of several reactors. Stabilising the operation of a reactor and providing cooling to remove the decay heat are important and expensive engineering tasks. At Fukushima Daiichi they were overwhelmed by exceptional conditions beyond the design specification of the reactors. The result was an accident of the kind usually labelled an Act of God in discussion of insurance risk. Put another way, there is no human design that cannot be overwhelmed by nature. Nobody was to blame for this and, furthermore, nobody was hurt, not even those who worked at the plant under very difficult circumstances and took important decisions, such as to release the excessive reactor pressures. For that they deserve praise and thanks.

But we can ask,

Among the workers at Fukushima how many deaths due to radiation might there be as a result of the accident in the next fifty years?

Thirty workers are reported to have received doses as high as 100-250 mGy, but the lowest dose suffered by any worker at Chernobyl who died of ARS was 2,000 mGy – and they died within three or four weeks. So it is not surprising that no death from ARS has been reported at Fukushima, and none will be in the future. What about cancer in years to come? Of the 5,949 survivors of Hiroshima and Nagasaki who received doses in this range (100-250 mGy), 732 died of solid cancer (and 14 of leukaemia) against expected numbers of 691 (and 15) in the absence of radiation (calculated from those there but not irradiated). The difference, 40, is a measure of the number of cancer deaths caused by radiation – as a proportion, it is one person in 150. At Fukushima there were just 30 workers who received a dose in this range, and 1 in 150 of those is 0.2. That is less than one person on average, meaning
that it is unlikely that any worker at Fukushima will die of cancer from radiation, even in the next 50 years. The public have received far lower doses than the workers and are in no danger from radiation-induced cancer whatever.

The evacuation criterion and public exposure limit at Fukushima were based on 20 mGy per year, but there was great public pressure to lower the figure to 1 mGy per year. Such a limit could only be interpreted as additional to natural levels that show large variations anyway with soil type, altitude and latitude. Even 20 mGy per year as a chronic dose is 10,000 times lower than the monthly dose to healthy organs accepted by radiotherapy patients in Japan – and standards of medical care in Japan are among the highest in the world, as confirmed by life expectancy figures. The dose rate of 20 mGy per year is 60 times lower than the conservative safety threshold of 100 mGy per month suggested later in this chapter. Unfortunately the evacuation and clean-up regime imposed at Fukushima has had serious socio-economic consequences for the inhabitants of the whole region, without benefit of any kind, and was a tragic mistake. To this should be added the major economic and environmental cost of failing to restart the existing nuclear power plants and the related importation of fossil fuel.

The accident at Chernobyl was more than 25 years ago and questions about safety have been answered – what happened, who suffered and how, has been extensively reported in publications by the World Health Organisation, the United Nations and the International Atomic Energy Authority. The known loss of life as a result of radiation exposure includes the 28 firefighters who died of ARS and 15 children who died from thyroid cancer. These reports conclude that there is no firm evidence for any other loss of life due to radiation, either individually identified or statistically shown. The higher numbers sometimes quoted are paper calculations that use LNT-based risk coefficients (such as 5% risk of death per Gy) combined with measurements of Collective Dose. If the low doses of a large number of people received over many years are all added up, the result is a Collective Dose. This is without meaning except in the LNT model. Since 2007, even the ICRP, that still champions LNT, has cautioned that such calculations should be avoided.

**Radiation doses As High As Relatively Safe**

**Acute, chronic and lifelong thresholds of risk**

Suppose that you are building a bridge. Everybody agrees that it should be cost-effective and safe. But how safe? You would not advertise the bridge weight limit as the lowest that you might imagine by using the argument that the lower the weight limit applied the safer is the bridge in use. By lowering
the weight limit you might incur greater risks by sending heavier trucks on a long diversion route. Rather, safety thresholds should be set As High As Relatively Safe (AHARS) – conservative but mindful of other risks, which is where the relatively comes in. No extraordinary case should be made for radiation – the record shows that there are other aspects of life that are considerably more hazardous, and the risks and safety of radiation should be reckoned alongside other considerations. Nuclear is not a special risk and in fact is rather safe.

Following the discussion in Chapter 8, a sensible safety regime, conservative and based on modern radiobiology, might place safety thresholds on:

1. a maximum single acute dose;
2. a maximum chronic dose rate averaged in any month;
3. a maximum lifelong accumulated dose to limit damage, if any, that never gets repaired and escapes monitoring by the immune system.

The value of these high limits should be a matter for discussion based on conservatively interpreted scientific data. If people want to impose tighter limits in their own lives or in the care of their own families, they should be free to do so. What they should not be permitted to do is restrict the lives of others because of their own angst or that of a their chosen pressure group.

In 1951 the dose-rate safety level was set at 3 mGy per week (12 mGy per month, 150 mGy per year). Although the civil nuclear radiation safety record has remained exceptionally good since 1951, for no identifiable scientific reason the maximum dose recommended for the general public has been reduced by a factor 150, in pursuit of ALARA, whereas in the light of current knowledge of the effect of radiation on human life, the 1951 recommended value might reasonably have been increased by a factor of about eight. That would set the limit back close to 700 mGy per year, the value set by ICRP in 1934, before the era of angst and distrust began.

Now, 70 years after Hiroshima and Nagasaki, what should we say of the safety of radiation? It certainly can be deadly at high dose, especially if given to the same living tissue in a short period. An acute whole-body dose of 5,000 mGy, given all at once, has the same fatal effect on cells as more than 10 times that dose, spread out over six weeks in a course of radiotherapy treatment.

Wherever the line is drawn between what is safe and what is not, the safety mechanism should be understood. There should be evidence to confirm the threshold of damage, and the public should have confidence in how this is determined. The most simply justifiable safe limit is the highest that can be shown to cause no harm. To put it higher would not be conservative and
Illustration 2, A diagram showing monthly radiation dose rates represented by the area of circles.

- Red circle, 40,000 mGy per month, less than a radiotherapy dose rate that kills a tumour;
- Yellow circle 20,000 mGy per month, a dose rate that healthy tissue near a treated tumour receives and usually survives;
- Green circle 100 mGy per month, a benign and conservatively safe dose rate, As High As Relatively Safe, AHARS;
- Small black dot 0.08 mGy per month (1 mGy per yr), an unreasonably cautious rate, As Low As Reasonably Achievable, ALARA. (Also shown expanded for greater visibility.)
responsible. If it is put much lower the stricter regulations incur extra costs without any known benefit. Worse, when the public do receive a dose rate that is above the regulation level but below that which is harmful, there will be upset, claims for compensation, even panic, without reason. To set a safety limit As Low As Reasonably Achievable (ALARA) in a misguided attempt to appease public radio-phobia, is to invite public unrest, mistrust and misery, as happened at Chernobyl and Fukushima – as well as precipitating unjustifiable added costs and environmental impact.

**Radiation dose rates compared using a picture**

We may wonder what diagram Florence Nightingale might have drawn at this point to make the relative sizes of different dose rates plain for all to appreciate. Illustration 2, copied on page 227 with a more quantitative caption, shows monthly radiation dose rates as the areas of circles. The largest is the red circle describing the dose rate which is fatal to tumour cells given at 2,000 mGy in each daily treatment; the yellow circle at 1,000 mGy daily is the peripheral dose that carries a 5% risk of causing further cancer, as described in Chapter 8. There is no evidence for any life-threatening damage from an acute dose of 100 mGy and, as the clinical experience of radiotherapy has shown, a dose divided into daily doses spread over a month is substantially less harmful than a single acute dose. It follows that a chronic dose rate of 100 mGy per month should be even less harmful than the acute 100 mGy threshold found for survivors of Hiroshima and Nagasaki. So we show this monthly rate, the AHARS chronic dose rate safety threshold level as the green circle in Illustration 2. Also shown, in sharp contrast, is the ALARA safe dose rate limit recommended by ICRP, 1 mGy per year \[^{10}\] – the area of the tiny black dot within the green circle. This is so small that it has also been drawn in a magnified view. The AHARS dose rate is 1,000 times larger than the ALARA value but comparable with the safety threshold set in 1934.

This factor of a thousand is a measure of the extent to which ALARA exaggerates risk. Neglect of this factor is responsible for the socio-economic damage of recent nuclear accidents. Only a couple of weeks was needed to make an initial assessment of radiation exposures at Fukushima on this scale [SR8]. With an AHARS safety level, all the evacuated residents from the Fukushima region might then have returned to their homes to resume productive lives. Similarly power plants in Japan might then have restarted, and the rest of the world should then have returned to business as usual. Actually the first did not restart until 11 August 2015, still accompanied by protests. In due course the wreckage of the three damaged reactors has to be cleaned up properly but there is no reason why that should stop activity in the rest of the world.
**Largest lifelong dose that is safe**

But is this too hasty? Is there a limit to the total dose that living tissue can withstand in a lifetime? Even if we do not know if that is really necessary, we should use data to put a limit on it. As the years go by, this should be raised as further data and greater biological understanding become available. Certainly chromosome abnormalities accumulate, but it is the health of the immune system that is crucial. Anyway we should let mortality data answer the question. What figure do presently available data suggest? We saw in Chapter 6 that the threshold lifetime dose for cancer among the Radium Dial Painters is 10,000 mGy, a whole-body dose delivered chronically by the radium in their bones, although this alpha radiation is considered 20 times *more* damaging per Gy than beta or gamma radiation. So 10,000 mGy should be an underestimate of the lifetime tolerance for beta and gamma by a large margin.

There are two other estimates that are relevant. There is the threshold for a second cancer seen at about 5,000 mGy, Illustration 33 on page 197, although that dose is received locally in six weeks, not to the whole body in a lifetime. That means that the threshold 5,000 mGy, considered as a whole-of-life figure, could be a significant underestimate.

Finally there are the beagle data for a lifelong chronic dose rate of 100 mGy per month that showed no sign of life shortening until the dogs had received a total whole-body dose of between 6,000 and 9,000 mGy, Illustration 32 on page 187. This is the threshold value we are looking for, except that it is measured for dogs rather than humans.

Nevertheless there is some consistency between these three sets of data that suggests that 5,000 mGy would be a conservative value for a whole-of-life dose limit – it is as low as any of them. It corresponds to more than four years of receiving the AHARS maximum monthly dose rate of 100 mGy per month.

These safety thresholds are particularly cautious because they take no account of the beneficial adaptive effect of low-dose-rate radiation that can stimulate cancer resistance. This important possibility is really a matter for medicine, not safety regulation. But it does mean that in general there may be a dose-rate at which the positive stimulation balances the negative carcinogenesis. This has been called the No Observed Adverse Effects Level (NOAEL). However, it is too simplistic to see this as a single point on a curve. Its movement with the time profile of dose delivery and any subsequent morbidity will be important too.

**Origin of currently recommended safety limits**

Where did ALARA, the current ultra-cautious safety guidance, originate? As
we shall see in Chapter 10, it is a product of history and politics, not considerations of science or safety. Its parentage has ensured that it carries the full weight of a UN recommendation that leaves limited choice to national authorities. Only the bravest government would ignore the guidance provided by the ICRP, backed by the IAEA – and this guidance is to keep all radiation doses As Low As Reasonably Achievable. Any government that ignored such advice would risk being pursued by a frightened populace and soon be out of office. Worse, faced with any case brought to a court of law, any authority might wish it had played safe, as the law might see it. However, a court of law is a most inept forum in which to contest science. Education of the populace is a cheaper and more positive way ahead, but that takes time.

So, if national authorities are not to blame, it must be the fault of the ICRP who made such recommendations. Well, yes, but the original fault should be laid at the door of all those around the world who from the 1950s to the 1980s and even today, demonstrated, marched, sat in, chanted and voted with a popular voice for a world with minimal radiation. ALARA is the result and it is the fault of everybody who expressed their views so strongly at that time. However, now they should think again – and many have done so. Politicians and those with entrenched views should realise that times have changed and that radiophobia was never based on science in the first place.

What should be done now? If we do not want to succumb to the worldwide catastrophes that seem likely to accompany an ever more polluted atmosphere, we must reverse public perceptions of radiation and engage with nuclear energy as soon as possible. That will require a culture of public trust, based on a vigorous but sympathetic educational programme about radiation science. Should that be all so difficult? The public already has a fairly balanced attitude to radiation from the Sun and a degree of confidence about radiation in clinical medicine. Public perceptions can switch much faster than many imagine – just think how quickly attitudes to smoking have turned around, not just in one country, but almost universally. Perceptions of refugees change monthly as the public switch between identifying with their plight and otherwise.

New realistic safety regulations should bring major cost savings to any nuclear programme. Cheaper electricity would influence the public view, but first it needs to be offered. While no corners should be cut in respect of the control of reactor stability and its heat output, with justifiable safety standards, large parts of the cost of nuclear power could still be dramatically reduced, whichever flavour of future nuclear technology is chosen. Matters of nuclear waste, reprocessing and decommissioning should take their place lower in the list of priorities alongside other environmental problems requiring responsible and transparent solutions, like the disposal of hazardous chemical and biological waste.
We have survived on planet Earth, more successfully than other animals, through an ability to think rationally. In the past 60 years we have stopped thinking and become scared of the solution to our predicament. We should admit our error and turn about. That means public information, schools programmes, new national regulations, new working practices, new cost estimates. With the reach of television and the skills of people to harness social media to a cause that should be seen as theirs, it ought to be possible to make the change. Some will see this task as impossible, but they should heed the advice seen recently at the foot of an academic email: *Those who say it cannot be done should not interrupt those who are doing it.*

**Conscious thought and adaptation**

Life is a struggle, sometimes against unseen forces, often against intense competition. To an individual in society, success in life may be expressed in terms of money. Money is but a means of exchange, giving choice and access to the real goals of freedom from fear, access to food, water, warmth and shelter. To the ambitious, what is important may be a position in a virtual pecking order, but for society as a whole, success is marked by a healthy population at peace with itself. Natural calamities, epidemics, internal or external strife, and the effects of over-population endanger this. At a global level money is a means of organising how human effort is distributed and motivated, although it is often not effective at that.

If humans planned to live the simple life on earth, there would be no need for further adaptation of life through cognitive ideas. But that is not the case. We no longer have a small population with short lives limited by the natural diseases of ageing. So we need to understand the biology of life sufficiently well to modify it and understand, too, the social implications of the technologies we use and how they relate to health and the environment. These are questions for which evolution has not already prepared us. Everybody needs a more holistic understanding of life and the environment.

**Public attitudes towards nuclear technology**

In particular, we need to understand nuclear technology, its impact on health and what it can do for the environment. Even though few people currently understand it, there is no reason why the subject should be seen as more obscure than other branches of science. As a cure for cancer it has been an important part of the ability to extend life for over a century. However, its role in politics and the environment has been seen as destructive and in the interest of no one. The science has been shunned by many and the general population has not been encouraged to find out more. The number and status of the international committees who pronounce on nuclear matters has grown because of official and public ignorance. As both officials and the public become more knowledgeable, as they should, these committees and their
influence should be pruned.

The present clash of views over the safety of nuclear technology is remarkable, because there is no real danger – at least none comparable to the dangers of fire or road traffic. Reactors may have been destroyed at Fukushima, but there has been no significant detrimental health effect from radiation. Even at Chernobyl, where the reactor was utterly destroyed, there were only 42 known deaths actually caused by radiation. Radiation deaths from nuclear accidents are zero or few, except for theoretical phantoms based on paper calculations with LNT. So it would seem that, while the fire antis of long ago had good grounds for safety concern, the nuclear antis of today have none for low or moderate doses.

What about radioactive waste and nuclear terrorist threats? Public misinformation and panic apart, these are only dangerous to the extent that radiation is dangerous. If the dangers of radiation have been overestimated, then waste is less of a problem, and nuclear terrorism too. Up to now the public have viewed nuclear waste and the threat of terrorism as unbounded horrors. This is not justified by science – it is mistaken. Public fear and panic is a quite different problem that needs a quite different targeted solution. Nuclear waste, though nasty stuff, does not spread or infect like fire or the disease encouraged by biological waste. Because nuclear energy is so concentrated, little fuel is used and little waste is created – about a millionth as much as for fossil fuel. The waste needs to be cooled, reprocessed (to retain the valuable unused fuel) and the remainder buried after a few years – no bigger a task than handling many chemical waste products whose toxicity persists indefinitely. The effort and expenditure lavished on nuclear waste and plant decommissioning should be reduced; the cost saving should be substantial though vested interests would have their own reasons to argue against that.

If we follow the urgings of the anti-nuclear advocates, our prospects on planet Earth will be no better than animals, a massive reduction in numbers with a low standard of living. So we should study and apply knowledge, as our forbears did with fire. Though they were faced with a finely balanced dilemma, they did a better job at decision-making than we have done recently. Generally, those in authority have little understanding of science, although new prosperity depends on scientific innovation, as it has in the past.

Great rewards will be reaped by the countries that first set aside the legacy of the LNT model and embrace cost effective nuclear technology with sensible safeguards. As well as electric power, this technology can provide large quantities of fresh water by desalination, harmless and cheap food preservation by irradiation without refrigeration, and further advantages in
medical care. The world needs these opportunities to expand economically and socially, but the philosophy of ALARA and LNT stands in the way. The great eighteenth century economist, Adam Smith, said:

Science is the great antidote to the poison of enthusiasm and superstition.

He saw clearly that unless excessive activity caused by enthusiasm or the suppression of activity caused by superstition is properly rooted in science, its effect is poisonous. As we have seen fear of nuclear energy is a superstition without scientific foundation that should be exposed for what it is – or its demons exorcised, as the mediaeval church might have expressed it.

Notes on Chapter 9

3) Mortality and Cancer Incidence ... in the National Registry of Radiation Workers Muirhead CR et al, British Journal of Cancer 100, 206 (2009)
6) Environmental and other academic support for German nuclear power (2014) http://maxatomstrom.de/umweltschuetzer-und-wissenschaftler/
7) How can organisations learn faster? Schein EH, MIT Sloan School of Management http://dspace.mit.edu/bitstream/handle/1721.1/2399/SWP-3409-45882883.pdf?sequence=1
9) These data are discussed and tabulated in more detail, including references, in Chapter 6 Radiation and Reason [SR3]
Chapter 10: Science Distorted by Frightened Men

_Fear does not prevent death. It prevents life._

Naguib Mahfouz, 1988 Nobel Prize for Literature

**Evolution after Darwin**
- Faster development and greater personal threat
- When evolution met radiation: Hermann J Muller

**Nuclear weapons and the Cold War**
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**Evolution after Darwin**

_Faster development and greater personal threat_

To develop productively and peacefully, civilised society needs both trust and knowledge. Marie Curie gave both when she introduced radiation and nuclear technology into medicine. So the public acceptance of ionising radiation...
started well and she was active herself in organising the use of X-rays for the casualties of battle during WWI [1]. However, later in the twentieth century, when radiation and nuclear technology made an appearance in the form of nuclear weapons, knowledge was explicitly suppressed in the name of security and there was no figure like Marie Curie to instil public confidence. How did this go wrong? We need to go back in time.

In the nineteenth century Darwin introduced his revolutionary biological ideas of variation, selection and survival, as applied to living species. Over time most of human society came to understand and accept these, in spite of their revolutionary effect on our view of ourselves in the world. Perhaps this was because the changes that evolution described acted relatively slow, and an individual's perception of himself and his immediate family did not feel much affected. So, though knowledge was thinly spread, trust was not seriously impaired and variations in family ancestors, desirable or not, were safely removed to prehistory.

The principle of selective breeding of humans is a natural extension of the improvement of plants and animals, as practised from earliest times. But, independent of Darwin's ideas, the manipulation of human characteristics through planned breeding is widely seen as taboo and excites strong passions. Nevertheless, it was in fact Darwin's relation, Francis Galton, who in 1883, the year after Darwin's death, introduced eugenics, the name for this study.

Darwin developed his ideas to describe the development of populations of organisms – that is whole individuals. Later, the same ideas were applied to populations of cells including viruses and bacteria, where the timescales of change are much faster. With a cycle time of a few weeks cells can turn over hundreds of times in a human generation, and other constituents of microscopic life like bacteria and viruses evolve faster still. Evolution on this scale gave a picture of cellular life that might, even in the short term, be manipulated or artificially engineered for nefarious or political purposes. This picture alarmed the public in a way that Darwin, with his account of the characteristics of the finches observed on the Galapagos Islands, never did. However, what Darwin's theory did not describe was how the genetic record might be systematically changed, that is how mutations might be induced in the DNA. The power to manipulate would depend on controlling these mutations, but the structure of DNA would have to be found first.

It is not widely known that in the years before WWII X-rays were used with some success to control infection [2]. However, this work was cast aside in the enthusiasm for antibiotics when these became available to treat infections on the battlefield. If the current increase of antibiotic resistance continues, perhaps this use of X-rays should be considered again – but that is an aside.

After WWI there was increasing disquiet as the Soviet and Nazi authoritarian
regimes grew and industrialised military interests expanded with them. The Nazis engaged in experiments in eugenics in pursuit of their racial ideas although with limited success. However, a more significant development dates from the 1920s and even before, when it was shown that X-rays could create random mutations in fruit flies, as first studied by Hermann Muller. It was at this point that ionising radiation first entered the story that later became radiophobia.

**When evolution met radiation: Hermann J Muller**

Hermann Muller (1890-1967) was an American geneticist with outspoken political beliefs and an early interest in eugenics – he even named his son Eugene. In 1926 he published his experimental results on the production of mutations in fruit flies by X-ray radiation. Later, in 1946 he was awarded the Nobel Prize for this pioneering work. Significantly, in his lecture he claimed that any radiation dose produces genetic damage in direct proportion, all the way down to zero dose \[^{3, 4, 5}\]. This was the birth of the LNT model, but in making this claim he says *these principles have been extended to total doses as low as 400 r.* In modern units that is 4,000 mGy – which is a very high dose indeed, high enough as an acute dose to have killed the firefighters at Chernobyl. So he did not establish the LNT model for low or moderate doses found in the environment. Since then, other work has shown that the LNT model does not fit low-dose data for fruit flies \[^{6}\]. Nevertheless, he continued to claim that the response to such doses is linear all the way down to zero, as now enshrined in the LNT model.

Elsewhere in the middle of the twentieth century, biology became entangled with politics and made other wrong turns. In the Soviet Union, Trofim Lysenko, an agronomist, persuaded Stalin that Soviet agriculture should deny the principles of Mendelian genetics and develop crops based on the principle of the inheritance of acquired characteristics, as suggested by the Frenchman Lamarck (1744-1829). Unsurprisingly the programme failed and many inhabitants of the Soviet Union died of starvation as a result. The application of this fallacious pseudo-science was not finally halted until 1956.

Although both the LNT model and Lamarckism are mistaken, the former still has vocal supporters who are reluctant to look at the evidence. In the same way, even today, in parts of the USA, opposition to Darwin's ideas is seen as a belief – a political or religious question. Some people, it seems, live their lives knowing the answer as they see it, without ever looking at the evidence, but that is not an effective way to avoid danger.

However, the public perception of physical science was derailed in the middle of the twentieth century by a quite different mechanism, such that it was then seen as a closed book, shrouded in mystery and secrecy.
**Nuclear weapons and the Cold War**

A year that made history and buried truth

The end of WWII and other events in 1945 coloured how the birth of nuclear weapons was received. In that year the public of every nation were steeped in daily accounts of horror and war that are not easily forgotten, even with the passage of time. On 15 April British troops entered the Bergen-Belsen concentration camp, and in the following few days the public were shown press pictures of piles of naked bodies, evidence of tens of thousands dying of starvation and disease [7]. So the media were already experienced in the transmission of genuinely shocking news when in August the official reports arrived of the two nuclear bombs dropped on Japan. Each nuclear explosion caused a blast wave and a heat wave that destroyed buildings and killed most people within a radius of about 1 mile, and generated a fire-storm over 4.4 square miles [8]. The death toll was said to be less than in the conventional fire-bombing of Tokyo six months earlier [9], but peculiar to the nuclear explosion was the intense flash of X-rays and the lesser flash of neutrons emitted from the detonation point at a height of 500-600 metres. Because the explosion was high above ground there was less radioactivity released than would have been the case for a detonation at ground level. As a result, the inhabitants received acute doses of radiation, with less chronic dose from fallout.

The historical narrative that one usually reads is what the victors wrote, but more significant for the subject of this book is what the vanquished thought of the nuclear bomb. They learned of its power when at their lowest psychological point, and their national consciousness has been branded by the thought of it ever since. It is no coincidence that the most visceral reactions to the accident at Fukushima have come from Japan and Germany. But with the passage of years those reactions should be tested against science. When writing the account of Fukushima for the sake of future generations, the world has a duty to ensure the story is honest and scientific, not emotional.

**Dissent over nuclear weapons**

But after WWII the victors were troubled too. Though a scientist may respect the science and its reliability, his fear of what his fellow human beings may do with the power it gives them is increased by his technical understanding. Fears of Nazi Germany and the Soviet Union were rife in the twentieth century, but there were also worries on the US home front about politicians, military leaders, fellow scientists and foreigners who held a variety of views on how science should be used. Nuclear energy, by its very power, intensified questions of trust, confidence and secrecy [10]. Significant tensions built up
between individual scientists, and also between other groups involved; and these were not eased when peace came. Worries about war-time allies, particularly the Soviet Union, grew too.

Unlike science, history often provides several coherent accounts of a maze of events from different perspectives. Thus the military and political perspectives of the history of nuclear radiation are not based in science. In the development of nuclear weapons in WWII, the raison d'être of the Manhattan Project, there were many major players who were not scientists, and misunderstandings between them and the physical scientists continued to be important into the Cold War era. It could be argued that the lack of confidence and mutual trust between these two groups was as instrumental in the rise of radiophobia as the ingrained fears of the defeated populations.

Many of the physical scientists involved were in some shock when they realised the energy of what they had developed, and had little confidence in the readiness of the military to forego the influence of this muscle at the end of hostilities with the Axis Powers. Their concern was well founded, for other nuclear scientists threw themselves, without a second thought, into building the most powerful weapons possible, in particular the fusion device known as the hydrogen bomb. A conventional fission bomb is limited in size and power by the speed at which it is possible to assemble a large super-critical mass of explosive. But a fusion bomb has no such limit, and the Soviets tested a 50-58 megaton device, about 2,000 times the energy of the Hiroshima and Nagasaki explosions.

Political and military concern, particularly in the United States, was focussed on fears that other powers might obtain the secrets of nuclear weapons. As a result the development of the hydrogen bomb was supported amid tight security. Exceptional scrutiny was applied to root out any potential Soviet sympathisers, and the sharing of information with other allies, even the UK, was curtailed. A reign of anti-communist hysteria, verging on paranoia, ensued: there were the Senate subcommittee McCarthy-Army hearings of 1954 about claims of communist infiltration; there were the investigations of the House Un-American Activities Committee with its witch hunt for communist sympathisers; there was the investigation of the patriotic loyalty of Oppenheimer before the US Atomic Energy Commission. Dr Robert Oppenheimer was the physicist war-time leader of the Manhattan Project whose security status was revoked in 1954, largely on the testimony of Edward Teller, the Hungarian-born theoretical physicist who pushed the development of the hydrogen bomb. The late 1940s and early 1950s were a dark period in the USA – many liberties that we normally take for granted were suppressed. The lives of many eminent people were seriously damaged and they went into hiding, or went abroad, like Paul Robeson, the legendary actor and singer, and Charlie Chaplin, the film director and comedian. It is
helpful to appreciate this turbulent background when judging the scientists and scientific opinion of the day – opinion that led to the establishment of the LNT model and the suppression of contrary views for over 60 years.

How scientists express their concern on matters beyond their own immediate field varies, but their natural discipline makes them cautious – in fact considerably more cautious than those unused to scientific argument. Since few physical scientists and engineers appreciate much about biology, and biological scientists know very little of nuclear physics, they are frequently rather over-awed by their shared interdisciplinary questions. That was the case in the Cold War era in the matter of nuclear radiation and its biological effects, particularly genetics. At a crucial time in the 1950s as the official view was forming, the voice of biology was missing. In the confrontations between the main parties, the military and the physical scientists, nobody could speak to the biology with the required authority. There was no biologist on the Manhattan Project with the necessary clout, and the mode of scientific thinking in biology is quite different from that in the physical sciences, as explained in Chapter 4. And into this gap came Hermann Muller, recently anointed Nobel Laureate (1946), with his outspoken support for the LNT model, his concern about radiation, and his antipathy to Soviet ideology and Lysenko-ism. There was no competition.

**Illustration 36:** A graph showing the number of US and Soviet nuclear warheads deployed at different dates.

**The madness of the Arms Race**

In the post-war period political backing in the USA for the growth of nuclear armaments was very strong. It was seen as the means to impress Pax Americana on the world, and other nations, friend and foe, were very much
Nuclear is for Life. A Cultural Revolution

aware of that. Those that were able to do so reacted by developing and deploying their own nuclear weapons. When the allies, Britain and France, did so, it was seen as politically undesirable and a loss of security, but no worse. However, when the Soviet Union exploded test devices, that was seen in the USA as an existential threat.

In the intervening decades remarkably few nations have bothered with nuclear weapons. Though they may wield influence at the conference table, they are very expensive in technical manpower and mostly useless in the field from a military perspective. In his work John Muller of Ohio State University has explored why nations consider nuclear weapons such an undesirable waste of resources [see Selected References on page 279, SR4]. Nevertheless, a few have flexed their muscles in practice (China, India, Pakistan) or in theory (Israel, Iran, South Africa), leaving North Korea as the only state likely to consider using a nuclear weapon in anger.

The US paranoia about nuclear weapons was exacerbated by Soviet behaviour in taking over Eastern Europe. So was started the Cold War, as recorded by Churchill in March 1946 [11]. As the US nuclear arsenal built up, it was no surprise that the Soviet Union, no stranger to national paranoia, felt threatened and joined the nuclear Arms Race (see Illustration 36). For many years the system for delivering nuclear warheads was manned bombers, patrolling around the clock and ready to respond to any attack. Later, these were replaced by missile delivery, at first of limited range. But with the launch of the first satellite, the Russian Sputnik, in 1957, came the realisation that inter-continental rockets would be able to deliver nuclear warheads to anywhere on Earth with minimal delay, and that the Soviet Union had the lead in this technology. Later developments included missiles carrying multiple warheads and missiles launched from submarines that can remain submerged and hidden for months at a time, ever ready to deliver a revenge counter attack should the other side mount a first strike. International politics at this time was dominated by the tension between the USA and the Soviet Union, said to be stabilised by the mutual fear of the consequences of nuclear war and the balance between their arsenals. The end of the Cold War came at a summit meeting in Iceland in 1986, coincidentally six months after the Chernobyl accident. Although technically quite unrelated, the Soviet political self-confidence in nuclear technology seems to have collapsed generally at this time, and by 1991 the Soviet empire, as such, appeared to be no more.

**Chronology of nuclear turning points**

- 16 July 1945: Trinity test of the plutonium bomb, 21 kiloton.
- 6 August 1945: Uranium bomb dropped on Hiroshima.
- 9 August 1945: Plutonium bomb dropped on Nagasaki.
29 August 1949: First Soviet nuclear test.
3 October 1952: First British nuclear test.
1 November 1952: First US hydrogen bomb test.
1 March 1954: The voyage of the *Lucky Dragon* (more below).
9 July 1955: Russell-Einstein Manifesto (more below).
1956: Recommendation from the BEIR1 Committee that Radiological Safety should no longer be assessed against a threshold but using the LNT model (for reasons expanded upon later in this chapter).
4 October 1957: Soviet Union launch of Sputnik, the world's first Earth-orbiting artificial satellite.
1958: Petition to UN by Linus Pauling and others (more below).
17 January 1961: President Eisenhower's valedictory speech, in which he warned of the power of the Industrial Military Complex that had built up, distorting the free exercise and funding of much scientific academic work in universities, as discussed further in *Radiation and Reason*, Chapter 10.
March 1962: Letter from Linus Pauling to President Kennedy (see page 248).
October 1962: Cuban Missile Crisis (see page 250).
5 August 1963: Partial Test Ban Treaty (Soviet Union, USA, UK) banning atmospheric nuclear testing.
11 October 1986: Meeting in Iceland between Presidents Reagan and Gorbachev, often seen as marking the end of the Cold War.
1988: The report of the BEIR IV Committee attempted to close the door on evidence-based thinking, claiming as [12]

... a matter of philosophy, it is now commonly assumed that the stochastic effects, cancer and genetic effects, are non-threshold phenomena and the so-called non-stochastic effects are threshold phenomena. Practical limitations imposed by statistical variation in the outcome of experiments make the threshold-nonthreshold issue for cancer essentially unresolvable by scientific study.
Because the proponents saw the question as untestable, they were not prepared to scrutinise it.

- 10 September 1996: UN Comprehensive Test Ban Treaty banning all nuclear explosions (still not ratified by the USA).

- 2004: Repudiation of the biology of the LNT model in a unanimous joint report by the French academies of science and medicine [26].

- 2007: ICRP Report 103. An excerpt from paragraph 36 indicates their non-scientific thinking [13]:

  At radiation doses below around 100 mSv in a year, the increase in the incidence of stochastic effects is assumed by the Commission to occur with a small probability and in proportion to the increase in radiation dose over the background dose. Use of this so-called linear-non-threshold (LNT) model is considered by the Commission to be the best practical approach to managing risk from radiation exposure and commensurate with the ‘precautionary principle’ (UNESCO, 2005). The Commission considers that the LNT model remains a prudent basis for radiological protection at low doses and low dose rates.

  Far from being the best practical approach, as they suggest, the LNT model has been used to justify the most inhuman response to nuclear accidents.

**Public exposure to radioactivity from weapons**

**Nuclear testing in the atmosphere**

The radiation from weapons testing in the atmosphere was caused by the extreme heat of the detonation carrying radioactive material high into the stratosphere where it spread over the whole Earth and descended gradually, giving an exposure of radioactivity at the surface known as fallout. This was measured, and annual values in the UK are shown in Illustration 37. The decrease after 1963, the end of atmospheric testing by the USA, Soviet Union and UK, was due to natural depletion of atmospheric radioactivity by the action of the weather and radioactive decay. The small blip in 1986 is the effect of Chernobyl, evidently far smaller than the effect of weapons testing that lasted for many years. Nevertheless, all these exposures are small, as the scale shows: at its peak the exposure from fallout was 0.14 mGy per year. This may be compared to the average annual natural radiation dose of less than 2 mGy per year, and to 10 mGy from a modern diagnostic scan which is beneficial.
Much more worrying to the world population in those years were the thousands of nuclear warheads that were stockpiled, principally by the Soviets and the United States (see Illustration 36). These could have been fired in semi-automatic response by a few people in error or in an ill-considered response to an international incident resulting in worldwide fallout on a scale a thousand times larger than testing – that is a few hundred mGy per year. The effect of this global radiation dose would have been in addition to that of the local blast and fire in the regions where the warheads exploded. The need to cease adding more missiles, to cease testing and to decommission these stockpiles was clear; it generated semi-permanent public protest around the world with many scientists taking part. Nevertheless, few people understood the numbers and that the dose from the testing alone was harmless. Although the LNT claim that *every dose, however small, is harmful* is not substantiated by reliable measured evidence, the belief that it would be harmful was important in the political decision to halt the Arms Race, as will become clear.

**Anti-nuclear demonstrations in free countries**

Everyone alive at the time of the Cold War may prefer to forget what it was like, and it is seldom explained to later generations what a pall of dread hung over every man, woman and child on Earth who could read a newspaper or listen to the radio. The effect of a nuclear attack was seen as more than just a remote region devastated by blast and fire – in those days everyone could still recall the pictures and news from the total ruins that were Berlin, Hamburg and Tokyo after WWII. A nuclear war was visualised in the media as an escalating tit-for-tat leading to the destruction of *thousands* of cities, given that the arsenals of the two sides had several *tens* of thousands of missiles ready to fire (Illustration 36).

*Illustration 37: A graph showing the fallout from nuclear weapon testing (and Chernobyl 1986) as measured in the UK.*
The result of such a nuclear exchange was seen as even worse, because of the reported effect of the radiation from the fallout, spread far and wide around the Earth, the combined effect of all the warheads – and lasting for centuries.

Anti-nuclear movements started at national level, first advocating nuclear disarmament then opposition to nuclear power. They mounted large public demonstrations, marches and occupations, in particular the famous annual 52-mile march from London to the Atomic Weapons Establishment at Aldermaston, which was held from 1958 to 1962 and attracted many tens of thousands of participants. The leading anti-nuclear peace movement organisations around the world at various times – the Campaign for Nuclear Disarmament, Greenpeace and Friends of the Earth – have attracted a large following, including many distinguished intellectuals, church leaders and public figures.

Mobilisation of public opinion on this scale influences political parties in a democracy, and politicians are obliged to take note. In many countries both nuclear energy and nuclear weapons have been made illegal. Nations that are currently opposed to nuclear power in principle include Australia, New Zealand and many EU countries.

**Fallout in fact – The Lucky Dragon**

The US test of a hydrogen bomb on the Bikini Atoll in the Pacific Ocean on 1 March 1954 was exceptional \(^{14}\). It was designed to use lithium deuteride (LiD) as a solid fuel in which the minor component, lithium-6, provides the tritium needed when bombarded by a neutron. It was not known before the test that the major component, lithium-7 (92.5%), would also react with a neutron, thereby increasing the energy released from 6 megatons to 15 megatons, the highest energy test ever detonated by the USA and nearly 1,000 times the energy of the Hiroshima or Nagasaki device. As a result, the area that had been kept clear of shipping to avoid high levels of fallout was far too small. Further, the fallout was particularly large because the device was detonated at ground level, thereby creating much additional radioactive material and propelling it into the upper atmosphere.

Most heavily contaminated by the fallout was the *Daigo Fukuryu Maru*, the *Lucky Dragon No. 5*, a 140-ton Japanese fishing boat with a crew of 23. The exact position of the boat at the time of the explosion is not known, but it is thought that it was about 80 miles away. The crew suffered severe beta burns on their skin and when they reached Japan they were treated for ARS although, unlike those contaminated at Goiania and Chernobyl, none died of it in the next few weeks. One crew member died after seven months of cirrhosis of the liver – radiation is unlikely to have been the prime cause. Like survivors of Hiroshima and Nagasaki, the crew were stigmatized because of the Japanese public’s fear of radiation exposure, believing it to be
contagious or inheritable. Another crew member reported that when the fallout came down he had licked it to test it – in 2013 he was reported to be alive at 79 years old. In 2014 another crew member was reported to be alive at the age of 87. Many details are missing, but, as in other nuclear accidents, the mortality that many had feared or expected at the time, has not been realised \cite{15}.

The incident was a diplomatic disaster for the USA, and did nothing for the reputation of the radiation and its safety either. As often happens, an attempt was made to make amends by paying compensation, although litigation and compensation muddy the water for the scientific record by persuading voices to remain silent or change their story. But after more than 50 years we can say that the effect on human life may have been no more than several cases of intense beta burns, similar to sunburn in fact. However, absolutely nobody believed that at the time, and nobody has corrected the public perception since. No erratum ever makes a good news story.

**Fallout in fiction – *On the Beach***

Fear of nuclear technology has stimulated 70 years of sensational entertainment that has gripped the world. One of the most famous novels, *On the Beach* by Nevile Shute published in 1957, is set in Australia where a surviving southern outpost of life watches as the radioactive fallout, liberated by an all-out nuclear war in the northern hemisphere, creeps gradually south, extinguishing all signs of life as it does so. The story is thrilling, and was made into a popular film, but the science is flawed, although that did not prevent it making many conversions to the anti-nuclear cause; notably Helen Caldicott who says that when she read the book as a 12-year old *It scared the hell out of me*. Since then she has pursued an emotional anti-nuclear campaign which has been heavily attacked for its fear mongering and lack of any scientific basis \cite{16}.

No one who lived in the Cold War era could have failed to enjoy the talents of Tom Lehrer, the American singer-songwriter, satirist, pianist, and mathematician. Among his blacker nuclear songs was *We will all go together when we go*. It was a piece with a typically jolly tune and words about total nuclear death – the Cold War years encouraged such macabre humour. The words nuclear and radiation have entered the popular language as scare words, the adult equivalent of saying *BOO!* to a small child who then runs away and hides \cite{17}.

There were many more expressions of nuclear gloom and horror in the arts, but why should we make note of these here? Because we are going to need to counter them with equal talent if we are to overcome the legacy of 70 years of nuclear phobia. The effects of carbon fuels on our environment and our civilisation may be the alternative. So we need to find the sons of Nevile...
Shute, sons of Tom Lehrer, daughters of Jane Fonda, and of all those in the arts who performed in the anti-nuclear era. New artistic talents are urgently needed in the coming decades to reverse the message their parents and grandparents gave so brilliantly.

**Warnings from the intellectual elite**

**Russell-Einstein Manifesto**

By 1955 it was widely felt that mankind faced an existential threat from the nuclear powers, and with the prospect that many further nations might also acquire such weapons, the prospects looked dire. Joseph Rotblat, the only scientist to leave the Manhattan Project on moral grounds, remarked that he became worried about the whole future of mankind. In the following years he worked with Bertrand Russell, the eminent British philosopher, on efforts to curb nuclear testing and proliferation. It became apparent that only a joint declaration by a number of respected Nobel Laureates could hope to wield the moral authority needed to head off the danger – although, as will become apparent, even that was not sufficient.

The Russell-Einstein Manifesto was launched at a news conference in London on 9 July 1955. Albert Einstein had died shortly before, but after signing the manifesto. The other signatories were: Max Born, Percy Bridgman, Leopold Infeld, Frederic Joliot-Curie, Hideki Yukawa, Cecil Powell, Hermann Muller, Linus Pauling, Joseph Rotblat and Bertrand Russell. Of the eleven, ten had won, or would win, a Nobel Prize. This is a very distinguished list indeed, but, with the exception of Hermann Muller, not one of them was a biologist or medical scientist.

The manifesto started by calling for a scientific conference:

*In the tragic situation which confronts humanity, we feel that scientists should assemble in conference to appraise the perils that have arisen as a result of the development of weapons of mass destruction*

and went on:

*No doubt in an H-bomb war great cities would be obliterated. But this is one of the minor disasters that would have to be faced. If everybody in London, New York, and Moscow were exterminated, the world might, in the course of a few centuries, recover from the blow. But we now know, especially since the Bikini test, that nuclear bombs can gradually spread destruction over a very much wider area than had been supposed. It is stated on very good authority that a bomb can now be*
manufactured which will be 2,500 times as powerful as that which destroyed Hiroshima. Such a bomb, if exploded near the ground or under water, sends radioactive particles into the upper air. They sink gradually and reach the surface of the earth in the form of a deadly dust or rain. It was this dust which infected the Japanese fishermen and their catch of fish. [reference to the Lucky Dragon]

No one knows how widely such lethal radioactive particles might be diffused, but the best authorities are unanimous in saying that a war with H-bombs might possibly put an end to the human race. It is feared that if many H-bombs are used there will be universal death, sudden only for a minority, but for the majority a slow torture of disease and disintegration. Many warnings have been uttered by eminent men of science and by authorities in military strategy. None of them will say that the worst results are certain. What they do say is that these results are possible, and no one can be sure that they will not be realized. We have not yet found that the views of experts on this question depend in any degree upon their politics or prejudices. They depend only, so far as our researches have revealed, upon the extent of the particular expert's knowledge. We have found that the men who know most are the most gloomy.

The scientific conference that they called became known as the Pugwash Conference which still works today for world peace. With its co-founder, Sir Joseph Rotblat [10], the Conference was awarded the Nobel Peace Prize in 1995.

But scientists can make mistakes, particularly if they take their eye off the evidence. The signatories of the Russell-Einstein Manifesto did not know whether or not the crew of the Lucky Dragon would die from the radioactive fallout that covered them, but they assumed that they would. Today we know that was pessimistic, although records of the fate of the crew, distorted by litigation and compensation, are not fully available. We have more complete and optimistic evidence from Fukushima, and also from Goiania and Chernobyl. Except for a handful of cases, it seems that radiation is far less injurious to life than anyone expected, even the distinguished signatories to the Russell-Einstein Manifesto.

Linus Pauling to President Kennedy

The aim of the signatories to the manifesto was to stop the Arms Race; stop the testing, stop the stockpiling, then get rid of the stockpiles. What happened showed them that calling for a conference might be a good way to move scientists, but it did not have the desired effect at the political and military level, and so another way to tackle the problem had to be found.
After winning the Nobel Prize in Chemistry in 1953, Linus Pauling had become science's most prominent activist against nuclear weapons testing. He resolved to speak out with the backing of the wider public, and in 1958 with his wife he presented a petition to the UN with 11,000 signatures calling for an end to nuclear weapons. But still the testing and Arms Race continued.

The public initiatives of 1955 and 1958 had not been sufficient to create the magnitude of radiation scare required to stop the nuclear Arms Race. Therefore Linus Pauling and Hermann Muller, in particular, evidently felt that they needed to raise the rhetoric another notch. The only way they thought might be effective was to exaggerate the evidence for genetic harm to future generations caused by radiation. There was no scientific basis for what they claimed, and today we know that it is factually incorrect.

They realised that committees do not make radical decisions or changes of direction – only individuals are likely to do that. To ensure success, they needed to pin the responsibility personally on one person who could stop the testing – and that meant President John Kennedy. Linus Pauling's letter to Kennedy shows the strength of feeling and the lengths to which distinguished scientists were prepared to go. It read: [18]

March 1962 Night Letter Durham NC

President John F Kennedy

Are you going to give an order that will cause you to go down in history as one of the most immoral men of all time and one of the greatest enemies of the human race? In a letter to the New York Times I state that nuclear tests duplicating the Soviet 1961 test would seriously damage over 20 million unborn children, including those caused to have gross physical and mental defect and also the stillbirths and embryonic, neonatal and childhood deaths from the radioactive fission products and carbon-14. Are you going to be guilty of this monstrous immorality, matching that of the Soviet leaders, for the political purpose of increasing the still imposing lead of the United States over the Soviet Union in nuclear weapons technology? (sgd) Linus Pauling.

He could not substantiate the threatening prospect that he held out in this letter and today we can say that he was wrong in his claims. The concerns that he expressed were based on a political and human agenda, not science, but once such concerns are created, in this instance about the effects of small amounts of radiation, it is very difficult to switch attitudes back, even with the benefit of scientific evidence. Trust is fragile.

The dangerous road chosen by Linus Pauling led to two results: firstly the signing of the 1963 atmospheric test ban treaty; secondly the establishment of fallacies in the public mind, and in the mind of the authorities too, about the
effects of radiation on human life. The first was what he was trying to achieve, but the second created a mindset that distorted reactions by authorities, for instance at Fukushima. These fallacies were primarily the responsibility of Hermann Muller, for he was the biologist, not Linus Pauling.

**A game of nuclear chicken**

**Cuban Missile Crisis**

In a game of chicken each player prefers not to yield to the other, but the worst possible outcome for all concerned occurs when neither player yields.

For 13 days in October 1962 the USA and the Soviet Union came closer to full-scale nuclear war than at any time, before or since. New US missiles in Turkey had put Moscow in range for the first time and the Soviet Union had started constructing missile bases in Cuba, just 90 miles from the coast of the USA. A US *U-2* spy plane produced clear photographic evidence of the missile facilities being readied in Cuba, and so a naval blockade was established to prevent further missiles from entering Cuba. The US demanded that the weapons already in Cuba be dismantled and shipped back to the Soviet Union. After tense negotiations and days when the world felt it was living on a knife edge, agreement was reached between Kennedy and Khrushchev. The Soviet Union would dismantle its missiles in Cuba and the US would dismantle those in Turkey and Italy – although this was not known to the public.

It was a chilling time for everybody worldwide, and there can be no doubt that it played a significant part in pressing the case for controlling the Arms Race. The first result was the Partial Test Ban Treaty of 5 August 1963 that ended the testing of weapons in the atmosphere. How much the Pauling letter to Kennedy contributed to this development we do not know, but the consequences of repeatedly stoking popular fears of radiation, even though they lack a scientific base, are with us still.

**Radiological protection and the use of the LNT model**

**US National Academy of Sciences genetics panel report**

After the bombing of Hiroshima and Nagasaki the physical science view of the world was in the ascendency. The power of mathematics and physics had been demonstrated and in case of doubt its supremacy was usually accepted.
This obviously had a profound effect on the judgement of those with research ambitions in biology and in other sciences. Major opportunities opened for those able to work by importing methods and ideas from the disciplines of mathematics and physics into biology, even if they struggled to understand them.

The question of the effects of ionising radiation on life was an important one for biology after WWII, and US science naturally took the lead in establishing international standards, rather as the British had done for maritime and geographical standards in earlier centuries. And so it was that recommendations to the ICRP came from the Genetics Panel of the US National Academy of Sciences, actually its Biological Effects of Atomic (later, Ionising) Radiation Committee (BEAR 1) of which, significantly, Herman Muller was a member.

Edward Calabrese has researched the history of what happened and found copies of original correspondence that suggest the BEAR/BEIR committee saw radiobiology as an appropriate vehicle to build funding for their interest in genetics. In addition, and perhaps more altruistically, there was the Arms Race. By reporting a worst case conclusion on the negative effects of radiation, they might achieve both goals. So it was that in 1956 the panel recommended that the use of thresholds in radiological protection be discontinued and the LNT model be used instead. Its conclusions were then adopted internationally by ICRP.

Safety not fit for purpose

Because the LNT model makes the administration of risk particularly straightforward, other areas of safety regulation have copied it, without establishing any scientific demonstration that it is appropriate. For example, it is assumed that any toxic chemical poses a risk in proportion to its mass, however small the quantity and however much it is concentrated or dispersed. But toxicity does not work like that – small quantities may be good for health, even essential, while excess may endanger life. This was already well understood by the physician Paracelsus in the 16th Century (see page 188).

Since BEAR1 in 1956 there have been further BEAR/BEIR reports, but none has reversed the adherence to the LNT model, and thence to ALARA, in spite of the overwhelming weight of evidence against it and the serious consequences it has had around the world in human and financial terms. Indeed, in 1988 BEIR IV dug itself further into a non-scientific position, as quoted on page 242. A review in 2014 of the most recent BEIR report by Calabrese and O’Connor brings the discussion up to date.

Fortunately, many eminent scientists and physicians are not impressed by the wishful thinking embedded in these reports. Lauriston Taylor (1902-2004),
who was a founder member of ICRP (1928) and first president of US NCRP, spoke out expressing his disquiet in an invited lecture as early as 1980 \[25\]. Some passages from his lecture are quoted on page 214.

In its 2007 report ICRP condemned the use of the Collective Dose to assess the number of deaths in a large population subjected to low doses. (The Collective dose is the sum of all individual doses added together and measured in man-sievert.) This was quite illogical as the ICRP committee failed to withdraw its support for the LNT model which, on its own, provides sufficient simple justification for the use of the Collective Dose in this way.

Internationally, there has also been support for fresh thinking, independent of NAS. In 2004 a unanimous joint report was published by the French Académie des Sciences (Paris) and the Académie Nationale de Médecine \[26\] that set out the biological case for a complete change in the regulation of radiation. It was highly critical of the use of LNT theory (see further discussion in Chapter 8).

In 2014 a new informal international group of professionals, Scientists for Accurate Radiation Information (SARI), was set up, dedicated to securing change both for radiological safety in general and also for a more enlightened use of radiation in health care. It posts important articles and correspondence \[27\] and its members make representations for change to major committees around the world, including UNSCEAR, NAS, NRC and the Health Physics Society (HPS). It has also been active in spreading a positive scientific message in Japan in collaboration with the Japanese Society for Radiation Information (SRI) \[28\].

There is great resistance from an entrenched clique to any change to the belief in LNT concepts that they have worked with all their lives. But like alchemy, ptolemaic epicycles, astrology, Lamarckism and other pseudosciences, LNT theory is not supported by the evidence. The necessary changes are:

- firstly, to acknowledge the crucial role of the reactive and adaptive cellular mechanisms in protecting life from attack by radiation which have been an essential feature of all life-forms for billions of years;
- secondly, to accept that the prime cause of cancer is immune failure rather than the generation of mutations that are present in any case and kept in check by the immune mechanisms;
- thirdly, to replace LNT-based safety regulations by ones based on scientific threshold dose rates and doses;
- fourthly, to foster a corresponding reform of public attitudes towards safety that teaches by explanatory education rather than \textit{ex cathedra} instruction issued by authority.

These are not matters for piecemeal or incremental improvements. Policy
should change completely and be re-based on science as soon as possible.

**Notes on Chapter 10**


7)  http://news.bbc.co.uk/onthisday/hi/dates/stories/april/15/newsid_3557000/3557341.stm


9)  A European eye witness report of the bombing of Tokyo  http://www.eyewitnessstohistory.com/tokyo.htm

10)  The first hand personal account of Sir Joseph Rotblat makes important reading  http://www.reformation.org/joseph-rothblat.html


14)  The background is described in this archival account which makes reference to the labs "rushing to develop", indicating internal competition in the Arms Race  http://nuclearweaponarchive.org/Usa/Tests/Castle.html


16)  Helen Caldicott - "Th" Thorium documentary A video by G McDowell  https://www.youtube.com/watch?v=Qaptvhky8lQ

17)  I am grateful to Sir John Polkinghorne for this enlightening analogy.

18)  The telegram written in Pauling's hand is shown in Figure 2 of the paper by Cuttler "What becomes of Nuclear Risk Assessment...." Dose Response 5, 80 (2007)  http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2477701/
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27) SARI http://www.radiationeffects.org
Chapter 11: Natural Philosophy of Safety

Tis not unlikely, but that there may yet be invented several other helps for the eye, at much exceeding those already found, as those do the bare eye, such as by which we may perhaps be able to discover living Creatures in the Moon, or other Planets, the figures of the compounding Particles of matter, and the particular Schematisms and Textures of Bodies.

Robert Hooke, *Micrographia* (1665)

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Safety in the world we see

Childhood and safety

As each human being comes to life and takes up his or her ability to think, the questions begin: *Where am I? Who am I? What do I want? Why am I here?* And such questions must start to be addressed before any sense can be made of the consequential idea of safety. In the early years of life, while parents provide some experience with which to build answers, safety is reduced to the security that comes with a warm parental cuddle. But the questions continue and the answers come with
education through formal instruction, individual study, personal experience and periods of reflection and mutual discussion. What kind of answers do we find? What do they tell us about safety?

**Stimulated by contrast**

A serious study can be made of the many coincidences among the fundamentals of physical science without which the universe, the solar system, the Earth, and life as we know them would not have been possible. That these coincidences are realised is called the *Anthropic Principle*. Although it is called a principle, it is not understood at all. Students seeking a lifetime of stimulation will be kept busy by consulting the Wikipedia entry for the subject \(^1\) and following the references, many written by outstanding cosmological thinkers.

The coincidences of the biological world that enable life are less enigmatic, since evolution has seen to it that life is tailored to its circumstances. However, the development of humans as thinking and studying beings has relied on one particular fortuitous coincidence.

From Earth, every now and again when the clouds part, a window opens and the universe may be seen. Beyond the atmosphere we can see the stars and galaxies of stars, far away and back in time to when it was only 1/40,000 of its present age. On most planets where life might be sustainable in some form, such a view would be permanently obscured by cloud or dust and no such extraordinary window on the universe would ever open. If that had been so for Earth, civilisation would not have developed as it has, and the same sense of wonder would not have been born. Since the dawn of civilisation it has seemed to humans that totally different rules apply to what is seen through that window. There, even the simplest observations display a constancy and regularity completely foreign to the Earth-bound everyday social experience – and modern cosmic data have only reinforced this early impression. From the earliest historic times human observers recorded these regularities and felt challenged to explain them.

This cosmic view has no connection to earthly success or failure, to life or death, to love or hate, but its constancy has been seen as a model for justice in our disturbingly chaotic social world, indeed for much that we seek in everyday life, but seldom find. The cosmos became the model for the divine, for a supreme being, for religion in its various forms. Among earthly creatures only man was able to appreciate this cosmic constancy and his special relationship to it gave him confidence and superiority, even if life on Earth in its other aspects was played apparently without rules and caused great irrational suffering from time to time. The environment close at hand, in particular the weather and even the seasons, proved unreliable and
unpredictable, including the cloud cover that intruded between man and his sight of the heavens. This fluctuating and unreliable environment gave little comfort to early man and he wrestled in a vain attempt to rationalise and prevent it endangering his life and that of his family.

**Predictability exploited**

Human's unique intelligence allowed us to stumble our way towards a better life and to improve the reliability of the world around us, and its predictability became more apparent as our studies slowly revealed how our surroundings worked, more like the cosmos than first appeared. Improving our standard of living was relatively objective, much of it related to physical science and mathematics, but study of our own being and biological science proved more enigmatic.

In the course of normal biological activity any change of circumstances can present a threat to life, so to survive such a challenge successfully in nature, life tests out many accessible responses, by random trial and error, to reach a viable solution. This basic evolutionary process described by Darwin is not a purpose-driven or cognitive search strategy. Indeed the wasted effort, the loss of individual life and the suffering encountered during this search are certainly not beneficial to the individuals involved. From their point of view, at least, any strategy of change that minimises the risk of personal injury would be seen as *good*. An organism that has the benefit of a developed central nervous system and brain can record its experiences and from them learn to improve its survival strategy. In its simplest form this additional facility is available to many creatures and gives them substantial advantage in the competition to survive. The larger the brain the more effectively an animal can compare its current situation to its past experiences. This is especially true for mankind. So an individual can recall patterns of experience and so predict the consequences of any development or course of action, and he or she may then make a choice that minimises pain and suffering. So predictability is necessary for safety, but the ability to think and understand is needed too.

That the world is ever predictable is itself quite unexplained. It could so easily be otherwise. A waking experience of an uneducated mind – or of an educated one in a dream – should be quite enough to show that the world *could be* unpredictable – possibly haunted and malicious, subject to whims of the imagination. But when predictability is harnessed by education and science, real danger can be avoided with some confidence and this is the proper basis of *safety*. It should be distinguished from an *ersatz* version of 'safety' that is laid down as a set of rules to be obeyed regardless of understanding; this brings order through coercion but no real confidence.

Real safety depends on the education and experience of an individual who
can then make reliable judgements. The principle applies to the safe interaction of an individual with other humans, just as much as his interaction with the physical world and other forms of life. Reliability and predictability are the essence of trust and good personal relationships, and the same is true in wider society all the way up to the level of international behaviour.

**Good and bad located**

In his inanimate world man first found the predictability that he sought in the sky – the Sun, Moon, planets and stars. He was fascinated to find that their motion was even more regular and predictable than he suspected, quite unlike anything else in his seemingly unpredictable and dangerous environment on the Earth. The experience taught him to be mathematical and scientific, a skill that he has applied in recent centuries to much of the rest of his observations of the physical world. But this experience of the celestial sphere was always the archetype and a model for good. Naturally, *heaven*, the seat of all that is good and reliable, came to be seen as *up there with God* as its personification. Unfortunately misunderstanding of this personification has caused much trouble in the history of the world, but there is no reason why it should have done so.

If we found that the world above our heads was reassuring, what was our experience of other directions? A warning cry *Look out!* brings a reaction to look forward, to the left and right, and then behind. The eyes and ears of animals and birds are positioned on the front or sides of their heads, like ours. Why is that? Sources of danger usually come from these directions. Only as an afterthought do we look upwards in case something threatens from above, and we seldom look down: the last direction worth looking for an impending attack. So a sense of direction has become part of the most basic experience that enhances our ability to survive – of safety, in fact.

Beneath our feet nothing is to be seen – all is hidden, and in this direction our ability to detect an approaching danger has not advanced much since the days of early man. Today we may understand the basic general mechanisms of the inner workings of the Earth, but we are nowhere near being able to predict when these forces might be unleashed – and the earthquake and tsunami of 11 March 2011 were a demonstration of that. Much of the time the earth is almost totally quiet, but when it does move, great fissures may open up, rocks tumble and otherwise solid structures shake with a terrible noise. Volcanoes may spit sulphurous fumes, fire and great boulders fly high into the air – they may spill rivers of molten rock down mountainsides. And, while we have learnt where these eruptions are likely to occur, their ferocity and unpredictability are extraordinary. No imagination is needed to see that early man would get the message – unpredictability and evil are *down there in hell*, a place of consuming fire, often personified as the *Devil*. This divide, the
polarisation between hell and heaven, was an early element of basic human culture. Never mind the Higgs Boson and the Big Bang, physical science has some unfinished business improving the predictability of the material world just below our feet.

But we also experience other quite distinct theatres of existence that play to seemingly separate rules. There is the close-by here of everyday life – somewhere between heaven and hell, between the apparent predictability of the stars, and the capricious and wayward destruction of the volcanic Earth. Here are plants and animals, friends and enemies, love and war.

The success of science has spread its predictability into many aspects of life on Earth and rolled back the fear of most natural forces, bringing a harmony and ease to life that those living in earlier times would not recognise. However, the success has not been complete. Science still struggles to predict the weather reliably and to understand long-term influences on the climate. But it has clarified many phenomena such as light, mechanics and electricity, so reducing the scope of the unpredictable and frightening.

That leaves the task of telling more people about it: many are still unaware that hell has retreated and that, if they were to study with care and attention, many worries would be assuaged. To a scientist it seems odd that everybody should not choose to study as much science as they can, for it brings reassurance and confidence that is otherwise not available. This failure of education persists in part because science and the necessary mathematics are thought to be difficult. This is worth challenging and the challenge pays off, as I have seen as a teacher over many years.

**Art and society in a wafer**

Within the thin shell of the Earth's atmosphere, a tiny region indeed, the world of human society appears self-contained as it encompasses all daily concerns for many people. This existence is portrayed in every popular novel, film and other art forms too. The range of absorbing experiences is driven by competition and money, ambitions and strivings; all the concerns of love and hate, confidence and laziness, honour and disgrace, death, hope, loyalty and many fine and enriching sensations are here, along with suffering and failure. In this society actions have purpose, some objects are beautiful but others ugly, some relationships are simple but many are unfathomably convoluted and complicated. As for centuries past, everything that most people experience in their social existence lies in this wafer. Science shows how this existence is very vulnerable to changing circumstances, and geological evidence confirms that such life-threatening changes have occurred not infrequently in the past. Most are not avoidable but there are others over which civilisation may have some influence – like surviving them, reducing them, or even not triggering them.
Safety in unexpected worlds

Further reality in evolution and quantum mechanics

But in addition to the world we see, up, down and around, there are other forms of existence that affect our lives. Few people choose to explore as Alice Liddell did when she stepped *Through the Looking Glass* and down the rabbit hole into *Wonderland*. If they did, they would find not just one but two further worlds, reached through scientific curiosity, education and adventure, each with its own topsy-turvy way of explaining and discussing existence. And like the characters that Alice met in her adventures, they have an unshakeable confidence in their own logic, which appears quite weird to those not familiar with them.

There is the world of biology with its cells and evolutionary logic: its subject is life, here and now, including ourselves. If it is realised anywhere else in the universe, it is likely to be radically different. But then there is the world of quantum physics, absolutely universal and all pervasive on every scale in space and time, although some of its most striking consequences are evident in the atom with its central nucleus. This quantum physics is a layer of existence where the rules of logic and description are totally unlike those of either the familiar world or biology. But understanding and working with these two worlds and how they fit together increases predictability and safety and therefore the confidence on which the viability of human civilisation and its economy depends.

Life through the lens

The invention of the telescope and microscope in the sixteenth and seventeenth centuries increased the range of what could be seen. An early leader in the field was Robert Hooke (1635-1703) who published his seminal book, *Micrographia*, in 1665. The quotation given at the head of this chapter is his prescient view of the development of modern science and technology, written 350 years ago. Although the invention of the telescope expanded the view of the heavens by a vast factor, it did not really introduce a fresh theatre of existence. However, the microscope introduced the beginning of something quite new, the biological basis of life and its cellular structure. The typical cells of life can just be seen under a simple microscope, as first described and illustrated by Hooke in extraordinary detail in his book:

*I ... found that there were usually about threescore of these small Cells placed end-ways in the eighteenth part of an Inch in length, whence I concluded there must be neer eleven hundred of them, or somewhat more then a thousand in the length of an Inch, and therefore in a square Inch above a Million, or 1166400. and in a Cubick Inch, above twelve hundred Millions, or 1259712000. a thing*
almost incredible, did not our Microscope assure us of it by ocular
demonstration; nay, did it not discover to us the pores of a body,
which were they diaphragm'd, like those of Cork, would afford us in
one Cubick Inch, more then ten times as many little Cells, as is
evident in several charr'd Vegetables; so prodigiously curious are the
works of Nature, that even these conspicuous pores of bodies, which
seem to be the channels or pipes through which the Succus nutritius,
or natural juices of Vegetables are convey'd, and seem to correspond
to the veins, arteries and other Vessels in sensible creatures, that
these pores I say, which seem to be the Vessels of nutrition to the
vastest body in the World, are yet so exceeding small, that the Atoms
which Epicurus fancy'd would go neer to prove too bigg to enter
them, much more to constitute a fluid body in them. And how
infinitely smaller then must be the Vessels of a Mite, or the pores of
one of those little Vegetables I have discovered to grow on the back-
side of a Rose-leaf.

In the following centuries, as the study of biology by Darwin and others
developed, the microscope revealed more of a world where the standards of
behaviour prized in the social world count for nothing. In the cellular world,
as for whole biological organisms, competition rules, leaving little room for
altruism and morality. Individuals are sacrificed to optimise the survival of
the species in the competition with other species. Fairness and equality of
opportunity carry no weight, neither does simplicity. Indeed, by exploring a
myriad of possibilities the selected response often turns out to be highly
evolved and far from obvious. The test for a response that is right is that it
should work effectively, but there may be many such correct possibilities,
each ensuring survival in a particular environment. Each is local to the
conditions at a point in space and time – there is no likelihood, even if life
exists elsewhere in the universe, that the particular realisations of life that we
are familiar with would have any viability elsewhere.

"Curiouser and curiouser", said Alice

Since the end of the nineteenth century the study of the structure and
behaviour of matter has penetrated to a scale far deeper than biology.
Biological cells are 100,000 times smaller than a metre; the atomic scale is
100,000 times smaller than that and the nuclear scale 100,000 times smaller
again. The atomic and nuclear scales have much in common; there the norms
of behaviour, that is of cause and effect, seem weird to a human mind
familiar with the social or biological world. This is the quantum world. When
first met, it seems confusing, but with some experience it is seen to be
decidedly simpler than the conventional or classical world. The rules in the
quantum world are extremely precise, even though they generally determine
(precisely) the probabilities of what might happen, rather than what actually
Having said that, the quantum world is not too hard to explain: it just seems totally different from what we all learnt on mother's knee as we stretched out with eye-and-hand coordination to grab the biscuit offered to us. The quantum world is always correct and has no exceptions – the familiar classical world is just a convenient approximation. Although he contributed to it in many important ways, Einstein never really believed that quantum mechanics was correct, but it has been giving the right answers for 90 years now, and most theoretical physicists today think that Einstein was wrong and that the quantum world is here to stay.

Curiously, the way that larger objects behave turns out to be identical in both the familiar classical and quantum pictures, and in the rare cases that they differ, it is the quantum picture that fits with what is seen when we do an experiment. This is not a book about quantum theory, but here is one simple everyday example, as an illustration. When we turn on an electric light, a stream of electrons (which are solid components of ordinary matter like any other) comes sliding through the solid copper wires that join the switch to the electricity generator station. They do this with very little resistance, slowed only by the fine wire of the lamp filament (or equivalent in a more modern bulb), where they deliver up their energy as light. It seems a nonsensical idea that the electrons should pass through the solid copper without hitting anything, but a precise understanding of why this is expected was just the first step in the development of electronics. Quantum mechanics is not just descriptive, but provides the calculated basis of all lasers and modern electronics that form the heart of much of today's prosperity – involving business, employment and all that follows. More people need to understand it if we are not to be left at the mercy of a small band of high priests in the matter.

**Individual and collective decisions**

**The importance of education and trust**

It is not realistic to suppose that everybody in society should understand everything. But there is a minimal level of education and professional knowledge required if the citizens of a healthy society are to be able to make decisions by consent. Just having experts in each discipline is not sufficient. A few citizens, at least, should fully appreciate the overlap of these areas, so that they can speak to the issues that arise when several disciplines are involved – for instance, nuclear, biology or medicine. Without such overlaps of individual knowledge the trust that is essential to society will be lacking and democratic decision-making will be at risk. The greatest leaps forward in the condition of mankind have occurred at the boundaries between disciplines. Conversely, the Dark Ages, a period of misunderstanding and narrow prescriptive education, coincided with deprivation and economic hard
times.

The most effective integration of ideas is achieved initially in the mind of a single person. In this respect narrow specialised education is unhelpful, because it is unlikely to contribute balanced judgements between disparate alternatives. The use of specialised expert opinions inhibits the emergence of a melded view, because experts tend to be possessive and confident about their own narrow fields, while naturally cautious of matters beyond their personal knowledge. Consequently, nobody is in a position to take the far-reaching interdisciplinary decisions, or worse, such decisions are taken managerially or politically without technical understanding and simply on the basis of conflated expert views. A conference or a committee leads naturally to consensus, the least unacceptable conclusion, rather than a far-reaching innovation. Unfortunately, in many modern societies enthusiasm for specialised education is the norm, and many decisions are taken by politicians after expensive expert enquiries. But such experts have their own vested interest in building the exclusivity of their advice, often through emphasising how difficult and demanding their speciality is. What is needed is an overarching view that explains the simplest and most comprehensible solution. On interdisciplinary matters like nuclear power and radiation safety the wrong conclusions have too often been reached – but almost nobody realises that. Here, wrong usually means unnecessary, unscientific and expensive, but designed to achieve legal protection. When conveyed to society at large, decisions reached in this way are defended on the basis that knowledgeable opinion has been consulted and a consensus has been reached. Not surprisingly, society is not always impressed and speculates whether other motives are at work. Issues may be seen as more political than scientific, while those involved hide behind the defence that proper procedures were followed. In a 1966 talk to high-school science teachers Richard Feynman famously said

Science is the belief in the ignorance of experts.

It was a provocative remark and many have been successfully provoked by it: it implies that experts should be more thoroughly cross-examined. That is only possible with more interdisciplinary education – more people to ask the questions and to understand the answers critically.

**Taboos, phobias and forbidden fruit**

**Altering ourselves**

So nuclear radiation should be taken off a list of taboos. If it is treated with care and kept isolated in the right place, we do not need to worry about it so much – similar to our attitude to high explosives or rat poison, for example.
But what is left by way of forbidden fruit? Are there other items on a list of taboos whose credentials we might usefully question?

In Chapter 10 we referred to the subject of eugenics, the study of human breeding to improve mankind's own stock. From the late nineteenth to the mid twentieth centuries this was a taboo discussed by Hermann Muller and others, but finally put beyond the bounds of the acceptable by the experimental activities of Dr Mengele during the Nazi regime. Since then, the technical possibilities have grown with the understanding of genetics and the decoding of DNA. The subject is still taboo, but what are we afraid of? If genetic modification is likely to give unpredictable consequences, that is certainly reason to shun it. But is that the situation now?

In the UK, as a result of good communication, there has been public and government approval for the 2015 application to permit the exchange of mitochondrial DNA, thereby correcting certain genetic disorders. This is not actually genetic modification, but the public issues are similar and it demonstrates what can be done if taboos and phobias are set aside and replaced by proper democratic discussion. As the effect of genetic engineering becomes more predictable and reliable, society should have the confidence to decide what is for the best, a step at a time.

The modification and improvement of crops is with us. Do we accept genetically modified food? We need to ensure enough genetic diversity, so that not all our eggs end up in one basket, so to speak. Lack of diversity would open our supplies to attack by a single specific virus or bacterium, and this is already a cause for some concern. Independent biologists rather than commercial interests should answer questions and educate the public at large, including children. We should move forward slowly, but simply saying no on principle, as some do, is short-sighted. The taboo of genetic modification should fade away, but we shall see whether public education is able to come to the rescue.

And the same with nuclear-phobia. There is a precedent for moving public policy that should make us pause. As described in Chapter 10, indiscriminate use of the fear of radiation was used to halt the Arms Race. Indiscriminate use of the fear of climate change should not be used to override radiation phobia. Radiation phobia should be dismissed on its own de-merits, even if climate change encourages us to get the right answers.

**Better care for our brains**

The fears that we do not have could be as important in the future as those issues on which we lavish undue caution. For example, changing the way we use our brains is not subject to taboos. Mind-altering drugs and alcohol are tolerated – at least they are not the subject of as much fear as they deserve to
be, perhaps because any effects are not inheritable. In any case, many of them are not new on the scene. But computers and smart-phones are, and they already invade our personalities and how we communicate and interact. As yet, there is no knowledge of their effects on the organisation of the user's brain and so no idea of any safety requirement that should be applied. This is surprising – a mind that does not need to think hard, will soon become slow and out of condition, like the body. This cannot be healthy. What sort of accident might trigger public awareness of this question? For that matter, what development might motivate more medical work on such questions?

Soon, it is likely that electronic real-time surveillance of our health – what our bodies are doing – will be taken over by digital technology in a similar way. Some developments will be beneficial, others will lead to damaging addiction, but the lack of open public discussion of new developments seems ill-judged. Should we not exercise more caution about the invasion of our innermost thoughts by silicon?

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Chapter 12: Life without Dragons

Cheap and abundant nuclear energy is no longer a luxury; it will eventually be a necessity for the maintenance of the human condition

Alvin Weinberg

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Evidence and communication
Selecting sources

In these chapters we have followed most of the major developments that have shaped views of the effect of radiation on health – Hiroshima and Nagasaki, the fishing boat Lucky Dragon, Chernobyl, Goiania, Fukushima and the experience of a century of using moderate and high radiation doses in clinical medicine to save lives. There are the accounts of research with mice and dogs who have received lifelong doses and doses at critical reproductive stages. All of these fit the picture of modern radiobiology, in which life has evolved
over thousands of millions of years specifically to cope with the dangers posed by oxygen and ionising radiation.

But there are many other results that have been omitted with smaller radiation doses, or a smaller number of people where the conclusions seem less certain. Often these are published and then reported in the press as showing that such-and-such *might* cause cancer, sometimes quoting a confidence level like 95%, which may sound rather convincing. But a 95% confidence level means that 1 in 20 such results should be wrong on average, and, further, if the experimenters made a few choices of how to analyse the data that emphasised their result – it can happen almost without realising it – the chance of getting the wrong answer can easily rise to 50% or more. In many sciences such results get rejected by referees and are not published. But it would be too much to ask the reader to follow detailed statistical arguments to expose such fallacies here. Fortunately, that is avoidable; if a similar investigation has been carried out with a larger dose or more subjects and no effect of the radiation has been found, then any effect apparent for the smaller, less certain experiment definitely *is* mistaken. This is why we have chosen the larger or higher-dose experiments, and ignored the others. So, for example, there is no discussion of child leukaemia in the neighbourhood of nuclear plants. The studies that claim there is such an effect involve doses that are very much smaller, even than the natural variation of the background dose from rocks and cosmic rays [1].

**Personal and professional voices**

It is curious how those in Japan professionally qualified to speak out have been reluctant to do so. As Jerry Cuttler has remarked:

> *It's so ironic that so much of the best research in radiobiology has been carried out in Japan and the essence of this work has not been communicated to the political leaders of Japan.*

We have not simply followed the opinions of individuals or authorities. These are often strident and emotional, and it is more scientific to look directly at the data that they have access to. However, the personal testimony of an evacuee is a primary source. The following was written two years after the accident, 10 March 2013: [2]

*...these young people, these households with children, will not contemplate going home, they think not of returning to the village, nor will they until the radiation level is below world standards, and it is possible to live safely, with a sense of security, living off the fruits of the land – until that happens, I think it is only natural to stay away from the village, and as a parent of children myself that is the best I can hope for. To avoid having to shut up our children and grandchildren indoors. That seems to be something that the officials,*
cabinet ministers and bureaucrats in the capital cannot apprehend. And as a matter of fact, although our village was a high-level radiation zone, we accepted evacuees from Minami-Soma and some of those from Namie whose escape had been delayed, and in each of the village’s twenty hamlets, we prepared food for those evacuees, thinking it was aid, but we fed them irradiated food, and unnecessarily increased their dose of internal radiation. The possibility of internal radiation poisoning implies heavy responsibility. We meant well .... We who gave them the emergency supplies are full of remorse that we knew not of the danger in what we were doing, and we pray from the bottom of our hearts that no harm to health will result.

Nobody seems to have given the public reply that such feelings deserve. A message of unqualified reassurance should have been given – there was no disaster that endangered life at the Fukushima accident.

But who should give this public message? Few people have attempted to explain the reassuring facts to the public and the press prefer to stick with the prevailing view, as they see it. Committees do not readily change their opinions – only individuals are able to do that. Unfortunately, many authors who have written on the subject, even recently, have preferred to persist with the ALARA story instead of examining the evidence [3]. The legacy of 70 years of accepted phobia is a barrier so high and nuclear energy is so inhibiting that writers avoid answering the searching questions. Nobody dares to stick their neck out and say what everyone must know. Take a bow, Hans Christian Andersen – you got the story absolutely right! We all know what happened to the Emperor's courtiers, but have not considered that the same might apply to us personally.

So it is still true, in spite of the medical evidence, that patients receiving X-ray scans are told by the IAEA: [4]

The risk for radiation induced cancer is low but additive. Each examination the patient undergoes slightly increases the risk. Keeping patient doses minimum while getting images of adequate diagnostic quality is therefore recommended. The probability for radiation induced cancer increases by 5-6% for every 1000 mSv of dose. Cancer risk increase arising from most examinations is relatively small as compared with the risk of naturally occurring cancer which ranges between 14% and 40%.

However, this is a line with which many medical professionals around the world profoundly disagree [5]. Risks from radiation are not cumulative as stated.

People are reluctant openly to acknowledge this message about the safety of
radiation, perhaps because its scope stretches beyond the expertise of each individual or the remit of any one committee. An article submitted in response to a request by the UK House of Commons Science and Technology Select Committee in 2011 was posted, but its message was ignored [see Selected References on page 279, SR9], as also have been some presentations to the press [6]. Yet the uncommitted public and the younger generations are interested to hear because it is a story that they have never been told before, and they eagerly ask questions [7]. Authorities in the nuclear industry have their own longer standing views and commitments.

What has happened

Public confidence lost by neglecting education

For many people, for as long as they can recall, the situation seemed clear – nuclear energy is dangerous, unpopular and simply avoidable – or so it appeared until doubts arose about the use of carbon fuels. They may still be alarmed by the possibility of deadly radiation from nuclear weapons of mass destruction (WMD), and such views, taken as scientific facts, are used by unscrupulous world leaders to influence political decisions and echoed in the media without question. Nobody has explained the scientific evidence to the public at large, and the public has stopped asking questions. Decades ago they lost interest and trust in voices that spoke in favour of nuclear energy. As a result many investors in nuclear technology reached the conclusion that the best financial returns are in contracts to decommission plants, dispose of waste and decontaminate land. In these cases the nuclear industry has been its own worst enemy – it has not spoken out when cornered by unscientific regulations that have driven up costs and inflated the nuclear safety bubble. This bubble will implode when safety is returned to a scientific basis and costs are halved. Only restrictive regulations – and the perceived self-interest of some third parties – stand in the way of realising carbon-free energy that is completely safe and far cheaper [8].

Climate change and the environment

The world’s expanding appetite for energy, the extra emissions involved and the evidence for a changing climate are now changing opinions too. If nuclear energy is shown to be both safe and necessary as the only reasonable base-load carbon-free supply, then sooner or later public opinion will demand changes in policy. Although there are different attitudes to radiation in each nation, with the authorities treating safety questions as matters for local decision, the public view of the threats to the environment is more universal, especially among the younger generation. The incomplete solution offered by renewables makes the case for nuclear energy more urgent. The experience of
the French and Canadian electricity utilities has shown that carbon could be almost eliminated from base-load supply with nuclear energy. With the growth in electric rail and road transport, major carbon reductions are possible. This would not halt climate change or the related release of methane by the melting of the permafrost, but it should be the best mitigating solution available.

Regimes such as those in Russia and China are continuing to invest in nuclear power plants, not only in their own countries, but in client countries around the world with less nuclear know-how. In democracies these developments have not been heeded, but only those sections of their industries which participate in building, investing and exporting can hope to avoid being left behind. A lack of know-how and ownership of nuclear energy supply form a threat to future competitiveness that many democracies seem to have ignored.

In the short term work continues to appease public opinion by investing large sums to make even safer the nuclear plant that has already been shown to be safe, or to decommission it without good reason while burning carbon fuels instead. In the medium term the bubble of this activity will burst as soon as the public learns how the costs are inflating the price of electricity to them and to industry, without benefit. The nuclear industry, rather than working to unnecessary standards on waste and decommissioning, would be more gainfully employed if it were encouraged to build the extra nuclear plant that is needed now.

**Stability and influence in a society**

**Effect of runaway fears and fashions**

In Chapter 3 we referred to the competition between many individuals that enables a population to survive; this is like the relationship between cells within an individual that helps that individual to survive. The parallel can be taken a step further by likening a society to an organism. A society is an evolutionary product of the circumstances in which it finds itself. It reacts and changes according to the challenges that impinge on it from time to time. It has structure – laws, education, traditions, rights and duties – that it applies to its members, and other norms that it applies externally to others. Its survival depends critically on whether these reactions are fit for purpose – if they fail to support its members, the society as a whole risks being invaded, economically, culturally or militarily. If it is swallowed up in some way, it loses its identity to another.

It is a moot point whether society thinks and acts effectively with purpose in anticipation of attacks upon it – that is a supposition, but does it happen?
Large sections of most societies behave reactively in pursuit of individual and personal objectives only, and an effective society is one that is able to channel such self-centred ambition to the good of the society as a whole. Many activities within the society are benign, even if they are not motivated by the common good. However there are others that increasingly drain the resources of the society, and cause public opinion to polarise in support of an irrational objective. These behave like malignant tumours, weakening the society and making it more likely to fall foul of some different hazard or suffer a steep decline in fortune.

Runaway inflation is an example, and a housing bubble with a building spree is another. Then the imperative is to do what everyone else is doing with all possible speed. This drives instability and leads to disastrous results. An irrational horror of radiation is a further example. The cost to the Japanese economy of keeping 50 reactors on stand-by and substituting fossil fuel is 30,000 million dollars per year [9]. The costs of the German policy of closing all their reactors by 2022 is less easy to read since about half continue, weighed down by extraordinary taxes.

When the irrational fear of nuclear energy spreads to a copy-cat fear of mobile phone masts and electricity pylons, because the label radiation is used in their description, then the disease has metastasised, like a cancer, and is liable to infect the perception of any application of modern science.

**Social contract for safety and stability**

In a society the people may contract to uphold the stability of the society in exchange for the safety that it can provide and for the personal freedom to bargain for the resources to satisfy their reasonable needs for food and shelter. The people also need employment to earn money and fulfil their side of the contract. Either by paying through taxation or by paying directly, people should be able to buy education to optimise their employment, present or future; and in a similar way they need access to health care.

If people are dissatisfied with their contract, the stability of society is at risk. Unemployment and inadequate education are likely causes; so too are disease and ill health. But controlling people through rules and laws does not add to motivation in the way that understanding does; the contribution of rules to stability is authoritarian, while understanding brings resilience and inbuilt assent. Education boosts confidence and provides an understanding of safety, without which it is no more than a set of rules to be obeyed.

Education makes democracy possible, because the people can then understand the issues. Over the decades, as science and technology have moved forward, the education level needed for a stable democracy has risen. Insofar as citizens have decided to turn their backs on any understanding of
science, democratic opinion has become uninformed and a source of instability.

Motivating people by regulation is less effective than by understanding, but what use can be made of money? Society can control behaviour with money more flexibly than with law. Instead of outlawing waste or litter, we could cost it according to whether it is hazardous. More generally cost would relate to availability, as well as the related enhancement of life or risk of death. This is a childish economic model, but we may learn a little by sketching it. Discharging biological waste would be very expensive. Many would never be able to pay, but this flags up the difficulties of this type of solution. Dumped chemical waste, and any form of carbon burning would be expensive, too, because of the effect on the environment. Fresh water should be expensive, as it is essential and often in seriously short supply. Penalising long-distance travel would cut the spread of diseases and encourage the substitution of electronic communication, which should be free. By these criteria nuclear waste would not be very costly, given that in quantity it is a millionth of fossil-fuel waste per unit of electrical energy, it would have no effect on the environment and would be recycled leaving only the small amount of unusable fission waste to be buried. But what about energy itself? To the extent that it is emission-free it ought to be free at source – energy, too cheap to meter, at last [8]. These suggestions may not currently be feasible but they indicate the direction in which to move.

**The way ahead**

**New safety standards**

Natural radioactive decay heats the Earth and drives tectonic plates, earthquakes and tsunami, creating the real disaster of March 2011 in Japan. The radioactive decay heat of the reactors at Fukushima, a contained local problem, harmed no one and was not a disaster at all. For years scientific opinion has stood by and watched while antinuclear-inspired political fear has run riot, wasting enormous resources and diverting attention from the real global threats to civilisation: socio-economic stability, environmental change, population, food and fresh water. Science should speak, and should have spoken earlier.

Science, not the result of litigation or a popular political vote, is the only firm basis for radiological safety and genuine reassurance. The international authorities (ICRP, UNSCEAR and IAEA) should change the philosophy of their recommendations to relate to real dangers, which would ensure that the world does not continue to be spooked by the one major energy source that could support future socio-economic stability without damage to the
environment. They should discard the use of the LNT idea altogether and replace it by the use of thresholds. The science base of the LNT model has been shown to be bogus and incompatible with modern biological science; its predictions do not fit the evidence.

Today it is known that there is no substantial risk for an acute dose less than 100 mGy, nor for chronic dose rates of less than 100 mGy per month. This turns out to be close to the threshold equivalent to 60 mGy per month set by ICRP in 1934. The maximum risk-free lifelong dose is not completely clear, but present evidence suggests that it is at least 5,000 mGy. These thresholds are arguable to factors of two or three, but, used in place of the fearful ALARA/LNT regulations, they should reduce social stress and defuse the exaggerated concerns and expense related to waste and decommissioning. In this way the public would be relieved of the excessive utility charges that arise from irrational regulations that do not contribute to safety in any way.

Equally they should be reassured that any diagnostic radiation scans that might be recommended are without any risk of cancer (up to about 10 per month) and their radiologists should be similarly reassured.

A fresh international outlook is needed that concentrates on climate, the environment and scientific education which includes radiation, biology and nuclear science. Current committees with an obsession for nuclear safety should be replaced by new ones with a remit to engage with actual risks instead of hypothetical ones.

**Enlightened education for the twenty-first century**

Programmes are needed to educate the public and explain how ionising radiation benefits everybody through medicine, carbon-free power, desalination and food preservation. To build trust this education should best come not from government or industry but through medical, university and school teachers, free of any suggestion of vested interest. A vital first step is to ensure that these teachers themselves are up to speed. Education takes time because it has to spread out from its sources. But social media and the press can speed this process. When informed and motivated, the press can spread understanding and confidence about science that may determine whether civilisation survives the coming challenges. The easy ignorance and reluctance to investigate that have blighted press-reporting of the nuclear story should not be accepted or continue – and the same applies to GM crops and other demanding matters on which our future depends. Still, the main thrust of education should come through schools and universities. This calls for worldwide support from disinterested academic bodies and philanthropic foundations, as well as national governments.
Deployment of nuclear technology

It is already late to benefit the environment by converting static power generation provided by carbon fuels to nuclear, but it should be done with minimal further delay. Nuclear plants that are idle should be restarted; further questions should be asked about those that have recently been closed on economic or safety grounds – judgements of the finance and the safety of nuclear power are suspect.

In the short term, new power plants should be built to available designs. Which design should be preferred is a commercial decision, but any such decision should be eased, planning and building times reduced and final costs lowered, with a proper relaxation of the present obsession with safety.

In the medium and longer term, fast-neutron reactors should be used to close the fuel cycle. This is not a new possibility, although there are a number of competing designs – earlier ones available now and newer ones that require further development. Some designs are said to be safer, but what is important is the higher rates of fuel burn-up, the ability to use recycled fuel from light-water uranium plants, redundant weapon fuel, plutonium, thorium, and depleted uranium \[^{10}\]. With recycling and current reserves of uranium and thorium, the world has an abundant supply of fission fuel for hundreds of years. The intense competition between new designs will be resolved by relative cost, reliability and availability – for instance, the economies that come through the use of modular off-site construction techniques. Whichever is chosen, the safety of ionising radiation and uneducated public sensitivity to it should not be the criteria.

Eventually fusion power will be available, but even before that, the pursuit of energy supplies that has dominated world politics and economics for hundreds of years should be over. The resource in shortest supply will be educational. Know-how and scientific understanding are not conserved; they can be spread by contact, by teaching, in fact.

Advances in radiobiology and clinical medicine

To support the picture of radiation impacting living tissue, we have tried to give evidence and argument instead of simply quoting authority. The reader has been encouraged to make up his or her own mind without undue reliance on what others have said or written. But now to sum up the biological effect of radiation, we quote Otto Raabe \[^{11}\], Emeritus Professor at University of California, Davis, in the fields of Radiation Biology and Biophysics. He was President of the American Academy of Health Physics (1989) and President of the Health Physics Society (1997). In 2014 he wrote: \[^{12}\]

*Ionizing radiation carcinogenesis is not a stochastic one-cell transformation and is not a function of cumulative dose but rather a*
whole organ process and a precise function of lifetime average dose rate to the sensitive family of organ cells. It is not a linear function of cumulative dose as is usually wrongly assumed.

In clinical medicine there is widespread concern at the effect that radiation phobia has on patients who express undue concern about diagnostic scans that would be in the interest of their health and without risk. It is clear that the public education that is needed to provide reassurance about nuclear power is also important for the acceptability of radiation for personal health. There is no need for research on the dangers of diagnostic scanning.

But there is scope for further research on the therapeutic effect of low-dose radiation (LDRT). This is distinct from the usual high-dose radiotherapy (HDRT) used to target and cure an identified cancer. With diffuse beam LDRT cancers may be prevented or suppressed by stimulating the immune system, that is hormesis [13]. More may be learned of the beneficial effects of such doses that many seem to enjoy at radon health spas. In any event this is peripheral to radiological safety and the use of nuclear power.

**Working for the world or cleaning up**

What to do with radioactive waste is a small problem that has exercised the public and over-excited the media. It is small because there is so little of it and also because it has a clean accident record. More importantly, it is valuable, because only about 1% of the fuel in it has been used. It would be better named slightly used fuel. With the advent of more fast-neutron reactors it will be burned up producing more energy. That will leave only the fission waste that really is spent and needs to be buried for a few hundred years before its activity returns to the level found in natural ores. The hullabaloo of vast and expensive spent fuel storage far underground appears to be a make-work project. Almost any mine that is reasonably dry should suffice.

Far more hazardous are some accidents in the fossil-fuel industry. An internet search for the names Centralia, a town in Pennsylvania, USA and Morwell, another in Victoria, Australia, reveal extraordinary stories. The coal seam under Centralia has been burning out of control ever since 1962 when it was carelessly ignited. As a result the entire town, 1.6 square km, has been abandoned and the US Postal Service has revoked its ZIP code, 17927. Such is the power of coal to force a town off the map. The fire at Morwell was ignited in February 2014 and burned for 45 days before it was put out.

Interested parties in the fossil-fuel industries have reason to thank the imposition of radiation safety levels that have suppressed the resurgence of nuclear power (see Illustration 10 on page 11). Public reactions in Japan and Germany against nuclear power have come as a bonus for them. But the public and the rest of the economy have the prospect of the higher electricity
prices that arise solely from expenditure on absurd nuclear safety levels to cover non-existent threats. The international committees retain their status and influence while everybody else suffers and the environment receives elevated carbon emissions.

But surely the nuclear industries object to this situation that prices them out of their market? It seems not. They are powerless to take on the regulators. Only the health scientists and other academics can attempt that. In the meantime radiation phobia swells the nuclear work force with much extra activity in the name of decommissioning and nuclear waste disposal, and then all the extra safety upgrades to existing plants. It appears easier to the nuclear industry to take contracts for these tasks than to engage with the construction of new plant and the real commercial risks of designing and promoting a new nuclear reactor. As they rightly say some investors will get their fingers burnt by the variety of competing designs and the costs of complying with regulations. The competition is intimidating and the regulation is out of hand because of ALARA safety and the safety payroll.

The following numbers show in a simple way how the majority of talent in the nuclear industry is concerned with safety compliance and decommissioning of nuclear power stations, not with designing and building the new ones that are needed to reduce the damage to the climate. It gives only a crude snapshot but consider the number of members of the LinkedIn Nuclear Safety Group and the interests they are signed up for: 5,998 are interested in nuclear decommissioning, but only 2,666 are interested in new nuclear reactor designs (as of September 2015). The nuclear industry and the regulatory authorities should concentrate on the work that needs to be done and stop living off contracts to mollify public fears.

Consider what would happen in the event of an unlikely repeat of an accident like Fukushima. The owners of the plant would lose their investment, but there would be no human radiation disaster, just as there was no such disaster in March 2011, only an ill-informed panic with inept action by authorities worldwide.

A real disaster? That description matches what happened:

- at the site of the dam failure in 1975 at Shimantan in China with 170,000 casualties;
- at Bhopal in India where in 1984 at least 3,787 were killed and 558,125 were injured by gases leaked from a chemical pesticide plant;
- at Deep Water Horizon in 2010 when an oil-drilling platform exploded, killing 11 crewmen, leaving an ocean-floor well gushing oil out of control for five months and polluting an entire region of the Gulf of Mexico;
Chapter 12: Life without Dragons

- at the coal mine accident at Soma, Turkey, in 2014 with 301 fatalities;
- at Tianjin, China, in August 2015, when 173 died in fires and chemical explosions in a warehouse at the port.

The way the world reacted to the Fukushima accident was a disaster, but the nuclear accident itself certainly was not. We have to do better in understanding dangers because civilisation has bigger problems to worry about.

Professional initiatives

There are professionals around the world who are acutely aware of the mistake that has been made in adopting the LNT model and ALARA. These include medical doctors, engineers, physicists, biologists and senior safety officers. They come from universities, government research laboratories, hospitals and industry. An international ad hoc group is Scientists for Accurate Radiation Information (SARI) with about 70 members from Canada, Poland, USA, Germany, UAE, UK, Japan and Israel, among other countries [14]. Its objectives include publishing appropriate rebuttals to unscientific articles that appear in the press and also in journals. These are often based on LNT ideas and need to be challenged in writing or in lectures, interviews and debates, whenever an opportunity presents itself. The group is also concerned by the curtailment of low-dose radiation research in USA, the distortion of the nuclear power debate, public education about radiation and the use of safety criteria that are not science-based and encourage fears of beneficial medical procedures and of radon in homes.

Members of the SARI group, individually and collectively, have also taken the initiative by writing to politicians, committees and public bodies. In particular, three petitions have been made to the US Nuclear Regulatory Commission (NRC) to amend its regulation of radiological safety that is currently based on the LNT hypothesis. The first [15] by Carol Marcus, Professor of Oncology at UCLA, describes how the LNT model assumes that all radiation absorbed doses, no matter how small, have a finite probability of causing a fatal cancer and that this enables regulators to feel justified in ratcheting down permissible worker and public radiation levels, either through actual dose limits or use of the ALARA principle, giving the illusion that they are making everyone safer (and creating ever increasing workload for themselves and their licensees). But she says that there has never been scientifically valid support for this LNT hypothesis since its use was recommended by the U.S. National Academy of Sciences Committee on Biological Effects of Atomic Radiation (BEAR I)/Genetics Panel in 1956 and that the costs of complying with these regulations are enormous. Marcus argues that ALARA should be removed entirely from the regulations because
it makes no sense to decrease radiation doses that are not only harmless but may be hormetic. For the same reason no distinction should be made in regulations between safety for the public and the workers. Equally no distinction should be made for doses to pregnant women, embryos and foetuses, and children under 18 years of age.

The other two petitions were also from members of SARI. The one submitted by Mohan Doss was signed by 24 members of SARI and made additional points: any potential future accident involving release of radioactive materials in the USA would likely result in panic evacuation because of LNT-model-based cancer fears and concerns, resulting in considerable casualties and economic damage such as have occurred in Fukushima. Recognition of a threshold dose by NRC would obviate the need for such panic evacuations, associated casualties, and economic harm when radiation is released in the environment.

On 23 June 2015 the NRC responded by inviting public comment [16]. On 6 September I submitted a comment including the following:

*The use of LNT and ALARA is not a domestic US matter. In the 1950s the world looked to the US for scientific leadership. In this case, the institutions of the US have been found wanting, not just by neglect but by deception, as exposed in the published work of Edward Calabrese. The reputation of the US and its scientific integrity is at stake: the US NRC should correct this error and put its house in order for the benefit of the world: its health, environment and socio-economic well-being.*

*The repudiation of LNT and ALARA would encourage the spread of public education and the realisation that 70 years of cultural fear of nuclear science have had little scientific justification and have restricted opportunities, principally at the expense of the free world.*

These and other initiatives are being pressed, and will continue to be pressed. Inevitably there are responses of fear and disbelief from the public. However, these are visceral reactions, not based on science. No doubt there will be responses of extreme caution emanating from various committees who are unable to contemplate the possibility of radical change. These too are expected, but their conservatism has to be measured against the social and economic damage and loss of life that extreme caution causes, as for example at Fukushima and to the environment as a whole.

There are no nuclear dragons to fear – but then there never were. The only dragon is the blind application of the Precautionary Principle.
Notes on Chapter 12

1) Epidemiological evidence of childhood leukaemia around nuclear power plants
2) The Rage of Exile: In the Wake of Fukushima.
   http://books.simonandschuster.co.uk/The-Age-of-Radiance/Craig-Nelson/9781451660449
4) IAEA advice (2002)
   https://rpop.iaea.org/RPOP/RPoP/Content/Documents/Whitepapers/leaflet-x-rays.pdf
5) Does imaging technology cause cancer? Debunking the Linear No-Threshold Model
6) Time for the scientific, environmental and economic truth about nuclear power
   Wade Allison, Foreign Correspondents Club Japan Press Conference 3 Dec 2014
   https://www.youtube.com/watch?v=A2syXBL8xG0&list=UUaY31Acbd k1WUQfn304VCZg with summary handout
7) The description Energy too cheap to meter is attributed to Lewis Strauss when he was describing the prospect of fusion power in 1954. In that year as a member of the US Atomic Energy Commission, Strauss lead the opposition to the renewal of Oppenheimer's security clearance.
Selected References

[SR1] Book by David MacKay Sustainable Energy – Without the Hot Air UIT


[SR3] Book by Wade Allison Radiation and Reason, the Impact of Science on a
Culture of Fear; 2009 http://www.radiationandreason.com


[SR5] Reference article by World Nuclear Association Nuclear Radiation and Health
Radiation-and-Health/Nuclear-Radiation-and-Health-Effects/

[SR6] Documentary by formerly anti-nuclear environmentalists who have changed
their views Pandora's Promise, by Robert Stone http://pandoraspromise.com/

http://t.co/puM2rwyBMH, also at https://www.youtube.com/watch?v=IEmms6vn-p8
and triggered pictures of wildlife at Chernobyl (2015)

[SR8] Article by Wade Allison We should stop running away from radiation

[SR9] Submission by Wade Allison to UK House of Commons Select Committee
http://www.publicationsparliament.uk/pa/cm201012/cmselect/cmsctech/writev/risk/m04.htm

# Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>adaptation</td>
<td>when the response learns</td>
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<tr>
<td>AHARS</td>
<td>a radiation safety acronym, As High As Relatively Safe, for radiation dose safety thresholds suggested here and also in <em>Radiation and Reason</em>, SR3</td>
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<tr>
<td>ALARA</td>
<td>a radiation safety acronym, As Low As Reasonably Achievable, based on LNT ideas and favoured by ICRP, IAEA, UNSCEAR, NRC and others</td>
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<tr>
<td>alchemy</td>
<td>the pseudo-science that attempts to turn base metals into silver or gold</td>
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<td>ANS</td>
<td>American Nuclear Society</td>
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<tr>
<td>ARS</td>
<td>Acute Radiation Syndrome</td>
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<tr>
<td>astrology</td>
<td>The pseudo-science that attempts to foretell earthly happenings from the position of Sun, Moon, planets and stars</td>
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<tr>
<td>BEIR or BEAR</td>
<td>Committee of NAS: Biological Effects of Ionising Radiation, Genetics Panel, including report of 1956</td>
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<tr>
<td>Bq</td>
<td>a radioactive decay rate, one per second</td>
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<tr>
<td>brachytherapy</td>
<td>radiotherapy where the radiation comes from an implanted or internal radioactive source</td>
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<tr>
<td>chain reaction</td>
<td>a reaction that progressively sets itself off, like the ignition of fire by a flame that then catches. Also, a neutron stimulated fission reaction of U-235 or Pu-239</td>
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<td>chemotherapy</td>
<td>drug based cancer therapy</td>
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<td>CND</td>
<td>Campaign for Nuclear Disarmament</td>
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<tr>
<td>CT scan</td>
<td>a 3-D radiation scan using an external X-ray beam</td>
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<tr>
<td>DNA</td>
<td>de-oxyribonucleic acid</td>
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<tr>
<td>DSB</td>
<td>a double strand break (of DNA)</td>
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<tr>
<td>ESR</td>
<td>Electron Spin Resonance. Like NMR but measures unpaired electrons, caused by irradiation of teeth or bone, for example</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>functional image</td>
<td>a medical image that differentiates tissue by activity</td>
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<tr>
<td>Gy or gray</td>
<td>a fundamental measure of accumulated radiation energy dose. 1 gray = 1 Joule per kg, that is 1 watt-second per kg.</td>
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<tr>
<td>HDRT</td>
<td>High-Dose Radio Therapy, conventional RT.</td>
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<td>hibakusha</td>
<td>survivors of Hiroshima and Nagasaki, literally explosion-affected people.</td>
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<td>hormesis</td>
<td>stimulation of enhanced natural protection by a history of low radiation doses or other stress agents</td>
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<td>HPS</td>
<td>Health Physics Society</td>
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<td>IAEA</td>
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<td>International Commission for Radiological Protection</td>
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<td>INES</td>
<td>International Nuclear Event Scale</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>LDRT</td>
<td>Low-Dose Radio Therapy</td>
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<td>LET</td>
<td>Linear Energy Transfer: the deposited energy density along an ionisation track</td>
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<tr>
<td>linearity</td>
<td>a process in which each causal element contributes its own independent additive effect unmodified by others</td>
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<td>LNT</td>
<td>Linear No-Threshold hypothesis or model favoured by ICRP and followers</td>
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<tr>
<td>megaton</td>
<td>the energy of a nuclear weapon equivalent to a million tons of high explosive TNT</td>
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<td>metastasise</td>
<td>the late spread of cancer via the bloodstream</td>
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<tr>
<td>mGy</td>
<td>a milligray, a thousandth of a Gy</td>
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<tr>
<td>morbidity</td>
<td>a diseased state</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging, a 3-D scan using NMR</td>
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<td>mSv</td>
<td>a millisievert, 1/1000 sievert: a calculated value for tissue damage based on the LNT model</td>
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<td>National Commission for Radiological Protection (USA)</td>
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<td>NMR</td>
<td>Nuclear Magnetic Resonance, the basis of MRI.</td>
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<td>NOAEL</td>
<td>No Adverse Effects Level, a threshold similar to AHARS</td>
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<td>NRC</td>
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<td>organelle</td>
<td>a sub-cell in a biological cell with a special function, especially mitochondria for energy production</td>
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<td>palliative treatment</td>
<td>therapy treatment given to delay the spread of cancer</td>
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<td>Positron Emission Tomography</td>
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<td>radiolysis</td>
<td>molecular break-up by ionising radiation</td>
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<tr>
<td>RF</td>
<td>Radio Frequency (of an Electromagnetic Wave)</td>
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<tr>
<td>ROS</td>
<td>Reactive Oxidative Species</td>
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<tr>
<td>RT</td>
<td>radiotherapy: radiation treatment to kill (treat) cancer cells</td>
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<td>SARI</td>
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<td>SMR</td>
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<td>SPECT scan</td>
<td>Single Photon Emission Computed Tomography</td>
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<td>SRI</td>
<td>Society for Radiation Information, a Japanese group of scientists and others</td>
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<td>SSB</td>
<td>Single strand breaks (of DNA)</td>
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<td>Sv or sievert</td>
<td>a measure of radiation damage based on the LNT assumption. For beta or gamma 1 Sv = 1 Gy</td>
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<td>TEPCO</td>
<td>Tokyo Electric Power Company, the owners of Fukushima Daiichi nuclear power plant</td>
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<td>threshold</td>
<td>maximum stimulus for which there is no (negative) effect</td>
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<td>UNSCEAR</td>
<td>United Nations Scientific Committee on the Effects of Atomic Radiation</td>
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<td>US FDA</td>
<td>US Food and Drug Administration</td>
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<tr>
<td>UV</td>
<td>ultraviolet</td>
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