1

The Emergence of Radioecology

1.1 Glowing in the Dark

On the frieze of the south-west facing Grenelle side of the Eiffel Tower in Paris, sandwiched between the names of Broca and Coriolis, is the name Becquerel. Paul Broca was a gifted physician and anthropologist and Gaspard-Gustave de Coriolis a famous engineer and scientist. Antoine César Becquerel, however, was a physicist who, with his son Alexandre-Edmund, had made major contributions to the study of electricity. Alexandre-Edmund was himself to make major contributions to science, not only in relation to the study of electricity but also to the early development of photography; he was very interested in the curious phenomena of luminescence and phosphorescence as well. But it was Alexandre-Edmund’s son, Antoine Henri Becquerel, who was to stumble upon a completely different phenomenon that was to change forever our understanding of the world around us, and that phenomenon was radioactivity. Just as fortunate, perhaps, was the fact that Henri did so only because of the very recent discovery of what we now know as ionising radiation by Wilhelm Conrad Röntgen, and that discovery had been very dramatic indeed.

Röntgen had been experimenting with the discharge of electricity in vacuum tubes that had metal plates sealed into their ends so that they could be connected to a battery or an induction coil. Such tubes, first produced by Johann Geissler in 1857, had been used by Julius Plücker in 1858 to study the nature of electricity, the flow of which caused a glowing light to emerge from the negative plate (the cathode) and then disappear into the positive plate (the anode). If the beams were energetic enough to hit the glass wall, it fluoresced. The emissions coming from the cathode, the ‘cathode rays’, could be deflected by a magnet, but not much else was known about them and virtually nothing was known about what caused the glass walls to fluoresce. And then late in the afternoon on 8 November 1895, Röntgen noted something very strange. He had been using a tube to which a thin aluminium window had been added in order to permit the cathode rays to ‘escape’, and a cardboard covering had been placed over that end of it to protect the aluminium window from damage. But in spite of this covering of cardboard, which was light-proof, he observed that a small screen painted with barium platinum cyanide, which had been placed close to the aluminium window end of the tube, was glowing. Röntgen further observed that this was not caused directly by the cathode rays but arose from an area of fluorescence on the side of the tube. Further careful study revealed that these rays, unlike the cathode rays, were not deflected by a magnet and thus, as they had been previously unknown, he simply termed them ‘x’-rays. He also
quickly discovered that these new rays passed through various objects placed in their way, although they did ‘expose’ photographic plates. Indeed, in less than two weeks after his initial discovery he took the very first x-ray picture: it was of the bones within a hand, and the hand was that of his wife, Anna Bertha.

About 10 weeks after the wave of excitement that inevitably followed Röntgen’s discovery, particularly the worldwide distribution of the sensational x-ray image of his wife’s hand (Figure 1.1), Henri Becquerel, who had become the third member of his family to occupy the physics chair at the Muséum national d’Histoire naturelle, recalled his father’s work on luminescence and phosphorescence and therefore wondered if materials such as uranium salts might also emit these penetrating x-rays when illuminated by bright sunlight. (In contrast to fluorescent materials, phosphorescent materials do not immediately re-emit the radiation that they absorb, such as light, but may do so several hours later, at a different wavelength.) His first experiments, using uranium salts and photographic paper, appeared to confirm his suspicions. But when he was preparing to repeat these experiments on 26 February 1896 Paris was cloudy and he put the unexposed photographic plate, with potassium uranyl disulphate placed on top of it, away in a drawer. When developing the plate on 1 March, he unexpectedly found very intense images that had obviously been caused irrespective of any previous exposure of the uranium salts to sunlight. Becquerel still
thought that the effect might have been the result of some strange form of luminescence but, following various careful experiments, he was able to demonstrate that the ‘rays’ causing the exposure of his photographic plates also ionised gases, and that their intensity in a sample could be measured using a crude gold-leaf electroscope.

Becquerel’s discoveries certainly lacked the dramatic impact of those of Röntgen, and were indeed subsequently regarded as being simply serendipitous, although perhaps it would be more accurate to describe them as being the result of deserved good fortune. The results were nevertheless eventually pursued with great interest by a young Polish student, Marie Skłodowska, and her new husband Pierre Curie, who were both at university in Paris. They showed that the element thorium also possessed the property that Becquerel had demonstrated with uranium, and it was the Curies who in 1898 coined the term ‘radio-actif’ in order to describe this phenomenon. The Curies went on to discover polonium and radium and to explore the radioactive properties of these elements. They also demonstrated the immense amount of heat generated in radioactive decay and hence the large amount of energy involved in the process. And they obtained the first information on the rates of radioactive decay.

But what of the magnetically deflected cathode rays? It had fallen to J. J. Thomson in Cambridge to elucidate their nature because in 1897 he described how he had set out to determine the ratio of charge to mass of the particles that constituted these rays and, as a result, demonstrated that such ‘electrons’, as he called them, were lighter than hydrogen. Fortunately, a young New Zealand physicist, Ernest Rutherford, was working under Thomson at the Cavendish Laboratory at that time and by 1899 he had discovered that there were in fact two types of rays being emitted by these uranium salts: one of them could be stopped by thick paper, whereas the other could not only pass straight through such paper but also expose photographic plates. He named them alpha and beta rays. Then, in 1900, it occurred to Becquerel that he could also measure the charge-to-mass ratio of the ‘beta’ particles by using the same method that J. J. Thomson had used to study cathode rays and indeed found them to be the same. He therefore suggested that the beta rays were, in fact, electrons. And to these two ‘rays’ the French chemist Paul Villard was, in 1900, to add a third and more powerful and penetrating type of ‘ray’ that he had discovered emanating from radium. These rays were recognised by Rutherford as being of a fundamentally different kind from the previously named rays and thus, in 1903, he named Villard’s rays gamma rays. Rutherford also noted that gamma rays were not easily deflected by a magnetic field, another property making them different from alpha and beta rays. Furthermore, in 1902 and then working at McGill University in Canada with Frederick Soddy, who was later to coin the term ‘isotope’, Rutherford developed a theory of atomic disintegration demonstrating, as indeed Marie Curie had previously suggested, that radioactivity was an atomic phenomenon. Rutherford and Soddy had remarkably shown that radioactivity involved the spontaneous disintegration of atoms into other types of atoms, and that one element could therefore change into another.

And so by the turn of the twentieth century the basics of ‘radioactivity’ had, literally, come to light. Röntgen was awarded the first Nobel Prize in physics in 1901, and the 1903 prize was shared by Henri Becquerel and the Curies. Sadly, Pierre Curie was killed in
a carriage accident in 1906, but Henri Becquerel continued to study various aspects of uranium salts and died, famous, at the age of 55. Marie Curie went on to receive another Nobel Prize, in chemistry, in 1911 and died of aplastic anaemia in 1934 at the age of 66. Rutherford received the Nobel Prize for chemistry in 1908, and Frederick Soddy was awarded the same prize in 1921. Rutherford then went on to become director of the Cavendish Laboratory at Cambridge University in 1919, although his greatest scientific achievements were yet to come. He died as Lord Rutherford of Nelson and was interred near Sir Isaac Newton’s tomb in Westminster Abbey. And having been awarded the Nobel Prize in 1906 for demonstrating that cathode rays, the electrons, were particles, J. J. Thomson was to see his son, George, receive the same prize in 1937 for demonstrating (equally correctly) that the electrons behaved like waves. But Röntgen, whose discovery of x-rays was immediately taken up and applied worldwide, with incalculable ultimate benefit to human health, and having declined to patent any of his discoveries, died a bankrupt in 1923 at the age of 77, having donated his Nobel Prize money to the University of Würzburg. A truly remarkable man.

The events over this short period of time were to spark a whole new era of science whose origins related in one way or another to the discovery of radioactivity. Much of the basic mathematics pertaining to the various aspects of what had been observed was quickly set out over the subsequent two decades, and by the 1920s the basic features of this new and exciting area of science were already the subject of extensive reviews [1–3]. As to be expected, after the initial investigations into the nature of the phenomenon of radioactivity, much scientific effort was expended on attempts to unravel the structure of the atom, which resulted first in the discovery of the proton by Rutherford in 1917 and then of the neutron by James Chadwick in 1932. Numerous experimental investigations were made, and the sheer genius of Albert Einstein with his theories of special and general relativity, together with the theoretical contributions of Erwin Schrödinger, George Gamow, Werner Heisenberg, Paul Dirac, and others, all contributed to unravelling the fundamental – as was then thought – structure and properties of matter and the energy associated with it.

Not many studies were made of the phenomenon of radioactivity in an environmental context, however, and it was generally believed that ionisation observed in the air was caused by radiation arising from radioactive elements in the ground, or by the radioactive gases they produced and emanated from it. As early as 1901 Hans Geitel and Julius Elster had extracted radioactive materials from the air and the following year C. T. R. Wilson extracted them from rain. Geitel and Elster examined air in caves and showed that radioactive gases emanated from the ground, resulting in higher concentrations within underground chambers. Measurements of ionisation rates above the ground also showed a decrease with increasing height, which researchers assumed partly resulted from the absorption of the ionising radiation by the air. This view was soon to change, however, because in 1909 Theodor Wulf developed an electrometer that measured the rate of ion production inside a hermetically sealed container, and he later used it to show that the levels of radiation were higher at the top of the Eiffel Tower than at its base. Perhaps not surprisingly, his results were not immediately accepted; but with a series of ascents in a balloon, starting on 17 April 1912, Victor Hess carried three ‘improved’ electrometers to
an altitude of 5,300 metres in a balloon flight on 7 August 1912 and found that the ionisation rate at such an altitude was almost an order of magnitude greater than at ground level. Hess also ruled out the obvious possibility that the source of this radiation was the Sun by making a balloon ascent during a near-total solar eclipse, achieving much the same results. It was Robert Millikan, however, who in 1922 extended observations up into the stratosphere and further demonstrated the extent to which such cosmic rays, as he termed them, penetrated material on Earth. Both Millikan (in 1923) and Wilson (in 1927) were awarded Nobel Prizes in physics, although for Wilson this was largely in recognition of his development of the ‘cloud chamber’ that became a vital tool for the detection of sub-atomic particles. Victor Hess belatedly received the Nobel Prize in physics in 1936, jointly with Carl David Anderson, for his contribution to the discovery and nature of cosmic radiation.

One aspect of radioactivity that was soon appreciated was its capacity to enable the age of rocks to be assessed. Acting on a suggestion made by Rutherford, Bertram Boltwood in the USA established that the final decay product of uranium was lead and, noting that the lead : uranium ratio was greater in older than in younger rocks, was in 1907 the first person to measure their age by the decay of uranium to lead. Another aspect that was seen to be of great value was the fact that extremely small (invisible) quantities of radioisotopes could be detected by suitable instruments, and thus could be used to trace the location and movement of elements in biological systems. George de Hevesy, a Hungarian physicist, was the first to use such a technique, using a radionuclide of lead ($^{212}\text{Pb}$). He carried out his first, but unpublished, experiment apparently when he was studying in Manchester under Ernest Rutherford between 1910 and 1913. He was convinced that his landlady was habitually recycling the leftovers of his meal, serving them up to him again the following day in a brown ‘hash’. He proved his point by first spiking his leftovers with the nuclide and then demonstrating, with a gold-leaf electroscope, how ‘radioactive’ the following day’s hash was compared with all of the other food on his plate, much to his landlady’s astonishment! But, more professionally, he later used the same nuclide to follow its absorption and subsequent translocation throughout the stems and leaves of broad bean plants, publishing his results in 1923. He was awarded the Nobel Prize in chemistry in 1943 for his key role in the development and use of radioactive tracers in biological systems.

One other important consequence of the discovery of radiation was that the x-ray photographs taken by Röntgen of Anna Bertha’s hand were immediately seen as having immense practical benefits, not only for the practice of medicine but also for biological sciences as a whole. Indeed, within a matter of weeks, Josef Maria Eder, a director of an institute for graphic processes in Vienna, and Eduard Valenta, a photochemist, produced Versuche über Photographie mittelst der Röntgen’schen Strahlen (Experiments in Photography by Means of X-rays), which was a portfolio of 15 positive and negative images including skeletal forms of animals (Figures 1.2 and 1.3), human limbs, and an assortment of various materials such as metal, wood, and glass.

Equally remarkable was the fact that the dangers of exposure to radiation were also quickly realised. With considerable foresight, Ivan Romanovich Tarkhanov, a retired Russian physiologist at St Petersburg University with a particular interest in electrophysiology had, early in 1896 and thus again within a few weeks of Röntgen’s discovery, exposed frogs and insects...
Figure 1.2  X-ray image of a snake taken by J. M. Eder and E. Valenta in Vienna in 1896. Public domain.

Figure 1.3  X-ray images (positive) of fish taken by J. M. Eder and E. Valenta in Vienna in 1896. Public domain.
to these newly discovered rays and concluded that not only did they ‘expose’ photographic plates but they could also ‘affect the living function’ of the organisms exposed to them. These experiments led him to believe that the impairment of reflexes that he had observed in animals after x-ray exposure resulted from changes in metabolism and blood circulation. Sadly, his considerable achievements in this field seem never to have been recognised.

One extraordinary pioneer at that time was Mihran Kassabian, an Armenian-American radiologist who became director of the Röntgen Ray Laboratory at Philadelphia General Hospital in 1902. His clinical work included the acquisition of fluoroscopic images and he first noted reddened areas of skin on his hands in 1900, which he initially thought was due to the use of chemicals. Two years later he sustained a serious radiation burn to his left hand and six years later two fingers were amputated. He kept a journal and took photographs of his hands as his tissue injuries (skin cancer) progressed (Figure 1.4). Within another two years he had further cancer-related surgery, this time to remove muscle from his chest, and died shortly afterwards on 14 July 1910.

Another pioneer was William Herbert Rollins, an obscure New England dentist who, more significantly, made experiments in 1901 and 1902 that not only demonstrated that this new ‘x-light’ could cause skin burns and even sterilisation, as had been noted by others, but also that it could kill adult animals (guinea pigs) and the foetuses of their pregnant females. Just as importantly, he also showed how partial shielding and other steps could reduce damage to animal tissues. Indeed he was, in effect, the founding father of what is now known as radiological protection. It is clear that Rollins was frustrated by the slow response of others to his findings, and hence with the lack of measures to do something about them.

Figure 1.4 The hands of the pioneer Mihran Kassabian, 1909.
The dangers associated with exposure to radiation did, however, become increasingly apparent over the first decade of the twentieth century, and a number of national committees started to appear prior to the outbreak of World War I to address them. Yet it took another decade after the ending of that war for some form of international approach to be developed. At the First International Congress of Radiology in London in 1925 various ideas were discussed, and at the Second Congress in 1928 two bodies were established: the International X-Ray Unit Committee, with the primary objective of defining a unit for the measurement of radiation as applied in medicine, and the International X-Ray and Radium Protection Committee. Essentially, the role of the former was to define the quantities and units and that of the latter to advise on how they should be used for the purposes of radiological protection. In 1950 their names were changed to the International Committee for Radiological Units (ICRU) and the International Commission on Radiological Protection (ICRP), respectively. The ICRP issued its first report in 1928 that, together with its initial recommendations, related to the medical applications of radiation. However, the critical ICRP reports that were to become a driving force behind the necessity to acquire data on the behaviour and fate of radionuclides in an environmental context were not to emerge until after a very momentous event in history that was to herald the dawn of the atomic age.

Indeed, it is important to bear in mind that the subject of radioecology did not arise out of mere academic curiosity but was a direct consequence of the development of nuclear weapons and, subsequently, of nuclear power, although it has in more recent years broadened in scope and its boundaries are still somewhat ill defined. So in order to understand why certain chemical elements have been studied more than others, to appreciate the controlled or uncontrolled nature of the experiments in relation to them that have been performed, and to recognise why only certain types of environments have been investigated rather than others, it is necessary to review very briefly the evolution of radioecology against the background of events that helped to end World War II. Perhaps even of greater relevance in many respects, it is also necessary to review it further against the rapidly changing world of science and politics that pervaded the Cold War that was to replace it. So let us begin with the former: the development of nuclear weapons leading up to, and eventually ending, the war in 1945.

1.2 An Explosive Entry into the Atomic Age

Many detailed accounts have been written of this crucial turning point in history, primarily in relation to the combined USA, UK, and Canadian programmes that resulted in the development and then deployment of the two bombs that ended World War II [4–6]. A reasonable starting point for this sequence of events is a grey morning in London on Tuesday 12 September 1933 when Leó Szilárd, a Hungarian physicist of Jewish descent who had fled to the UK from Nazi Germany, while waiting for the traffic lights to change opposite the British Museum, had a great idea. The idea related to the feasibility of a nuclear chain reaction sustained by neutrons, the critical mass necessary to sustain such a chain reaction, and the enormous explosion that would thus ensue. Having considered these ideas
further, on 28 June 1934 he lodged a patent for the idea (British patent 630726) under the innocuous title of ‘Improvements in or relating to the transformation of chemical elements’ and, after its acceptance in 1936, he assigned the patent to the British Admiralty so that it could be covered by the UK’s Official Secrets Act.

By coincidence Irène (the daughter of Marie and Pierre Curie) and her husband Frédéric Joliot-Curie had, in 1934, discovered that artificial radioactivity could be induced in stable elements by bombarding them with alpha particles, for which they were awarded the Nobel Prize for chemistry in 1935. Enrico Fermi had reported similar results when bombarding uranium with neutrons. Then in December 1938 Otto Hahn and Fritz Strassmann, working in Berlin, sent a manuscript for publication reporting that they had detected the element barium after bombarding uranium with neutrons. The paper was published on 6 January 1939. Lise Meitner, an Austrian physicist who had fled Nazi Germany and was exiled in Sweden, together with her nephew Otto Robert Frisch, who was working with Niels Bohr in Denmark, quickly and correctly interpreted these results as being due to the splitting of the uranium atom and considered the physics that lay behind such a reaction. They named the process fission because of its biological similarity to the splitting of one cell into two. Frisch also experimentally confirmed the Berlin studies, and two papers were rushed to press on Friday 13 January 1939, being published on 11 and 18 February. The implications of their insight sent a shock wave throughout the scientific community. News of Meitner’s and Frisch’s interpretations moved fast, and Frisch’s experiment was even replicated on 25 January 1939 at Columbia University, New York. Otto Hahn was awarded the Nobel Prize in chemistry for his work in 1944, but the all-important contributions of Meitner and Frisch in explaining what had been observed were shamefully never recognised by the Nobel Committee.

Just prior to these exciting developments, Arthur Jeffrey Dempster at the University of Chicago had in 1935 used a new technique called mass spectrometry to discover that uranium consisted principally of \(^{238}\text{U}\) plus a very small fraction of \(^{235}\text{U}\), the latter eventually being shown to be about 0.7% of the total. Considering the physics that lay behind the conclusions of Meitner and Frisch in their joint paper of 11 February 1939, their colleague Niels Bohr quickly realised that it was the recently identified \(^{235}\text{U}\) that was responsible for the fission and, together with the American John Wheeler, published his conclusions the following September, together with an extensive theoretical treatment on the mechanism of nuclear fission. In the meantime, Frisch and a colleague in the UK, Rudolf Peierls, had worked out a process by which an atomic device could be generated by simply using \(^{235}\text{U}\) and conventional explosives that would not only create an enormous initial blast but also a great deal of consequent nuclear ‘fallout’. Thus the concepts of fission, chain reactions, critical mass, and their explosive consequences had all come together on the eve of the outbreak of World War II.

There was no time to waste and thus research to construct a nuclear bomb quickly began in the UK under the code name of the Tube Alloys Project but, after the attack by the Japanese on Pearl Harbour in December 1941, the USA also began actively to pursue the same objective. This was to develop into the famous Manhattan Project, set up in August 1942 under General Leslie Groves with a scientific team led by Robert
Oppenheimer. The UK programme was well ahead of that of the USA, but the two were combined at the Quebec Conference of August 1943. Uranium was the key material and the initial challenge was to separate the lighter $^{235}\text{U}$ from $^{238}\text{U}$, clearly a difficult task because the two would need to be separated by physical rather than chemical means.

But another element was also of relevance: plutonium. The discovery of plutonium was no mere accident. The first transuranic element (beyond uranium in the periodic table) had already been created by Edwin McMillan and Philip Abelson in 1940 at the Berkeley Radiation Laboratory, University of California, which was a facility that had been founded by Ernest Lawrence as early as 1931. At first not named as such, this element was neptunium (specifically, $^{239}\text{Np}$). McMillan’s work was then further extended by a team led by Glenn Seaborg, who in 1942 succeeded in producing the next element, plutonium (specifically $^{239}\text{Pu}$) in sufficient quantities to be seen and weighed. They also realised that this specific nuclide was fissile and thus could also be used to produce a bomb; furthermore, being created from $^{238}\text{U}$, the two nuclides could easily be separated chemically.

There were, however, considerable differences and difficulties in triggering a $^{239}\text{Pu}$ bomb compared with the relatively straightforward means of creating and sustaining a critical mass of $^{235}\text{U}$, a problem solved by the mathematician John von Neumann. There was also the issue of creating $^{239}\text{Pu}$ in sufficient quantities. This required a controlled and sustained fission reaction that could be achieved only by building what was then called an ‘atomic pile’ – a nuclear reactor. In addition to the need for uranium as the fuel, there was also a requirement for the right material to act as a moderator to control the behaviour of neutrons in the atomic pile. Two possibilities were identified: ‘pure’ graphite and ‘heavy’ water. The former was pursued in earnest, and the first atomic pile (CP-1) was constructed at the University of Chicago using graphite as a moderator. It went critical on 2 December 1942. A multi-stage chemical process was then developed to produce larger quantities of plutonium, and this was further developed at the Clinton Engineer Works at Oak Ridge, Tennessee. The final, large-scale, production plant was established at Hanford, Washington State.

Meanwhile a group of scientists in France had considered the alternative possibility: the use of heavy water (deuterium oxide), a form of water in which the hydrogen atom has an extra neutron. Such hydrogen atoms occur naturally and deuterium had been identified in 1931 by Harold Urey; but only about 1 in 6,400 atoms are in this form and thus in water there is one molecule of heavy water per 3,200 molecules. Fortunately it was discovered that the two forms could be separated by electrolysis, and heavy water was already being produced at the Norsk Hydro plant (which provided a cheap source of electricity) at Vemork in Norway, simply as a by-product of the isolation of hydrogen for the production of ammonia as a fertiliser. Early in 1940 a group of scientists in Paris therefore asked the French Minister of Armaments to obtain as much heavy water as possible from Vemork. The French then discovered that Germany had already offered to purchase their entire stock, suggesting that the Germans were also pursuing the same route to an atomic bomb, and duly informed the Norwegians. Just prior to the German invasion of Norway on 9 April 1940, the Deuxième Bureau (the French military intelligence) removed 185 kg of heavy water from the plant in Vemork, the plant’s managing director having agreed to ‘lend’ the heavy water...
to France for the duration of the war. The French then transported it secretly via Oslo, and then via Perth in Scotland, to France. But the plant itself still remained capable of producing heavy water. The following month Germany invaded France and the entire stock of heavy water was then shipped back to the UK by Charles ‘Jack’ Howard (the Earl of Suffolk) on the collier *Broompark*, which left Bordeaux with a group of French scientists, including Hans von Halban (who had been working with Frédéric Joliot-Curie), plus about (today’s value) £40 million worth of diamonds from Antwerp. Arriving in the Cornish port of Falmouth on the evening of 21 June 1940, the heavy water was taken on a special train to London where, after a brief spell in Wormwood Scrubs prison, and by now having seemingly acquired a taste for exotic and expensive company, it was stored briefly at Windsor Castle, apparently along with the Crown jewels, until it finally ended up in Cambridge for safe keeping.

News travelled fast and uranium, too, was soon in short supply. Edgar Sengier, a director of the Shinkolobwe mine in the (then) Belgian Congo that produced by far the highest quality uranium ore in the world, had become aware of its possible use for making an atomic bomb. And so had the US government, President Roosevelt having been made aware of the risks of this source of uranium falling into the wrong hands by none other than Albert Einstein. In late 1940, fearful of its seizure by the Germans, Sengier therefore started shipping (by flying boat) the mine’s stockpile of ore to a warehouse on Staten Island, New York. The Shinkolobwe mine was then flooded. With a reasonable stockpile of uranium, the USA then considered three possibilities of separating $^{235}\text{U}$ from $^{238}\text{U}$: electromagnetic, gaseous diffusion, and thermal diffusion. Gaseous diffusion was selected and most of this work was also performed at Oak Ridge, Tennessee. The project’s principal research and design laboratory for producing the weapons was set up in Los Alamos, New Mexico.

It transpired that Germany had indeed considered using heavy water as a moderator in its attempts to create an atomic bomb, and after a number of brave but unsuccessful sabotage attempts by the UK, in February 1943 a team of Special Operations Executive (SOE)-trained Norwegian saboteurs (in Operation Gunnerside, one of the most successful acts of sabotage in World War II) eventually managed to destroy the Vemork heavy water production plant. But Germany’s progress in the development of nuclear weapons, pursued by Kurt Diebner and Erich Schumann under Werner Heisenberg, was in any case greatly handicapped by its pre-war loss of nuclear scientific expertise. A number of prominent German physicists had already fled the country, many of them to Denmark and from there to the UK or USA. The Niels Bohr Institute in Copenhagen was an important centre for such traffic, and it was there that de Hevesy, who had been working at the Institute since 1934, and having pioneered the use of radiotracers in biology, was yet again able to demonstrate his talent for knowing where something was when it could not be seen. When Germany occupied Denmark in April 1940, Bohr was worried that the Germans would find the Nobel Prize gold medals (awarded in 1914 and 1925 respectively) belonging to two German physicists, Max von Laue and James Franck, who had sent them to Bohr for safe keeping because it was essentially a capital offence to have sent any gold out of Germany. So de Hevesy dissolved the medals in *aqua regia* (HNO$_3$/3HCl) while watching the invading German troops march past the Institute, and placed the jar containing the solution...
on a shelf. After the war, and although the Institute had been occupied by the Germans since 1943, the jar was still there. Somewhat amazingly, de Hevesy, who had fled to Sweden that same year, then returned to precipitate out the gold and the Nobel Society subsequently recast the medals and gave them back to the two original recipients. Appropriately enough, de Hevesy was himself to receive the Nobel Prize for chemistry in 1943 for his (published!) pioneering work on using radionuclides as tracers in biological experiments.

The Germans persisted with their attempts to produce a nuclear weapon. Having also obtained uranium from sources in the Congo, an industrial-scale plant to produce uranium oxide was established in Oranienburg, and a form of nuclear pile was tested at Gottow. Following the Allied invasion of Italy in September 1943 a special task force called the Alsos Mission, commanded by Colonel Boris Pash, was set up to investigate the German nuclear bomb project. Quantities of uranium were discovered in Belgium and in France, all of which were shipped to the USA via Marseilles. On 15 March 1945 high explosives and incendiary bombs were dropped on the Oranienburg plant by the USA in an attempt to prevent it falling into the hands of the advancing Russian army. In the same month, a German scientific team was directed by Diebner to develop a nuclear device in Ohrdruf, Thuringia, in what was to prove a last ditch attempt to develop a bomb using an experimental nuclear reactor, hidden in a cave underneath a church at Haigerloch.

But the least known of these activities are the efforts made by Japan to develop nuclear weapons. At the Isotope Separation Laboratory of Osaka University, a small team using mass spectrometry, led by Yasushi Nishiwaki, was asked if this newly acquired technique could be used to separate the principal isotopes of uranium. Japan had no sources of uranium and so on 24 August 1943 the Japanese Ambassador to Berlin, Hiroshi Oshima, delivered an official request to Germany to send 4 tonnes of uranium to Japan. The response was by no means immediate but eventually, on the evening of 25 March 1945, a specially converted submarine, *U-234*, left Kiel with 500 kg of uranium oxide on board, plus two Japanese guards and a variety of personnel. Having stopped at Horten to have a snorkel fitted, and then stopping to refuel, *U-234* under the command of Lt Johann-Heinrich Fehler left Kristiansand, Norway, on 15 April and headed out into the Atlantic Ocean bound for Japan, running most of the time submerged at snorkel depth. On 10 May, *U-234* was informed that Admiral Karl Dönitz had become Germany’s head of state following the death by suicide of Adolf Hitler, that the war in Europe was lost, and that they were to surrender to the Allies. The two Japanese guards, Tomonaga and Shoji, promptly committed hari kari (in their case, ritual suicide) and were buried at sea. Fehler radioed that he intended to sail to Halifax, Nova Scotia, but actually headed south and on 14 May was intercepted by the USS *Sutton*. From there *U-234* was escorted to Portsmouth, New Hampshire, USA. Nishiwaki was to learn later that the uranium did, however, eventually arrive in Japan. Having discovered the nature of its cargo, General Groves had taken the *U-234*’s uranium oxide to the Y-12 separation plant at Oak Ridge, Tennessee, and it formed part of the Little Boy bomb that was released by the aircraft *Enola Gay* at 08:15 on the morning of 6 August 1945 and exploded 600 m above the city of Hiroshima.
This first ever use of a nuclear weapon in warfare had been preceded by the testing of a device called “the gadget”, at 05:30 on 16 July at the Trinity project test site in Alamogordo, New Mexico, using plutonium not uranium (Figure 1.5). But having proved that the more difficult plutonium bomb worked, and following the deployment of the uranium bomb over Hiroshima, a second (this time, plutonium) bomb, Fat Man, was detonated on 9 August 1945 above the Japanese city of Nagasaki, bringing World War II to an end six days later. These seemingly definitive events of destruction were nevertheless not only to usher in a new era of weapons manufacture and testing but also the gradual evolution of the crude atomic piles used for weapons manufacture into the nuclear reactors designed to generate electricity and nuclear propulsion that we use today. Collectively, over the following decades, both activities were to result in the further release of radioactive materials into the environment, and the studies that accompanied all of these developments were to form the backbone of the subject we now call ‘radioecology’.

1.3 Atmospheric Testing of Nuclear Weapons and the Pressures of the Cold War

Initially such studies were officially classified and, even when subsequently declassified, they were not well publicised because World War II had been supplanted by what was to become known as the Cold War, in which the possession of nuclear bombs was to become the principal metric of international power. The atomic bombs (‘A’ bombs) detonated above Hiroshima and Nagasaki were regarded very much as prototypes of what could be achieved and deployed, if necessary, in further military conflicts. The USA therefore continued to test...
such weapons after 1945 with its Operation Crossroads series at Bikini Atoll in the Pacific Ocean in 1946, and had conducted six such tests before the USSR detonated its first nuclear bomb on 29 August 1949 at Semipalatinsk in Kazakhstan (code named RDS-1 by the USA), with the help of information passed to them clandestinely from the West. Indeed, such was the quality of this stolen information that the USSR was able to catch up with the USA at remarkable speed. Its ‘Laboratory No. 2’ had been quickly set up in the suburbs of Moscow to house its F-1 uranium–graphite experimental reactor. A plutonium production reactor was operating in the southern Urals by June 1948; a reprocessing plant (Plant B) was operating by December 1948; and a plutonium finishing plant (Plant V) by February 1949. The rigours and time-scale demands of the Stalinist era nevertheless resulted in many corners being cut. Large numbers of ‘prisoners’ were used in meeting targets of construction and operation, and the doses received by personnel were exceptionally high and sometimes proved fatal. Little or no effort was made to limit radioactive discharges into the local environment, nor was there any regard for the consequences of the discharges for the local populations.

In contrast to the speed of the USSR, the UK joined the nuclear club rather late, having been deliberately delayed in doing so by the USA, its apparent wartime ally, as a result of the McMahon Act of 1946, which was itself influenced by the fear of infiltration by spies from outside the USA. But, thanks to the efforts of William Penney (later Baron Penney of East Hendred), who had expertly guided the Manhattan Project’s work on the modelling of complex shock waves (necessary for both the detonation of plutonium bombs and in maximising the blast effects of any nuclear bomb), on 3 October 1952 the UK finally became a member of this select club with a weapon’s test (code named Hurricane) on Trimouille, in the Montebello Islands off the north-west coast of Australia.

The USA then established a test site in Nevada but continued to use the Marshall Islands (the Pacific Proving Grounds) for extensive weapons testing, ushering in a new era with the development of a thermonuclear device that included fusion as well as fission. The first such device, Ivy Mike, was tested at Enewetak Atoll on 1 November 1952, completely destroying the island of Elugelab upon which it was detonated. This was then followed by Castle Bravo, on 1 March 1954 (Figure 1.6), a true ‘H’ bomb that greatly exceeded its design expectations and resulted in widespread contamination. As to be expected from the espionage networks operating at that time, the USSR was soon to follow the Ivy Mike test with the testing of its own first ‘H’ bomb on 12 August 1953.

The UK carried out two further tests at the Montebello Islands and others at the Maralinga and Emu Field test sites in southern Australia, as well as at Malden Island in the Pacific Ocean. The crucial period, however, was that between the development, and thus possession, of the fusion (‘H’) bombs rather than the fission (‘A’) bombs. With an impending global treaty banning nuclear tests it was important for the UK to demonstrate that it, too, had the capability to use the former. Its own tests of such weapons, however, had not been entirely successful so, through the energy of William Penney, on 31 May 1957, on Malden Island in the Pacific Ocean, it exploded a ‘boosted’ fission weapon, Orange Herald, which used lithium deuteride to enhance the fission yield, which the UK passed off as an ‘H’ bomb. The ruse obviously worked and thus, on the restoration of the ‘special relationship’
that had ceased in 1958 under the 1946 McMahon Act the UK gained access to vital USA data. On 8 November 1957 it then exploded its own true ‘H’ bomb on Christmas Island and tested other devices throughout 1958. A ‘global’ moratorium was introduced on 31 October 1958, but France then joined the nuclear club with its first test of a weapon in the Sahara desert at Reggane, Algeria, on 13 February 1960, and from 1966 to 1996 it used the islands of Moruroa (then known as Muroroa) and Fangataufa in French Polynesia. The plutonium needed to do so was produced at Marcoule.

Extensive radiochemical studies were subsequently made of environmental materials in relation to all these early tests, which revealed the presence of entirely new elements, such as einsteinium and fermium. But such data were a militarily sensitive issue, particularly with regard to the quantities of $^{237}\text{U}$ observed because, collectively, they were the means of deducing much about the construction of the weapons tested and of their explosive yield.

Throughout all of this period the nuclear arms race was truly on, and from that first test in 1945 up until 1980 more than 500 further nuclear tests were conducted at various sites around the world, injecting radioactive material into the atmosphere. The USA continued testing at Enewetak and Bikini up until 1958, another 12 tests being conducted at Johnston.
Island between 1958 and 1962 and a further 24 near Christmas Island in 1962. A few additional high-altitude tests were conducted in the South Atlantic and Pacific oceans, and underwater tests were conducted in the Pacific Ocean. In the Russian programme, 116 atmospheric tests were conducted at their Semipalatinsk site. Both surface and air detonations were used, the majority being the latter. In 1955 testing began at Novaya Zemlya, an island in the Arctic Ocean, and most of the large thermonuclear tests were conducted at that site, including that of the ‘Tsar Bomba’ on 30 October 1961, which had the largest explosive yield ever recorded. Testing also occurred at Totskoye (1954 and 1956) and Kapustin Yar (1957 to 1961).

In 1963 the USA, USSR, and the UK signed a new Partial Test Ban Treaty, pledging to refrain from testing nuclear weapons in the atmosphere, underwater, or in outer space but not including underground nuclear testing. France continued atmospheric testing until 1974 and China, which had not started until 1964, continued until 1980. Underground tests resulted in only limited contamination of the surrounding environment and continued in the USA until 1992, in the USSR until 1990, and for the UK (but not in the UK) until 1991, and both China and France until 1996. In signing the Comprehensive Test Ban Treaty in 1996, all of these states pledged to discontinue all forms of nuclear weapon’s testing. India and Pakistan tested nuclear weapons underground up until 1998, and North Korea carried out such tests in 2006, 2009, and 2013 and was still carrying them out in 2017.

Between 1957 and 1975 the USA, and between 1965 and 1989 the USSR, both trialled the use of nuclear explosions for civil engineering purposes, although only one significant construction resulted, and that was a dam in Kazakhstan. Other possibilities were also examined for the use of what came to be known as Peaceful Nuclear Explosions (PNEs). The USA’s main programme was called Plowshare. Only fission devices were used, and it was assumed that there would be no releases of radionuclides into the atmosphere or surrounding aquifers. But the second PNE test (Sedan), which took place at Yucca Flat on the Nevada Test Site in July 1962, resulted in dust plumes that deposited radioactive material downwind, with the highest concentrations in Iowa and South Dakota. The USA also had a Project Orion, which was the first serious attempt to develop the concept of using nuclear explosions to provide the thrust for spacecraft. It was in many ways successful, but the idea was largely scuppered by the signing of the 1963 Partial Test Ban Treaty. The USSR carried out far more PNEs than the USA, and its equivalent to Plowshare was the Peaceful Nuclear Explosions for the National Economy Programme. Many of them resulted in local contamination. Subsequent to the 1970 Non-Proliferation of Nuclear Weapons Treaty (NPT) a Peaceful Nuclear Explosions Treaty (PNET) was agreed between the USA and the USSR that was designed to allow the investigation of the potential peaceful uses of nuclear explosions without promoting weapons development. It was signed in May 1976 and came into force in December 1990.

The atmospheric weapons tests during the 1950s and 1960s inevitably had political consequences, and these were to have an influence on how the subject of radioecology was to evolve over the subsequent decades. The framework for such consequences can be traced back to 26 June 1945 following the end of the war in Europe when the Charter of the United Nations was signed by 50 countries, although, with the exception of perhaps one or two of
them, none were remotely aware of the imminent deployment of atomic bombs over the cities of Hiroshima and Nagasaki a couple of months later. The Charter nevertheless entered into force on 24 October 1945, by which time the use of these atomic weapons had reverberated all around the world, and the post-war series of atmospheric testing of far more powerful weapons, by countries on either side of the east–west ideological divide, did little to qualm fears of the increasing risks of mutual annihilation. Such fears were considerably heightened by the Castle Bravo test in March 1954. Not only did this bomb exceed its design expectations, but resulted in the exposure to radiation of Japanese fishermen on board the vessel _Daigo Fukuryu Maru_ (Lucky Dragon No. 5) that was, unbeknown to the USA, in the test area at the time. The fishermen received high radiation doses and one subsequently died of a secondary infection. It was no coincidence therefore that, following US president Dwight D. Eisenhower’s address to the UN in 1953, the First UN International Conference on the Peaceful Uses of Atomic Energy was held in 1955. In response, proposals were made the following year to create a new organisation, the International Atomic Energy Agency (IAEA), with the requirement to pursue the safe, secure, and peaceful uses of nuclear sciences and technology. The IAEA was thus finally established in Vienna in 1957, occupying the Grand Hotel on the Ringstrasse that had previously been used by the Red Army until the end of 1955. Vienna was certainly an interesting choice for its location, with the city being a noted European centre for espionage activities by both NATO and Warsaw Pact countries, and for which an international organisation provided excellent cover.

While the IAEA was being established, and in seeking to deflect a proposal from India calling for an end to all nuclear explosions, the UN also agreed to establish another body with the remit of studying the effects of radiation on human health, which would complement and underpin the work that the ICRP had been doing for almost three decades. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was therefore duly established in 1955, based originally in New York but later moved to Vienna; and although its origins were those relating entirely to military activities, it was destined to become a leading international authority on both the sources and effects of radiation.

With respect to the environment, the atmospheric weapons tests had obviously resulted in world-wide nuclear fallout and a large number of countries set up monitoring and surveillance programmes to measure it, particularly in relation to the consequences that such fallout might have for the human food chain. By this time there were already a number of ‘national’ laboratories engaged in research into radiation in the environment across North America including Argonne, Battelle Pacific Northwest, Brookhaven, Oak Ridge, Lawrence Livermore, Los Alamos, Sandia, and Savannah River in the USA, as well as a number of small groups working at universities and marine laboratories, plus Chalk River in Canada. Elsewhere there were moderately large programmes and facilities such as those at Harwell and Lowestoft in the UK, Roskilde in Denmark, Karlsruhe in Germany, and Trombay in India, and many other laboratories soon quickly acquired sufficient analytical instruments and techniques to measure global fallout. But use was also made of the fact that these injections of radioactive materials on a global scale effectively labelled components of the environment, particularly the oceans, which could therefore be put to scientific advantage.
There were, however, other consequences in relation to weapons testing because, in order to produce the nuclear weapons, it was also necessary to establish nuclear facilities capable of producing weapon’s grade plutonium. The USA already had the necessary sites and reactors established to do so: at Hanford the water-cooled reactors were built 5 miles apart and were a long way from any sizeable population. But in the UK the first experimental atomic piles were built at Harwell, just outside Oxford: the air-cooled reactor GLEEP went critical on 15 August 1947 and BEPO shortly afterwards in 1948. And then a chemical plant was built at Springfields to provide the necessary quantities of uranium, and a former 1942 Royal Ordnance Factory at Sellafield on the Cumbrian coast (which five years later was renamed Windscale, apparently in order not to confuse it with Springfields), was chosen for the construction of two air-cooled reactors, termed ‘piles’, to produce plutonium from it. Construction started in September 1947 and the two reactors went critical in 1950 and 1951 respectively. Dual-purpose reactors were then designed to produce not only plutonium but also sufficient heat to produce electricity as well, which could then be fed into the national grid. These were known as PIPPA (Pressurised Pile Producing Power and Plutonium) reactors and the first two were built on the Calder Hall site, next to Windscale (Figure 1.7), using natural uranium clad in a magnesium alloy as fuel and cooled by carbon.

Figure 1.7 Calder Hall and Windscale works, UK, 1957, showing the four Calder Hall reactors and their cooling towers, plus the two Windscale piles with their chimneys topped by their distinctive Cockcroft filters. (Photo courtesy of Sellafield Ltd.)
dioxide in a pressurised circuit. Under management by the United Kingdom Atomic Energy Authority (UKAEA), which had been created in 1954, the Calder Hall site was opened with due ceremony and apparent precedent by Queen Elizabeth II on 17 October 1956. (The site then became known as the Windscale and Calder Works in 1956 but, after the creation of British Nuclear Fuels Ltd (BNFL) in 1971, the majority of the site, but not all, was renamed Sellafield in 1981, thereby managing to confuse everyone!)

But in spite of the ceremony that accompanied the opening of Calder Hall, electricity had in fact first been generated by a nuclear reactor on 20 December 1951 at an experimental station near Arco, Idaho (which produced about 100 kW), and this pioneering event had been followed on 27 June 1954 by that of the USSR’s Obninsk Nuclear Power Plant feeding about 5 MWe into its local power grid. The future development of nuclear power reactors was, however, poised to go in very different directions.

In the USA the potential of nuclear reactors to generate electricity was soon pursued with vigour by the military. One obvious application was the propulsion of submarines. As a result of the persistence of Hyman G. Rickover, a reactor was developed that used ordinary water as a coolant and moderator, and enriched uranium (235U at about 20%) as fuel, which could easily be accommodated within a submarine. The first such vessel, USS Nautilus, entered into service in 1955. The reactor design was a very good one and such pressurised water reactors (PWRs), on a much larger scale, were to become the most widely used civil nuclear reactors for electricity generation around the world. Not to be outdone, a USSR nuclear-powered submarine was launched in 1958.

In a similar spirit of competition, the (then) US Army Air Force set up what was to become the Aircraft Nuclear Propulsion (ANP) programme. The first stage of this endeavour, from 1946 to 1951, led to the development of quite ingenious nuclear-powered jet engines, culminating in the successful X-39 engine. A large number of test flights were made with such nuclear engines on board in order to study shielding designs for aircrew in relation to the reactors. But the reactors were not used for propulsion, and were never tested in that mode, the entire project being abandoned in 1961. A similar project using Tupolev Tu-119 aircraft took place in the USSR but this, too, was eventually cancelled, partly because by then the development of inter-continental ballistic missiles (ICBMs) had made the use of such aircraft, which were intended to remain airborne for very long periods of time, essentially redundant.

A prime need during these years was that of data on the lethal and sub-lethal effects of radiation on plants and animals in order to plan survival strategies in the event of a nuclear war. Thus at what was to become the Oak Ridge National Laboratory (ORNL) in Tennessee, radiation effects studies on large populations of mice began in 1948 by William and Liane Russell in order to derive data that could be used to elucidate the effects of radiation on human beings. This work was then expanded and by 1953 Orlando Park, joined later by Stan Auerbach, was carrying out large-scale experiments to reproduce the effects of nuclear fallout on terrestrial and freshwater ecosystems, as well as investigating the consequences of the disposal of radioactive wastes that were already rapidly building up. Such wastes had been discharged into White Oak Lake on the ORNL site, which in turn drained into the Clinch River. The lake was subsequently drained and its bed then used to study the accumulation of radionuclides by vegetation. Facilities at the ORNL were also capable of making a wide range
of radionuclides and these were used in both laboratory and field studies. Large-scale field experiments were also made to measure the effects of external radiation, as well as joint studies with scientists at Los Alamos in relation to the Nevada Test Site. Emphasis was placed on what was then termed an ‘ecosystem approach’ and, in 1963, experiments were started using an unshielded fast neutron reactor (HPRR) to irradiate large stands of trees and their associated biota. These experiments were designed to compare the effects of neutrons with other sources of radiation, earlier experiments having been performed in Georgia using another unshielded reactor in Dawsonville, run by Lockheed in connection with the aircraft nuclear propulsion programme. This unshielded reactor was kept in a large water-cooled chamber and then raised to ground level for irradiation experiments, including the irradiation of forest ecosystems. Large-scale field tests were also made at Oak Ridge on the effects of radiation on small wild mammals, bees, wasps, and various forms of vegetation.

In comparison with the USA, sites in the UK were very cramped. Large volumes of liquid radioactive waste could not be discharged into rivers and lakes and therefore the UK’s plutonium reactors being constructed at Windscale were of necessity going to have to discharge their wastes into the Irish Sea. So on the morning of 1 May 1947 it was decided that urgent research was required to determine the consequences of these anticipated discharges on the fishing industry. By August of the same year a site was therefore eventually chosen (in fact an old torpedo store) for the setting up of a research laboratory at Hamilton Dock, Lowestoft, Suffolk by the (then) Ministry of Agriculture and Fisheries to study the accumulation of radionuclides by fish, and the radiation dose rates required to harm them. These initial experiments, conducted by a small team led by Fred Morgan, were completed by the end of 1948 and subsequently complemented by experiments in 1949 to determine the movements of commercially valuable fish off Windscale, so that by the time the plant started operating in 1950 it was possible to set controls on its radioactive discharges into the sea in order to safeguard the public with respect to seafood consumption [7]. Further studies were begun in 1952 by Alan Preston at Hamilton Dock – which was to become the Fisheries Radiobiological Laboratory (FRL) – in order to compare the effects of radiation on fish with those that had been observed on mice. A special Radiobiological Laboratory at the UK’s Agricultural Research Centre was also established in 1957 under Robert Scott Russell to study the accumulation of radionuclides by, and the effects of radiation on, various crops and farm animals, primarily in relation to nuclear fallout and the potential consequences of a nuclear war.

All of this early work took place within national borders. Perhaps surprisingly, a USA report did appear in 1950 on the effects of atomic weapons [8], but at that stage no one else possessed them. As the Cold War developed, there was little in the way of exchange of data among the general scientific community and very little of it was openly published, except in the proceedings of special symposia.

### 1.4 Environmental Contamination by Design and by Accident

But the rapidly expanding nuclear weapons industry was also rapidly accumulating radioactive wastes, and some of these were disposed of into the sea, beyond territorial waters. Such activities began as early as 1946, with the USA dumping waste about 80 km off the
Californian coast. In 1956 this practice was reviewed jointly between the USA and the UK, which had also started dumping at sea in 1948, on the condition that such activities should continue only if they were accompanied by supporting research programmes. Within a few years several other countries had also begun to use this practice: New Zealand, Japan, Sweden, and then, by the 1960s, Belgium, France, Switzerland, the Netherlands, Germany, Italy, South Korea, and, it was later to emerge in spectacular fashion, the USSR. As to be expected, not long after dumping operations began in international waters awkward questions were being asked about the safety of such activities. And by then there was no shortage of international organisations to get involved in such issues.

With a great sense of theatre and, presumably, as a gesture of its impartiality towards all maritime coastal states, in 1958 the UN held its first Conference on the Law of the Sea in landlocked Geneva, Switzerland. The resultant convention contained a recommendation that called for, among other things, action to be taken to control the dumping of radioactive wastes at sea. Furthermore, it called for the newly created IAEA to be the competent body to advise on what might need to be done. The result was the Brynielsson Report, which made various sensible recommendations, but it was not until the inauguration in 1975 of yet another UN body, the London (Dumping) Convention, with a secretariat provided by the Inter-Governmental Maritime Consultative Organisation (IMO), that real progress was made. This Convention had a remit to control the dumping of all materials from ships and aircraft, and the IAEA published its first Definition and Recommendations Concerning High-Level Waste Unsuitable for Dumping at Sea in 1975, which was revised in 1978 and then again in 1986. The IAEA’s work provided a focus for the development of mathematical models to describe the distribution of radioactive materials in the aquatic environment and, of course, the various databases necessary to feed into them.

These models were developed to define what could not be done (the dumping of high-level radioactive wastes), which was not of course the same thing as describing what would happen if something actually was done (the dumping of low-level radioactive packaged wastes) at a specific site. This latter challenge was taken up by yet another organisation, the Nuclear Energy Agency (NEA), which had been established in 1958 under what was to become the Organisation for Economic Co-operation and Development (OECD). Thus the research to accompany the practice of sea disposal that had been called for back in 1956 finally materialised by way of a Co-ordinated Research and Environmental Surveillance Programme (CRESP) that ran from 1981 to 1995, and which from 1986 also looked at coastal water discharges. But in 1983 the London (Dumping) Convention placed a moratorium on these deep sea dumping practices, which had nothing whatsoever to do with any scientific evidence, and then introduced a total prohibition that was effective from 1994. And notwithstanding the legal ban on the disposal of high-level radioactive wastes into the oceans, a programme to examine the technical feasibility of the disposal of exactly such wastes into deep sea oceanic sediments had begun in 1977, and ran until 1987, under the auspices of the NEA. It concluded that such a route of disposal was both feasible and viable, if only society (and thus international law) would accept it. This programme also provided a considerable stimulus for both the modelling and data acquisition of radionuclide transfer within the marine environment, and by this stage there was a good deal of international collaboration. It had not always been so.
As a result of a conference held on the general subject of the disposal of radioactive wastes, organised by the IAEA in November 1959 in the Musée Océanographique de Monaco, an agreement was negotiated to establish an International Laboratory of Marine Radioactivity (ILMR) in the Musée, initially for a period of three years, starting in 1961. The intention was to get scientists from various countries working together, and to serve as a centre for information exchange. The ILMR was to prove a highly successful and dynamic centre of radioecological research, and a locus for analytical comparison and information exchange. One of the most useful endeavours of its first director, Ilmo Hela, was the establishment of regular ‘contact group meetings’ involving other Mediterranean laboratories, initially those at Fiascharino in Italy and at Rovinj in what was then Yugoslavia, but later extending to many other countries and usually held in the wonderful Villa Girasole in Monaco. Attempts to involve scientists from the USSR were less successful; there had been much disagreement over some of their experimental work, which purported to show adverse effects of radiation on fish eggs and larvae, the results being neither plausible nor reproducible.

Indeed, it had proved difficult, in view of the circumstances of the Cold War, to obtain any data at all relating to radioecology from within the USSR. Some information did arise via an Israeli translation service, but it was not until the late 1970s that such literature, and evidence from other sources, implied that very large scale radioecological studies had taken place in terrestrial and freshwater environments somewhere in the Urals. These were hardly the types of studies that would have been made in planned scientific experiments, and a scientist visiting ORNL, Zhores Medvedev, had already indicated on 4 November 1976 [9] that some form of accident had taken place within the USSR. But it was the careful piecing together of the published and non-published data by John Trabalka at ORNL, with the help of others, that eventually established the area as being that of Kyshtym, although it was not until 1989 that the first official admission was made that a major accident had indeed taken place there more than three decades earlier. The accident occurred on 29 September 1957 at the Mayak plant (the site of ‘Plant B’ and ‘Plant V’ that had been producing the USSR’s weapons plutonium) when the cooling system on a tank storing high-level radioactive waste exploded, heavily contaminating the surrounding area including the Techa River that flowed into the river Ob – a river that was, in any case, already heavily contaminated from the operation of this site.

By a strange coincidence, a rather different accident occurred less than a fortnight later in the UK, at the nuclear plant at Windscale. On 10 October 1957 a fire started inside the graphite core of Pile No. 1 during what was considered to be, at the time, a routine and safe procedure in the regular maintenance of the reactor. As a result of the fire, and the attempts to put it out, over the next couple of days an atmospheric plume of radioactive material passed across the UK and much of Europe. Steps were immediately taken by teams led by Bill Templeton and John Dunster to limit its effects on human health by banning the consumption of various dairy products and destroying them [10].

A subsequent accident arising from the failure of a pressure-release valve at the Three Mile Island (TMI) commercial reactor in Pennsylvania in March 1979 resulted in the release of only a very small quantity of radioactive material into the environment, thanks to its
surrounding containment building. The accident at Chernobyl in the Ukraine eight years later was, however, very different. This occurred in a type of water-cooled graphite reactor (an RBMK design) that was inherently difficult to control at low power levels. The reactors did not have containment structures over them but were housed in buildings with sufficient head room to enable reshuffling of the fuel rods in order to maximise the production of weapons-grade plutonium as well as generating electricity. An experiment had been planned for some time, following others in 1982 and 1984, to answer a specific question: in the event of a power failure, would there be sufficient momentum in the still-spinning turbines to provide enough electricity, by way of a new design of voltage regulator, to control the reactor for a minute or so before the stand-by generators became fully operational. The answer to the question will never be known, however, because the experiment that was designed to provide it began in conjunction with the routine shut down of reactor Unit 4 but ended with disastrous consequences. As the power levels dropped, the required operating procedures were not followed and within a fraction of a second, at 01:23 hours on 26 April 1986, two explosions took place in rapid succession that blew the reactor apart and the graphite core caught fire.

The fire lasted for 10 days and many lives were lost in the process of extinguishing it. Because of variable wind patterns the resultant release of radioactive materials high into the atmosphere was spread widely over parts of the USSR and northern Europe. The first indication of the accident was the discovery by Cliff Robinson that the reason the alarms went off when he turned up that morning at the Forsmark Nuclear Power Plant in Sweden was because of radioactive materials that had accumulated on his shoes on his way in to work! A network of personal communications led by Ragnar Boge alerted laboratories in other countries before any official announcements were made.

The Chernobyl disaster not only spread radioactive material all over Europe, but also cast a shadow over the entire nuclear power programme worldwide that has still not gone away. Various accidents had previously occurred, one of which resulted in widespread contamination when the USA’s satellite SNAP-9A failed to reach its orbit and disintegrated on 21 April 1964 above Madagascar, injecting about 1 kg of $^{238}$Pu, which was the satellite’s power source, into the atmosphere. In 1966 a USA B-52 bomber carrying four nuclear weapons crashed while refuelling in mid-air over the Mediterranean Sea, three of them landing on the ground near Palomares in Spain, causing local contamination with plutonium, the fourth being eventually recovered intact from the sea. Then, in 1968, another USA B-52, again carrying four nuclear weapons, crashed onto the ice-covered Bylot Sound close to Thule in Greenland, releasing plutonium, most of which was recovered from the ice but some of which remained in the underlying sediment. And at 11.53 GMT on 24 January 1978 the USSR’s Radar Ocean Reconnaissance (RORSAT) satellite Kosmos 954, having failed to boost into a higher orbit as planned, re-entered Earth’s atmosphere over western Canada, scattering debris over 124,000 km$^2$ of its Northwest Territories. It had been powered by a nuclear reactor containing around 50 kg of $^{235}$U. The launch of a previous (number unknown) RORSAT satellite had failed on 25 April 1973, and its reactor had fallen into the Pacific Ocean, north of Japan. Yet another (Kosmos 1402) RORSAT also failed to boost into a ‘storage orbit’ and fell into the South Atlantic Ocean on 7 February 1983.
At least eight entire nuclear-powered submarines have been ‘lost’ at sea (a ninth, K-429, sank but was recovered, only to sink again two years later at its moorings) [11]. It is thought that all sank as a result of accidents, with the exception of the USSR’s K-27, which was deliberately scuttled. This vessel was, however, in good company because, in complete and utter breach of the initial London (Dumping) Convention’s requirements and the 1983 moratorium, to all of which the USSR had been a Contracting Party since 1976, it first emerged in 1993, and with more information since then [12], that the USSR had up until 1992 dumped at least 20 nuclear vessel reactors at sea, 6 with fuel and 14 without; a shielding assembly from the icebreaker Lenin; more than 150 ‘large objects’ including reactor lids; plus at least 6,000 containers of radioactive wastes, either individually or on barges, and all in coastal waters of depths ranging from as little as 12 m to 135 m or, in the Novaya Zemlya Trough, at a depth of only 380 m. The USSR had actually started dumping in 1959, and for many years had forcefully insisted at the IAEA Board of Governors that there should be a complete prohibition of the ‘Western European’ practice of dumping low-level nuclear waste at sea. It did not cease dumping until 1992.

All of which helped to explain why research vessels from the UK and elsewhere had always been refused to enter waters east of 30° when planning cruises to study the distribution of radionuclides that had been discharged from Windscale as they were dispersed by ocean currents to the north of Norway. Yet at the same time, the engines of USSR ‘trawlers’ had acquired the curious habit of breaking down just off the Windscale site while travelling through the Irish Sea, although the starting up of a nearby military firing range just along the coast usually ensured a speedy and effective repair. The situation off Novaya Zemlya also explained why seaweeds that had washed up on the shores of Greenland, having been carried there trapped in ice flows, had been observed by Asker Årkrog of Denmark to contain a variety of short-lived radionuclides for which no plausible source could be identified.

1.5 Fluctuating Nuclear Fortunes

France was to spearhead the expansion of reactor construction following the 1973 to 1974 oil crises, increasing its nuclear-powered electricity generation from about 7% to over 77% in a couple of decades. World-wide, from 1966 to 1985, some 420 nuclear reactors were built. These varied considerably in design, and thus their operational discharge requirements also differed from site to site [13]. The Americans even deployed a (somewhat unreliable) reactor (PM-3A) in the Antarctic to provide energy for the scientific team at McMurdo Station. It ran from 1962 to 1972 and was based on a similar design to one that had been used in northern Greenland. In addition to a rapidly expanding network of nuclear reactor sites, the discharges from fuel reprocessing plants such as that at the renamed Sellafield, plus the French site at Cap de la Hague on the north French coast, which started reprocessing operations in 1976, provided excellent opportunities to learn more about the behaviour of a wide range of radionuclides, particularly in the marine environment.

The majority of these radioecological studies, however, focussed primarily on ensuring that discharges from routine operations at nuclear sites did not result in exposures of the public that would exceed dose limits set by national authorities. At the time of the Windscale
accident in 1957, the dose limits recommended by the ICRP for workers assumed that they were exposed at a relatively constant rate throughout the year. There were no recommendations or specific guidance with regards to acute exposures during accident or emergency situations. And the dose limit for the public (described as ‘large populations’) was derived simply by reducing the dose limit for workers by a factor of 10. Dose limits for members of the public living in the neighbourhood of nuclear installations were first introduced by the ICRP in 1959, with different values for adults and children, and the majority of radioecological studies made thereafter were focussed on the need to understand the transfer of radionuclides through food chains, or other pathways such as inhalation, that might result in such human exposures. Some of this material was published in the open literature, particularly in journals devoted to health physics, and experimental studies were published in quite a wide assortment of journals. But much of the basic data appeared only in the annual reports of government bodies and their supporting laboratories that were charged with ensuring public health and safety with respect to such facilities. Regular reports from government bodies also appeared in relation to nuclear fallout.

The ability to measure various radionuclides in the environment, both directly and by laboratory analyses, greatly improved (as did most other areas of science) as a result of advances in such basic technologies as microelectronics, the arrival of electronic calculators and, subsequently, of small but powerful computers. Complex mathematical models of radionuclide distribution and behaviour were then made, but in terms of on-the-ground observations, the sites amenable to study were nevertheless limited to those that had been contaminated by weapons testing, by accidents, or by the authorised and controlled releases from, predominantly, nuclear fuel reprocessing facilities. Naturally occurring radionuclides were, however, increasingly being used to study the rates of environmental processes in various media as more sensitive and accurate radiometric techniques, and the facilities to house them, became available.

Controlled laboratory studies on the accumulation of radionuclides by biota required specialised facilities, and the nuclides necessary to carry out such experiments were often in short supply. Experiments in laboratories in different countries sometimes had to be synchronised to make use of rare batches of a specific nuclide being produced. Irradiation facilities were even more scarce and expensive to maintain. Many radiobiological studies were made on certain groups of mammals, but virtually all of them were designed to obtain data of relevance to the protection of human beings rather than for any form of application to such animals in a natural, environmental, context.

An early and what proved to be a continuing concern was the potential effect of (what was then termed) ‘atomic radiation’ on fisheries, particularly marine fisheries, and the USA’s National Academy of Sciences had already by 1957 published a comprehensive and very detailed report on the subject [14]. Indeed it was the marine environment that attracted most attention and early reviews were those of John Mauchline and Bill Templeton in 1964 [15] as well as, remarkably, a pioneering tome by the Russian scientist Gennady Polikarpov [16] from Sevastopol in the same year, although it was not translated into English until the following year, and that was by the Americans Vincent Schultz and Alfred Klement who had only just published their own book on radioecology [17]. The
USA then produced a comprehensive, multi-author review on radioactivity in the marine environment in 1971 [18].

Symposia devoted to radioecology in general were held at various locations, with the USA holding its first national symposium at Colorado State University in 1961, a second at Ann Arbor in 1967, and a third and very successful one at Oak Ridge in 1971. But the showcase for advances in such studies soon became the series of conferences held by the IAEA, usually in Vienna but also elsewhere, during the late 1960s through to the 1980s. The IAEA also published many technical reports on a wide range of topics which were the product of formal specialist working groups held at their offices (by 1979 at the new ‘UN city’ in Vienna), augmented by less formal evening ones at the Café Hawelka. It was not until 1984 that a specialist journal (the Journal of Environmental Radioactivity) appeared as a vehicle for such papers.

Over the previous decade, however, the fortunes of nuclear power had fluctuated considerably, and with them the funding for such radioecological studies. Support for many small national laboratories first started to decline in parallel with the decline in atmospheric fallout from weapons testing. Both public sentiment and the sheer economics of electricity generation had their effects, and the accidents at Three Mile Island and Chernobyl also had inevitable repercussions at a social and political level with respect to the commercial development of nuclear power. In 1969 Robert Anderson funded the formation of Friends of the Earth with the specific mission of preventing the further development of nuclear energy in any sphere. Greenpeace, a ‘direct action’ group, was created shortly afterwards by Jim Bohlen, and Irving and Dorothy Stowe, to protest against the underground testing of nuclear weapons. Many countries scaled down their nuclear programmes, particularly in Europe and the USA, and from 1986 only 71 new nuclear plants were built over the subsequent two decades. It was a roller coaster period for all things nuclear. Laboratories that had once specialised in radioecology diversified into the application of radionuclides to study other environmental contaminants; many closed altogether.

In 1982 a new organisation, the International Union of Radioecologists (IUR), which had been set up as a result of the sustained efforts of ‘Stan’ Myttenaire within the CEC, hosted a workshop in Brussels on 30 March to review the current state of radioecological research and the capabilities of the various labs that were doing it. This included inputs from Austria, Australia, Belgium, Brazil, Denmark, Finland, France, FRG, India, Italy, Japan, Monaco, the Netherlands, Norway, Poland, Portugal, Sweden, the UK, and the USA, as well as the CEC itself. Notable by its absence was anything from the USSR, and Stan put some effort into trying to build bridges (or tunnels) between scientists behind the Iron Curtain and those in the West. But within a few years, most of these laboratories, if they still existed at all, had closed down their radioecological research programmes.

1.6 Back to Basics: The Origins of Atoms and Elements

As if in a parallel universe, while scientists in many countries after World War II were studying the environmental behaviour of the novel and unstable elements created by nuclear fission, plus the radioactive and thus unstable forms of existing elements that were produced...
simultaneously, other scientists were still pondering over the question of where all of the elements, stable or unstable, had come from in the first place. And in trying to solve this question, the Manhattan Project played an unexpected part.

It had long been assumed that the chemical elements were somehow formed as part of the creation of the universe as a whole; but how this could have happened remained a mystery. Another mystery was the source of the heat and light from the Sun, and it wasn’t until 1920 that Arthur Stanley Eddington first suggested that stars obtained their energy by fusing hydrogen into helium, and even this idea was not generally accepted because there was no indication whatsoever about how such a reaction could be sustained. However, the problem was to be solved by a young Jewish physicist, Hans Bethe, who in 1933 had been instantly dismissed from his job (by Hans Geiger) at the University of Tübingen when Hitler came to power. He then fled to the UK and hence to the USA. It was on a train journey from Washington, DC to New York in the spring of 1938, having attended a conference organised by George Gamow, when he famously worked out in theory how the Sun could indeed be powered from the fusion of hydrogen by a complex cycle involving carbon. Such a theory also explained how some light elements could be formed. But experimental studies by Willie Fowler at the California Institute of Technology after the war failed to substantiate this theory. The possibility of other elements being formed within stars seemed even more impossible, because the necessary temperatures (energy levels) necessary to do so were seemingly impossible to attain in stars such as the Sun. This apparently intractable problem was eventually to be solved by a genius, Fred Hoyle.

An English mathematician turned astronomer, Fred Hoyle, in company with many of his bright contemporaries during the war, had been detailed to carry out research into radar, and it was in that capacity that he had flown to the USA late in 1944. Two things happened while he was there: on a weekend visit to the Mount Wilson Observatory in Pasadena, Hoyle learned from Walter Baade about the newly discovered supernovae deep in space, and while stuck in Montreal by bad weather on his way home, together with former colleagues who were now involved in the Manhattan Project, Hoyle linked the concept of implosion (that by then had been found necessary to explode a plutonium, but not a uranium, bomb) with the processes that might well be taking place within supernovae. The result was that in March 1945, back in Cambridge and using data compiled by Otto Frisch who had recently returned from Los Alamos, Hoyle worked out in 1946 how the core of a massive star, at the end of its life, would collapse, heat up, and create at least some of the heavy elements. But there were many problems to be solved, not least the inability to confirm the processes outlined by Hans Bethe. Having by then moved to the USA, it was not until 1953 that Hoyle calculated what is known as a resonant nuclear thermal equilibrium state for $^{12}\text{C}$, a fundamental bottle neck in the theoretical creation of heavier elements, and a specific state which all previous experiments had shown not to exist. Hoyle insisted that it must exist, and effectively challenged Willie Fowler to what turned out to be a 10-day series of experiments that eventually proved Hoyle to be absolutely right (Hoyle’s calculations differed from the experimental observations by about 1%).

It was Hoyle who wrote the first papers ever published on the synthesis of elements heavier than helium by the processes of nuclear reactions within stars. These papers showed
how the cores of stars evolve to temperatures of billions of degrees and thus, at such high temperatures, iron can become increasingly abundant. Furthermore, Hoyle demonstrated that elements heavier than iron cannot be synthesised by such processes but require specific nuclear fusion reactions in old and massive pre-supernova stars. The processes required for the creation of all the elements eventually turned out to be very complex indeed, but Hoyle went on, as leader of a group of very talented experimental and theoretical physicists, to continue working on the problem. All of these processes involved various forms of nuclear transformation, and the manner by which they do actually create the range of elements of which the universe is now composed was published in the famous B²FH paper of 1957 [19]. This insight was, like those of Einstein, to transform our understanding of the world around us for ever. The paper did not explain the origin of all of the elements, but these missing processes were soon also to be unravelled by others. Willie Fowler received the Nobel Prize for Physics in 1983; Fred Hoyle, disgracefully and to the everlasting shame of the relevant Nobel Committee, never did.

The fact that elements were continuing to be created was startlingly illustrated in 1952 when Paul Merrill detected the spectral signature of the element technetium in ageing, red giant, stars. This element is completely unstable and had therefore not been detected on Earth, although it had been artificially created and isolated in 1937 and thus its spectral signature was known. In fact minute traces of it were eventually found, in 1962, in pitchblende from the (then) Belgian Congo [20]. And there can be little doubt that it had also once existed elsewhere, together with other ‘missing’ elements that were still present at an extraordinary, and so far unique, place on the planet, the discovery of which was all the more satisfying because in 1956 the Japanese chemist Paul Kuroda had theorised that, if certain physical and chemical conditions could be sustained, the nuclear fission reactions that are engineered to take place within a reactor could also occur naturally. These predictions were then shown to be remarkably accurate because the analysis of uranium ore deposits from the banks of the Okelonéné River (universally known as Oklo) situated in the Gabonese Republic (Gabon), by French physicist Francis Perrin, provided evidence for just such a natural reactor having been active there in the past. The announcement of its discovery was made by the Commissariat à l’Énergie Atomique (CEA) on 25 September 1972. This finding was also of interest because of the presence and ratios of other radionuclides present at the site relating to events of the distant past.

The relevance of time in relation to the presence or absence of unstable elements had itself been an interesting question, which was eventually answered by calculating the age of Earth using the products of the decay of different isotopes of uranium. Geological dating using a variety of isotopes had been a growing field of interest, particularly following the development of a new method for measuring lead isotopes in igneous rocks by Harrison Brown of the University of Chicago. His student, Claire Patterson (who was to go on to become a most single-minded campaigner of the need to reduce the input of lead from human sources into the environment) used the technique to measure the age of meteorites on the assumption that they were remnants of the creation of the solar system and thus contemporaneous with the age of Earth. Using the latest mass spectrometer then available, at Argonne National Laboratory (ANL) Patterson determined, and
subsequently announced at a meeting in Wisconsin in 1953, that the age of Earth must be about $4.55 \times 10^9$ years, plus or minus about 70 million years, a figure very close to the one accepted today ($4.54 \times 10^9$ years).

Thus while anti-nuclear groups were expounding on how dangerous and unacceptable it was to create radionuclides on Earth, even simply to generate electricity, the picture was emerging that the entire universe and everything in it had arisen, and indeed was continuing to arise, as a result of radioactivity. In the meanwhile, again as if on an even far more distant planet, another group of scientists were gradually unravelling the interior structure of atoms and, in doing so, unravelling the mechanisms that ultimately (at least for now) explain the phenomenon of radioactivity that Henri Becquerel had first stumbled upon back in 1896. The results of these studies would have amazed Becquerel, Marie Curie, Rutherford, and indeed an entire generation of physicists and chemists that followed them. In the 1950s the development of improved particle accelerators and particle detectors allowed scientists to study the interactions of atoms moving at high energies. Neutrons and protons were found to be composed of even smaller particles, called quarks, which explained some of the fundamental processes of some forms of radioactive decay, particularly the inter-transformation of neutrons and protons. Indeed, discoveries after the war followed thick and fast in a dizzy see-saw between theory and experimental observation. New particles were discovered each decade, usually in line with theory: the pion and kaon in the 1940s; the antiproton and electron antineutrino in the 1950s; the muon neutrino and various forms of quarks in the 1960s; other forms of quarks, and the gluon in the 1970s; and even more forms of quarks and other fundamental particles since then, all of which culminated in the confirmation of the existence of the Higgs boson in 2013. Collectively this combination of theory and observation now forms the Standard Model, the greatest achievement so far of human intellectual endeavour, and which goes some way (again, at least for now!) in describing and explaining the ultimately unstable nature of existence.

1.7 The What, Why, and Wherefore of Radioecology

So, in the light of everything that has been set out in the preceding pages, what exactly is radioecology? It is certainly more than just the study of radioactive elements or materials in an environmental context, because to describe it as such would be to exclude the important contribution made by cosmic and solar ‘rays’ to the radiation background, a source that has many consequences. But equally, if it were to include the entire spectrum of electromagnetic radiation impinging upon Earth, it would also include the impact of the visible and other wavelengths, which is not what the subject is about. A useful demarcation is that of the effects of both electromagnetic and particle radiation to cause the ionisation of matter. Ionisation is the process by which an atom or a molecule acquires a negative or positive charge by gaining or losing an electron to form ions, often in conjunction with other chemical changes. As a result, sub-atomic particles arising from radioactive decay, or different forms of electromagnetic radiation, can cause damage to living and inert materials, necessitating management actions to be taken. And it is this same property that enables them to be measured to a level of sensitivity and accuracy that results in their widespread use as...
clocks and tracers of a wide range of environmental processes. For the purpose of this book, therefore, radioecology is taken to be the study of the origins, nature, behaviour, distribution, use, and effects of ionising radiation in an environmental context. But if that is what radioecology is, why study it now, in view of the fact that many radiation sources are no longer a major feature of the world around us, in view of the cessation of the atmospheric testing of nuclear weapons and the strict controls placed on any emissions from civil nuclear power plants? The reasons are many.

First, the generation of electricity from nuclear power continues to grow, and the number of countries making use of it is still slowly increasing. In view of the uncertainties of the effects of carbon dioxide on the atmosphere, such a trend is likely to continue. As of 2020 there were 443 nuclear power reactors operating in 30 countries, with 44 under construction; in addition, there were more than 180 small reactors on board marine vessels (in some 160 or more ships) including aircraft carriers, ice breakers and (the majority) nuclear submarines. There are also a number of research reactors worldwide. While all of these reactors are undoubtedly safely maintained and run, as in any industry, accidents can and do happen, as clearly demonstrated when a 15 m wave overtopped the wall of the Fukushima Daiichi Nuclear Power Plant in Japan at 15:45 hours on 11 March 2011 as a result of the tsunami following an earthquake that had hit the power plant an hour earlier. Such accidents as this inevitably raise concerns over the possible siting of nuclear reactors in the future, and thus any future environmental impact assessments or evaluations will clearly need to include the potential consequences of accidents and accidental releases of radioactive materials, and hence have to call upon the need for radioecological expertise.

Second, ever since the early days of nuclear weapons’ construction and the subsequent development of nuclear power, radioactive wastes have been accruing and, except for relatively low-level wastes, very little of them have been disposed of around the world in a designed and permanent fashion. These wastes include spent fuel for which there is no intention to reprocess the contents into useful nuclear fuel, and such wastes are currently accruing at the rate of about 12,000 t per year. This is admittedly a very small amount, and issues relating to its disposal are primarily social and economic (and thus political) rather than the result of insufficient science or technology. To these wastes must now be added those arising from the decommissioning of nuclear facilities that date back to the cold war and the early days of civil nuclear power development, plus an entire cocktail of wastes arising from the use of radionuclides in diagnostic and therapeutic medicine. There is also a world-wide increase in the use of naturally occurring and artificial radionuclides in many spheres of industry, to which now can be added the prospects of exposing members of the general public to cosmic radiation arising from the pursuit of space travel as a recreational activity.

Third, international conflicts still arise in such a manner that the use of nuclear weapons cannot be ruled out and, far more likely, terrorist groups will surely one day use a ‘dirty bomb’ or some other device containing radioactive material to create panic and confusion, even if the risks of widespread casualties arising from any resultant radiation exposure may be fairly low.
But there is, one might argue, yet another and even more compelling case to be made, and that is the fact that the totality of looking at the natural environment by way of the origins, nature, behaviour, distribution, use, and effects of both ionising electromagnetic and particle radiation collectively forms an interdisciplinary subject that is deserving of far more academic attention than it has done in the past. Ionising radiations are all-pervading, but no biological mechanism of detecting them has ever been identified. And yet by studying them, instrumentally, a slightly different window on the world is opened. It views it through a different prism: not the conventional one of much of environmental chemistry and biology, which relies on the fact that most elements are stable and can thus form long-lasting interactions with each other, but one that views the environment from the perspective of the instability rather than the stability of many elements, and considers the consequences for both the inert and the living materials around them. The following chapters therefore attempt to give a very brief introduction to these particular aspects of environmental science.

References