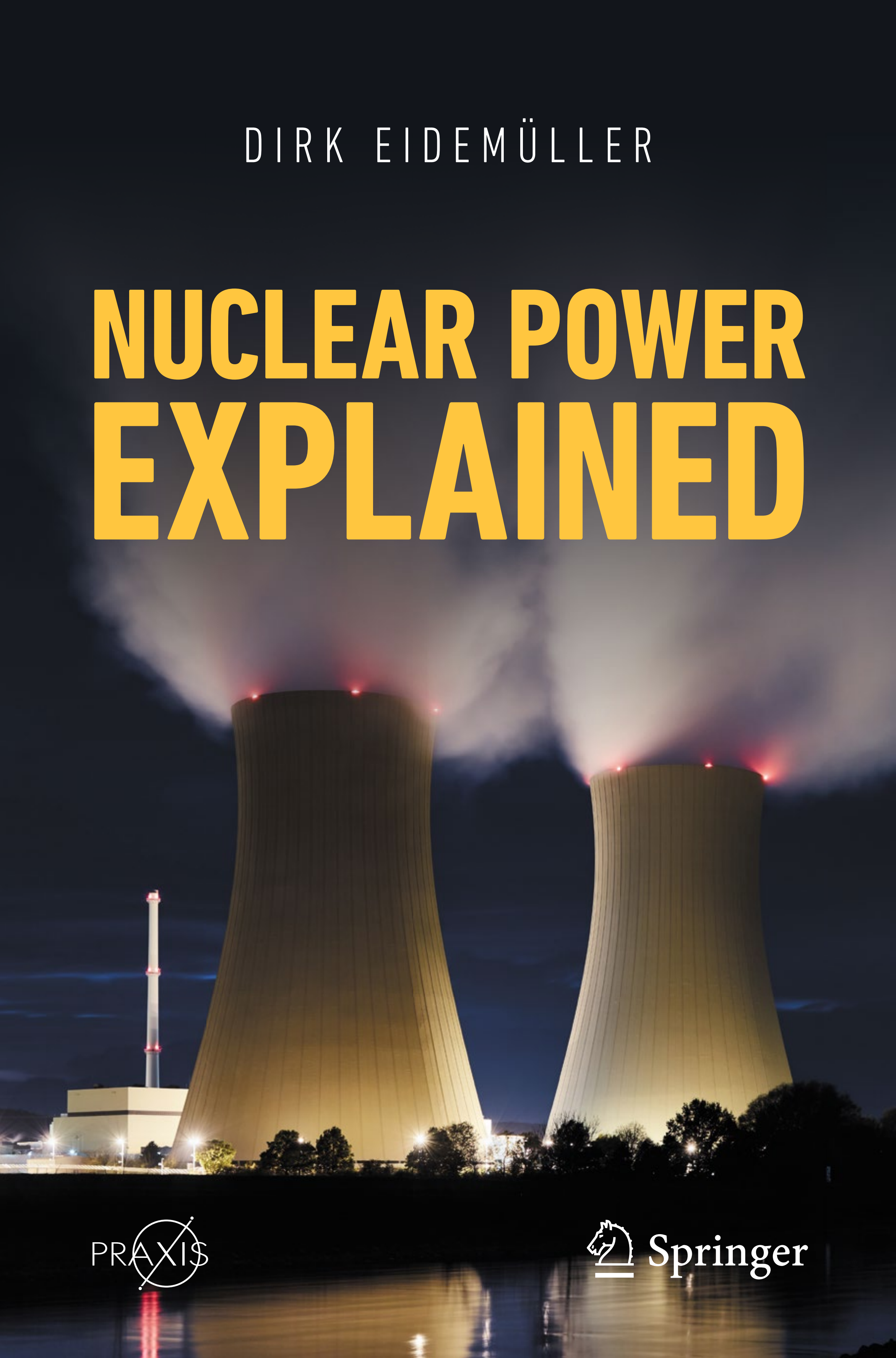
DIRK EIDEMÜLLER

NUCLEAR POWER EXPLAINED



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Dirk Eidemüller
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Front cover: Grohnde nuclear power plant in full power operation. Image: Bernhard Ludewig

Back cover: Research mine for high-level radioactive waste, Gorleben. Image: Bernhard Ludewig

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Preface

Nuclear physics has brought to earth the power that makes the stars shine. Our mastery of the mighty forces of nature that govern the behavior of atomic nuclei has given humankind abilities that were hardly imaginable before. The insights gained by this branch of science are both fascinating and intimidating. It has enabled us to understand the building blocks of matter, the burning of the stars, the hazards of radiation and the origin and transmutation of the elements. Thanks to nuclear physics, the old dream of the alchemists – to transform one element into another – has become a reality.

Without doubt, nuclear physics has shaped the geopolitical face of the modern age more than any other basic research. Only the more recent advances in information technology and now biotechnology have triggered similarly strong impulses in society. Nuclear energy remains one of the most controversial technologies of our time. It raises many important issues, such as power generation, independence of energy resources, technological leadership, geostrategic considerations and military ambitions. Since the discovery of nuclear fission, access to uranium and nuclear technology has gained decisive importance, both in military terms and for power generation. The nuclear arms race of the superpowers during the Cold War was frightening. Yet, the worldwide peaceful use of nuclear power plants for electricity generation demonstrates the beneficial side of nuclear technology. In addition, nuclear physics has brought about enormous progress in medicine and materials science. Modern diagnostics and cancer therapy rely to a large extent on its findings. This peculiar dual nature of nuclear physics, being capable of both serving civilization and destroying it, has impressed me since my youth.

Already as a teenager, I had developed a deep fascination for the field. As a child, I had heard about the Chernobyl accident and found myself wondering what actually happened there. Later in life, I continued to witness discrepancies between the scientific facts on the one hand and the public discourse on the other. The news about nuclear energy was often polarized, sometimes oscillating between hysteria and trivialization.

Although I followed the developments of nuclear energy closely, it was not my interest in that topic, but rather my general scientific curiosity that led me to study physics and finally to specialize in nuclear and astroparticle physics. After receiving a PhD in natural philosophy on the interpretation of quantum physics and its relation to evolutionary epistemology, I became a science journalist. Since then, knowledge of nuclear physics has often been useful to me, especially when writing articles about topics such as nuclear energy, nuclear waste, fundamental physics research and particle accelerators. Guided tours of nuclear power plants and research reactors, numerous visits to institutes and public events as well as discussions with leading scientists, technicians, politicians and also activists of the anti-nuclear movement made it possible for me to gain a comprehensive picture of the technological and social aspects of nuclear energy.

But as the public debates following the Fukushima reactor accident have shown, the public's understanding of nuclear power and the true dangers of radioactivity shows potential for improvement. This is what motivated me to write a book that would make the entire complex of nuclear energy comprehensible, from its first physical principles to final disposal. I wanted to make the difficult matter understandable, showing readers all relevant connections between various technologies and key players without overloading the book with too many details. Of course, one can write an entire series of books on every single topic mentioned here. But this book is intended as a compact summary of the most important aspects of nuclear energy. It is meant to introduce the inexperienced reader to the field and to provide a brief and practical overview for anybody already familiar with the subject.

This book is the revised and enhanced English edition of the book that was first published in German. Since I am completely independent and not bound by any interests, the content should represent a position that is as neutral as possible. With this book, I wish to contribute to a deeper understanding of the groundbreaking scientific discoveries underlying nuclear technology, to give a thorough overview of its applications and to provide a basis for informed discussions about the use of this technology. My hope is that people with very different attitudes toward nuclear energy can profit from it; that an unbiased reader will feel well informed after reading it; that a supporter of nuclear energy might have learned to think critically about this or that aspect again; or that an opponent of nuclear energy will assess the problems more realistically or perhaps with a different weighting than before.

Different aspects of nuclear energy are interlinked in intricate ways. Thus, the structure of the chapters does not follow the narrative style that has become popular in non-fiction books. Rather, it follows scientific logic. We begin with the basics of nuclear physics and radiology, then discuss the principles of reactor operation and security technology, and finally, we address societal problems stemming from its use. This includes the often neglected topic of uranium mining as well as the production of nuclear weapons and the relationship between civil and military nuclear technology. We also discuss in detail the most important accidents involving nuclear reactors and radioactive substances. Finally, we consider the numerous problems associated with the storage of nuclear waste.

When calculating the residual risk in the operation of nuclear power plants or in the search for final disposal sites, we sometimes overlook that it is always *people* who operate nuclear facilities, who benefit from this technology and who are confronted with its consequences. We therefore keep an eye on the human factor in all of these topics.

We start with a brief stroll through history, from the discovery of nuclear fission, through the subsequent Manhattan Project, into the Cold War and onto the first nuclear power plants. These first years of the nuclear age were highly dramatic and have shaped the face of international politics to this day. There are many interesting books that cover various aspects of that period – the secluded life of the atomic bomb experts at Los Alamos; the organizational accomplishments of the Manhattan Project chief scientist Robert Oppenheimer and the military chief Leslie Groves; the struggle of the survivors in Hiroshima and Nagasaki; the futile attempts of the German physicists to build at least a working nuclear reactor; the spy network of the Soviet Union, which helped to shortcut their path to the bomb; the widespread contamination after the many aboveground atomic bomb tests during the Cold War arms race; and many other stories. In this book, we can only touch on these topics.

Since many books center on the major technological and political developments, we focus our stroll through history in part on the activities of Leo Szilárd, the man in the background who discovered the principle of nuclear chain reaction and who was the driving force behind all important early developments, both in building the bomb and in insisting that it never be used. One can explore more valuable material on these fascinating historical matters on the website of the Atomic Heritage Foundation, which, in partnership with the National Museum of Nuclear Science & History, also gives access to numerous interviews on its website The Voices of the Manhattan Project. In the literature section at the end of this book, there is a list of recommended reads that cover a wide range of topics, including the history of the nuclear age, although this list is by no means comprehensive. Interestingly, there are still new historical findings coming up thanks to new analyses and declassified documents.

While the first application of nuclear fission led to devastation, soon thereafter, scientists wanted to prove that it could be used for the benefit of humankind. The early phase of nuclear energy – despite all the tension and ideological differences between East and West – was accompanied by a euphoria that is hardly comprehensible today. It was hoped that the "peaceful atom" and its promised energy would end all conflicts over raw materials – still a decisive *casus belli* today – and many believed it would usher in a new age of civilization.

As a result of the oil crises of the 1970s, the major industrial nations pushed the construction of nuclear power plants in order to increase their energy-political self-sufficiency. After the Chernobyl accident, however, this development stagnated abruptly. But the world's energy demand continued to rise, not least due to the industrialization of China, India and other emerging economies. But just as nuclear energy began to recover, the Fukushima accident happened. This again damaged the reputation of nuclear energy, especially because several reactors of Western design were destroyed.

In view of the global climate crisis, pressure is increasing on all countries to reduce greenhouse gas emissions as much as possible. Carbon-free electricity generation is the first and most important step in the transition to a post-fossil energy regime. Once again, there is a growing interest in nuclear energy. Some even speak of a renaissance of nuclear energy. Many countries are planning the construction of nuclear power plants or are already building them. Comprehensive plans to extend the lifetimes of existing nuclear reactors are currently under review. Some note, however, that in several cases military-geostrategic considerations are the true driving forces behind the decision to opt for nuclear power. Some also criticize the high costs of nuclear energy, as many expenses are not included in the electricity prices but are rather passed onto society and future generations. We will discuss all these points in individual chapters.

Irrespective of one's personal stance against or in support of nuclear energy, it is already part of modern society, in democracies as well as in dictatorships. It is a source of energy and profit and a geostrategic instrument. On the one hand, it allows an extraordinary amount of electricity to be generated with only a small amount of uranium. A modern nuclear power plant with one gigawatt of electrical power covers the electrical energy needs of over one million people. It consumes only just over 3 kilograms of a specific uranium isotope per day. A comparable conventional power plant needs about 8000 tons of hard coal to produce the same amount of electrical energy, and during normal operation it emits similar amounts of radioactive particles into the environment as a nuclear power plant. This is because coal also contains small amounts of uranium and other radioactive substances that are released during combustion.

On the other hand, nuclear reactor disasters can release quantities of radioactivity that make entire regions uninhabitable for long periods of time. And for some states, the mastery of nuclear energy serves above all as an intermediate step to enable the construction of nuclear weapons or at least to keep this option open.

Moreover, the problem of safe final storage remains unsolved. Over the necessary time scale of about one million years, we cannot foresee how future generations will judge our choice of a final storage site for nuclear waste. The public learns very little about these quite controversial debates within the scientific community. Some experts warn that we must at least create safe, permanent interim storage facilities until hopefully one day, better solutions emerge. Other experts prefer final storage deep underground but argue for retrievability of the nuclear waste at least for some hundred years. Another option would be to transform the very long-lived radioactive waste into short-lived waste by special transmutation reactors. Then, nuclear waste would only have to be stored for about one thousand years, not one million years. The cost of such treatment is likely to be expensive. However, the costs of a final storage site becoming unsafe in many thousands or hundreds of thousands of years are much less assessable today – not even factoring in our moral responsibility towards future generations.

Questions concerning the welfare of our society and coming generations should not be left to experts alone. An informed public has the right and the duty to discuss such questions and weigh up the different consequences. This book aims to contribute to a better understanding of nuclear energy and a sober consideration of its most important aspects.

At this point, I wish to thank all those who have contributed to this book. First, I would like to thank Hannah Kaufman, who accompanied this project at Springer Nature. I would also like to thank Angela Meder at Hirzel Publishing House for her cooperation in the realization of the original German version. I would also like to thank all the experts, scientists and the many people interested in nuclear energy, who over the years have helped me to collect material for this book and to find a good structure for it, especially Rolf Hartmann, Thorsten Jostock, David von Stetten and Ingo Wolff. I also wish to thank my family with all my heart for their great support. Not least, I am grateful to my brother Markus, who heads the Radiation Risk Research Group at Helmholtz Zentrum München and is a member of the German Commission on Radiological Protection, and who advised the corresponding chapters with a critical eye.

I also owe a very special thanks to Bernhard Ludewig, who as a professional photographer has compiled the most comprehensive photographic documentation of nuclear energy to date (www.thenucleardream.com). This impressive, self-financed endeavor lasted several years. All photographs in this book where no other author is mentioned are from this project and he kindly provided them.

Berlin, Germany Dirk Eidemüller

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Reactors, Bombs and Visions: A Brief History of the Nuclear Age

When radiochemist Otto Hahn and his assistant Fritz Strassmann conducted their experiments at the Kaiser Wilhelm Institute in Berlin in 1938, they could not remotely imagine what would become possible with their discovery just a few years later. Unexpectedly, when they irradiated uranium atoms with neutrons and then examined the reaction products, barium was also formed. What initially looked like an unusual scientific discovery in fact heralded a new geopolitical era and the dawning of the nuclear age.

Barium is about half as heavy as uranium. Hahn could only guess that the neutrons had caused some uranium nuclei to burst. His experiments were motivated by similar experiments by Enrico Fermi, who had already irradiated uranium with neutrons in 1934. The aim of these experiments had actually been to find out whether uranium transforms into even heavier elements – the so-called transuranium elements – by the addition of neutrons. Physicist Lise Meitner, Hahn's close and long-time collaborator, had convinced him to repeat Fermi's experiments with greater precision.

The Discovery of Nuclear Fission

The idea that uranium atoms could be split was in complete contradiction to knowledge about atomic nuclei at that time. Up to that point, it was only known that atomic nuclei could be transformed into something heavier by the addition of neutrons. The experiments were very demanding; only thanks to their remarkable radiochemical abilities were Hahn and Strassmann able to detect the tiny quantities of barium, which had not been noticed by anyone

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in earlier experiments. However, the two experimenters in Berlin could not provide an explanation for the strange behavior of the uranium atoms. Hahn first informed Lise Meitner, who, because of her Jewish origins, had already fled to Sweden to escape Nazi persecution. Under the given political situation, this was a very courageous act on Hahn's part and a sign of his personal integrity, as he could well have been punished for sharing such information only with her at first and not with any of the physicists at his institute.

In Sweden, the brilliant theoretician Meitner and her nephew Otto Frisch, who had also emigrated, racked their brains over the strange results. During a walk in the snow, the two of them finally came up with the decisive idea that by capturing the neutron, the uranium nucleus is made to vibrate so strongly that it splits into two parts of similar size. This releases an enormous amount of energy. Frisch gave this unknown reaction the name nuclear fission, which became internationally accepted.

Lise Meitner's passion for science was as extraordinary as her talent for physics. She was Germany's first female professor of physics, being appointed professor of nuclear physics in 1926. Yet as a woman, she continued to find herself in a difficult position in the scientific community. Her contribution to the discovery of nuclear fission was not recognized either by the Nobel Prize Committee, which awarded Hahn the Nobel Prize in Chemistry in 1944, or by many other of her male colleagues. The element Meitnerium was later named in her honor. Interestingly, it was especially in nuclear physics – at that time a niche discipline in science – that women found possibilities to work at the frontiers of research and make groundbreaking contributions.

Marie Skłodowska Curie, co-founder of nuclear physics, received the Nobel Prize for Physics in 1903 together with Henri Becquerel and her husband Pierre for their shared discovery of radioactivity. She was also honored with the Nobel Prize for Chemistry in 1911 for her discovery of the elements radium and polonium. Her daughter Irène Joliot-Curie was awarded the Nobel Prize for Chemistry in 1935, together with her husband Frédéric, for the synthesis of a radionuclide. In 1933, they had succeeded in transforming aluminum atoms into silicon by bombarding them with alpha particles. They were also able to create a radioactive nitrogen isotope from boron and a radioactive aluminum isotope from magnesium. In 1937, they irradiated uranium with neutrons – as before Fermi – but were unable to detect barium. The Second World War might perhaps have taken a different turn and, in the best-case scenario, would have been a little shorter and less catastrophic if they had succeeded.

A Message Hits Like a Bomb

When Hahn and Meitner published their results in early 1939, this caused a shock among nuclear physicists worldwide. The discipline of nuclear physics was still very young, and nobody had expected such a surprising result. Since the early 1930s, nuclear physicists had gained experience in shooting alpha particles or neutrons at various elements. Every now and then, they succeeded in transforming elements – the old dream of the alchemists. However, these processes were not suitable for releasing energy: in order to make an atomic nucleus burst, charged alpha particles were needed at that time. These particles are strongly repelled by the likewise charged atomic nuclei, so hits are extremely rare. Ernest Rutherford thought in 1933 that it was an absurd idea to try to generate energy in this way. Albert Einstein said that the whole thing would be as profitable as shooting at "birds in the dark in a country where there are few birds."

This picture changed radically when news of Otto Hahn's experiments with uranium and neutron beams spread around the world. Until then, it was thought that neutrons could only attach themselves to atomic nuclei but not split them. Neutrons are electrically neutral and can therefore easily interact with atomic nuclei, unlike charged alpha particles. Now on the eve of the Second World War, at a time when dictatorships all over the world were increasing their armament efforts, it became clear to nuclear physicists that a completely new source of energy was arising – one that concentrated much more energy than humanity had ever had at its disposal before.

According to Lise Meitner's calculations, uranium could not only be split by neutrons, but it could also release a lot of energy and other neutrons. An old speculation of the theorist Leó Szilárd had suddenly become a serious possibility. Szilárd had already worked out the concept of a nuclear chain reaction in 1933: if enough fissile material comes together, the released neutrons can trigger further nuclear fissions, so that the reaction rate remains the same or even continues to increase. All that is needed is a so-called critical mass of fissile material, above which a self-sustaining or self-reinforcing nuclear chain reaction is possible.

Leó Szilárd was the key figure in the transition from basic nuclear physics research to the new geostrategic era of the nuclear age. He was not only an excellent theoretician, but also possessed an outstanding political and social farsightedness. It is said that he predicted both world wars and their outcome. Born in Hungary with Jewish origins, he went to Berlin to study after the First World War due to the increasing anti-Semitism in his home country. He had to leave Berlin again in 1933 when Hitler came to power. Via Vienna, he first fled to England, where he was declared “enemy of the state” by the Nazis, and then continued onto the United States. For the rest of his life, he would always have two suitcases packed, prepared to escape from any new outbreak of fascism.

The at first only hypothetical idea of a nuclear chain reaction with its potentially massive release of energy became his personal “obsession”, as Szilárd called it later. But when the young researcher tried to talk about it to the famous nuclear physicist Rutherford in 1934, he was thrown out of his office – the time was not yet ripe for his idea. But only a few years later, when Szilárd read of Hahn’s results, he immediately recognized the possibility of building a bomb whose energy release would eclipse everything that had been done before. He also realized the bitter reality: whoever was the first to have such a weapon would win the war. Thanks to his sober view of the political situation, soon after his discovery he handed over the patent in which he had worked out his concept of a chain reaction to the British Admiralty, thus preventing a publication that might have spurred the efforts of German or Japanese nuclear physicists. Many other researchers continued to publish all their nuclear physics results without any political considerations.

An insight from Albert Einstein’s theory of relativity explains the new way of generating energy through nuclear fission. According to Einstein’s most famous formula, $E = m c^2$, energy and mass are equivalent. The mass difference that exists between the initial atomic nucleus and the fission products is released as energy. Einstein had derived his formulas from completely fundamental, theoretical considerations about the relationship between space and time, which seemingly had nothing to do with nuclear physics at all. At the time when Einstein was formulating his theories, there was not even such a thing as nuclear physics in the strict sense of the word; physicists back then were still just trying to understand the basic structure of atoms and the phenomenon of radioactivity, without a clear idea of what could happen in the nucleus of an atom.

A Letter Writes World History

As Szilárd observed in the months after the discovery of nuclear fission, no further scientific reports on this topic appeared from Germany. Together with his colleagues – the Jewish-Hungarian nuclear physics luminaries Edward Teller and Eugene Wigner, who had also fled from Europe – Szilárd could only interpret this as meaning that the Nazis had recognized the importance of this research field and were now pursuing it as a secret project. But one question remained open. In order for a chain reaction to be possible at all, enough neutrons had to be released during uranium fission. Szilárd, together with his colleague Walter Zinn, conducted experiments on this in the laboratories of Columbia University in New York. His assumptions were once more correct. Only days later, Fermi in New York and Frédéric Joliot in Paris were able to confirm these results. It was now clear to Szilárd that a completely new type of bomb was conceivable.

As an immigrant, however, he could not make himself easily heard by the American government. So, he went to see Albert Einstein in Princeton still in 1939. Both were friends since their Berlin years – an amity that even resulted in a joint patent on refrigerator technology. Einstein had also emigrated due to the National Socialist racial mania and had established a new existence overseas. But it was not only their friendship and Einstein's fame that made him the right person for Szilárd's plans. "The one thing most scientists are really afraid of is to make a fool of themselves. Einstein was free from such a fear and this above all is what made his position unique on this occasion," Szilárd later described.

When Szilárd, Teller and Wigner informed him about the discovery of nuclear fission and the possibility of using his formulas to build nuclear weapons, Einstein was completely shocked, because he immediately understood what incredible destructive power such a weapon could unleash. He therefore signed a letter prepared by Szilárd to President Roosevelt in which he asked to start a research program to analyze the possibility of developing nuclear weapons. It would be extremely important to forestall a possibly war-critical atomic bomb of Hitler-Germany. They also mentioned that Germany had stopped selling uranium from occupied Czechoslovak mines.

It is worth noting that Einstein later regretted having signed this letter following the bombing of Hiroshima and Nagasaki. After the war, he said that if he had known that the Germans would not succeed in making an atomic bomb, he would have done nothing.

The letter was to be delivered by Alexander Sachs, an acquaintance of Szilárd and a friend of Roosevelt. However, after Germany's invasion of Poland, the president's time was short and he had no great interest in nuclear physics. After weeks of waiting and an initial rejection, Sachs came up with the crucial idea of how he might be able to convince Roosevelt of the need for a large-scale nuclear research program after all. At their second meeting, he described the encounter between the American inventor Robert Fulton and Napoleon, in which Fulton had proposed to the emperor the construction of a fleet of steamships to invade England. At the time, ships without sails seemed so absurd to the French ruler that he sent the inventor away, who later went to the competitors. Roosevelt understood and said: "Alex, what you are after is to see that the Nazis don't blow us up."

Thereafter, the physicists received the desired green light from the President. A scientific committee was set up that included Szilárd, Teller and Wigner. However, some military officials were rather skeptical about the ideas of these newly arrived academics and wanted to keep all expenses to a minimum. A colonel responsible for financial matters told the physicists, rather gruffly, that wars were not won with weapons, but by the morale of the men, whereupon Wigner replied that perhaps it would be a good idea to cut the funds of the War Ministry and distribute them to the population – that would raise morale quite a bit. The first $6,000 were subsequently granted to buy material for a first operational reactor, and the Manhattan Project began.

But the expenses would soon be increased manifold. After the beginning of the Second World War and the surprisingly rapid initial successes of the Axis powers in Europe and East Asia, the Allies needed to pursue not just huge conventional armament efforts: if the nuclear physicists were right, they also had to win the race for the atomic bomb – no matter how high the price.

The First Nuclear Reactor: Chicago Pile-1

Soon, the development of the atomic bomb within the framework of the Manhattan Project became a large-scale scientific-industrial enterprise. Given the size of the project – orders of magnitude greater than other research projects – numerous physical, chemical and technical difficulties had to be overcome. The decisive point in the project was the question of whether the neutron multiplication necessary for the chain reaction, as postulated by theory, could also be carried out in practice.

To answer this question, a group of highly renowned physicists, including Enrico Fermi and Leó Szilárd, designed the first nuclear reactor ever built by humans. This provisional arrangement, christened "Chicago Pile-1" or CP-1 for short, was a giant box of 360 tons of graphite blocks as moderator material, containing 5.4 tons of pure uranium metal and another 45 tons of uranium oxide. The pile was fixed with wooden slats, and the regulation was done millimeter by millimeter by pulling out or pushing in the central control rod by hand. The construction was located beneath an unused grandstand of the University of Chicago's football stadium.

On December 2 1942, the day finally came to test it. Fermi (who, like many of his colleagues, had fled fascist Europe, in his case because of his wife's Jewish origins) made the extensive calculations and meticulously planned the start-up of the reactor. At the time, the neutron multiplication rate was not yet known – the experiment was to provide it.

The researchers were quite afraid that something might go wrong. If the chain reaction had gotten out of control, a worker with an axe would have cut a rope with an emergency control rod hanging over a reactor opening from above. In addition, there was an automatic emergency shutdown system as well as staff standing on a platform above the reactor to flood the reactor with a cadmium salt solution. Cadmium is a good neutron trap and stops any chain reaction. All in all, this was an astonishing mixture of emergency measures whose diversity laid the groundwork for the fundamental safety rules of modern reactor technology.

After carefully pulling out the control rod for hours, the scientists finally managed to get the reactor running at minimum power and to start a chain reaction that was just about self-sustaining. Due to the low power of just half a Watt, neither cooling nor radiation protection measures were necessary. After half an hour the measurements were completed and the chain reaction was stopped by pushing back the control rod. The experiment was successful, the scientists made a thoughtful toast with a sip of Chianti from paper cups. But Leó Szilárd, the initiator and guiding spirit behind the entire Manhattan Project, did not feel well at all. He stayed on the balcony until almost everyone had left. Then he turned to Fermi, squeezed his hand and said prophetically that this was a "black day for humanity."

The Chicago Pile-1 was followed by other experimental reactors such as the X-10, whose purpose was to produce plutonium for first experiments. This element was expected by the theorists to be highly suitable for bombs. The bomb-grade plutonium was then supplied by much larger reactors such as the "B Reactor" in Hanford with a power of over 200 megawatts. The highly enriched uranium, which is also suitable for bomb-making, was supplied by several huge isotope separation factories that, until the end of the war, could only supply material for exactly one bomb. After the end of the war, Leslie Groves commented that the first criticality of Chicago Pile-1 was the most important scientific event of the entire Manhattan Project. Never has a physical experiment been more decisive for the entire world order.

The Uranverein

Also in other countries, research programs were launched – at first still restrainedly – to explore the feasibility of a bomb or an energy-producing nuclear reactor. In Germany, several research groups worked within the framework of the so-called "Uranverein" ("Uranium Association"), partly independently of each other. In England, the German-Austrian emigrants Otto Frisch and Rudolf Peierls initiated the creation of the "MAUD Committee" (Military Application of Uranium Detonation). This gave birth to the British-Canadian "Tube Alloys" secret project, which did essential preliminary work for the American Manhattan Project.

In particular, Frisch and Peierls were able to show that a small amount of nuclear fissile material theoretically had the explosive force of thousands of tons of conventional explosives. In Liverpool, James Chadwick and his colleagues found out that the critical mass of a nuclear bomb was only a few kilograms and not much more, as was believed by some. Additionally, they arrived at the conclusion that nuclear fission happens fast enough for a nuclear bomb to achieve huge explosive power before the developing heat disintegrates the whole device. Chadwick, who had won the 1935 Nobel Prize in Physics for his discovery of the neutron three years earlier, was convinced that now a "nuclear bomb was not only possible, but inevitable." In light of this, he had to start taking sleeping pills: "It was the only remedy."

France was quickly occupied in the war, and its nuclear research material was brought to Germany. The Soviet Union worked on the atomic bomb with only little effort, because it needed all its reserves in defense against the Nazis. In Japan, too, nuclear research proceeded slowly. Although Japanese physicists had recognized the potential of uranium for a bomb, they estimated the effort to be so gigantic that they did not expect a bomb to be finished in the coming war years. They also had too little uranium ore of sufficient quality to set up a major project themselves.

The German nuclear physicists in the Uranverein, which included world-renowned luminaries in the field such as Werner Heisenberg, Carl Friedrich von Weizsäcker and Walther Gerlach had also recognized the basic possibility of building a bomb. They had sufficient amounts of uranium but were unable to achieve only a single essential preliminary stage for a bomb. Even their last research reactor, hidden from air raids in a rock cellar in southern Germany at the end of the war, could not reach the state of criticality and could not break through the threshold of a controlled chain reaction, as Fermi and Szilárd had already managed in Chicago in 1942.

The comparatively harmless experiments of the German physicists – as well as the lesser known Japanese nuclear project – were from the outset under the conceivably unfavourable star of having to demand expensive material from their – fortunately! – anti-scientific governments in times of war. Some influential Nazis regarded quantum physics and the theory of relativity – the two fundamental ingredients of nuclear physics – as worthless "Jewish" physics and preferred the established "Aryan" physical theories of classical mechanics and electromagnetism that could be used to build ships, planes, radio sets and radars. At some point, Heisenberg was even attacked as being a "white Jew" because he worked on quantum physics. He was sharply interrogated several times. After some time and debate, work on these topics could be taken up again, but with much less financial support than in the US and without many leading scientists, who had already emigrated.

To a certain extent, the rather hesitant efforts of the German researchers in the uranium project can perhaps be understood in terms of their psychological situation. Working on a secret project protected their staff from being used as cannon fodder at the front like millions of others. But if this project had progressed more quickly and had at least promised something like a reactor for a submarine, the whole project would probably have been placed under the supervision of the SS – along with the strict personal monitoring by the regime.

The Manhattan Project

The situation was completely different on the other side of the Atlantic. After the successful experiments with the Chicago Pile-1, the American atomic bomb project proceeded at full speed. The Manhattan Project developed into a tremendous effort that eventually involved more than 150,000 people. The tasks that had to be accomplished in the construction of the bomb were extremely varied; in fact, even more chemists than physicists were involved! Everything was done under the highest military secrecy. With the exception of the leading scientists and military personnel, nobody knew what was actually being worked on until the news of the destruction of Hiroshima. For a steep two billion dollars – an immense sum at the time – and within very short time, the leading scientist, nuclear physicist Robert Oppenheimer, and the military leader, General Leslie Groves, built a top-secret nuclear research center at Los Alamos, a remote place in New Mexico, and a nuclear industry that was spread across the country, with a size comparable to the entire

American automobile industry of the time. The reason for these enormous investments was above all the fear that the German nuclear physicists could be the first to succeed in building an atomic bomb.

In the Los Alamos Laboratory, also called Project Y, the actual bomb design was being researched. There were also several other important research centers and huge uranium and plutonium production facilities, including the Metallurgical Laboratory (Met Lab for short) at the University of Chicago, headed by Nobel laureate Arthur H. Compton. The Met Lab was not only responsible for developing the first nuclear reactors, but also for examining the new element plutonium and the means to its production.

At Oak Ridge, Tennessee – the "Atomic City" – several huge isotope separation plants were built to provide highly enriched uranium: two diffusion separation plants – one of them being the largest building in the world at the time – and one plant for electromagnetic separation. These plants were part of the Clinton Engineer Works, as the complex at Oak Ridge was called. They worked together and provided the uranium for "Little Boy", the code name for the Hiroshima bomb. Essential for the success of the uranium enrichment was a special type of particle accelerator called the calutron, which had been developed by Ernest Lawrence at the Radiation Laboratory of the University of California. A similar invention – the cyclotron – had already earned Lawrence the Nobel Prize in Physics in 1939.

At the Hanford Site on the Columbia River in the state of Washington, large reactors were built to breed plutonium from uranium. First one, then three reactors sent regular deliveries of plutonium to Los Alamos. From this material, the bomb of the Trinity test, codename "Gadget", and the Nagasaki bomb, codename "Fat Man", would be produced. The first, still tiny amount of plutonium was extracted from irradiated uranium by chemist Glenn Seaborg in August 1942, but the production methods would soon be scaled up considerably. Seaborg received the Nobel Prize in Chemistry in 1951 for his role in the discovery of plutonium and nine other transuranium elements. After the war, he became chairman of the US Atomic Energy Commission and also participated in working out the Partial Test Ban Treaty, which he regarded as one of his most important achievements.

Other important scientists in the project were Szilárd, Teller and Wigner, as well as John von Neumann, also a Hungarian of Jewish origin. These four and several other researchers of similar origin earned themselves the nickname "Martians" because of their extraordinary intellectual abilities and their little-known homeland. Frisch and Peierls also went to Los Alamos after they had been classified as "enemy aliens" and a security risk in England despite their important preliminary work. About half of the leading scientists in the Manhattan Project were immigrants.

With these facilities and the large number of outstanding scientists, Groves and Oppenheimer had almost unlimited resources and pursued every – really every – potentially interesting technological path on the way to the bomb with full commitment. They could not allow themselves at any price to be outpaced by the Germans, who presumably had fewer resources but perhaps the right intuition for which technological path to take.

However, the Manhattan Project only truly reached its goal after the capitulation of the Third Reich. The devastating flashes of the atomic bombs over Hiroshima and Nagasaki were the final acts of the Second World War, as they forced Japan – which was otherwise determined to fight for every meter – to surrender. The most terrible weapon ever devised by humankind had sealed the end of the bloodiest conflict in history. It also heralded a new geopolitical epoch. In the following Cold War era, the possession of nuclear bombs would determine how ideological differences were to be fought out around the globe.

Most people today associate the term "nuclear age" with the iconic design and architecture of the 1950s and 1960s, besides the regularly present images of nuclear bomb tests and "duck and cover" drills. Some historians identify the end of the nuclear age with the collapse of the Soviet Union. But today's world order is still based in essence on the undeniable potential for mass destruction with nuclear weapons.

Incidentally, it is not absolutely clear whether the atomic bomb would have been used against Germany if it had not already capitulated before the bomb was completed. Some American scientists had expressed concern that in the event of a misfire or a crash of the bomber, German scientists would have received decisive clues into the technology and, above all, valuable bomb material. This might have enabled them to build a bomb for Hitler and thus possibly turn the certain defeat into a nuclear stalemate. In Japan, this danger was not as apparent. The progress of the German uranium project, operated by only a few scientists and technicians, was highly overestimated by the Allies. As recent historical analyses have shown, German nuclear physicists had not performed some of the fundamental calculations on the functioning of an atomic bomb, or had done so only provisionally and incorrectly. The American physicists on the other hand were confident enough with their calculations to use the uranium-based Hiroshima bomb design completely untested, so that no valuable uranium had to be wasted for test purposes. The stocks of highly enriched bomb uranium were only sufficient for this one bomb.

The more sophisticated plutonium bomb design had been successfully tested during the so-called Trinity Test in New Mexico in July 1945. This was the first nuclear bomb explosion. The heat of the fireball melted the sand around ground zero to glass. Weapons-grade plutonium is easier to obtain than weapons-grade uranium, but the ignition of such a bomb is more difficult. Robert Oppenheimer is said to have commented on this explosion with words from the Bhagavad Gita, a sacred Hindu text: "Now I have become death, the destroyer of worlds." Leslie Groves wrote "What an explosion!" in his memorandum to newly sworn president Harry Truman. Fermi, meanwhile, estimated the explosive force of the bomb surprisingly accurately with the help of scraps of paper he had let trickle to the ground when the blast wave set in. Szilárd again wrote a letter to the president in which he and dozens of other researchers urgently warned against using the bomb against civilian targets. But this time, the letter probably never reached Truman.

Another document initiated by Szilárd that did reach highest government circles was the "Franck Report", written by leading Manhattan Project scientists around James Franck, who had won the 1925 Nobel Prize in Physics and had also emigrated from Germany. In this report, the scientists discussed possible geopolitical consequences of using nuclear bombs against civilian targets. They warned of a nuclear arms race that would follow and spoke out for a demonstration of the new weapon over barren land. Among the signatories were Szilárd; Seaborg; Joyce C. Stearns, director of the Met Lab; and Eugene Rabinowitch, who later was one of the founders of the Bulletin of the Atomic Scientists. This organization is still in existence and, since 1945, seeks to provide essential information about nuclear weapons and its dangers to the public.

The plutonium supplies were enough for exactly two bombs. The second bomb after the Trinity Test was the one that destroyed Nagasaki, which eventually led to the Japanese surrender. From that point on, American nuclear facilities were able to produce more bombs every month. The US government's plan was to continue to drop atomic bombs on Japan until it surrendered. Szilárd had warned that the USA would make itself a pariah of the world community if it were to use such a cruel weapon against cities, since it does not discriminate between soldiers and civilians or adults and children. It is little known in Western media that for decades, propaganda in the Soviet Union capitalized on the cliché of bloodthirsty capitalist imperialists who did not shy away from an aggressive nuclear first strike against civilians and who morally were little better than the Nazis.

One year after the war, Szilárd, together with Albert Einstein, founded the Emergency Committee of Atomic Scientists to warn the public about nuclear weapons and to work for world peace. Szilárd foresaw a highly dangerous nuclear arms race and proposed the establishment of a direct telephone line between the White House and the Kremlin. He also organized conferences with scientists from East and West to discuss new ways to achieve security and peace.

The Cold War Nuclear Arms Race Starts

After the end of the Second World War, the USA was the only nation to have nuclear weapons for a couple of years. However, thanks to excellent espionage work, the Soviet Union had caught up quickly and was able to break this nuclear monopoly. It detonated its first atomic bomb in 1949. The idealism of a number of informative nuclear researchers played a role in this. They were of the opinion that it was not good if only one superpower had such a weapon at its disposal – but also one with a different model of society. In the early years, the most important uranium supplies for the Soviet atomic bomb came from the German Democratic Republic, then called the Soviet Occupation Zone.

Shortly after the Second World War, at a time when the USA still had a de facto nuclear monopoly, the Korean War broke out. Here, capitalism and communism faced each other for the first time on the battlefield in an ideologically charged struggle. The US had demobilized a large part of its conventional armed forces after the Second World War and considered itself superior thanks to the atomic bomb. Yet despite a difficult course of the war, the American government decided against using nuclear bombs. Ethical concerns and the fear of a loss of international reputation weighed more heavily than the tactical advantage atomic bombs could have brought. Fortunately, this nuclear restraint has since prevailed, even as further late-colonial and proxy wars of the great powers broke out – especially with the Indochina and Vietnam War.

At the same time, the other powers who had been on the winning side of the Second World War saw the Korean War as a confirmation that the ideological conflict between East and West was hardening, and so increased their own nuclear armament efforts. Great Britain, which had done important preparatory work for the Manhattan Project, was able to detonate its first atomic bomb in 1952. France followed in 1960, and the People's Republic of China in 1964. The five states that were the first to have the bomb are still the five permanent representatives on the UN Security Council today.

Soon, scientists on both sides of the Iron Curtain came up with the idea of developing so-called hydrogen bombs, which would be even more destructive than uranium or plutonium bombs. These immensely powerful devices, called thermonuclear bombs, are not based on the principle of nuclear fission, but on the principle of nuclear fusion. Here, heavy atomic nuclei are not split into smaller ones, but instead, very light atomic nuclei are fused into heavier ones. This process allows much greater explosive forces to be achieved than would be possible with standard atomic bombs – up to several thousand times more powerful than the Hiroshima bomb. Their principle of energy generation is the same as that which takes place deep inside the sun, supplying our entire Solar System with energy. However, since this only occurs at extremely high pressures and temperatures, hydrogen bombs require an atomic bomb to ignite. In uranium or plutonium bombs, conventional plastic explosives are used to compress the material and ignite the fission reaction, which in turn can act as a trigger for the nuclear fusion of a hydrogen bomb.

In the development of these super bombs, the paths of the "Martians" separated. Szilárd, Wigner and von Neumann turned to different areas of science. Edward Teller, who despised both communism and fascism because his family had suffered greatly under both, became the leading architect of the hydrogen bomb. In his eyes, only this ultimate weapon could protect the free world from the communists. As early as 1952, Teller and his team succeeded in completing a hydrogen bomb, which was tested that same year. It had 800 times the explosive power of the Hiroshima bomb. The following year, the Soviet Union responded by detonating its own first hydrogen bomb.

With the development of these incredibly powerful weapons, not only Szilárd and like-minded scientists, but also many other involved people faced conflicts of conscience. This time, even Fermi, who had been rather apolitical throughout his life, opposed it. In 1949 while working as an advisor to the US government with a panel considering whether or not to develop thermonuclear weapons, Fermi, together with his friend and fellow physics Nobel laureate Isidor Rabi, warned in a memorandum that this would be a weapon "which in practical effect is almost one of genocide… Any postwar situation resulting from such a weapon would leave unresolvable enmities for generations. A desirable peace cannot come from such an inhuman application of force… It is necessarily an evil thing considered in any light."

In addition, Oppenheimer quit his activities. He was highly decorated after the war, but now spoke out against the development of the hydrogen bomb, stating in a declaration with other scientists that "in determining not to proceed to develop the super bomb, we see a unique opportunity of providing by example some limitations on the totality of war and thus of limiting the fear and arousing the hopes of mankind." Later during the McCarthy era, he would be denounced as a sympathizer of communism, whereupon he was no longer allowed to participate in government projects.

In the communist world as well, researchers and politicians became more and more afraid of the forces they were unleashing. Igor Kurchatov, Oppenheimer's eastern counterpart as director of the Soviet nuclear program, said after witnessing a thermonuclear explosion that this was "a terrible, monstrous sight. That weapon must never be allowed to be used!" And Nikita Khrushchev, after receiving his first full briefing on the nuclear situation following his appointment as the new head of state, said, "I could not sleep for several days. Then I became convinced that we could never possibly use these weapons, and when I realized that I was able to sleep again."

Nuclear physicist Andrei Sakharov, Teller's eastern equivalent as "father" of the Soviet thermonuclear bomb, later became an activist for peace and disarmament. He was regarded as a dissident in the USSR and awarded with the Nobel Peace Prize in 1975. Sakharov recalls reading a short story by Szilárd, called *My trial as a war criminal.* In this piece, written in 1947, Szilárd describes himself as a defendant in a hypothetical trial for his involvement in the creation of weapons of mass destruction. When Sakharov and a colleague read a Russian translation of this story in 1961, they understood the moral implications Szilárd was pointing at, and the piece expressed ideas they themselves had been thinking about. Sakharov would go on to change the focus of his work to curbing the deployment of nuclear weapons instead of creating new ones.

But the military-industrial-political machinery of the Cold War would not stop because of the burdened conscience of some intellectuals. During these years, thousands of nuclear and hydrogen bomb tests above and below ground or underwater were conducted, with accompanying propaganda ensuring a balance of terror, as Szilárd had feared. Of course, one cannot know whether a nuclear arms race would also have occurred if Hiroshima and Nagasaki had been spared.

In retrospect, it is quite hard to believe what immense efforts and costs the two power blocs west and east of the Iron Curtain put up to expand their threat scenario of multiple overkill. The crude logic behind this decades-long arms race and the absurdity and inhumanity of every operational scenario of mutually assured destruction of course do not shed good light on the political and military leadership on both sides. Of course, the people in charge were able to secure their influence within this system, but only at the price of the potential destruction of the entire human civilization on our planet.

Several times, the nuclear poker game could have gone extremely wrong. During the Cuban Missile Crisis in October 1962, both superpowers were repeatedly on the verge of a military escalation that could have quickly led to nuclear war. Only after the Cuban Missile Crisis was resolved did a "red telephone" get set up between Moscow and Washington, forming a direct connection between the highest government offices, as Szilárd had already requested at the end of the Second World War. This "Washington–Moscow

Direct Communications Link" is still active today as a secure computer link. Two years before the Cuban Missile Crisis, in 1960, Szilárd had met Nikita Khrushchev in New York in a private two-hour meeting and gained the Soviet leader's sympathy for establishing such a hotline to prevent an accidental nuclear war. Around that time, Szilárd also fell ill with bladder cancer, which he was able to defeat with the help of a radiation therapy he had devised himself. A few years later, though, he died of heart attack.

The world was probably closest to a nuclear war on September 26, 1983, when Soviet satellite surveillance reported an American first strike. The Lieutenant Colonel on duty, Stanislav Petrov, could have sounded the alarm according to regulations, which would have meant immediate preparations for a nuclear counterstrike. Instead, he considered the observations a technical failure, which in retrospect proved to be correct: An unusual constellation of the celestial bodies had caused sunrays to be reflected in the satellite sensors, thus simulating rocket launches from the USA. Only the cool head of the commander prevented further escalation here. It is not clear whether the Soviet high command and the party leadership, aged and prone to a certain level of paranoia, would have refrained from a nuclear escalation in the event of a major alarm.

Atoms for Peace

Initially, nuclear reactors were only used to "breed" plutonium for bombs, and not for electricity generation, for which there were tried and tested conventional power plants. Yet, while the military was busy building new bombs, visionaries on both sides of the Iron Curtain were dreaming of a better nuclear-powered future. One of these visionaries was Glenn Seaborg, who expressed his hopes after the Second World War that one day nuclear-powered shuttles would fly from Earth to the Moon and plutonium would heat large swimming pools. Others dreamt of nuclear-powered airplanes or even cars, or wanted to blow huge canals into the landscape with atomic bombs.

But progress usually takes place in small steps. The first reactor to actually produce electricity went into operation on December 20, 1951, in the Idaho National Laboratory. This EBR-I (Experimental Breeder Reactor I) was also the first functioning breeder reactor – a type of reactor that produces more fissile plutonium than the fissile uranium it consumes. It can therefore produce multiple amounts of energy from the same mass of uranium ore as conventional reactors. Until then, the breeding process had only been theoretically expected but had not been experimentally proven. The EBR-I ran with a primary and secondary circuit made of a liquid sodium-potassium alloy. The latter transferred its energy via a heat exchanger to a water-steam cycle, which in turn drove a generator via a conventional turbine. At the time of commissioning, the power was sufficient to light four light bulbs. After a short time, the electrical output could be increased to 100 kilowatts.

On December 8, 1953, US President Dwight D. Eisenhower gave his famous "Atoms for Peace" speech to the General Assembly of the United Nations. In it, he not only outlined the horrors of a possible nuclear war, but also the hopes that nuclear technology could bring for the development of human civilization. Eisenhower offered support to all nations that would follow the United States on the road to a better, nuclear-powered future. His speech was accompanied by an extensive media campaign, aimed primarily at domestic audiences, to dispel the fear that was growing during the accelerating nuclear arms race.

Interestingly, the first contractors to accept Eisenhower's offer included Iran, Israel and Pakistan. The first nuclear power plants in these countries were built by the company American Machine and Foundry, which was later also to supply research reactors to Germany. These exports were made possible by amendments to the Atomic Energy Act, in which the American government released the findings on reactor construction – hitherto traded as military secrets – and opened them up to the civilian sector.

The plan behind "Atoms for Peace" was both geostrategic and economic. Anyone who wanted to participate in this program had to submit to an inspection and control regime under UN supervision. Those who renounced the bomb were allowed to participate in the benefits of civil nuclear power in return. For the American leadership, it had also become clear through their analysis of the German uranium project that whether or not a country can develop nuclear weapons is essentially a question of political will and time.

American leadership believed that if a large number of states developed nuclear weapons, this could have led to a fragmentation of world politics and would have made the use of nuclear weapons in regional conflicts much more likely. Instead, it would be strategically better to involve these states in a civilian nuclear program. It was to be expected that some of these states were looking for the fastest possible access to nuclear technology and wanted to keep a secret military option open. Nevertheless, the program was a great success in political terms. The Soviet leadership had similar interests and copied the idea. Also their program worked and, together with the American counterpart, helped curb the proliferation of nuclear weapons, thus enabling the later Non-Proliferation Treaty, still the basis of the geostrategic world order today.

The First Nuclear Power Plants

The first real nuclear power plant that was to feed electricity into the public electricity grid went into operation on the east side of the Iron Curtain. The operators of the APS-1 Obninsk (Atomic Power Station 1 Obninsk) had clearly been inspired by Eisenhower and wanted to appear equally idealistic; their reactor bore the designation AM-1 (Атом Мирный, Atom Mirny), which stands for "peaceful atom". The plant, which began operating in 1954, only delivered around five megawatts and only for five years. After that, it was used for decades without major incidents for the production of radioisotopes and as a research reactor. The next Soviet plants in Tomsk and Beloyarsk were already large power stations and had an electrical output in the range of 100 megawatts.

No time was wasted west of the Iron Curtain either. In 1956, the first nuclear power plant that produced electricity on an industrial scale went into operation in Calder Hall, near Windscale in England, initially with 50 megawatts and later with 200 megawatts of electrical power. The first American nuclear power plant in Shippingport was in operation a good year later with a similar output. Its first reactor core came from a cancelled project for a nuclear-powered aircraft carrier and used highly enriched uranium.

Even if the major step towards cheap electricity from nuclear power plants was not yet done, the feasibility alone spurred further inspirations, and the military and politicians had little reason to put a brake on this.

The Year 1955: Geneva Nuclear Conference and USS Nautilus

The great atomic euphoria of the era was best reflected in the first major nuclear conference of the United Nations. On August 8, 1955, in the beautiful Swiss city Geneva, at the time the largest scientific conference in history, called the "International Conference on the Peaceful Uses of Atomic Energy," began. More than 1500 participants from East and West exchanged previously secretive results with surprising openness and aroused the curiosity of the world public. The promises were many: with unlimited nuclear energy, deserts could be made fertile thanks to seawater desalination plants; polar regions could be made habitable; and ships, airplanes and locomotives would no longer need oil and coal. In only twenty years, nuclear fusion would apparently be mastered. A new epoch in history was about to dawn.

The biggest eye-catcher at the conference was a fully functional research reactor presented by the United States. A bright blue glow at the bottom of a seven-meter-deep water tank showcased the power of nuclear fission, while visitors jostled for spots along the railing at the top. The strange bluish Cherenkov radiation – named after the Russian nuclear physicist Pavel Alekseyevich Cherenkov – is produced by the high-energy particles released during nuclear fission. This almost mystical glow, which seems to emerge from nowhere and illuminates the reactor pool, cast a spell on observers. Meanwhile, British companies were already offering five different types of reactors at the conference.

As the scientists in Geneva were talking about a new age, military and political strategists also set to work. In particular, nuclear-powered submarines promised completely new strategic possibilities. For this purpose, American engineers developed a new, compact reactor design: the pressurized water reactor. This type has many advantages and is used today in the vast majority of all nuclear power plants. The first nuclear submarine, the USS Nautilus, set sail with such a reactor in January 1955. Thanks to its nuclear propulsion, it was able to do things that no other submerged ship could do. The Nautilus dived longer and went faster than any other submarine. One of her great successes was the first dive under the pack ice of the North Pole over a distance of more than 2000 kilometers. She later collided with an aircraft carrier during an exercise, but the damages were repaired quickly. The Soviets answered a few years later with the K-3 Leninski Komsomol, their first nuclear-propelled submarine. A fire damaged its reactor in 1962 and in another accident in 1967, 39 sailors were killed. In 1960, the US navy presented the first nuclear-powered aircraft carrier, the USS Enterprise, which thanks to its eight nuclear reactors had virtually unlimited operational range.

Frontlines of the Cold War

Over the years, the superpowers perfected their mutual deterrence. Initially, for several years, heavy bomber squadrons were in the air around the clock, ready to retaliate in case of a surprise attack. The most important operation of this kind was called "Chrome Dome." It was depicted with bitter irony and remarkable historical detail in Stanley Kubrick's masterpiece "Dr. Strangelove." Several aircraft crashes happened during these long patrols, which needed in-flight refueling.

In a single accident over the Spanish coastal town Palomares in 1966, four thermonuclear bombs were lost. Three went down around the town. They were found quickly but contaminated the ground. Only recently have the decontamination works been completed. The fourth bomb had fallen into the Mediterranean Sea and was missing. Immediately after the accident, the US Air Force issued the code word “Broken Arrow,” which means the loss of nuclear weapons. This was a case for the High Command of the Strategic Air Force, because the Soviets were certainly also very curious about these weapons. At this level of command, the rule was that at least two people had to be on any long-distance call, each with the order to shoot down anyone who gave false orders or information.

The military tried to keep the entire salvage operation secret, but the international press had already guessed that the large silver boxes that had rained down from the sky were thermonuclear weapons. Some of the official press conferences seemed like a credit to the Theater of the Absurd. A spokesman for the US Department of Defense once replied to a journalist: “I don’t know of any missing bomb, but we have not positively identified what I think you think we are looking for.” Only after 80 days and several unsuccessful attempts, the recovery of the fourth bomb was successful thanks to the tips of a Spanish fisherman. Due to advances in rocket technology, it was soon possible to terminate the bomber patrols that were so prone to accidents. They were replaced by intercontinental missiles in bunkered silos and strategic nuclear submarines.

Berlin, where Hahn had once discovered nuclear fission, had meanwhile been divided into four sectors. The divided Germany became the major military deployment area of the Cold War, both for conventional and nuclear forces. While elsewhere the big decisions of world politics were made, in the 1950s the two German states were just beginning, step by step, to find their way back into the circle of civilized nations after the period of Nazism. In East Germany, this happened under the strict surveillance of the Soviet Union, while West Germany was able to perform a surprisingly quick economic recovery due to its liberal social system and a more efficient economic order. What the superpowers on both sides of the Iron Curtain initially did not want to give the Germans, however, was access to nuclear technology. Here, it was not only distrust of their former opponents that played a role. Military and geostrategic considerations also made it less advisable to build nuclear facilities with highly sensitive nuclear technology in the immediate vicinity of the Iron Curtain. On the other hand, it was difficult to deny German scientists any access to nuclear technology if the great powers wanted to treat them as allies and not as occupiers. Additionally, the German researchers feared that they would lose touch with international scientific developments. Everyone was talking about the atom; only they were denied it.

The 1955 Geneva Atomic Conference had already shown the dynamics within which this field of research was developing. These debates gave rise to the International Atomic Energy Agency (IAEA), which was officially founded in 1957 and since then has been monitoring and promoting the peaceful use of nuclear energy as a worldwide control instrument. 1955 was also a key political year. It was the year in which the Paris Treaties came into force, which restored conditional state sovereignty to West Germany and from then on allowed it to conduct civil nuclear research. After protracted negotiations, the US government agreed to supply research reactors. Similar developments took place in the communist East. The German Democratic Republic was not to be left behind in the development of nuclear technology – the success of the communist model of society was ultimately to be demonstrated also in science, and not least in nuclear physics.

While the scientists were primarily concerned with nuclear physics as basic research and, in keeping with the spirit of the era, were also in favor of civil reactor technology, the interests of their politicians were not purely pacifist. It was not without strategic reasoning that the German government flirted with the idea of an own nuclear bomb. In its early years, the Federal Republic's ties to the West were not yet fully established. Of course, the interests of the victorious powers on both sides of the Iron Curtain were clear that under no circumstances would they allow their respective geostrategic rival to expand.

But NATO, the western alliance, was still young. And shortly after West Germany joined NATO in 1955, the communist countries founded the Warsaw Pact in response. This put West Germany under some pressure. What would happen if, for example, a more isolationist government came to power again in the US? If the American people refused to risk their own existence for the freedom of Western Europe in a nuclear exchange? In such a case, West Germany could have lost the nuclear protection by the western alliance and would have been easy prey for the USSR if it did not develop its own nuclear weapons. Of course, most leaders of the western powers did not want to lose West Germany as a stronghold against communism. The American "duck and cover" propaganda was meant to disperse concerns about a possible nuclear war and to strengthen the population's support of nuclear armament and deterrence.

France was also not always sure if it could rely on Anglo-American support in the worst case. The French planning games for this scenario led not least to the short-range nuclear missile "Pluton", named after the ancient Greek god of the underworld and illustrating the preference of French generals to assign distinctive names for their nuclear weapons systems. 120 of these missiles were stationed on the French eastern border. With its range of just 120 kilometers, a missile could at best have reached German or Swiss soil in order to nuke advancing units of the Warsaw Pact. This weapon system was only decommissioned in 1993.

The Göttingen 18 and Approval in the East

Most German scientists were better aware than their political leaders that nuclear armament would not have provided any security advantage. It was a time of mutual paranoia in the game of the superpowers, a time of propaganda and of research into ever more powerful nuclear weapons and new carrier systems. In such a situation, a new, medium-sized actor would only have complicated and destabilized the situation. Through their contacts with international colleagues, nuclear physicists also knew the mood abroad better than most others.

When the German Chancellor Konrad Adenauer trivialized tactical nuclear weapons in a speech in 1957, calling them a "further development of artillery," 18 leading heads of nuclear physics took action and a few days later published their "Göttingen Manifesto" in several large national newspapers. They announced that none of them would be available for work on nuclear weapons, about whose devastating potential one should not have any false ideas. Instead, the nuclear researchers – among them Nobel Prize winners Otto Hahn, Werner Heisenberg and Max Born – advocated the peaceful use of nuclear energy: a courageous and logical act in the spirit of Leó Szilárd.

Adenauer was outraged by this interference of scientists in political decisions – the term "civil courage" was still somewhat new at the time – but he soon had to bow to increasing public pressure and declare his renunciation of any nuclear armament of the German armed forces. Much less well known is the fact that the Göttingen Manifesto also found resonance in the communist East, where many leading nuclear researchers spoke out against the development of nuclear weapons and for the peaceful use of nuclear energy – not exactly to the bliss of their political and military leadership. In the years to come, research reactors went into operation in the west and east of Germany – initially, however, at the greatest possible distance from the Iron Curtain on both sides.

In the meantime, the arms race between the nuclear powers accelerated. Hundreds of tests of ever more powerful nuclear and thermonuclear bombs were conducted. Only after the Cuban Missile Crisis was resolved, in 1963, did the major powers finally sign the Partial Test Ban Treaty, which prohibited all nuclear tests except for underground tests. Although China and France have not signed this treaty until today, it greatly helped to reduce radiation exposure by overground nuclear bomb tests. Instrumental in preparing the Partial Test Ban Treaty and also other treaties on nuclear weapons control and disarmament were the Pugwash Conferences on Science and World Affairs, where experts from east and west could openly discuss such matters. Inspired by the Russel-Einstein Manifesto on the dangers of nuclear warfare, which Bertrand Russel had finished shortly before Einstein's death in 1955, this conference series first took place in 1957 and continues to the present day.

Since the end of communism in Eastern Europe and the fall of the Berlin Wall in 1989, the two superpowers have substantially reduced the numbers of nuclear warheads but still have large stockpiles. While several treaties have been signed on nuclear weapons control and disarmament, there are activities on both sides to develop new types of nuclear weapons. In 1996, the United Nations General Assembly adopted the Comprehensive Nuclear Test Ban Treaty, which prohibits all nuclear tests, including underground tests. This treaty has yet to enter into force, as several important nations have not yet ratified it.

Visions and Reality of Nuclear Fission: Electricity, Research and Ships

It is very interesting to contrast the current use of nuclear fission with the promises of the past. The great utopias and visions of the 1950s have not come true. Neither nuclear airplanes nor mini power plants in private homes are desired by anyone today. With the exception of research, military or prototype reactors and a few small satellite reactors, all reactors today are used either for power generation or in the marine sector. Today, nuclear power provides around ten percent of the world's available electrical power – but more about that later.

Especially in the field of research reactors, enormous progress has been made. There are only a few areas of science, industry, technology and medicine that do not benefit in one form or another from the knowledge gained from research reactors. The strength of their imaging and analytical capabilities as well as the possibilities for producing useful radionuclides have increased enormously in recent decades, which is why they or their successors – the spallation sources – have become an integral part of the modern research landscape.

Nuclear reactors are also on the move on the world's oceans. Nuclear submarines, aircraft carriers and other heavy warships benefit from the almost unlimited energy that a nuclear reactor provides. This allows for months of operational readiness and range around the globe without having to refuel, thereby reducing vulnerability.

Civilian nuclear ships represent a special case. The first civilian ship using nuclear propulsion was the Soviet icebreaker "Lenin." Commissioned in 1959, it housed three nuclear reactors and was in operation – with some nuclear incidents – until 1989. The second civilian ship with nuclear propulsion was the American "Savannah," commissioned in 1962 as a freighter and passenger ship. But its focus was on testing nuclear propulsion, and therefore the ship never achieved economical operation and was decommissioned in 1972. The third civilian nuclear ship was the German "Otto Hahn," intended for use as a freighter and completed in 1968. But due to its nuclear reactor, the ship could only call at a few ports, most of them in South America and Africa and usually only with one-time special permits. This attempt proved to be a failure, and the reactor was shut down in 1979.

The Japanese nuclear freighter "Mutsu" had also started in 1974 with great hopes, but had to struggle with public resistance after a minor radiation accident, until finally the reactor was removed in 1995. The last ship from the era of nuclear-powered cargo ships is the Russian "Sevmorput," a container ship with icebreaker qualities. Everything else today that sails over or under the oceans driven by nuclear reactors is either a Russian nuclear icebreaker or a warship of the great nuclear powers.

Up and Down: Oil Price Crises and Chernobyl

In the 1950s and 1960s, many countries launched nuclear programs, starting with small research reactors and eventually leading to large nuclear power plants. Different reactor types with different safety precautions were developed in West and East. The oil price crises of the 1970s gave a further boost for nuclear power. Suddenly, the highly industrialized countries realized that they could only maintain their lavish lifestyles by importing large quantities of energy sources. In the course of decolonization, however, they lost much of their influence on the regions of the world from which their urgently needed raw materials came. And in the ongoing competition between capitalism and communism, between exploiters and comrades, between the free world and one-party dictatorships, neither side wanted to show itself to be too imperious, which could have weakened its sympathies in developing countries.

Nuclear energy, which requires only relatively small amounts of uranium, offers a wonderful way out of this dilemma. For one, it makes it possible to present oneself as a modern and technologically advanced nation, and in addition it reduces dependence on raw material imports and helps diversify the energy sector. Last but not least, access to nuclear technology also increases the geostrategic reputation on the international stage. On top of this, military nuclear ambitions become much easier if civilian nuclear technology is already mastered. Several countries have pursued secret nuclear armament programs under the guise of civilian use. We will come back to the most important cases in the chapter on nuclear weapons proliferation.

In the 1970s and 1980s, many large, industrialized nations drew up optimistic plans to build a comprehensive nuclear energy industry. This included not only a large number of nuclear reactors and uranium factories to supply the fuel, but also the use of breeder reactors to produce more fissile material and reprocessing plants to recover materials from spent fuel. But breeder reactors and reprocessing plants – both originating from military use – repeatedly proved to be accident-prone and struggled with construction problems, release of radioactivity and popular resistance.

Nearly all plans for a comprehensive nuclear economy were scrapped when a catastrophic reactor accident occurred in Chernobyl in 1986. The meltdown burned in open air and released huge amounts of radioactivity, which contaminated large areas and killed thousands of people. Even the biggest supporters of nuclear power realized that this technology carries potentially immense consequences. The public mood slowly tilted against this supposedly safe and clean form of energy. Most of the new reactor projects were subsequently abandoned. Italy withdrew completely from nuclear energy after a referendum. Austria had already held a referendum several years earlier, also deciding against nuclear power, and an already completed nuclear power plant was not put into operation. For years, hardly a single new nuclear power plant was built worldwide.

Knockdown and Resurgence: Fukushima and Climate Crisis

In the period after Chernobyl, the nuclear power industry had become rather quiet. Power plant operators and nuclear energy advocates no longer sought publicity, as they had done in the years of nuclear euphoria. Instead of the technology's wonderful promises, its worst concerns had come true. Yet slowly, the argument was gaining ground that the Chernobyl catastrophe was mainly due to the negligent, unsafe construction of the Soviet type of reactor. Western and also modern Russian reactors have a protective shell and inherent safety systems designed to prevent such disasters.

Step by step, the nuclear industry seemed to be recovering. Especially in Asia, the rapidly growing economies demanded more energy without relying on coal, oil and gas as the only energy sources. Then in 2011, the multiple meltdown of Fukushima occurred. In one fell swoop, three reactor vessels of western design were destroyed. The cause for this disaster was the inadequate security of the emergency power supply. All over the world, new power plant construction plans were put on hold, reactors were shut down for safety checks and alternatives to nuclear power were sought once more.

In recent years, and especially in view of global warming, the call for more nuclear energy has become louder once again. At least as a bridging technology, low-CO_2 nuclear energy should secure the energy supply until the second half of the 21th century, until renewable energy is able to guarantee the energy needs of mankind. The IAEA suggests that nuclear power plants are to replace coal and other fossil power plants. New types of reactors are to ensure greater safety and higher fuel efficiency. At the same time, some of the modern construction projects have to reckon with massive cost increases and years of delays. The handling of highly radioactive nuclear waste also remains largely unsolved. Research is being conducted in all these areas. It remains to be seen what share of global electricity production nuclear power will have in the coming decades. Hopefully, the spirit of international cooperation, which many researchers have upheld since the discovery of nuclear fission, will prevail over the raw logic of power politics.

Part I

Basics of Nuclear Physics and Radioactivity

2

Nuclear Physics and Its Applications

The power of nuclear reactions is what makes stars shine for billions of years and what can make them shatter in supernovae explosions. Usually, we notice little of these incredible forces. Nearly all atoms that we and all matter on our planet are made of have stable nuclei, except for the few radioactive ones. While most people associate nuclear physics with nuclear power plants, they are usually not aware of how many areas of life are already affected by the scientific results of this discipline. In modern materials research, in medicine and across all natural sciences, the findings of nuclear physics have become indispensable. Nuclear physics helps to diagnose and treat cancer, to investigate the origins of meteorites and to analyse archaeological artefacts. Here, we can only present the most important basic principles and applications of this highly complex and fascinating discipline.

The Structure of Atoms

When the ancient Greek philosophers first started thinking about the essence of matter, they related it to familiar concepts in everyday life. Matter was thought to be like water, because it could change its form, or like fire, because it could burn and change from a solid to a gaseous state. Around 2500 years ago, Leucippus and his pupil Democritus came up with the idea that all matter consisted of tiny atoms. Our modern word "atom" derives from the ancient Greek term "atomos," which means "indivisible." The reasoning behind this concept was strikingly logical: matter can be split again and again. But at

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_2

some point, it becomes impossible to split it anymore, because one has arrived at the very basic building blocks of matter.

As accustomed as we have become to the concept of atoms today, it is remarkable that as recently as the 19th century, when physics and chemistry were well developed, scientists still argued over whether atoms existed or not. Only by modern atomic physics could that argument by settled. Today we know that atoms can be split and that they are made up of even smaller elementary particles. These in turn cannot be split; such elementary particles are actually what the ancient Greek atomists had in mind when they coined the term "atomos."

Atoms consist of an electrically positively charged atomic *nucleus* and a shell of negatively charged *electrons* orbiting it. The atomic nucleus in turn consists of *protons* and *neutrons*. These two nuclear components are also called *nucleons*. The well-known pictogram shown in Fig. 2.1 is quite misleading in terms of its proportions.

The atomic nucleus is absolutely tiny compared to the dimensions of the entire atom; it is about 10,000 to 100,000 times smaller. One atom is about a tenth of a nanometer in size. A nanometer (also written as nm) is a billionth of a meter, i.e. an atom is only 0.000 000 000 1 or 10^{-10} meters in size, which is about a millionth the thickness of a strand of hair. Accordingly, an atomic nucleus measures only 10^{-15} to 10^{-14} meters. If an atomic nucleus were as big as an apple, the diameter of the atom would be 3 kilometers. Yet, practically the entire mass of an atom is concentrated within the atomic nucleus. The electrons in the shell of an atom weigh very little compared to the protons and

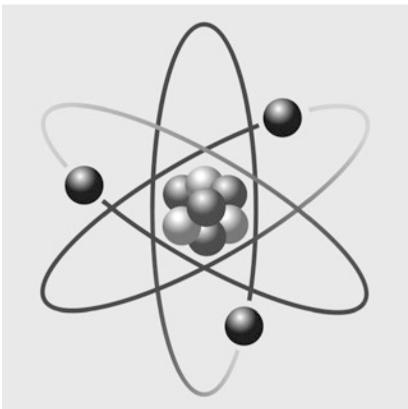

Fig. 2.1 Structure of an atom. Around the nucleus made of protons and neutrons, the much lighter electrons are circling

neutrons in the nucleus; the electron is about 2000 times lighter than a proton or neutron.

These three components – protons and neutrons in the nucleus and electrons in the shell –make up all atoms. Protons are positively charged, neutrons are neutral and electrons are negatively charged. While electrons are elementary particles, protons and neutrons do have a substructure: they consist of two different types of *quarks*. This peculiar name describes a certain class of elementary particles being studied by elementary particle physics. But since the quarks inside protons or neutrons are bound together extremely strongly, this substructure only plays a role in rather academic fields of nuclear physics. For all practical applications, including nuclear power, medicine, and materials research, one can leave the particle physics aside.

The Forces in the Atomic Nucleus

Physics knows four elementary forces: the gravitational force, the electromagnetic force and the strong and weak nuclear force. The gravitational force is responsible for the mutual attraction of all bodies that have mass; compared to the other forces, however, it is very weak and only plays a role in large amounts of matter. Gravitation is the dominant force in cosmology, but it is irrelevant in atomic and nuclear physics.

The electromagnetic force acts between all electrically or magnetically charged bodies. Similarly charged bodies repel each other, while oppositely charged bodies attract each other. Like gravitation, the electromagnetic force is effective over any distance. But it is many orders of magnitude stronger than gravitation. It is so strong that the electromagnetic force determines the structure of atoms. It lets the positively charged protons inside the atomic nucleus repel each other and also binds the negatively charged electrons to the atomic nucleus. Since the electric charge of electrons and protons is opposite in sign but identical in size, every chemical element has as many electrons as protons. The electrons of the atomic shell can interact with those of other atoms and thereby form chemical bonds, which leads to molecules, salts, crystals, etc. All chemical processes are determined by the electromagnetic forces of the electron shell.

The strong and weak nuclear forces only act at extremely short distances, namely on the tiny distances of individual components of the nucleus. The strong nuclear force is the strongest of all forces of nature and provides the cohesion of atomic nuclei. It is responsible for the extremely strong attraction between the protons and neutrons of the atomic nucleus; it has no effect at all

Fig. 2.2 Block 2 of the Angra nuclear power plant on the Brazilian Atlantic coast

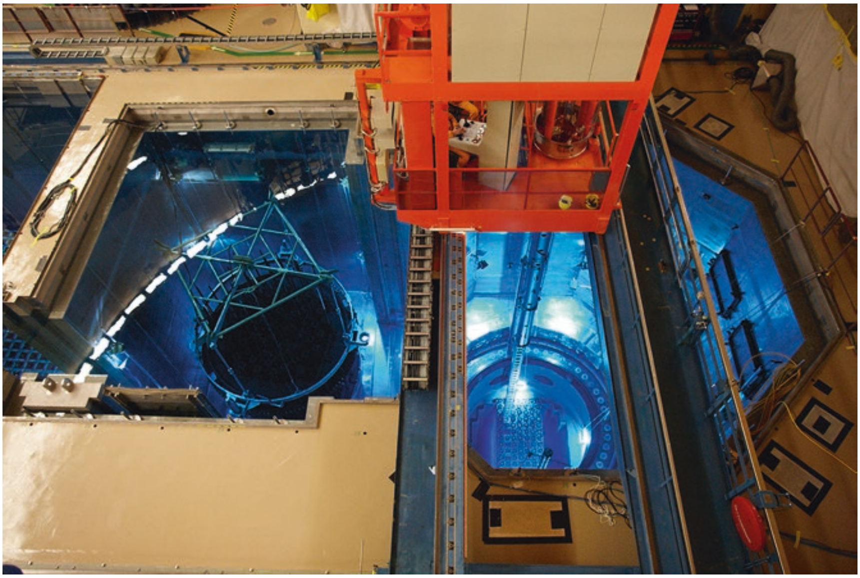

Fig. 2.3 View into the reactor pool of the Grafenrheinfeld pressurized water reactor during annual revision in 2006. The loading machine is changing the fuel elements between the reactor and the spent fuel pool. The burnt elements remain constantly under water to shield radiation and guarantee cooling. The blue-violet shimmer in the bottom left of the reactor is Cherenkov radiation emanated from the fuel rods deep down in the reactor

on electrons. It counteracts the electromagnetic repulsion between the protons and thus allows for the stability of the atomic nucleus. The electromagnetic force decreases with the square of the distance, thus, it increases enormously when approaching very small distances. In the narrow space of an atomic nucleus, the repulsion between the protons is extremely strong. The strong nuclear force is strong enough to compensate for this electromagnetic repulsion. However, it only acts between neighboring particles in a nucleus, while the protons inside a nucleus feel the electromagnetic repulsion of all other protons. For this reason, there is a limit to the maximum size of stable atomic nuclei.

In the case of very heavy atomic nuclei beyond lead, the electrical repulsion becomes so strong that the nuclei become fundamentally unstable and eventually decay radioactively. The enormous forces acting in the atomic nucleus mean that the binding energies of atomic nuclei are about a million times greater than the chemical binding energies that stem from electron interactions. Processes such as nuclear fission, which make use of these forces, are accompanied by energy transmissions that are a million times higher. To generate the same amount of energy, nuclear reactions accordingly require around a million times less material than chemical processes. The explosive force of a few kilograms of uranium or plutonium in atomic bombs is equivalent to thousands of tons of conventional explosives; this is also why nuclear reactors require orders of magnitude less fuel than fossil fuel power plants.

The weak nuclear force in turn is – as its name suggests – much weaker than the strong nuclear force. Among other things, it is responsible for the conversion of protons into neutrons and vice versa in certain nuclear processes. It also enables the fusion process in the sun, without which there would be no life on our planet. Additionally, it is involved in all the radioactive processes in which beta radiation is emitted.

In modern particle physics, the weak nuclear force plays an important role because it violates several symmetries, such as the mirror symmetry between left and right. It is also the only force through which neutrinos interact with normal matter. These ghostly particles can pass through entire stars or planets without interacting. Although hard to measure, neutrinos can provide a way of looking into the center of the sun, into distant supernovae, into nuclear processes deep inside the earth, and also into running nuclear reactors. Neutrino detectors may therefore become interesting tools for controlling international non-proliferation agreements. Yet, a more detailed discussion of these fascinating possibilities is reserved for books on particle and neutrino physics.

The interplay of the repulsive electromagnetic and the attractive strong nuclear force is also responsible for the shape of atomic nuclei. While in most popular books atomic nuclei are depicted as spherical, this is not always the case in nature. Some nuclei have elongated shapes and resemble a rugby ball; others are rather flat and look more like a discus. On top of this, nuclear physics is a special branch of quantum physics, as there are energetic shells of protons and neutrons and different quantum-typical couplings between the particles inside a nucleus. Sometimes, neutrons and protons in a nucleus even form a kind of dancing couple for a brief moment, increasing their already lightning-fast inner-nucleus movement speed from a quarter to half the speed of light! While being the basic building blocks of matter, atomic nuclei are highly complex physical systems, and much of their inner behaviour is still not precisely understood and tricky to investigate.

Elements and Isotopes

The relative number of protons, neutrons and electrons in an atom is determined by several relationships. Due to the electromagnetic attraction between the protons in the atomic nucleus and the electrons in the atomic shell, the number of protons determines the number of electrons and consequently the chemical behaviour. The number of protons, and thus the *nuclear charge number*, hence also determines the chemical *element*.

The periodic table of the elements shown in Fig 2.4 is accordingly sorted by increasing nuclear charge number. The periodicities in the structure of the electron shell then determine the chemical behaviour, with similar behaviour occurring in elements with similar outer electron shells.

Noble gases, for example, have closed outer electron shells and therefore chemically react only with extreme reluctance. Alkali metals and halogens, on the other hand, have one electron more or less than the energetically much more favourable closed electron shells and are therefore highly reactive. However, this does not play any role for the atomic nucleus, because the forces acting inside the nucleus are many orders of magnitude stronger than the chemical forces of the electrons in the atomic shell. Whatever the electrons do, even when an explosive charge goes off, does not affect the nucleus any more than a fly landing on an elephant.

While the chemical element is determined by the number of protons, the quantity of neutrons in the nucleus of a certain element can vary. The number of neutrons determines the respective *isotope* of this element. In general, a certain type of atom with a certain number of protons and neutrons is also

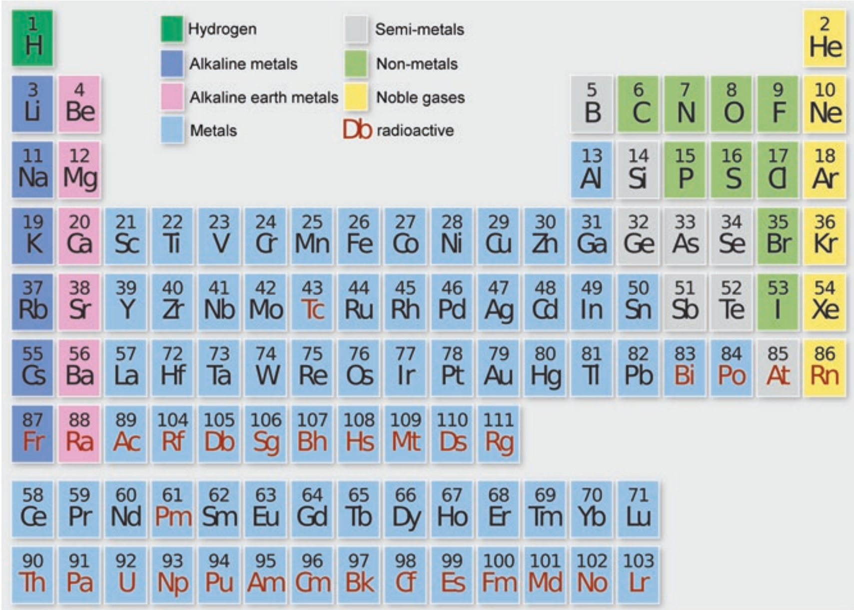

Fig 2.4 Periodic table of the elements. The two lower rows are to be inserted behind the elements lanthanum (La, atomic number 57) and actinium (Ac, atomic number 89), respectively, which is why these elements are also called lanthanides and actinoides. Of special interest for nuclear energy are the heavy elements uranium with atomic number 92 and plutonium with atomic number 94

called a *nuclide*; radioactive nuclides are accordingly called *radionuclides*. The equilibrium of electromagnetic repulsion between the protons and the attraction by the strong nuclear force between protons and neutrons must be given, however. But you also cannot have an excessive amount of neutrons as "glue" between the protons, because single neutrons are not stable and decay to protons via the weak force. Only bound together with protons inside a nucleus can neutrons be stable. The stability of a nucleus thus depends on a finely balanced interplay between the electromagnetic, the strong and the weak force.

The result of all these opposing forces is that for all elements, a stable atomic nucleus can only exist with certain ratios of protons and neutrons. Apart from very exotic reactions, the neutrons have no influence on the chemical properties – they only change the weight and the nuclear physical properties of the corresponding atomic nucleus.

In the lightest of all elements, hydrogen, the atomic nucleus consists of only one proton without neutrons. This hydrogen isotope, called "protium," is stable and makes up the large majority of 99.98% of naturally occurring hydrogen. Equally stable is the next heavier hydrogen isotope, which has a

Table 2.1 The isotopes of hydrogen

	Simple hydrogen (Protium)	Heavy hydrogen (Deuterium)	Superheavy hydrogen (Tritium)
Protons	1	1	1
Neutrons	0	1	2
Nuclear charge number	1	1	1
Mass number	1	2	3
Symbol	^1_1H	^2_1H	^3_1H
Half-life	stable	stable	12,3 years

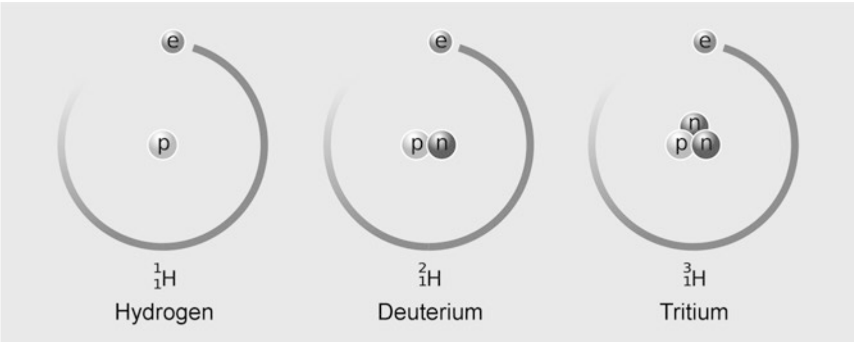

Fig. 2.5 The isotopes of hydrogen: protium, deuterium and tritium

neutron in the nucleus in addition to the proton; this isotope is called heavy hydrogen, or "deuterium." The next hydrogen isotope is called superheavy hydrogen, or "tritium," and has two neutrons. It only occurs in traces in nature. Tritium is unstable and decays on average after 12.3 years (Fig. 2.5).

This decay time is called *half-life*. It is used to characterise the time after which exactly half of a radioactive substance has decayed. Radioactive decay is a purely stochastic process, i.e. it has no memory. A tritium nucleus that has not decayed after 100 years will still decay with exactly 50% probability in the next 12.3 years, and not with a higher or lower probability. After two half-lives, only a quarter of a radioactive substance is left, after three half-lives only an eighth, and after ten half-lives only about a thousandth. This value of ten half-lives is a practical measure for estimating when a radioactive substance has emitted most of its radiation and only a very small amount remains. However, if the original amount of a radioactive substance was very large, you have to wait even more half-lives. Accordingly, after 20 half-lives, only one millionth of the original substance is still present. Depending on the element and isotope, half-lives can be very different and range from tiny fractions of a

Table 2.2 The isotopes of carbon

	Carbon-12	Carbon-13	Carbon-14
Protons	6	6	6
Neutrons	6	7	8
Nuclear charge number	6	6	6
Mass number	12	13	14
Symbol	${}^{12}_{6}C$	${}^{13}_{6}C$	${}^{14}_{6}C$
Half-life	stable	stable	5730 years

second to billions of years. This extreme variability in half-lives is also the reason why storage of nuclear waste is such a demanding task.

The nomenclature for the different isotopes is defined as follows: The so-called *mass number* corresponds to the total sum of protons and neutrons in the atomic nucleus. Since the number of protons is already determined by the element, the mass number also indicates the number of neutrons and thus the isotope. When using symbols, one writes the mass number in the upper left corner by the element symbol, the *nuclear charge number* (also called *atomic number*) in the lower left.

Since the number of protons is already defined by the element symbol, it is usually not written, so that for tritium you can simply write ${}^{3}H$ or also hydrogen-3 or H-3. Natural uranium mostly consists of the isotope with 92 protons and 146 neutrons. Thus, it has the mass number 238 and is called ${}^{238}U$ or U-238. Radioactive elements are usually only found in traces in nature; nearly all naturally occurring isotopes are stable. Some elements have only one stable isotope, such as gold (${}^{197}Au$) or iodine (${}^{127}I$). Besides hydrogen, carbon also has two stable isotopes (${}^{12}C$ and ${}^{13}C$), as does silver. Some elements such as tin have up to ten different stable isotopes, all of which occur naturally, with varying frequency.

Lead is the heaviest stable element. But there are also two elements lighter than lead, which do not have stable isotopes but can only be produced artificially. These are promethium and technetium. All other elements up to lead have at least one stable isotope.

In nature, some radioactive isotopes can be found. These can come from various sources. For some, their half-lives are so incredibly long that they have not decayed since they were created before the earth was formed. This is the case with bismuth, thorium and uranium, for example. These extremely long-lived isotopes are also known as *primordial radionuclides*. They are very useful for long-term dating of billion-year-old rocks, which is done in geological analyses both for terrestrial rocks or meteorites.

The half-lives of the two most important uranium isotopes, U-235 and U-238, are 700 million years (U-235) and over 4 billion years (U-238). All other uranium isotopes are much more short-lived and have already decayed. The earth and our solar system are about 4.5 billion years old; of U-238, a good half has decayed since then, of U-235 much more. As a result of this difference, natural uranium today contains less than 1% U-235 and more than 99% of U-238. The decay products of uranium are in turn radioactive, so that certain radioactive isotopes occur everywhere in the rocks of the earth's crust, which eventually decay further to stable lead isotopes. These radioactive nuclides, which have originated from primordial radionuclides, are called *radiogenic radionuclides*. But uranium-238 is not the longest living known radioisotope.

Until a few years ago, bismuth was considered the heaviest element with at least one stable isotope. But bismuth-209, which is present in natural bismuth at almost 100%, is unstable – only its half-life of 19 billion billion years is about one billion times greater than the age of the universe. This is such an incredibly long duration that such atoms only decay extremely rarely. This is why nobody noticed the radioactivity of this material for a long time and why the element lead, one position below bismuth, has only quite recently gained the title of the heaviest stable element. But there is an even more long-lived radioisotope than bismuth-209: xenon-124, which decays about a thousand times slower. Such rare decays can only be observed in very meticulous and extremely well shielded experiments that suppress any other possible radioactive signals.

Another source of radioactive isotopes lies in cosmic radiation, which is why these are called *cosmogenic radionuclides*. From the cosmos, high-energy particles from various processes are constantly raining down on the upper atmosphere of our planet. One of these sources is the solar wind, a plasma stream that constantly flows around our earth. In the highest energy range, however, there are also extremely high-energy protons, atomic nuclei and gamma radiation from supernovae, pulsars or those that were enormously accelerated by the huge magnetic fields around black holes. Today's physics is not yet able to provide an explanation for the most energetic of these particles. When the high-energy cosmic ray particles collide with the atoms of the earth's atmosphere, they can smash these nuclei to pieces and can thus also produce radioactive isotopes. In particular, the radioactive carbon isotope C-14 is produced in this way.

By nuclear conversion of nuclides, we create artificial radionuclides that do not or no longer occur in nature, as they have completely decayed in the millions of years after their formation. These substances are called *artificial*

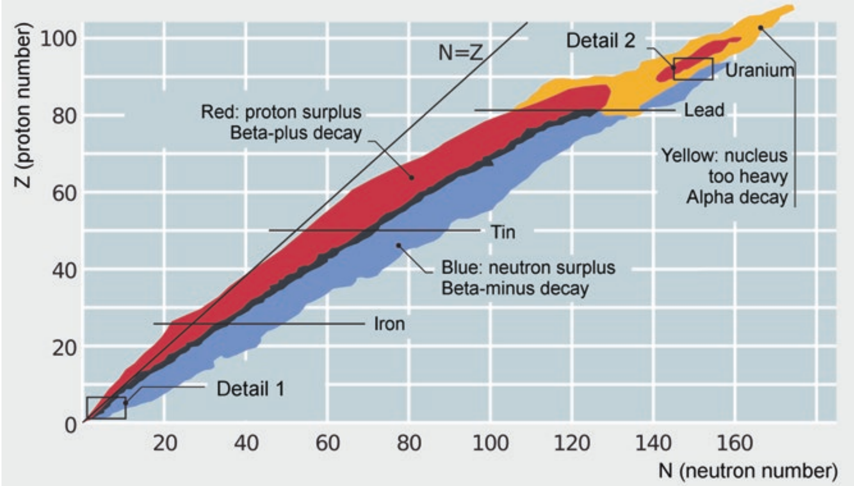

Fig. 2.6 Simple overview scheme of a nuclide map: The different elements and isotopes are ordered to the right with increasing neutron number and to the top with increasing proton number. Each element occupies a row, with the lightest isotopes of that element (with the lowest neutron number) on the left of the row and the heaviest on the right. Each step to the next row upwards is a step to the next element of the periodic table. The stable nuclides are shown in black; the other colors indicate the most important decay types in the different regions of the nuclide map. You can see that above lead there are no more stable elements, but the half-lives of some extremely heavy elements like uranium are very long, so that they are still present in the rock. The diagonal with N = Z indicates nuclides with the same number of protons and neutrons. The heavier a nuclide is, the greater the deviation from this diagonal. In total, nuclide maps are composed of hundreds of boxes; compare the two sections on the following page

radionuclides. Some of them are radiologically very dangerous, so they must be handled with great care. *Radio-epidemiology* describes the effects of radioactive radiation on the human organism.

If Tables 2.1 and 2.2 are extended and summarised to include all other known isotopes, we obtain a so-called *nuclide map*. In this map, the known elements are arranged in sequence with their respective isotopes. See Fig 2.6 for an overview and Fig 2.7 for details. Due to this arrangement, the overview of the periodicity of the chemical properties, as given by the shell structure of the electron orbits and as found in the periodic table of the elements, is lost; but in return, nuclide maps provide an excellent overview of the nuclear physical relationships and possible material transformations.

The nuclide map also shows that the ratio of neutrons to protons increases as the atomic nuclei become heavier. For light elements it is approximately 1:1; thus the most common carbon isotope C-12 consists of 6 neutrons and 6 protons, whereas the heavy uranium-238 consists of 146 neutrons and 92

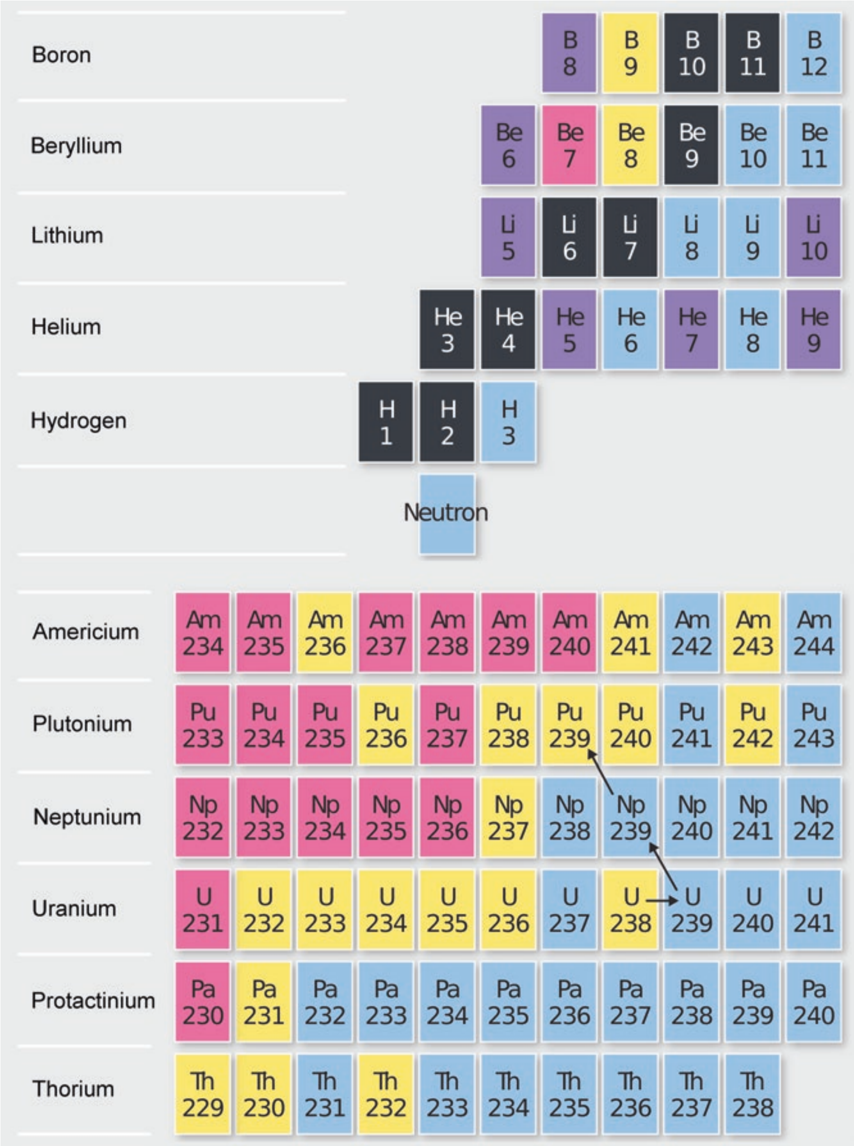

Fig. 2.7 Two sections of the nuclide map for the lightest elements from hydrogen to boron and for some superheavy elements like uranium and plutonium. The different colors indicate the different types of decay: black means stable, yellow stands for alpha decay, blue for beta-minus and red for beta-plus decay, purple for other, more exotic decay types. One can see immediately that uranium-238 and plutonium-239 are alpha emitters. The arrows from uranium-238 to plutonium-239 indicate the breeding reaction, with which plutonium-239 is produced in nuclear reactors

protons. This is because the electrical repulsion between the many protons becomes so extraordinarily strong that this must be compensated by the attraction of many neutrons.

Because of this banana-shaped curvature of the nuclide map, when nuclear fission takes place and the number of neutrons and protons is approximately halved, the fission products cluster below the stable elements. These *daughter nuclides* of a nuclear fission inherit the excessive number of neutrons from their uranium "parents" and are therefore usually highly radioactive.

Material Transformations and Nuclear Reaction Equations

With the help of nuclear physics it has become possible to transform chemical elements into different ones, and thus to realize the old dream of the alchemists. Theoretically, you could even transform lead into gold! Only, the yield is so small and the effort so great that this would not be a worthwhile source of profit. With every transformation between elements (also called *transmutation*), or between isotopes of the same element, the composition of the nucleus in protons and neutrons changes.

Nuclear reactions are described by equations that are very similar to chemical equations. However, they differ from them in that the elements can change, whereas in chemical processes they always remain the same. In nuclear physics processes, however, the sum of the nuclear charge numbers (lower left) on both sides of the equation remains the same, because charge is a conserved quantity. Nowhere in the universe, according to the current state of physical knowledge, is charge generated from nothing or lost. The same applies to mass, which is why also the sum of the mass numbers (upper left) on both sides of the equation always remains the same. A typical nuclear reaction, such as that which takes place in the hot center of the sun, looks like this:

$$ {}_{1}^{1}\mathrm{H} + {}_{1}^{1}\mathrm{H} \rightarrow {}_{1}^{2}\mathrm{H} + {}_{1}^{0}\mathrm{p}^{+} \tag{2.1} $$

This reaction is the first stage in the simplest and most dominant fusion process in the sun (the so-called *hydrogen burning*), through which the sun generates energy. In this process, a heavy hydrogen nucleus (deuterium) and a positron are produced from two light hydrogen nuclei (protium). This is possible because one of the protons in protium transforms into a neutron and a positron.

The positron ($_{1}^{0}p^{+}$) is the antiparticle of the electron, i.e. it has exactly the same mass, but it is positively and not negatively charged. Electrons on the other hand are designated $_{-1}^{0}e^{-}$ or simply e^{-}. As can be seen from its description, it is not a nuclear particle, as its mass number is 0, therefore it is shot out of the atomic nucleus with high energy immediately after its production.

You can see immediately that the emission of the positron is necessary in this reaction, because otherwise the sum of the charge numbers (lower left) on both sides of the equation would not be the same. Additionally, it must not contribute to the mass number on the upper left because the resulting deuterium nucleus with its proton and neutron already balances the two initial protons.

This reaction also produces a neutrino, which has virtually no interaction with other matter. For this reason, neutrinos are left out of all subsequent considerations. They do, however, play an important role in nuclear physics because they have angular momentum and are responsible for the conservation of energy, momentum, angular momentum, as well as certain other conservation quantities. Since neutrinos are produced in large quantities in the sun as well as in nuclear reactors, neutrino detectors make it possible to monitor these processes.

Shortly afterwards, the newly created positron annihilates with its antiparticle – viz. with some electron from the hot dense plasma in the interior of the sun – to gamma radiation. The deuterium nucleus then reacts with another protium nucleus to form light helium (He-3), which has two protons and only one neutron:

$$_{1}^{2}H + _{1}^{1}H \rightarrow _{2}^{3}He \tag{2.2}$$

Two light helium nuclei each can react further to form normal helium, which has two protons and two neutrons each; in addition, two light hydrogen nuclei (protons) are released, which can then react further:

$$_{2}^{3}He + _{2}^{3}He \rightarrow _{2}^{4}He + _{1}^{1}H + _{1}^{1}H \tag{2.3}$$

As can be seen, in every nuclear reaction, the charge and mass numbers on each side of the reaction equation have to sum up equally. When taking all steps in this process together, a total of 4 protons are converted to a helium nucleus and two positrons. The overall nuclear reaction equation reads as follows:

$$ {}_1^1H + {}_1^1H + {}_1^1H + {}_1^1H \rightarrow {}_2^4He + {}_1^0p^+ + {}_1^0p^+ \quad (2.4) $$

This fusion process describes the basic energy conversion of the sun and thus the source of all life (Fig. 2.8). The total energy released during this process is about $4 * 10^{-12}$ Joule, i.e. about 4 millionths of a millionth of a Joule per 4 hydrogen nuclei. This doesn't sound like much at first, and for a single proton such a process takes on average about 10 billion years to occur. But considering the gigantic number of hydrogen nuclei in the sun, it becomes clear why our star can shine so brightly for many billions of years. Such processes heat up the interior of the sun to about 15 million degrees Celsius, while the outer visible layers only have about 5,500 degrees Celsius. The hard gamma radiation generated by this process is converted into thermal radiation on its long journey through the inner and outer layers of the Sun. The high kinetic energy of the particles involved is distributed by collisions with neighboring particles and converted into heat.

The energy unit Joule is very practical for technical purposes because it is made up of the basic units kilogram, meter and second. But it is not a good

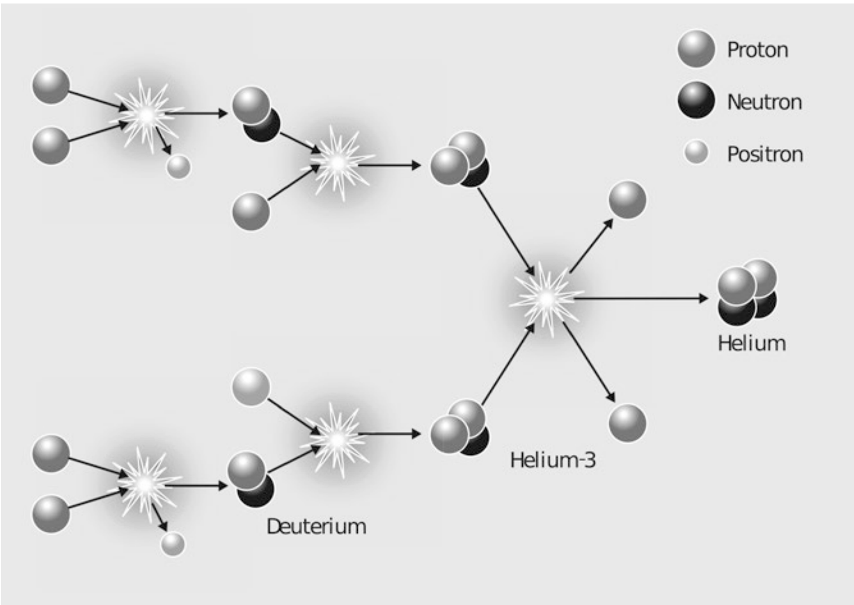

Fig. 2.8 The hydrogen burning in the sun, its basic source of power and origin of all regenerative and fossil energy on earth. Four protons merge to become a helium nucleus. Additionally, two positrons are created that very soon annihilate with electrons to pure energy

choice in nuclear physics. To describe such elementary processes, nuclear physicists have devised another unit of energy that can be converted directly into Joule. This unit is called *electron volt*, or eV for short. 1 eV corresponds to the energy an electron possesses after it has been accelerated by 1 volt – provided that the acceleration takes place in a vacuum so that it does not loose energy by impact to other particles. The hydrogen burning of 4 protons produces about 26 mega-electronvolts, or in short, 26 MeV. "Mega" is a prefix for one million, so the energy yield is 26,000,000 eV.

The difference between chemical and nuclear-physical processes is very clearly visible in the unit electron volt. Chemical processes typically involve energy transfers in the range of a few electron volts or less; nuclear processes typically involve thousands to several million electron volts. In the unit eV, it is therefore easier to see what energies we are dealing with at the atomic level.

During the fission of uranium, even about 200 MeV per atomic nucleus are released. Uranium can split into many different combinations of atomic nuclei; a typical equation looks something like this:

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{139}_{56}\mathrm{Ba} + {}^{94}_{36}\mathrm{Kr} + {}^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n} \tag{2.5} $$

In this process, a uranium-235 nucleus splits into barium and krypton. First it captures a neutron and transforms into the excited, unstable intermediate state uranium-236. Since this intermediate state is very unstable, after an extremely short time span it splits into the daughter nuclei barium and krypton; in addition, 3 neutrons are released which can trigger further nuclear reactions. Such a fission of uranium-235 is the standard reaction in nuclear reactors and in atomic bombs. Nuclear fission can also occur spontaneously in some heavy radioactive nuclei without previous capture of a neutron, but this is quite rare.

The release of the neutrons is explained by the fact that heavy nuclei possess a disproportionately high number of neutrons, as can also be seen in the nuclide map. During fission into lighter nuclei, the daughter nuclei therefore have a significant surplus of neutrons. Some of the surplus neutrons are directly shot out of the atomic nucleus with high energy; these neutrons are available for a fast chain reaction. But a few neutrons are emitted from the daughter nuclei with a short delay. These so-called "delayed neutrons" are crucial for reactor control, as the instantaneously emitted neutrons alone would not make it possible to build a stable and continuously operated reactor, but only atomic bombs or experimental, pulsed reactors. However, a large part of the excess neutrons remains in the daughter nuclei, which therefore have greatly increased neutron content and are therefore unstable and radioactive.

Sooner or later, these excess neutrons are converted into protons and electrons, producing beta radiation. Almost all fission products are therefore strong beta emitters, until they finally decay to stable elements over several conversion steps. The lifetimes and radiotoxicities of the fission products produced during nuclear fission are extremely variable. This is the main reason for the hazardousness of spent nuclear fuel.

Origin and Synthesis of the Elements

In the early days of the universe, when the enormous temperatures after the Big Bang had finally dropped, only the lightest elements were present: mostly hydrogen, some helium and a little bit of lithium. So where do all the other elements come from? What processes generated carbon, oxygen, nitrogen, iron, gold, and all the other elements that our planet and our bodies are made of?

In the beginning, from the lightest elements, the first stars formed. In the nuclear fusion processes deep inside these stars – starting with the burning of hydrogen over further stages – the first heavier elements were produced. In nuclei there are differently stable and energetically more or less favourable constellations – similar to electron shells, but a bit more complicated, as there are two different types of particles and the interactions are much stronger and the involved energies much higher. The most important trend here is that energy is released during fusion from light atomic nuclei up to iron (with 26 protons). Above that element, energy must be expended for fusion. Conversely, during the fission of heavier atomic nuclei beyond the atomic number of iron, energy is released, but not below iron. Iron is therefore the most stable and energetically most favourable substance in nuclear physics.

Stars can draw energy from nuclear fusion until the lighter elements in their centers have fused to iron. However, this only happens in very heavy and older stars, which provide the necessary pressures and temperatures for such a reaction. The reason for this: the heavier the atomic nuclei involved in fusion, the greater the electrical repulsion that must be overcome before the strong nuclear force can provide attraction. Since the strong nuclear force can only act on the extremely small distance between individual protons and neutrons, the atomic nuclei must first approach “touching” distance. The heavier the nuclei involved and the higher their nuclear charge number, the greater the energy required for such an approximation. Normally, the fusion of light hydrogen into helium is the main source of energy for the stars' brightness. However, very heavy and hot stars can draw energy from nuclear fusion in various stages up to iron.

The existence of heavier elements than iron is not due to nuclear fusion. Rather, they are produced by neutron capture. Since neutrons are not electrically charged, they do not experience electrical repulsion. Thus, in contrast to protons, they can interact with heavy atomic nuclei very easily. But the strong nuclear force still acts on them. They are therefore quickly absorbed in matter. The effect on the absorbing atomic nucleus can be very different and depends on the type of atomic nucleus and the stability of the new nucleus that is created.

Neutron capture can produce either a stable isotope or an unstable radioactive isotope, which in turn decays into another stable or radioactive isotope. The half-life of radioactive isotopes can be very short or very long, but there are also so-called excited intermediate states that usually decay extremely quickly, such as in the nuclear fission of uranium-235. Unstable nuclei can decay in different ways. Some decay in only one way, some decay in different ways with certain probabilities. The creation and transformation of elements in such processes is also known as *chemical evolution*, *nucleosynthesis* or *cosmic element synthesis*. The bombardment of certain elements with neutrons in research reactors is used to produce isotopes for medical diagnostics or industrial applications.

There are a number of different processes that are responsible for the creation of the elements. To some part, the formation of heavy elements occurs in slow processes and over a long period of time inside giant stars. In their center, many highly energetic reactions take place over a long time, creating a steady flux of neutrons. This leads step by step to the creation of heavier and heavier elements. But there is a limit to how heavy the products can be: if the resulting nucleus is radioactive and decays before the next neutron can agglomerate, then a dead end is reached and the element synthesis stops here. So this process is responsible for about half of all elements heavier than iron up to lead.

So what is the origin of all the other heavy elements? The answer is cataclysmic: if at the end of their active time massive stars explode in a gigantic supernova, or if neutron stars collide, the astronomical amount of released energy causes innumerable atomic nuclei to shatter, leading to an intensive neutron shower. Neutron stars are incredibly dense leftovers of heavy stars that have already undergone a supernova explosion. They concentrate all the matter of a star inside a sphere of exotic, ultradense matter around 20 kilometers wide, like a giant nucleus. Most of their matter in the outer shells consists of neutrons, but science still wonders what might be inside. When two such stars collide, an immense shower of neutrons is ejected from their edges, while the cores merge to become a black hole. Such a process has for the first time in history been found by gravitational wave observatories and subsequently by normal telescopes in August 2017.

The ejected neutrons are caught by the atomic nuclei in the expanding envelope of these former stars, whereby heavy atomic nuclei are formed in complex processes. The newly synthesized elements are also distributed in the galactic environment, where they can serve as source materials for new stars, planets or smaller bodies.

Since beyond lead all elements become unstable, the production of heavier elements is only possible by an extremely intensive neutron bombardment, especially because some of the superheavy elements with very long-lived isotopes, such as uranium or thorium, are far off in the nuclide chart from lead via elements with very short-lived isotopes. The addition of neutrons must therefore take place very quickly, otherwise the intermediate products would already have decayed again.

Especially the very heavy elements like gold, platinum, bismuth, thorium and uranium stem nearly exclusively from the collision of neutron stars. Supernovae are not even sufficiently violent: only an incredibly intense bombardment with neutrons makes it possible to produce the heaviest of elements. Ultimately, the energy that we get from nuclear fission of uranium is the energy that was stored in the ejected heavy nuclei eons ago when two super massive neutron stars collided to form a black hole. Although such neutron star mergers occur only rarely in a galaxy, this creates such a large amount of heavy elements that it can explain the abundancy of these elements on earth.

The philosophically interesting conclusion of these insights of nuclear physics is that – apart from hydrogen and some helium and lithium – all other elements that occur in the universe, including planet earth and ourselves, consist of the ashes of stars that have long since burned up and from which other celestial bodies have then formed.

Important Applications of Nuclear Physics

Nuclear physics has long since left the stage when it was still pure basic research. Apart from weapons technology and energy production, nuclear physics has led to a whole range of important fields of application, from age determination, structure determination of chemical compounds and material analysis to medical diagnostics and therapy.

For archaeology, the so-called *radiocarbon method* has proven to be an excellent means of age determination. The radioactive carbon isotope C-14 is continuously generated in the atmosphere by particle bombardment of cosmic radiation. The process is such that the high-energy cosmic particles shatter atomic nuclei in the earth's atmosphere, releasing neutrons. This process is called *spallation*. These neutrons can be captured by the nuclei of the nitrogen molecules in air, releasing one proton. In this way, stable nitrogen N-14 becomes unstable carbon C-14. The reaction equation looks like this:

$$ {}^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{p} \tag{2.6} $$

The carbon-14 atom then decays back to nitrogen with a half-life of 5730 years. An electron is also produced:

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}^{-} \tag{2.7} $$

This is beta decay, as it will be discussed in the following chapter on radioactivity. The carbon-14 is normally absorbed with food by all living organisms together with the non-radioactive carbon (which is mostly carbon-12 and some carbon-13). Although this isotope is only a tiny fraction of the stable carbon isotopes C-12 and C-13, it is still easily measurable in a good laboratory. Since C-14 is constantly being produced in the atmosphere, this creates a balance between the rate of production and decay, so that all living organisms carry a certain amount of radioactive C-14 in their tissues. Once an organism – whether animal or plant – has died, it no longer absorbs any more carbon. The stable isotopes remain, but the radioactive isotope decays more and more over time. Thus, the remaining C-14 content makes it possible to determine the age of organic material – as long as it is not so old that practically all C-14 has decayed and no meaningful statement can be made about its age. This is the case at about ten times the half-life, i.e. after about 60,000 years. For older material, other trickier methods have to be employed.

In addition to the radiocarbon method, there are also other types of radioactive atoms (or *radionuclides*) that can be used to determine age, some of which date back much further into the past. They are mainly used in the geosciences. Some of these methods, like uranium-lead dating, can reach back billions of years to the beginnings of our solar system and measure the time of creation of the first rocks on earth or of ancient asteroids.

An extremely helpful and high-resolution instrument for such measurements is the mass spectrometer. It uses the mass difference of different isotopes of the same element and achieves an extremely sensitive and exact resolution when detecting and separating different isotopes. Once filling a whole room, these devices have now been miniaturized to such an extent that they are now even used on Mars rovers to determine the element composition on our neighbor planet. They are extremely sensitive. Their fields of application range from astrophysics to archaeology to forensics; however, they work with such small amounts of material that they are not suitable for the large-scale enrichment of isotopes.

Nuclear physics methods also play an important role in chemical structure determination. Since chemical processes are completely independent of the isotope of the element involved (with very few exotic exceptions), certain physical parameters can be changed by substituting certain atoms with other isotopes. This changes the masses or certain magnetic properties and thus the vibrational spectra of the molecules involved, allowing certain structural properties to be resolved spectroscopically. Nuclear-physical analysis methods are also used in materials science to detect structural damages or alterations.

Perhaps the most important application of nuclear physics is in modern medicine. A particularly non-invasive form in diagnostics is magnetic resonance imaging (MRI), of which there exist several variants. Here the magnetic moment of atomic nuclei is measured, which allows high-resolution three-dimensional images of the interior of the body. Such images and X-ray screening can often be enhanced by nuclear medical contrast agents, which show certain features of the body. Scintigraphy and positron emission tomography are also widely used for diagnostics. For these two imaging methods, a small amount of a radiopharmaceutical (a radioactive pharmaceutical) is injected into the body, where it binds to specific tissues. The radioactive decay can be measured from the outside, creating images of organic structures and processes.

On the therapeutic side, nuclear medical therapies have established themselves as an effective weapon against cancer. The harmful effect of radioactive radiation, which is responsible for radiation damage, is directed against the tumor tissue to damage and destroy it. This radiation can be applied from outside of the body or by the application of radionuclides to the tumor. Research is also currently underway to develop special forms of radiation that place even less stress on the surrounding healthy tissue and promise greater healing success.

3

Radioactivity – The Physics and Biology

There are several types of *radioactive radiation*. Humans have no sensory organ to detect these, so we have to use measuring instruments instead. What all types of radioactive radiation have in common is that they occur artificially as well as naturally, and additionally, they have a harmful, ionising effect on organic tissue. This is why we also speak of *ionising radiation*. While the term "ionising radiation" is scientifically more precise, "radioactive radiation" is also commonly used.

Alpha, Beta and Gamma Radiation

The particles of electromagnetic radiation are called *photons*. Visible light, radio waves or infrared radiation also belong to electromagnetic radiation (see Fig. 3.1) but are biologically harmless due to their low energy. However, as the energy increases, electromagnetic radiation becomes increasingly dangerous. Beyond the optical spectrum there is ultraviolet (UV) radiation, which is responsible for skin aging and can increase the risk of skin cancer when exposed to high levels of radiation. After UV radiation, X-rays begin, with which – depending on their intensity – the body or even entire containers can be screened. Even stronger and more energetic than X-rays is *gamma radiation*, which is released during radioactive processes. Gamma radiation is the most penetrating of all standard radiation types. In air, it can travel up to several hundred meters. It can only be reliably shielded by meter-thick concrete walls or thick lead blocks. The heavy element lead has excellent radiation

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_3

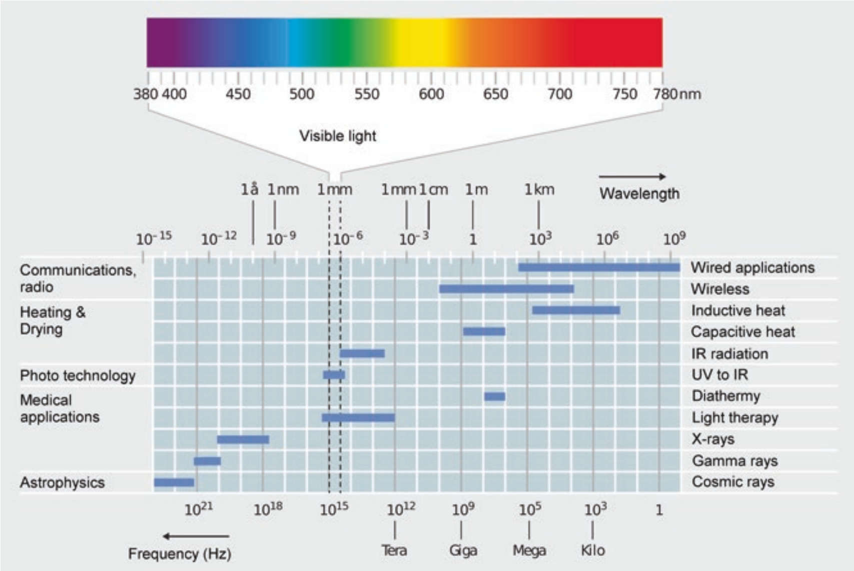

Fig. 3.1 The spectrum of electromagnetic waves with possible applications, roughly structured by production and use. The visible light makes up only a very small frequency and wavelength range. Gamma radiation is extremely energetic and particularly penetrating and therefore very dangerous

shielding properties; it is the material of choice in all laboratories worldwide, as well as for X-ray examinations.

The two other main types of radioactive radiation are alpha and beta radiation. Both consist of fast, charged particles.

Alpha radiation consists of helium nuclei, i.e. particles with 2 protons and 2 neutrons. Unlike gamma radiation, it loses its energy over a very short distance, therefore it can be completely shielded by a sheet of paper. This is because the heavy helium nuclei interact so strongly with matter that they are slowed down extremely quickly.

Beta radiation consists of electrons or positrons (the positively charged but equally heavy sister particles of the electrons). Beta radiation is several times more penetrating than alpha radiation. It can penetrate matter superficially, but can already be reliably shielded by a thin aluminium sheet. If negatively charged electrons are released by beta radiation, we speak briefly of beta-minus radiation (β^-), while positively charged positrons are called beta-plus radiation (β^+) (Fig. 3.2).

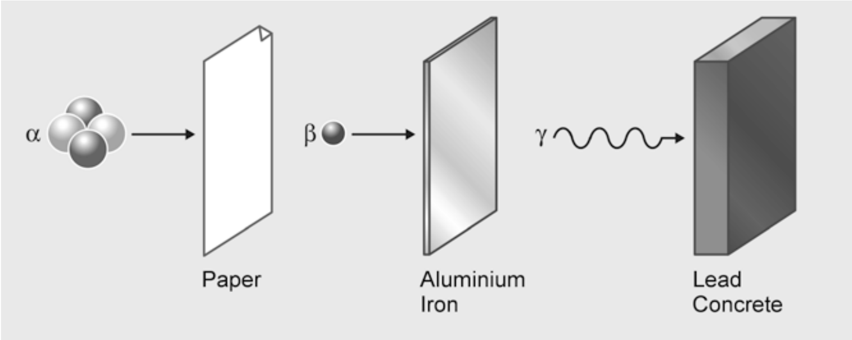

Fig. 3.2 Shielding different types of radiation. Alpha radiation is already reliably shielded by a sheet of paper, beta radiation by a thin aluminium sheet. High-energy gamma radiation can only be reliably shielded by concrete walls several meters thick. The range in air is a few centimeters for alpha rays, a few meters for beta rays and up to several hundred meters for gamma rays

All these types of radioactive radiation can break chemical bonds and thus cause damage in cells. This is done by excitation or ionisation, i.e. by the radioactive rays causing electrons to be excited or knocked out of the shells of atoms, thereby triggering biochemical processes that can lead to cell dysfunctions or, if the DNA is affected, to mutations. The energy of alpha, beta and gamma rays can also vary strongly between different isotopes. Some radionuclides, like tritium, emit only rather soft beta rays and no gamma rays at all. Others, like cobalt-60, are extremely strong gamma emitters. These differences are ultimately rooted in the complex nuclear shell structure of different isotopes, which – similar to electron shells – possess different energy levels with corresponding transitions between them.

There is also *neutron radiation*, i.e. free neutrons which, although not directly ionising, can have a double effect. First, they can collide with nuclei, pushing them to high energy so that these in turn have an ionising effect. Second, neutrons can be trapped by atomic nuclei. Since neutrons have no electrical charge, they are very penetrating, more or less like gamma rays. Like light, gamma rays always travel at the speed of light, but neutrons are slowed down when they come into contact with matter. When they are slow enough, they are more and more likely to be captured by atomic nuclei. Free neutrons that are not bound in atomic nuclei are unstable and decay into a proton and an electron with a half-life of about 15 minutes, but this is practically never observed, since neutrons usually enter into a nuclear reaction long before that. Intensive neutron radiation is mainly found in places where nuclear reactions take place, as inside atomic reactors or in nuclear explosions – places where people are better off not being around anyway. For that reason, neutron shielding does play an important role in reactor design. For radiation protection when handling radioactive material, the other types of radiation play a much greater role.

The capture of neutrons can produce radioactive isotopes depending on the source nucleus. This process is called *activation*. It turns stable isotopes into radioactive material. An example of such activation is the above-mentioned production of radioactive carbon C-14 from stable nitrogen N-14. In nuclear reactors, the strong neutron flux also activates materials, such as pressure vessels, pipes and filters that are irradiated by the neutrons produced in the reactor. These materials also become radioactive waste, although they are much less problematic than the nuclear fuels themselves. For example, the stable iron Fe-58 can be activated in the reactor pressure vessel:

$$^{58}_{26}\mathrm{Fe} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{59}_{26}\mathrm{Fe} \tag{3.1}$$

The radioactive Fe-59 then decays via beta-minus decay with a half-life of around 44 days into stable cobalt-59:

$$^{59}_{26}\mathrm{Fe} \rightarrow {}^{59}_{27}\mathrm{Co} + {}^{0}_{-1}\mathrm{e}^{-} \tag{3.2}$$

Such reactions are responsible for the fact that the inner areas of nuclear reactors have to decay for several years after the end of operation before they can be dismantled. If cobalt-59 takes up another neutron, it becomes the hard gamma emitter cobalt-60, which is widely used in radiation therapy, but which also contributes to the high levels of radiation in freshly shut down nuclear facilities.

Material transformations in radioactive processes are always accompanied by the emission or capture of certain particles. Nuclear transformation processes, in which an atomic nucleus is transformed into another element, are therefore always associated with alpha and beta radiation, or with fusion or fission. During such a transformation, in many cases the resulting daughter nucleus is in an excited state, which can be imagined as a strong vibration. This excited state changes into the ground state by emitting gamma radiation. Gamma radiation is therefore usually a side effect of alpha or beta radiation. In some decays, like that of tritium, no gamma rays are emitted. The small excess energy of the reaction after the expulsion of the alpha or beta particle is solely taken up by the kickback of the nucleus. But gamma emission also

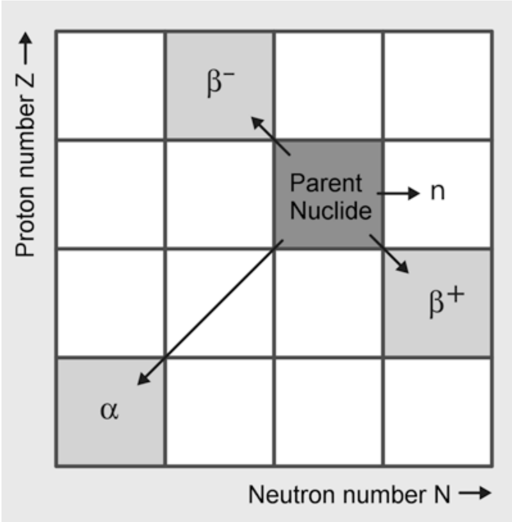

Fig. 3.3 The different types of radioactive decay as well as neutron capture (n) and the resulting daughter nuclei, with their effects in the nuclide chart (compare Fig. 2.7)

occurs when an electron and a positron destroy each other and radiate to pure energy. The energy of radioactive radiation is approximately in the range of 0.1 MeV to 10 MeV for all types of radiation – around a million times above chemical reactions, as usual in nuclear physics. Thus, a single particle of radiation can correspondingly cause many chemical reactions, which in turn might damage a living cell or degrade material properties.

Apart from alpha, beta, gamma and neutron radiation, there are also other types of radioactive radiation, but they are not relevant to the nuclear energy complex. Cosmic radiation, for example, consists mainly of fast protons, and partly also of heavy nuclei. These particles are also used in particle accelerators. Heavy nuclei are the heavy brothers of alpha radiation, so to speak, which consists of helium nuclei. It is now technically possible to accelerate much heavier atomic nuclei such as gold or lead; these nuclei are used in certain areas of basic research. With the help of so-called heavy ion colliders, it is possible to clarify the structure of matter and to recreate the extreme material conditions in the first moments after the Big Bang.

A very promising application of this research is in cancer therapy. Because heavier particles lose more energy over a shorter space, the range in which heavy

Fig. 3.4 Collection of historical radiation protection signs at the Berlin research reactor

nuclei transfer their energy to biological tissue can be adjusted much better than with lighter particles. Massless photons (usually X-rays or gamma radiation) are the most penetrating rays in radiation therapy. Cancer therapy with protons or even with heavy nuclei like carbon, on the other hand, can target the tumor tissue very specifically and be gentler on surrounding tissue.

In principle, all fast, high-energy particles can be called radioactive radiation. However, since, apart from the particles mentioned above, all other elementary particles known to modern particle physics are unstable and decay within an extremely short time, they are only relevant in the laboratory or in cosmic radiation.

On the earth's surface, muons, the much heavier and unstable brothers of electrons, can be detected. They are generated during collision processes of cosmic radiation with the upper layers of the atmosphere and can be detected under certain conditions even far below the earth's surface. Muons are extremely penetrating – even more than gamma rays – and make certain highly sensitive experiments on the earth's surface impossible. This is why some nuclear and particle physics laboratories are located deep below the earth's surface, for example in the tunnels of disused mines. Thanks to their highly penetrating properties, muons have also been used to search for unknown rooms in the Egyptian pyramids.

Very popular for radiation shielding of ultra-sensitive experiments in underground laboratories is old lead from medieval church towers, which accrues during repair work. Lead from freshly extracted ore is still contaminated with various radioactive isotopes from the ground. Thus, this lead still has a low intrinsic radioactivity despite its strong radiation shielding properties. After centuries on the roof of old buildings, however, this radioactivity has almost completely decayed, which is why it then provides unmatched shielding.

Decay Series

By looking at the nuclide map, the different types of radiation and their effects on the nuclei become easily visible. The emission of an alpha particle reduces the number of protons and neutrons in the atomic nucleus by 2 each, so that in the nuclide map there is a jump of 2 to the lower left. With beta-minus radiation, a neutron is converted into a proton and an electron, which corresponds to a step of 1 to the left and upwards. In the case of beta-plus radiation, it is correspondingly the other way round, one step to the bottom right. Neutron capture pushes the nucleus one step to the right, as shown in Fig. 3.3.

If the resulting daughter nucleus is itself radioactive, it decays further until a stable isotope is finally reached. Thus, uranium-238, which is present in very low concentration everywhere in the earth's crust, finally decays via a whole series of intermediate radioactive isotopes to the stable lead isotope Pb-206. An important link in this chain is the radioactive noble gas radon, which is an important source of natural radioactivity and accumulates especially in poorly ventilated rooms; see Fig. 3.5.

Biological Effects of Radioactive Radiation

Radioactive radiation poses different kinds of danger to organisms according to its different ranges and energy transfer rates. *Alpha radiation* is already shielded by the uppermost layer of the skin, the dead cells of the epidermis. External alpha radiation is therefore not dangerous. However, it becomes very dangerous when the radiating particles are inhaled or absorbed into the body with food or through skin wounds. Because alpha emitters "pump" all their energy into a very small area of space, the damage in this area is therefore very severe and can overpower the body's healing mechanisms, which is why their

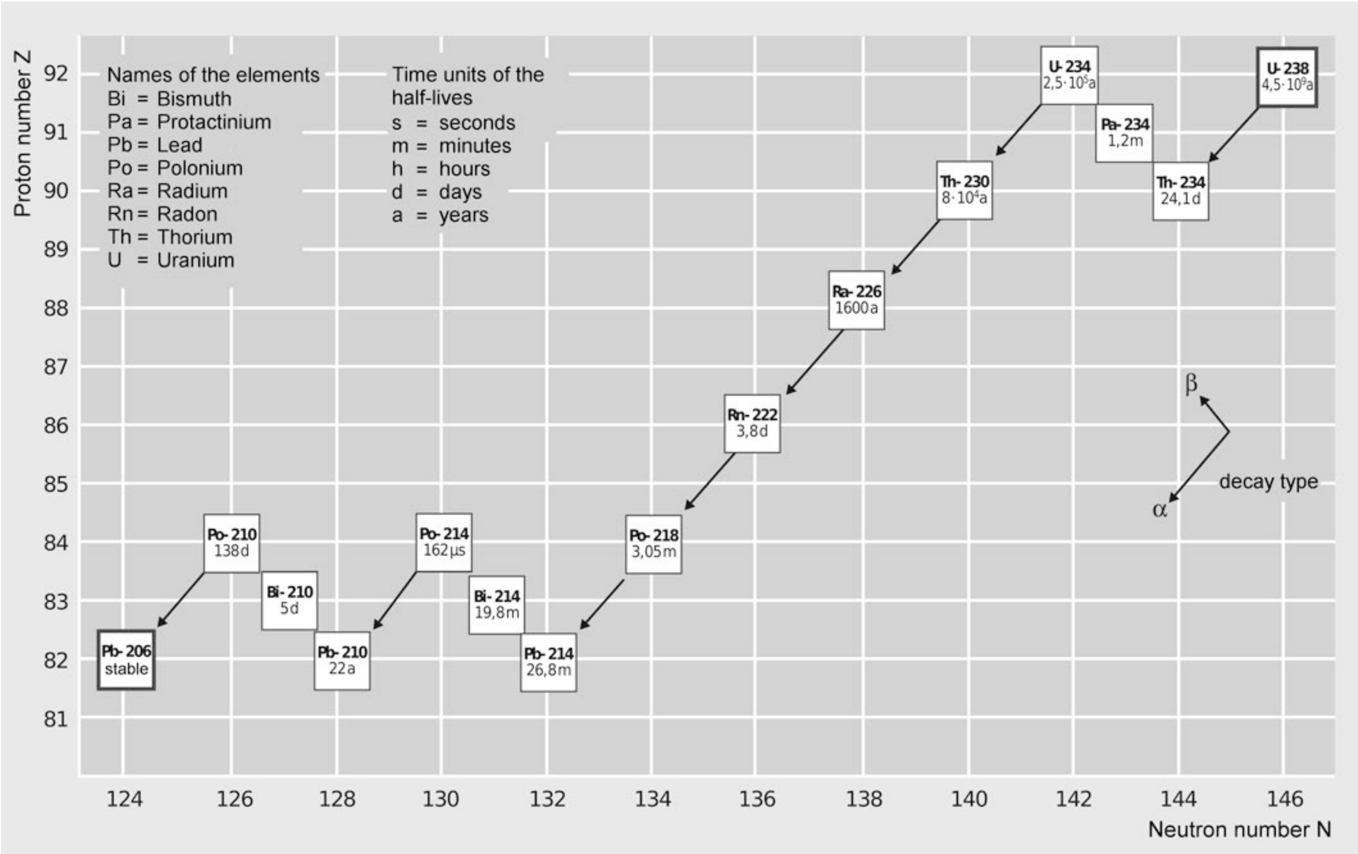

Fig. 3.5 The decay series from uranium-238 via radium-226 and radon-222 to the stable lead-206. The radioactive noble gas radon-222 poses a great danger, especially in uranium mines. This decay series is also called the uranium-radium decay series

biological hazard is weighted 20 times more heavily than that of beta or gamma radiation, for the same amount of energy emitted.

External *beta radiation* does not penetrate deep enough into the body to damage the internal organs. It can, however, lead to burns and radiation damage of the upper layers of skin. If the eye is affected, this can result in clouding of the lens. When absorbed into the body, beta emitters damage a larger area of the body than alpha emitters, but not as intensively as alpha radiation.

Gamma radiation penetrates matter like X-rays, of which it is the stronger version. It therefore makes no difference whether it comes from outside or inside the body. Since it is usually a companion of alpha or beta radiation, it is also important to avoid absorbing the corresponding substances as much as possible.

Radiation damage of any kind is more severe the longer the exposure lasts and the more intense it is. Distance and time thus are decisive factors in radiation protection. The further away you are from a radioactive source, the less radiation hits you and the more attenuated it already is. The duration of exposure in turn is directly correlated with the intensity of radiation damage. This applies to both external radiation and internally absorbed substances. The body excretes some substances much faster than others; this can be supported by certain drugs.

The human body has a number of repair mechanisms to mend radiation damage. In evolution, organisms always had to deal with a certain amount of natural radioactivity and unwanted chemical reactions. Although there is no known lower limit below which radiation is considered completely harmless, the human body can deal very well with radiation that does not strongly exceed the range of natural radioactivity. However, only statistical statements are possible here, as it can never be proven whether, for example, cancer has been caused by harmful radiation, genetic processes, environmental toxins or a combination of all these factors. It is generally not possible to determine the cause of a tumour.

There are different measurement units for radioactive radiation. The number of radioactive decays per second is called *activity* and is measured in the unit *Becquerel*, named after Antoine Henri Becquerel, the French Nobel Prize winner in physics and co-discoverer of radioactivity. For example, natural potassium contains an average of 0.0012% radioactive potassium-40, whose half-life is 1.25 billion years. Accordingly, in 1 kilogram of potassium nearly 32,000 potassium-40 atoms decay per second. 1 kilogram of potassium therefore has an activity of just under 32,000 becquerel.

However, the pure activity tells little about the biological effects of radiation. This depends on which type of radiation hits which body organs and

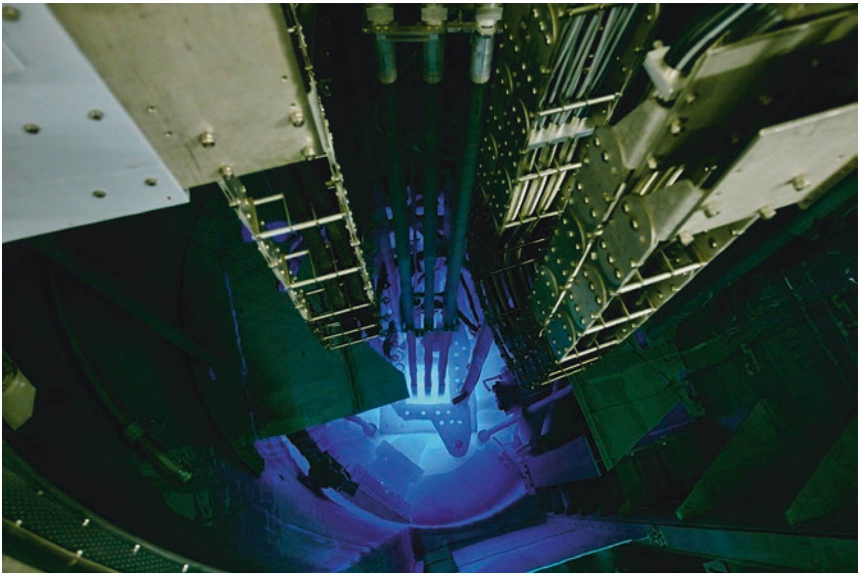

Fig. 3.6 Research reactor BER II in Berlin. View into the reactor pool during operation with strong Cherenkov radiation. Several meters of water shield all radioactive radiation well enough to enable looking down at the nuclear reaction without any risk

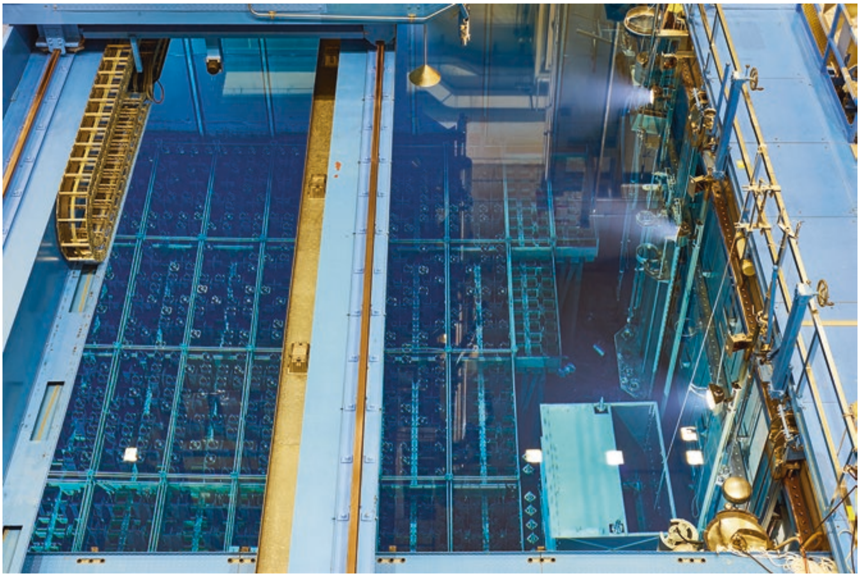

Fig. 3.7 Spent fuel pool at the Krümmel nuclear power plant. The fuel elements are under several meters of water to provide cooling and radiation protection

how much radiation energy it deposits there. The activity is therefore first used to determine the *absorbed dose*, which describes the energy transfer to the tissue. Its unit is *Gray*, in honour of the British physicist and founder of radiation biology Louis Harold Gray.

The biological effect is described by the so-called *equivalent dose*. Its unit of measurement is *Sievert*, named after the Swedish physicist and radiation protection pioneer Rolf Maximilian Sievert. The equivalent dose already takes into account the different interactions of the different types of radiation and the different sensitivities of the individual types of tissue to radioactive radiation. For example, bone marrow and gonads are much more vulnerable than the bone surface or the skin.

The equivalent dose is the globally recognized measure of the radiation exposure of organisms. It also takes into account the fact that alpha radiation can cause particularly severe and difficult to repair tissue damage. Depending on whether a radioactive substance was inhaled or, for example, ingested with food, dose conversion factors can be used to calculate radiation exposure.

The step from the physical units Becquerel and Gray to the medical-radiological unit Sievert is thus based (1) on how many radioactive decays take place in which time, (2) what amount of energy this introduces into a tissue by which type of ionizing radiation and (3) how receptive the different types of tissue are for radiation damage. For example, the consumption of 200 grams of slightly contaminated mushrooms, which have an activity of 4000 becquerel of the radionuclide caesium-137, leads to a beta-ray exposure in the body of 0.01 millisievert (mSv), i.e. 0.000 01 Sv. This is way below normal annual environmental radiation levels. So anyone who does not constantly eat such contaminated mushrooms will not increase his or her dose of natural radioactivity in any significant way.

Natural and Artificial Radiation Exposure

The total radiation exposure is composed of the *natural ambient radiation* and the civilizational or *artificial radiation*. The average natural radiation exposure varies somewhat globally, but usually lies between 1.5 and 3.5 mSv (millisievert, i.e. thousandth of a sievert) per year. It is made up of various sources. The radioactive noble gas *radon* accounts for the largest share of about half of this. It is formed as a decay product of heavy elements in rock and masonry and then escapes as an inert noble gas. Depending on how rich in radon-producing elements the rocks in a region are, this gas can accumulate significantly in poorly ventilated rooms. Thus, regular ventilation is recommended to avoid higher radon concentrations in living spaces, but also in cellars and especially in mines. The concentration of radon depends on the predominant rock layers in the soil and can vary greatly from region to region. In the lowlands, for example, it is usually lower than in some hilly regions or mountain ranges.

Radon is considered as one of the most underestimated dangers in everyday life. A major European study estimates that this radioactive noble gas causes a significant proportion of lung cancer cases. Smoking is the biggest risk factor and is responsible for 80 to 90 percent of lung cancer cases. However, the second largest risk factor is indoor radon, which is responsible for almost ten percent of lung cancer cases and for about two percent of all cancer deaths in Europe – and probably for similar effects in other parts of the world. Depending on local conditions, radon prevention may require structural measures, such as sealing off parts of buildings that come into contact with the ground, or at least regular natural or mechanical ventilation should be provided in particularly affected spaces.

Other sources of natural ionising radiation are radiation from the soil and cosmic radiation in high altitude. *Terrestrial radiation* comes from the decay products of the long-lived isotopes of uranium and thorium, which are found in very low concentrations everywhere in the earth's crust. Radon is just one

Fig. 3.8 Control room of block 3 of the Greifswald nuclear power plant, Soviet WWR440 type

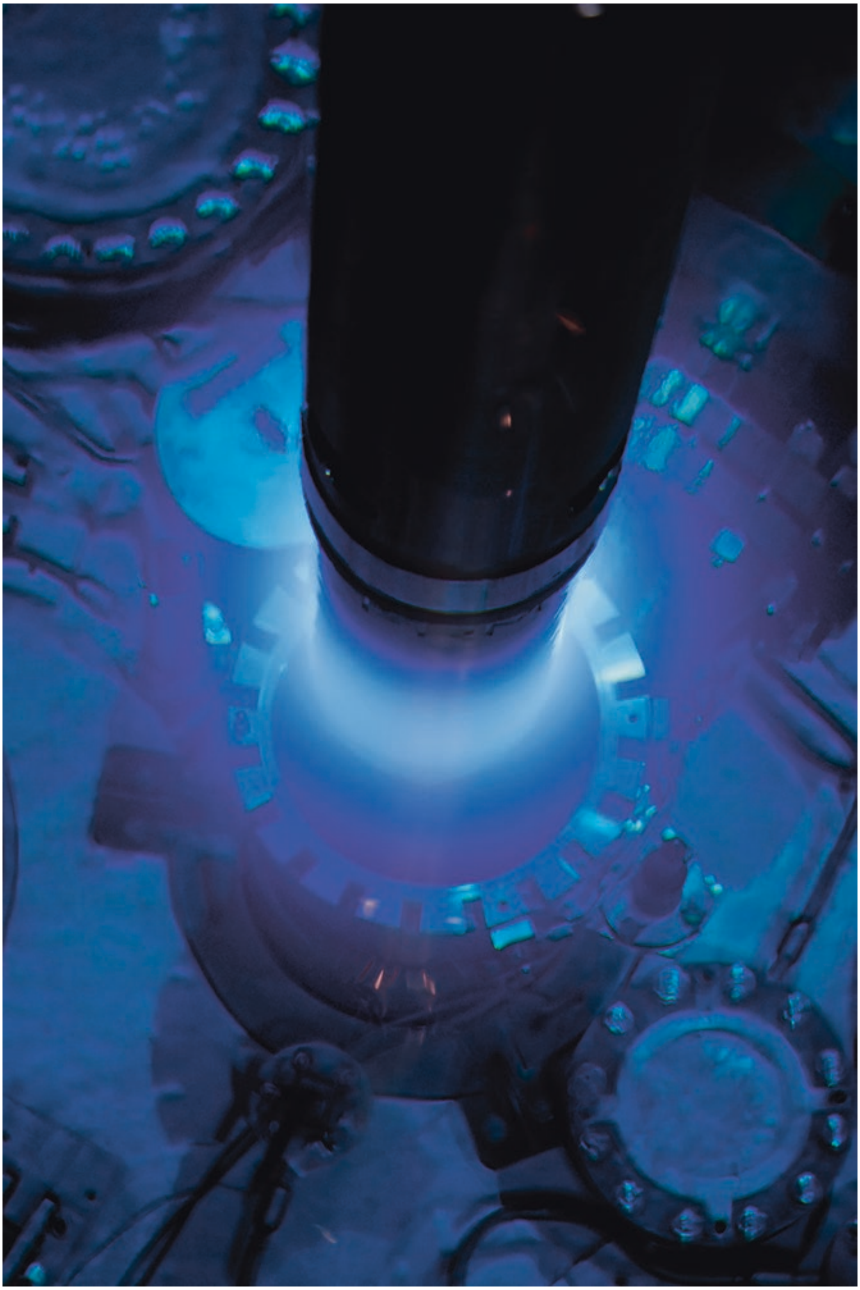

Fig. 3.9 Change of the sole compact fuel element at the research reactor FRM 2 in Garching. The freshly burnt nuclear fuel creates shining blue Cherenkov radiation. This reactor type is moderated by heavy water and cooled by light water

of the products resulting from these decays. In certain regions of India, Iran and Brazil, the concentration of uranium in the soil is so high that the natural radiation exposure is more than ten times higher than usual. In some places it is even up to 40 times higher and exceeds many times the critical values to which employees in nuclear facilities in many countries may be exposed. (The limit value in the UK and Germany is a maximum of 20 millisievert additional radiation exposure per year; internationally; sometimes up to 100 mSv per year are allowed for employees working with radiation.) So far, however, little can be concluded about the danger of this increased radiation, since life expectancy in these regions is not particularly high for other reasons as well.

Cosmic radiation is weak on the ground because our planet's atmosphere filters it quite efficiently. But it increases more and more with altitude. In the thin upper layers of the atmosphere in which cruise planes operate, the cosmic radiation is already much stronger than on the ground. At an altitude of 10 kilometers it is about 100 times stronger than on the earth's surface. Flying personnel are therefore exposed to higher radiation levels than their colleagues on the ground. Staff on long-haul aircraft in particular can easily double their yearly overall natural radiation exposure. The effect is stronger during flights over the polar caps than at the equator, because the earth's magnetic field lines converge above the poles, pulling the particles of the solar wind towards earth, and also because the atmosphere there is less extended due to the low temperatures. Thus, the shielding from cosmic radiation is weaker. However, the doses achieved in this way do not pose a great danger, as can be seen from the fact that flying personnel do not suffer a noticeable increase in cancer incidence.

Apart from these external sources of radiation, the human body itself is also a source of *internal radiation*, since the metabolism cannot distinguish between the radioactive and stable isotopes of the elements and therefore also utilises radioactive substances. These natural sources of radiation include various radioactive isotopes, especially potassium-40, but also carbon-14. In bananas, potassium-40 occurs in such high concentrations that radiation epidemiologists – with a slight twinkle in the eye – use this tropical fruit as a unit for the smallest quantum of action in their discipline. Eating one banana corresponds to a dose of around 0.0001 mSv. In the human body, 9000 radioactive nuclei decay every second on average. So each human being radiates on average with about 9000 becquerel, with significant differences depending on where they live and their eating habits.

Artificial radiation exposure is caused for the most part by medical applications. Computer tomographies account for the majority of this, while modern X-ray examinations no longer produce a significant radiation exposure.

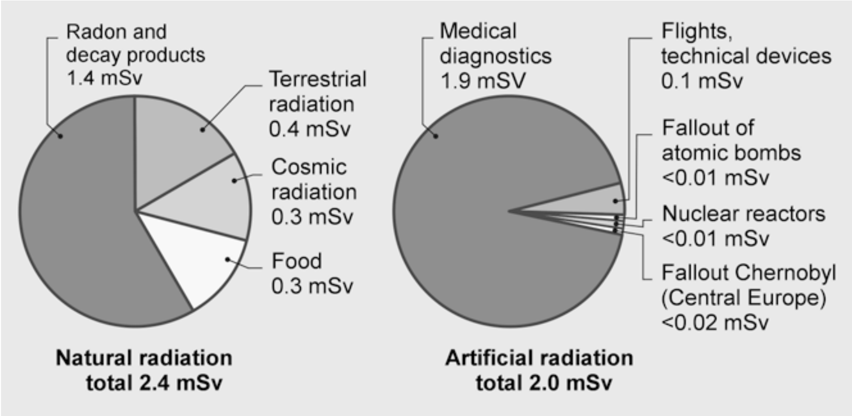

Fig. 3.10 Annual natural and artificial radiation exposure on a European average. With some regional deviations, similar values occur worldwide

Artificial radiation exposure is on average similar to natural radiation, so that a person absorbs a total amount of about 4 mSv of radioactive radiation per year. This is normally completely within the bounds of what the body's own repair mechanisms can cope with. However, it cannot be ruled out that even such low levels of radiation may minimally increase the probability of cancer.

X-ray exposure, for instance, varies greatly in the population and depends on the type of examinations. A dental examination only leads to a load of 0.01 mSv, a mammography up to 0.6 mSv, a computer tomography of the chest up to 7 mSv and an examination of the intestine up to 18 mSv. In medical radiation therapy, local cumulative doses of 20 to 80 Grays over several therapy sessions are usually used to kill cancer cells. These would be absolutely fatal as whole-body doses. The art of radiation medicine is to focus as much radiation as necessary on the tumor, while exposing the surrounding tissue as little as possible. This is possible because cancer cells respond more strongly to radioactive radiation than healthy tissue.

Other sources of artificial radiation exposure include the radioactive fallout from the Chernobyl reactor disaster and the numerous above-ground nuclear bomb tests of the 1950s and 1960s, as well as radioactive particles released by nuclear and coal-fired power plants. On average, however, these contributions are significantly lower than the medical and natural radiation doses. In some parts of Western Europe, the radiation exposure from the Chernobyl fallout reached an initial annual dose of 1 mSv and thus came close to the normal natural radiation exposure, but this has decreased significantly to date.

With the exception of special cases, nowadays technical radiation sources are extremely weak due to very strict legal limits. For example, there has been an accumulation of cancer cases among military radar technicians, probably due to poorly shielded hard X-rays from radar generating equipment. More common sources, such as weak alpha emitters in smoke detectors, have negligible effects unless they are eaten in larger quantities.

Even old cathode-ray tube televisions produce some radiation, which consists of very weak, very low energy X-rays. 1000 hours in a television armchair at a distance of 2 to 3 meters corresponds to just 0.00006 mSv. However, the crate of beer at a distance of 1 meter from the television armchair generates about three times as much radiation; this comes from the potassium and uranium in the bottle glass. These elements are also found in window glass and all other types of glass.

Another factor that has so far received little attention in the public is radioactivity in cigarette smoke. Tobacco plants concentrate certain radioactive decay products of the uranium in the soil. It is also suspected that fertilizers with high phosphate content could play a reinforcing role. Such fertilisers have been in use since the 1960s and have the potential to bind uranium and its decay products. The dangerous isotopes here are mostly polonium-210 and also lead-210. Polonium-210 is a hard alpha-emitter and deadly in small amounts of micrograms. A heavy smoker consuming one packet a day or more can increase his or her natural radiation dose several times over, equivalent to up to several chest X-rays a year – and in certain places where tar collects, even up to 200 X-ray radiographs.

However, it is difficult to analyse how many medical problems – especially lung cancer – are caused by radioactive particles. Firstly, multifactorial effects are difficult to break down between chemically toxic and radiotoxic causes. And secondly, too little is generally known about the cancer risk of low-dose continuous exposure to radiation. It is certain that the lung cancer risk of smokers, which is about 20 times higher than normal, is largely due to chemically toxic factors. According to some studies, however, a good ten percent of the lung cancer risk from smoking could be caused by radioactive substances.

One might therefore think that even the indication of the specific radiotoxicity of the respective tobacco variety would not be a bad indicator for the toxicity of tobacco products. This would be a motivation for the tobacco industry to look for radiologically more favourable cultivation areas and fertilisers – even if the packaging note “poor in polonium” may not sound too sales-promoting at present. Tobacco companies have probably been trying in vain for some time to reduce the polonium content in cigarettes. But neither genetic modifications nor special filters seem to have achieved much.

The most famous victim of polonium-210 was the Russian ex-spy Alexander Litvinenko, who was killed in London in 2006 after having defected to the British secret service. He was poisoned by a cup of tea containing a lethal dose of polonium-210. While tiny amounts of this highly potent poison in the microgram range are sufficient for such a murder, such quantities cannot be obtained from cigarettes.

Polonium-210 can be produced in research reactors or particle accelerators by shooting neutrons or protons at bismuth atomic nuclei. In this way, only around 100 grams of this extremely expensive and highly controlled substance are produced worldwide each year, which are used in technical ionisation sources, for example. Due to its short half-life of only 138 days, this material can only be stored for a limited time.

Radiation Damage

Radioactive radiation causes various types of damage to organic tissues. This damage is caused either by direct damage to the cell nucleus or other cell components by the radiation or by the generation of free radicals, which among other substances can form the strong cell poison hydrogen peroxide. The cell damage can appear in many different forms, from damage to various cell organelles to double-strand breaks of the DNA, which are particularly difficult to repair and can lead to mutations or cell death.

Depending on the type of damage, one divides between *somatic damage*, which affects the individual, and heritable *genetic damage*, which can occur in the offspring if it damages the germ cells. The somatic damage is in turn divided into *early damage* and *late effects*; the latter can be either malignant (cancer or even metastasizing cancer) or non-malignant.

Heavy radiation can cause massive damage to body cells, which is accompanied by loss of function or death of these cells. Such *early damage* only occurs at higher doses, but inevitably, especially if these doses are absorbed in a short period of time. If the dose is spread over a longer period of time, the body's repair mechanisms can already repair some of the damage. After a short-time exposure of about half a sievert, i.e. about 250 times the annual natural radiation exposure, the symptoms of radiation sickness begin, which are indicated by reddening of the skin or burns, nausea, changes in the blood count, hair loss and an increased risk of infection. The lighter forms are also called "radiation hangover." The "acute radiation sickness" begins above one sievert. Above

Table 3.1 Radiation sickness and its consequences

Radiation dose	Effects and symptoms
1 to 5 mSv (0.001 to 0.005 Sv)	Average annual radioactive dose
from 100 mSv (0.1 Sv)	Increased cancer risk statistically demonstrable
0,5 to 1 Sv	"Radiation hangover": headaches, nausea, fatigue and increased risk of infection
1 to 2 Sv	Acute radiation sickness: 10% deaths after 30 days, moderate nausea, vomiting, delayed wound healing, fatigue, loss of white blood cells, greatly increased risk of infection
2 to 3 Sv	35% deaths after 30 days: severe nausea, frequent vomiting, massive loss of white blood cells, severely increased risk of infection, hair loss all over the body. Recovery takes up to several months
3 to 4 Sv	50% deaths after 30 days: additional symptoms diarrhoea, uncontrolled bleeding in the mouth, under the skin and in the kidneys
4 to 6 Sv	Up to 90% deaths after 30 days: symptoms as above, but strengthened; infections and bleeding as causes of death after a few weeks
over 6 Sv	100% deaths after 14 days: after initial symptoms short recovery phase ("walking ghost" phase), then death phase with rapid cell death in the gastrointestinal tract, massive diarrhea, intestinal bleeding and water loss. Febrile delirium, coma and circulatory failure. Extremely high doses lead to death in hours due to massive damage to the central nervous system.

4 sieverts, only 50% of affected persons survive. Beyond 6 sieverts, radiation sickness almost certainly leads to death within a few days or weeks due to internal bleeding and infection. Only few people have survived incidents with higher doses, maybe because of a favourable genetic disposition or because the estimated dose were higher than the actual ones (Table 3.1).

These early effects are also called *deterministic damage*, as they are certain to occur above a certain radiation dose. Compared to other organisms, humans are not particularly resistant to radiation. Hamsters, goldfish and trout tolerate twice to three times as much radiation, bats 30 times as much, wasps 200 times as much. The incredibly radiation-resistant bacterium *Deinococcus radiodurans* can survive the apocalyptic dose of 10,000 sieverts or more, which is why it is the subject of intensive research. Its resistance against ionising radiation stems from its ability to repair DNA defects with extraordinary speed and efficiency. This is an evolutionary byproduct of its ability to cope with extreme environmental conditions. For this reason, this bacterium is not only found in the intestines of humans and on rocks in Antarctica, but also in the cooling water circuit of nuclear reactors, where it has little competition to fear.

Long-term health effects, like increased risk for certain types of cancer, are also called *stochastic damage*, because they do not necessarily occur at a certain dose and can also be caused by low doses. In individual cases, however, they are difficult to distinguish from other non-radiological causes, so only probability statements can be made. No threshold can yet be stated below which radioactivity is completely harmless. This is the point where the various expert opinions differ, because different views on the danger cannot always be clearly decided on the basis of the available statistics. Nor is there a consensus on how much risk one judges as acceptable for a large number of people, including above-average vulnerable groups like children and pregnant woman. To agree on this is always a societal problem, not a problem of experts only.

Long-term health effects include in particular radiation-induced tumours, which in the worst case can also form metastases. They are caused by genetic changes in the body cells. Even without the exposure to radioactive radiation, mutations in the DNA of the cell nucleus occur regularly. Radioactive radiation increases the rate of these mutations. It is important for understanding carcinogenesis that stem cells must undergo several mutations before all cellular protective mechanisms have been switched off and the cell can degenerate into a cancer cell. For this reason, cancer often does not develop until many years after exposure to radiation. Perhaps some mutations have already been triggered by radiation, but it can take years and decades for further mutations to accumulate, which eventually leads to cancer formation. This also means that often there is not just a single cause for cancer, but possibly a multitude of factors (radioactivity, chemical-toxical exposure) with different probabilities.

Long-term effects can also damage the cardiovascular and the immune system. Especially at higher doses, an increase in heart diseases can be seen. Sometimes also higher infection rates or inflammations are reported years after an exposure to radiation. But the scientific results on the immune system effects are still somewhat unclear and inconclusive.

Another possible long-term effect is heritable *genetic damage*, which can be very hazardous. It is caused by irreversible genetic damage to germ cells. This damage is passed on from the affected parent to her or his offspring. Excessively damaged germ cells may die or the affected embryos are often not viable, or a number of defects like malformations may occur. The mechanisms leading to genetic damage are the same as those causing somatic long-term damage, however, they do not affect the DNA of somatic cells but the DNA of germ cells and can lead to hereditary diseases. Again, the radiation-induced amount of mutations is usually small compared to the chemically induced mutations – apart from the absorption of high radiation doses. In the children of the atomic bomb survivors from Hiroshima and Nagasaki, no such effects were visible, even decades later when these people had grown up. Obviously, germ cells possess particularly functional repair systems. For this reason, contrary to some older assumptions, genetic damage fortunately occurs less often than other long-term damages.

It is assumed that a radiation dose of 1 sievert approximately doubles the natural mutation rate from one generation to the next. However, most of the germ cells mutated in this way die, either immediately or as embryos, so that only a small proportion of the mutations can be transferred to the offspring. Temporary sterility occurs in males from 0.15 Sv, in females from 1.5 Sv; permanent sterility begins for both sexes at doses from 4 Sv, which are often already lethal as a whole body dose.

Radiation Risk: Cancer and the Linear No-Threshold Model

For radiation protection purposes, it is assumed by the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) that the cancer risk caused by exposure to radiation increases in a linear way with the dose received. This is statistically well confirmed for higher doses above 100 mSv, but not yet clear for lower doses.

To this day, the most important insights into the harmfulness of radioactive radiation are drawn from the medical lifetime data of the atomic bomb survivors, as this data best meets the epidemiological-statistical requirements of homogeneous population distribution, a large number of well-documented cases over decades and good estimates of the individual radiation dose received.

On the basis of the survivors of the atomic bombing of Hiroshima and Nagasaki, it was also possible to demonstrate that some long-term effects like cancer can occur even up to 60 years after exposure. In addition to carcinogenesis, an increase in cardiovascular diseases has also been observed in these studies. Incidentally, most of the immediate victims of the atomic bombs did not die from radioactive radiation but from the enormous heat and pressure effects of the nuclear explosion, whereas most of the later victims died from radiation-related long-term damage.

Recent scientific evidence suggests that a dose of 0.1 Sv, i.e. 100 mSv (50 times the annual natural radiation exposure), received within a short time, increases the natural cancer risk by approximately 5% in relative terms. There is strong evidence that the risk increases approximately linearly with the dose. Thus, a doubling of the dose also doubles the cancer risk. However, the relative factor of 5% additional cancer risk per 100 mSv or 50% per sievert is not entirely uncontroversial. Due to the fact that human experiments are ethically unfeasible and that the radiation dose received in accidents cannot always be easily estimated, the figures fluctuate to a certain extent.

The linear relationship between dose and cancer risk seems to hold well for values above 100 mSv. But it is still uncertain how well this relationship holds for low doses. The statistics become blurry and it is not exactly clear, if and how well the linear relationship extends to very low doses. This is a major point of dispute between proponents and opponents of nuclear energy, because it is neither proven nor disproven that small amounts of radiation really increase cancer risk. Sometimes, opponents of nuclear energy calculate large numbers of victims from nuclear disasters, because in their analysis they often consider huge areas with a correspondingly high number of inhabitants who receive a very low dose. Multiplying a very large number of people with a small radioactive dose can still lead to a considerable number of cancer cases. But such numbers cannot be proven, even decades later, because many people would have suffered from cancer later in their life anyway.

The statistical problem is this: in industrialized countries, about 40% of the population will develop cancer during their lifetime, and about 20 to 25% will die of cancer. The individual risk depends both on coincidences and on genetic predisposition and lifestyle. Thus, in a population of a million people, a few hundred or even thousand cancer cases more or less will be statistically invisible, because the normal fluctuation of disease rates overshadows such small deviations.

This also means that it is not clear if only doses above a certain minimal dose are dangerous and if our cellular repair mechanisms can eliminate all effects of small radioactive doses. For this reason, in order not to expose people to unnecessary risks and to minimize any possible damage, the International Commission on Radiological Protection has developed the so-called *Linear No Threshold model* (LNT model), which extrapolates the dangerous long-term effects of radiation from the established values at higher doses in a linear way down to zero radiation. If this is true, then there would be no lowest secure level of radiation, not even the normal low level of natural radiation. While the LNT model is certainly very useful for radiation protection, it is difficult to assess to what extent this model is suitable for estimating disease rates after an exposure to small doses of radiation. If the LNT model really describes reality, then even very low levels of radioactivity can still play a part in cancer formation. However, this proportion is so small that it hardly plays any detectable role compared to other mechanisms.

Let us have a deeper look into these statistics with a simple example. In industrialised countries, out of 100 people, about 40 will develop some form of cancer and 20 will die of it. If all these people are exposed to a single dose of 100 mSv in a short period of time, the cancer incidence increases by about 5%. That means that two more persons will develop cancer, of which one case will be fatal. Of course, these considerations are only rough estimates over average effects and the true individual radiation dangers depend on which type of radiation has affected which organ in which way and how medical treatment and natural repair mechanisms can cope with that.

But as a very rough ballpark figure, one can use this rule of thumb: One short-term dose of 100 millisieverts per 100 people leads to 1 death from cancer. This dose corresponds to more than 40 years of natural radiation exposure received in a short time. Of course, regular medical monitoring and early treatment can reduce mortality, but for the sake of simplicity, let us neglect these effects for the following examples.

As the radiation dose of 1 Sv is 10 times stronger than 100 mSv, the risk of cancer increases accordingly, so that not just one additional person but 10 people out of 100 will die of cancer. If the overall mortality due to cancer increases from the natural 20% to 30% as a result of a radiation exposure with 1 sievert, then it can also be said that 10% of the people exposed to radiation have died of radiation-related cancer. But due to the probabilistic nature of cancer formation, it is impossible to say which 10 of these 30 people have died of radiation-related cancer and which would have developed cancer even without radiation. There are ongoing research projects which are trying to find specific genetic markers that show if cancer has been provoked by radiation, but such markers are difficult to find and the outcome is still uncertain. There are, however, statistical tools which can help to estimate if a cancer has been caused been by exposure to radiation. In the US, the application IREP, and in Germany, a software package called ProZES can be used to estimate the corresponding cancer probabilites which are relevant for instance for compensation in work-related radiation exposure.

If the intake of a certain radiation dose extends over a longer period of time (days, weeks or longer), the probability of dying of cancer could be reduced by half or somewhat less than half, thanks to the repair effects of our body. This is because our cells regularly fix damage to the DNA before it accumulates to dangerous levels. However, the mitigation factor is not very clear;

different studies give different values and hint to a decrease of a factor between one and two.

The difficulty of statistically proving the harmfulness of low radiation doses can be briefly illustrated by this example: Out of 1000 people in highly developed countries, about 200 die of cancer. If all these people are exposed to a single radiation dose of 0.02 Sv or 20 mSv (a typical maximum permissible annual dose for employees in nuclear facilities), according to the LNT model the death rate by cancer would increase by 0.2% in absolute terms, i.e. on average two additional people would die of cancer, and this after years or even decades. The statistical fluctuation of the natural number of cases is much larger than these two cases. Therefore, it is not possible to prove that radiation has played a role here.

Due to these statistical effects, there are therefore no epidemiologically clearly tenable statements for radiation doses below 100 mSv. Some studies show a slightly higher mortality for workers in nuclear facilities which have been exposed to low doses. But there are also disputes about some of these studies. Usually, individual factors such as smoking, nutrition, sports etc. have a much higher effect and make it difficult to detect the statistical influence of radiation.

While the statistics are unclear, there are radiobiological and biophysical considerations which speak at least somewhat for the LNT model. The rationale behind these considerations can be seen in this example: in a dangerous event with high doses of gamma radiation which leads to an overall exposure of 1 sievert, each single cell in the body is hit by many rays, of which some will cause damages to the cell and maybe harmful mutations. Going to lower doses somewhat below 100 mSv, each cell is only hit by few to none gamma rays. Going further down to very low doses in the range of the natural radiation levels (around 2 mSv), some cells are still hit by maybe one gamma ray but most cells remain unhit – the number of affected cells decreases. This means: comparing low and very low radiation levels, the damage to an affected cell remains more or less the same, only the number of damaged cells changes. So if low radiation levels do pose a threat (as the LNT model suggests and as some radioepidemiological studies hint at, even with high error bars), then there are reasons to assume that also very low radiation levels are not irrelevant and that the LNT model also applies all the way down to very low levels. But it is not clear at all if the radiation-damage-relationship is in fact linear, or if cellular repair mechanisms mitigate this somewhat at low doses. This means that the LNT model is some kind of “worst-case” model which could correspond to the true danger or maybe overestimate it for low doses.

How to deal with such risks is a difficult ethical question, which often gets discussed only superficially. In order to protect the wellbeing of people, the ALARA principle (As Low As Reasonably Achievable) is usually cited. But of course, opinions on what “reasonably” means can differ quite substantially. Often, energy companies and governments have cynically neglected this principle – usually without any personal or legal consequences, as we will see further down in the corresponding chapters.

It is occasionally speculated that low doses of radiation could even have a positive health effect. This is called the “hormesis hypothesis.” Some plants, for example, are stimulated to grow by low to medium doses of radiation. What this means for human beings is unclear. Some thermal bathes offer “radon cures” which are said to alleviate rheumatic ailments and stimulate the immune system. But even if a radon cure or similar treatment can stimulate the body’s own defences in the short term, in the long term this could nevertheless be accompanied by at least a minimally increased risk of cancer due to the linear relationship between dose and cancer risk. For older patients, the positive effects may largely outweigh the negative side effects. But this does not mean that low radiation doses are always healthy. Children especially have a higher general risk, because they are more receptive of radiation and have a long life in front of them.

Cardiovascular Diseases

In addition to cancer, radiation also increases the risk of cardiovascular diseases. While cardiovascular diseases include many diagnoses, the most important and fatal ones are heart attack and brain stroke. Globally, these diseases are responsible for about twice as many deaths as cancer. The underlying cause of these diseases is often arteriosclerosis: over the course of many years, plaques form within arteries of the vascular system. The amount of plaque formation is individually very specific and depends for example on genetic predisposition or cholesterol levels. It is possible that a plaque ruptures and that the ruptured plaque blocks the blood flow in the artery. Depending on the location, this can lead to heart attack if heart vessels are affected, or to stroke in the case of brain arteries. Studies from radiotherapy patients, atomic bomb survivors and several other affected groups have found a significant and consistent increase of risk of cardiovascular diseases from exposure to radiation.

The best estimate of cardiovascular risk after an exposure of 0.1 Sv is about 1% in relative terms, compared to the risk of cardiovascular diseases without radiation. This is five times smaller than the relative risk for cancer. Therefore, even taking into account that the absolute risk for cardiovascular diseases is higher than for cancer, the overall long-term health risk from radiation is still dominated by cancer. Nevertheless, in certain situations of radiation exposure, the risk for heart diseases can become the dominant factor, for example in breast cancer therapy, where the heart receives large radiation doses. Interestingly, the mechanisms for how radiation increases or accelerates the process of plaque formation in the arteries are not yet well understood and are under intense scientific debate. It is also not clear if the risk increases linearly with dose: some studies indicate that risk per dose might be smaller at lower doses than at higher doses, but this is difficult to judge without improved understanding of the underlying mechanisms. Further complications arise from the unknown dependence of radiation-induced cardiovascular risk on sex, age, or risk factors such as body mass index or cholesterol levels.

When comparing these statistics, one should also keep this in mind. We as human beings always look for reasons. If someone gets cancer or a stroke and has been exposed to radioactivity in some way, that person quickly thinks that the radiation was the cause for this illness. In fact, among most of the liquidators who were involved in the clean-up work in Chernobyl, the only cause of death that is statistically significantly higher than in the average population is suicide. General psychological problems also occur much more frequently, both for liquidators and the population in the wider region. These include sleeping disorders, post-traumatic stress disorders up to severe depressions and suicide, abuse of alcohol, drugs and medicines, obesity, associated diabetes and similar problems. These are so common that some researchers regard mental problems as the most serious consequence of radioactive contamination. Psychological problems can lead to an unhealthy lifestyle, which in turn increases the risk of cardiovascular diseases or cancer, even without a substantial exposure to radiation.

Cellular Repair Mechanisms

The human body possesses a range of different repair mechanisms with which it can repair damage in the cells. Biochemical processes cause different types of damage in each cell every day. The most important damage affects the DNA of the cell nucleus. All the information that regulates the functioning of a cell is stored in the cell nucleus. In a germ cell, this information controls the development of a new organism. Damage to the DNA can lead to mutations or cell death. These can be harmful, neutral or – very rarely – positive. Overall, the body's own repair mechanisms are very effective, and they have to be because of the regularly occurring damage.

Normally, the biochemical mutation rate is much higher than that caused by radioactive radiation. Damage to cells becomes much more dangerous, however, when not only the cell nucleus but also the repair mechanisms and all other cell components are damaged so severely at high radiation doses that massive cell death occurs. This explains the rapid increase in mortality when radiation doses exceed 1 sievert.

The repair mechanisms are based on the action of some very specific enzyme complexes which are able to detect and repair damaged areas in the cell nucleus. Some of them are extremely effective and precise; others are more like emergency repair programs designed to somehow ensure the survival of the cell. Some of them start before cell division, others only after. During cell division, repair mechanisms are powerless against mutations. Mutations can then accumulate strongly. This explains why tissues whose cells divide rapidly are particularly affected by radiation. This includes the haematopoietic bone marrow as well as the constantly renewing intestinal mucosa.

But this effect also includes cancer cells and explains why radiation therapy works: cancer cells grow in a fast, uncontrolled way and have an increased metabolic and cell division rate and are therefore particularly sensitive to radiation. The whole idea of radiation therapy is to expose the affected tumour region to very high levels of radiation in order to kill as many cancer cells as possible while damaging most of the healthy cells only up to the level where they are just about to survive. Obviously, in the surrounding region, healthy cells are damaged. They regenerate over time. But, of course, this somewhat increases the risk for follow-up cancer in the affected organ or surrounding tissues.

The dependence of carcinogenesis on cell division rates also explains why children and especially embryos in the womb are at much greater risk from radiation than adults. The rapidly growing tissue of children reacts much more sensitively than that of adults. After a computer tomography, in which a certain amount of X-rays is absorbed, a one-year-old child is several times more likely to develop a malignant tumor than a 50-year-old exposed to the same dose of radiation. In addition, tumours usually need a certain amount of time to grow – from years to decades – before they develop to dangerous stages. This was one of the reasons why some older workers at the Fukushima nuclear power plant volunteered to get the disaster under control. And those who are diagnosed with early-stage cancer at the age of 80 years may not die from that disease, even without treatment. On the other hand, children and embryos are much more affected by radiation than average adult statistics seem to show. One should always keep this in mind when working with ballpark figures for radiation exposure.

4

Types of Radioactive Substances

There are many radioactive substances with very different properties. Some are gaseous, others liquid or solid. Some are highly chemically reactive, others inert. As radioactivity depends only on properties of the nucleus, any substance can contain radioactive isotopes without changes to its chemical properties. This is very important when evaluating the biological impact of radioisotopes, because some can be bound for long times and in different locations in the body. Some substances pose serious problems both in terms of release in the event of catastrophic reactor accidents and in terms of their long-term storage.

It is also not easy to formulate general rules for lighter or heavier nuclei, because nuclear physics is a very complex business. Minor changes of just one proton or neutron can dramatically change the quantum physical state, shape and stability of a nucleus. In general, the proportion of alpha decay is higher for very heavy isotopes, while beta decay dominates for lighter isotopes. The accompanying gamma radiation can be either strong or weak or completely absent, depending on the atomic nucleus. The half-lives also vary strongly, depending on the isotope.

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_4

Fig. 4.1 Decommissioned nuclear power plant Stade on the Elbe River, one of the first pressurized water reactors in Germany

Fission Products, Transuranium Elements and Activated Materials

The most important and most dangerous radioactive substances are usually classified according to the way they are produced during reactor operation. First, there are the direct *fission products*, the daughter nuclei resulting from the nuclear fission of uranium or plutonium. Then, there are the so-called *transuranium elements* such as plutonium, which are produced from uranium by neutron enrichment. The transuranium elements are heavier than uranium and are also all radioactive. In addition, there are *activated materials* that become radioactive when bombarded with neutrons in the reactor. These include pipelines, filters, water and of course the inner pressure vessel and its components. All these types of radioactive substances are dangerous for various reasons.

The least problematic substances are the *activated materials*. They include radioactive isotopes of carbon, iron, cobalt, aluminium, magnesium and zinc. Their half-lives range mostly from a few minutes to about 5 years. When a reactor is shut down and the fuel assemblies have been removed, these activated materials continue to radiate for several years. However, this period is manageable. Some longer-lived isotopes do not radiate very strongly. Many fission products and the transuranium elements radiate many times longer; in addition, they radiate 100 to 1000 times more strongly than the activated materials. But the radiation of the activated materials is still strong enough to cause serious health damage, especially since up to several thousand tons of activated material are present in a reactor. Among others, the strong gamma emitter cobalt-60 is generated as part of the activated materials. The reactor can therefore not be entered for some time after shutdown until most of this radioactivity has decayed. Most of the activated materials are solids; they must be safely stored as low- or intermediate-level waste. Activated materials are produced not only during reactor operation, but also during the reprocessing of fuel assemblies. This class of materials includes tritium, carbon-14 and cobalt-60.

The operation of a nuclear power plant also produces a small amount of gaseous radioactive substances, which are discharged into the air in a highly diluted form via high chimneys – not via the iconic cooling towers. These substances include above all the hardly filterable noble gases krypton and xenon. Small quantities of these gases escape from the fuel assemblies in which they were created. Tritium also accumulates in the cooling water. The exposure of the population to the emission of these substances is normally very low, however, and is only about one per one thousandth of the natural radiation that is always present anyway.

The *fission products* are medium-heavy elements. Some of them, like krypton and xenon, are gaseous. All fission products are radioactive because they contain too many neutrons. They are formed by the fission of very heavy neutron-rich elements, whereas as medium-heavy elements, they can only have a smaller proportion of neutrons in order to be stable. Almost all of these fission products therefore decay into stable elements through a cascade of several beta-minus decays, usually with short to medium half-lives between a few seconds and a few dozen years. This gives them quite high activity, because the shorter the half-life of a substance, the faster it decays and the more radioactivity it releases in a short time. These fission products are very dangerous in the short and medium term. However, most of them decay almost completely in periods ranging from a few days to a few hundred years. A few fission products also have very long half-lives of up to over a million years. They pose special problems for long-term storage, because they are more mobile in the ground than heavier elements.

The activity of fission products freshly generated in the reactor is extremely high; unprotected, even only 1 kilogram of them can have a lethal effect on a nearby person within a few seconds without being inhaled or ingested. The gaseous fission products must therefore also remain safely enclosed in the fuel assemblies. Among the most important and dangerous fission products are strontium-90, iodine-131 and caesium-137.

The heavy *transuranium elements*, on the other hand, are bred from the natural uranium U-238 by neutron capture in the reactor; the already extremely heavy uranium nucleus transmutes to even heavier nuclei through single or multiple neutron accumulation and subsequent decay. Such processes produce above all the various plutonium isotopes as well as isotopes of the elements neptunium, americium and curium. Some of them have very long half-lives. They are mostly alpha emitters. They all belong to the heavy metals and are preferentially incorporated in the human body in the liver and bone marrow.

Fig. 4.2 Control room of the decommissioned research reactor FR 2 in Karlsruhe, the first working heavy water research reactor in Germany

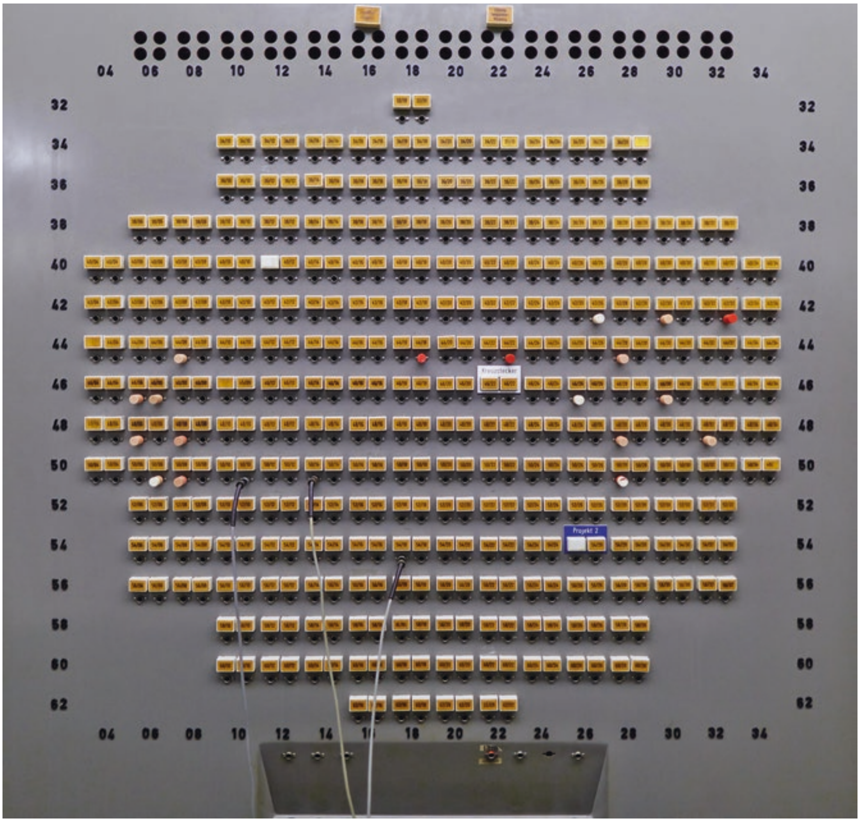

Fig. 4.3 Control panel of the FR 2 reactor core

Due to their often very long half-lives, transuranium elements pose a great disposal problem for radioactive waste. However, those substances with extremely long half-lives – such as uranium-238 or plutonium-244 – also have a correspondingly lower activity than the more short-lived isotopes. Plutonium-239, which is also suitable for the construction of atomic bombs, is particularly problematic in terms of controlled storage. We will discuss long term storage and final disposal in the last chapter of the book in greater detail.

Important Radioactive Isotopes

Tritium or superheavy hydrogen is the lightest radioactive isotope. It is produced by neutron capture processes in the water cycle of nuclear reactors and also as a rare direct fission product of uranium or plutonium. Its half-life of

Fig. 4.4 Grafenrheinfeld nuclear power plant, post-operational phase

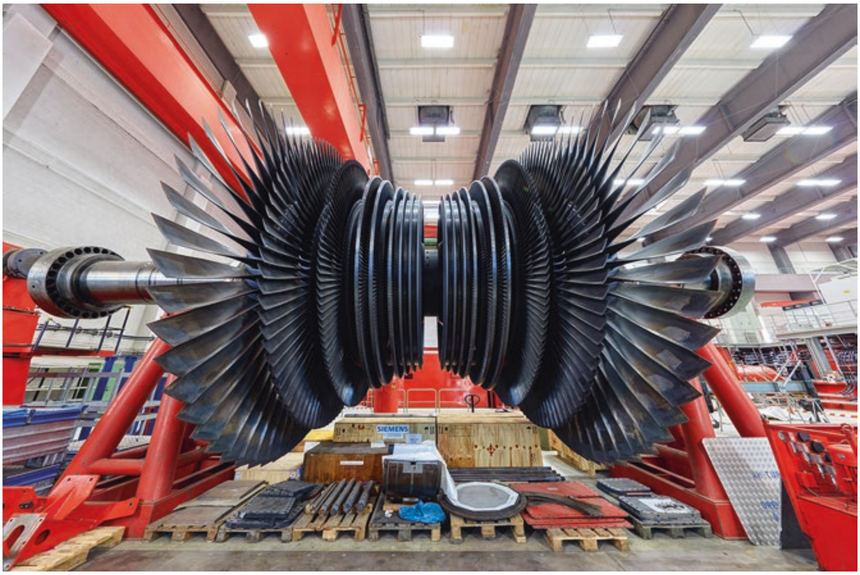

Fig. 4.5 One of the low pressure turbine rotors in the turbine hall of the Biblis nuclear power plant

12.3 years is rather short, leading to high activity after a release. But it does not accumulate strongly in organic tissue. In addition, as a soft beta emitter it does not pose the greatest radiation hazard. However, tritium as a component of the water molecule cannot be filtered out of contaminated water. Therefore, the control of water containing tritium plays an important role when, as in the Fukushima disaster, the cooling circuit of a nuclear power plant becomes defective. Because tritium does not emit gamma rays, it is used in modern luminous dials of watches and navigation instruments, instead of the previously used, more dangerous radium. The soft beta electrons remain in the fluorescent paint and make it glow.

Carbon-14, with its medium-long half-life of 5730 years, is not only interesting for dating archaeological finds (radiocarbon method), but it is also relevant in radiation protection. It is produced by neutron capture processes during reactor operation. Since carbon is the basis of all organic molecules, this beta-emitting isotope remains in the biosphere for a particularly long time and, unlike heavier elements such as plutonium, does not settle as sediment in the soil. Although often overlooked as a danger, its affinity to biological tissue and particularly to DNA has aroused the interest of radiation protection experts to monitor this isotope. The numerous above-ground atomic bomb tests in the 1950s and 1960s led to a steep increase in atmospheric carbon-14 concentrations, which have fallen significantly since the ban on such tests.

Cobalt-60 with its half-life of 5.27 years is produced as a by-product of reactor operation by neutron capture in steel. It is a beta emitter, but it also releases particularly strong and penetrating gamma rays. This makes cobalt-60 a versatile radiation source for medical and technical applications. These include the sterilization of medical equipment or food as well as radiation therapy, but also industrial radiography, for instance to x-ray welding seams and other structural elements to detect possible flaws. It is specifically produced for these purposes. Cobalt-60 has achieved a certain notoriety through the idea of a "cobalt bomb:" by encasing an atomic bomb in cobalt-59, the neutrons released would produce a large amount of cobalt-60, making a huge area uninhabitable for decades because of the hard radiation. However, this has never been implemented due to its lack of military reasonableness.

Strontium-90 has a half-life of nearly 30 years. This beta emitter is mistaken by the body for calcium and is therefore incorporated into the bone marrow, where it remains permanently and has a carcinogenic effect. There, in the haematopoietic tissue, it can lead to tumours or leukaemia. It is not as volatile as iodine or caesium, which is why it is not spread over a larger area in reactor disasters. However, it is one of the most dangerous residues of nuclear bomb explosions.

Iodine-131 has a short half-life of only 8 days. It is highly volatile and can spread quickly over large areas. As a major fission product of uranium and plutonium – roughly 3% in terms of the mass of fission products – it is present in high quantities in recently used fuel assemblies. Due to its short half-life, it practically disappears after only a few months, but during this time it can cause severe damage due to its high activity. It accumulates in the leafy green of plants and therefore also gets into all dairy products. Once ingested, it accumulates mainly in the thyroid gland, where our body also stores iodine. As a strong beta emitter, it can cause thyroid cancer. This affected thousands of people, especially children, after the Chernobyl disaster. Luckily, thyroid cancer is very well treatable. With the help of iodine tablets, the thyroid gland can also be saturated with iodine to such an extent that it no longer absorbs any further iodine – in particular radioactive iodine – so that any intake is excreted directly. This can prevent it from being absorbed into the body, for example in the case of a radioactive cloud. However, this only makes sense if very strong radiation from iodine is imminent. It is not recommended to take high-dosed iodine tablets without acute danger, as they can otherwise increase the risk of thyroid disease. Oddly enough, very high doses of iodine-131 have a lower probability of producing cancer, because instead of causing mutations, very high doses just kill the surrounding tissue. For this reason, iodine-131 is used today in radiotherapy mostly in high doses in special situations.

Caesium-137 has an average half-life of 30 years. It is used in some medical radiation therapy devices for cancer treatment and for some industrial purposes, such as to measure the flow of liquids through pipes or the thickness of materials. In small amounts, it is also used for calibrating radiation-detection equipment. Caesium-137 is highly volatile and can therefore contaminate large areas for decades. The body confuses it with potassium because of its chemical similarity and builds it up mainly in muscle tissue, from where it is excreted after an average of 100 days. It can lead to solid tumours. It is particularly persistent in forest soils and is constantly transported back into the humus layer via needles and leaves, so that it only settles very slowly into deeper soil layers. Some mushroom varieties, the chestnut tree and also some forest berries accumulate caesium through their roots. In some areas, red deer and especially wild boars are also strongly affected. After the Chernobyl and the Fukushima disaster, caesium-137 in particular was responsible for the long-lasting closure of large areas to human settlement. How volatile this element is can also be seen by how far it travels in the atmosphere. In Central Europe and in the Alpine region, which were more severely affected by the Chernobyl disaster than other parts of the continent, caesium levels are still monitored today.

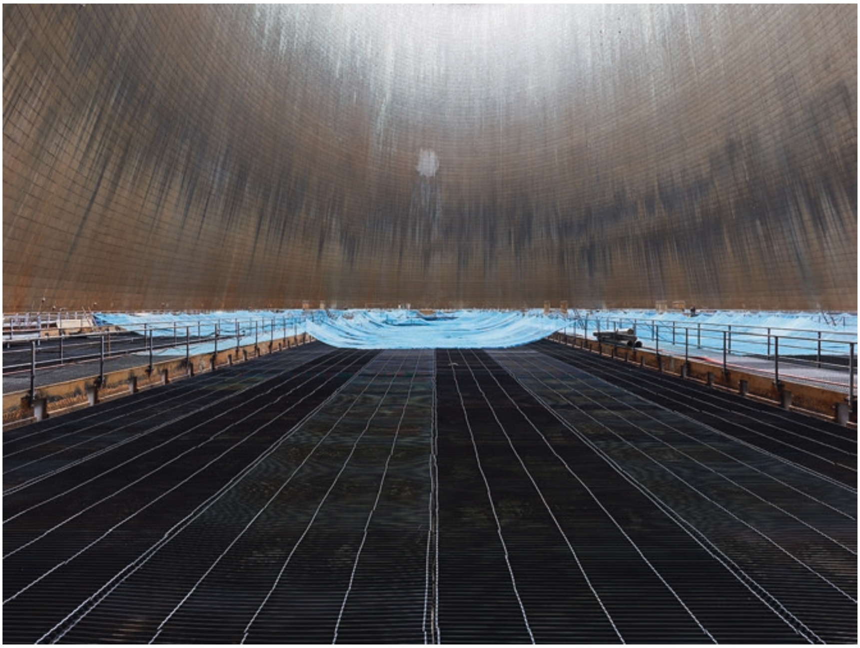

Fig. 4.6 Lamella level in a cooling tower during revision, Gösgen

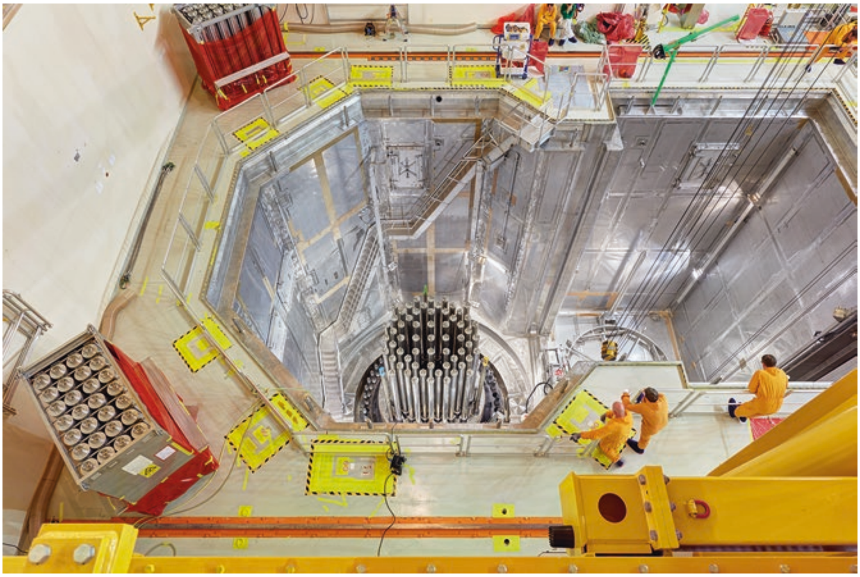

Fig. 4.7 Annual revision at the nuclear power plant Brockdorf. The large silver cylinders are the control rod drives. The ring of bolts around them are holding the reactor vessel head. After powering down, these bolts are removed piece by piece, before the vessel head can be lifted

Some measurements, especially in forest regions, still show high values, but only rarely exceed the permissible limits. The sister radionuclide caesium-134 poses similar problems but decays faster with a half-life of only 2 years.

It is feared that terrorists might use "dirty bombs" that distribute radioactive material. While dirty bombs are not weapons of mass destruction, they can make large areas uninhabitable and expensive decontamination measures necessary. Only around half a gram of caesium-137 could be enough to render an area of one square kilometer uninhabitable for years. In contrast, about 100 kilograms of highly toxic chemical substances would be needed. According to their half-lives, other radioactive substances pose similar dangers. Similar amounts to caesium-137 would be sufficient for strontium-90 and only around a tenth of that for cobalt-60. Due to their higher half-lives and respective lower radioactivity, the corresponding amount of plutonium would be around 700 grams, and of natural uranium, several dozen tons.

Plutonium-239 has a long half-life of around 24,000 years. This transuranium isotope accumulates in large quantities in nuclear reactors and in the production or disarmament of nuclear weapons. As a heavy metal, it is not readily volatile but can be released, for example, during a nuclear meltdown. Its half-life exceeds any concept of controlled storage that can be planned today. However, it is still short enough to generate a high level of activity and a certain amount of heat. At the same time, plutonium-239 is suitable for the construction of atomic bombs and is highly toxic in addition to its strong alpha radiation. The radiotoxic effect, however, clearly surpasses the chemical-toxic effect. Although the vast majority of plutonium is quickly excreted from the body, the absorbed rest remains in the body for a very long time. A few milligrams of Pu-239 absorbed into the body will almost certainly lead to the development of cancer in the lungs, lymph nodes or liver. If inhaled, plutonium-239 is even around 100 times more dangerous. At the Soviet plutonium factory Mayak in the South Urals, workers had an increased mortality rate for lung cancer according to the amount of plutonium they had taken in.

The sister isotope plutonium-238 is far more short-lived. It is a powerful alpha emitter and has a half-life of only 87 years. It generates a lot of heat – more than half a watt per gram of Pu-238 – which is why it is used for so-called isotope batteries. These batteries supply energy to satellites far from the sun, where solar sails are no longer sufficient to generate electricity. Furthermore, plutonium-238 was also previously used in pacemakers because its alpha radiation is shielded by the metal casing and its gamma radiation is extremely weak. According to experts for radiation protection, in case of cremation or when the pacemaker is melted down for scrap metal, radioactivity can still escape, but not in dangerous quantities if handled properly.

Part II

Nuclear Power Plants

5

How to Operate a Nuclear Reactor

The energy present in atomic nuclei can be harnessed either in an uncontrolled way in atomic bombs or in a controlled way in nuclear reactors. In this way, humans can tap into a source of energy that is not based on the principle of chemical combustion, as is the case with fossil fuels like coal, oil and gas. Fossil energy carriers are based on solar energy stored over millions of years, which has accumulated in the ground through the sedimentation of dead plants. The renewable energies of hydropower, wind power and solar energy also use the energy of solar radiation, but directly, without consuming stored carbon compounds and releasing them into the atmosphere as carbon dioxide.

Renewable energies do not change the concentration of climatically active gases in the atmosphere. Fossil power plants instead release large amounts of carbon dioxide that was accumulated as carbon compounds in the soil over millions of years, and thereby change the concentration of climate gases substantially. Nuclear energy, on the other hand, uses the energy stored in the nuclei of heavy elements that were produced before our solar system was created. Since the decay of radioactive elements is a major source of the heat in the earth's interior, geothermal energy can also be considered a nuclear energy source, at least partly. The heating power of the radioactive decaying elements in the earth's interior – especially uranium and thorium and their daughter nuclei – is estimated to be approximately equivalent to 20,000 large nuclear power plants. However, these are only decay processes and not nuclear fission. This generates about half of the heat that flows out through the earth's crust. The other half is the residual heat that has been present since the formation of the earth.

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_5

The Principle of Power Generation by Nuclear Energy

The possibility of obtaining energy from nuclear fission results in part from the nuclear physics knowledge described so far. There are two additionally important aspects: the concept of *critical mass* and the *geometrical arrangement*. These two points determine the answer to the question: How many atomic nuclei are split by the neutrons released during a single nuclear fission? This multiplication factor in the neutron balance from one nuclear fission to the next is called *criticality*.

The crucial difference between atomic bombs and nuclear reactors is exactly how many new nuclear fissions are caused by a single fission. In atomic bombs, the aim is to fission the largest possible number of atomic nuclei within the shortest possible time. Therefore, one tries to achieve the largest possible multiplication factors, i.e. the greatest possible criticality from one fission generation to the next. For example, if an average of 2 out of every 3 neutrons released trigger a new nuclear fission, the number of fissioned nuclei quickly doubles exponentially, so that within millionths of a second, a large part of the nuclear explosive is fissioned and the energy released vaporizes all the material and causes a nuclear explosion.

In a nuclear reactor, on the other hand, to ensure stable operation, the multiplication factor must always be kept very close to one to prevent sudden, exponential changes in power. In order to even come close to a self-sustaining chain reaction, a so-called *critical mass* must be present. The critical mass is defined as the amount of a certain substance from which a self-sustaining nuclear reaction can take place. Less material is called subcritical mass, more is called supercritical mass. These values are defined for different materials by an optimal spherical arrangement. With special material arrangements, which reflect neutrons back into the nuclear fuel, the critical masses can be reduced, in some cases even significantly.

In nuclear weapons, the chain reaction is triggered by conventional explosives concentrating subcritical masses into one supercritical mass. Since nuclear reactions take place extremely quickly, this process must be very precise and timed exactly, otherwise the vast majority of the possible energy yield remains unused and the bomb achieves only a very low explosive yield. This is one of the difficult challenges in the construction of nuclear bombs. Such a fizzled nuclear detonation can still generate a certain explosive force, similar to a conventional bomb, but it is orders of magnitude away from normal nuclear bombs. However, just like so-called "dirty bombs," which use

Fig. 5.1 Control room of Angra nuclear power plant block 2 during operation. The red, round turbine power indicator in the center, nicknamed "parrot," shows full load

Fig. 5.2 Material airlock to the reactor room of Angra block 2

conventional explosives to disperse radioactive substances in the air, it produces radioactive fallout that can contaminate a large area.

Natural uranium has no critical mass because it is too poorly fissile. Even large quantities of natural uranium do not produce a stable chain reaction. This is due to the fact that uranium-238, with its concentration of over 99% in natural uranium, is extremely difficult to fission. However, uranium-235, with its natural concentration of less than 1%, is excellently fissile. In order to achieve the rapid fissionability required in nuclear weapons, the uranium-235 content must be highly enriched; enrichments of over 80% are required. Such an enrichment is a difficult technical challenge. For operation in nuclear reactors, a much easier to achieve enrichment of 3 to 5% is sufficient. Some reactor types, which regulate the neutrons with special materials, can even be operated with unenriched natural uranium. However, they are not very common internationally.

The fissionability of a material also depends strongly on the speed of the neutrons with which it is bombarded. Fast neutrons fly very quickly past the atomic nuclei and therefore interact with them only slightly. If they are slowed down, they are much more likely to trigger nuclear reactions. Therefore, neutron brakes – so-called *moderators* – are needed to absorb the enormous kinetic energy of the released neutrons. The *fast neutrons* become so-called *thermal neutrons*, i.e. neutrons whose kinetic energy is no longer in the MeV range (megaelectronvolt, the typical energy range of radioactive radiation), but only less than a millionth of that, and which are correspondingly slower. The neutrons reduce their kinetic energy by colliding with the atomic nuclei of the moderator material, which slows them down. A good moderator must also not catch too many neutrons.

Water is a very good moderator. It can also be used for cooling and for removing the heat in a reactor. Also, as heated steam, it drives the generator turbines with which electricity is generated in nuclear power plants. Therefore, in practically all modern commercial reactors, water is used in this multiple function as moderator, coolant and drive medium for the turbine.

The construction of nuclear reactors thus follows the principle that a sufficient amount of nuclear fuel and necessary moderator materials are combined in suitable geometrical arrangement. The fissile properties of the material also change over time, as uranium-235 is slowly consumed, thus decreasing the fissile capacity, while plutonium-239 is produced by neutron capture from uranium-238, thus increasing the fissile capacity of the material in the fuel rods a little bit once more. So the two fundamental nuclear reactions for understanding nuclear power plants look like this:

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{139}_{56}\mathrm{Ba} + {}^{94}_{36}\mathrm{Kr} + {}^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n} \qquad (\text{nuclear fission}) $$

$$ {}^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}^{-} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}^{-} + {}^{0}_{-1}\mathrm{e}^{-} \qquad (\text{breeding reaction}) $$

The reaction of uranium-235 to barium-139 and krypton-94 is only one of many possibilities. (See also Chap. 2 on “Material transformations and reactor equations.”) Uranium-235 can split into a whole range of different fission products, which are usually highly radioactive. Uranium-238, on the other hand, can transform itself into short-lived uranium-239 via neutron capture. With a half-life of 23 minutes, it decays by beta-minus decay into neptunium-239, which in turn decays again by beta-minus decay into plutonium-239 with a half-life of a good 2 days. This is the so-called *breeding reaction*, by which the highly fissile plutonium-239 is produced from natural uranium. It takes place in all nuclear reactors. The breeding reaction can be very well understood in the nuclide map section in Fig. 2.7; compare the graph of decay types in Fig. 3.3.

Like uranium-235, plutonium-239 can be very well fissioned by slow neutrons and produces very similar fission products. These two very easily fissionable substances, uranium-235 and plutonium-239, are the two standard fissile materials for both the operation of nuclear reactors and the construction of nuclear weapons. However, since reactor uranium is only enriched by a good 3% with uranium-235, it is not suitable for the construction of nuclear bombs without further and extremely complex enrichment; therefore, practically all power reactors are operated with lowly enriched uranium. This enrichment is possible by a series connection of high performance centrifuges with extremely fast rotation speeds.

Plutonium-239 plays an important role in the construction of nuclear weapons, since it can be chemically separated from other substances – under appropriate safety precautions in a reprocessing facility – and is directly suitable for the construction of nuclear weapons. Chemical separation is much faster than isotope separation for uranium, but it requires reprocessing facilities. Thus, unlike when building a uranium-235 bomb, no complex enrichment technology is needed to build plutonium bombs.

Since, however, large amounts of plutonium-239 have been accumulated in the meantime, both in power plant operation and in the production and disarmament of nuclear weapons, research is increasingly being conducted worldwide to study the extent to which plutonium can be added to normal

Fig. 5.3 Live steam pipes from the steam generator to the turbine building

Fig. 5.4 Turbine hall of Angra block 2 during power operation. The three large green cylinders in the center are low pressure turbine rotors. The generator section is on the right. The smaller high pressure turbines are on the left below the pipes

uranium fuel rods. These are the so-called mixed oxide fuel rods, also called MOX fuel rods. The use of MOX fuel rods can both reduce the stocks of plutonium and increase the energy yield from a certain amount of natural uranium; however, due to the hazardous nature of plutonium, special care is required when handling these fuel rods.

Fuel rods are typically about several meters long, just over 1 centimeter thick and made of special high-strength material. Inside are about 200 pellets of uranium or MOX nuclear fuel. The cladding material completely blocks alpha and beta radiation, but it must be permeable to neutrons. In addition, it must remain absolutely stable under the extreme conditions in the reactor and must not release the highly radioactive fission products generated in its interior. Above all, the fuel rods must be gas-tight, because some of the most dangerous fission products are gaseous. As long as the fission products are safely enclosed in the fuel rods, large-scale contamination is not possible. Although the radioactivity present in the cooling water and plant components is also dangerous, it is many orders of magnitude less than the fission products and transuranium elements contained in the fuel rods. Depending on the reactor design, usually about 50 to over 200 of these fuel rods are combined to form fuel assemblies. A typical fuel assembly contains about half a ton of uranium, 15 kilograms of which is uranium-235 as fuel.

Several dozen fuel assemblies are usually included in the inventory of power reactors, so that there can be over 100 tons of uranium in the reactor core. A reactor vessel thus contains many times the critical mass, which is also necessary because many neutrons are lost through absorption in the cladding materials, in the moderator or to the outside. The chain reaction is controlled in such a way that this large amount of fissile material burns off over a long period of time. Nuclear weapons, on the other hand, contain little more than the necessary critical mass.

Depending on the design of the reactor, the nuclear fuel burns off at different rates in different parts of the reactor. This leads to more or less frequent and expensive revisions and replacement or rearrangement of the fuel rods. The art of building nuclear reactors lies in choosing a geometric arrangement of the nuclear fuel and moderator materials in such a way that one can achieve a nuclear reaction that is as constant as possible, while sufficient cooling, controllability, ample security margins as well as long-term economical operation are guaranteed. It turned out that in common power reactors, the fuel rods can be used for about 3 years until they are burnt out. Every year, one third of the fuel rods are replaced with new, unused ones and the rest are exchanged to ensure a balanced burn-up. This is because the neutron density is higher in the center of the reactor than at the edges, so the burn-up is greater in the center. During such an annual revision, maintenance work is carried out and the number of people working at the reactor site multiplies, compared to the rather few people that are present during standard operation.

In a large power reactor with one gigawatt of electrical power, about 50 to 60 spent fuel assemblies accumulate per year. This corresponds to a consumption of just under one ton of uranium-235 per year. A large nuclear power plant consumes about 3 kilograms of uranium-235 per day and generates enough electrical energy for around 1.3 million people.

A vital factor for choosing the site of a nuclear power plant is access to a large reservoir of cooling water. Since nuclear power plants are mainly profitable if they operate at high power for a long period of time, and since only about a third of their heat can be transformed into electricity, the remainder of the immense amount of heat must be dissipated to the environment. Air cooling alone is insufficient. Thus, due to the high demand of cooling water, nuclear power plants are always built close to larger flowing waters or the sea. Technologically, the giant cooling towers, which are a prominent feature even from a far distance, are some of the simplest components of a nuclear power plant. Some cooling towers are operated regularly, others are only put into operation when, for example, the temperatures in the adjacent river are already so high that additional warming could have negative ecological consequences. If temperatures are very high, some coal-fired and nuclear power plants must reduce their performance to avoid large-scale fish mortality.

Control of the Chain Reaction

Special control rods serve to regulate the chain reaction. In contrast to moderators, these consist of a material that absorbs neutrons as effectively as possible. The elements boron and cadmium are very well suited for this purpose. As the neutrons flying around in the reactor are filtered out by the control rods, they are no longer available for a chain reaction, which slows down the reaction.

When a new operation cycle of a reactor starts, the reactor core is filled with fuel rods according to its specifications. The control rods are still fully extended into the reactor and absorb so many neutrons that no stable chain reaction is possible. Due to the rare spontaneous radioactive decay of uranium atoms, there is always a small neutron flux. When the control rods are fully extended, however, this is not sufficient for a chain reaction.

The reactor is then started up by slowly moving the control rods out of the reactor core, which increases the *criticality*, i.e. the neutron increase factor. Apart from control rods, by adding boric acid, which contains the neutron catcher boron, to the cooling water, the neutron number and thus the criticality can be controlled. Since nuclear reactions take place extremely fast – much faster than one could control them with control rods – one has to be very careful to avoid so-called *prompt criticality*, which means a neutron

Fig. 5.5 Revision at Emsland nuclear power plant. The massive reactor vessel head is being pulled up. It radiates so strongly that it is dangerous to stand close to it. On top is the insulation hood. In between, the control rod motors can be seen

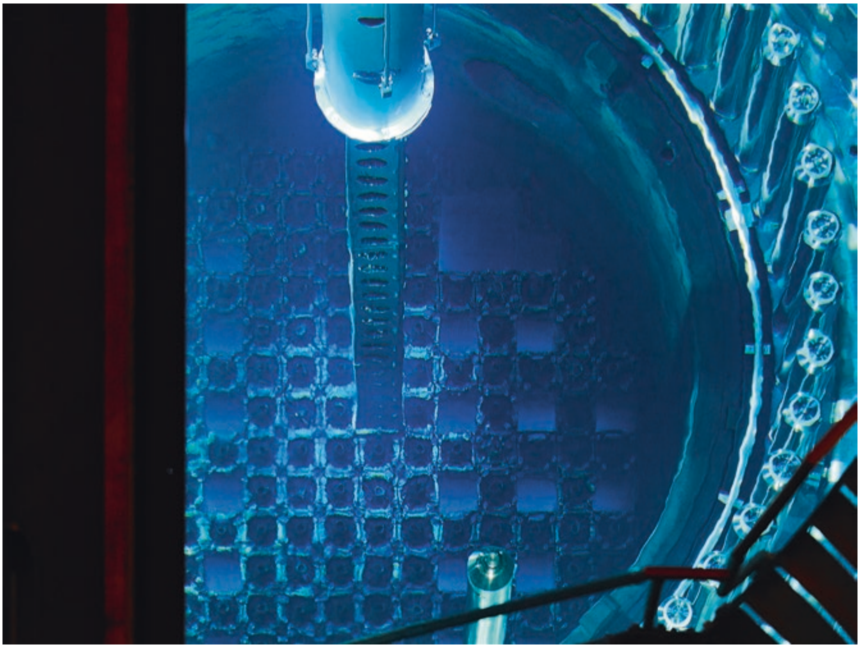

Fig. 5.6 Change of fuel elements during revision at the Gösgen nuclear power plant

multiplication factor greater than one. From this point on, the number of neutrons and nuclear fissions increases exponentially which can lead to enormous overheating of the reactor within a very short time. This is exactly what happened in the Chernobyl accident.

But how can nuclear reactors be started up and operated stably at all if the neutron balance is not allowed to become positive? This is only possible because not all neutrons are emitted immediately during nuclear fission; rather, some neutrons are only released from the fission products after seconds to minutes. These are the so-called *delayed neutrons*. In particular, two fission products, the radionuclides bromine-87 and iodine-137 contribute to these. Delayed neutrons make up less than 1% of all neutrons released. Thanks to these delayed neutrons, it is now possible to control reactors by ensuring that the number of instantaneously released neutrons is just below the criticality threshold. The delayed neutrons then increase the total neutron growth to slightly above one. Since the delayed neutrons are emitted much slower than the other neutrons, a nuclear reactor can be started up slowly in this way and regulated accordingly with the help of the control rods. This is also called *delayed criticality*. All power reactors are operated in this way; prompt criticality can lead to dangerous power excursions and must therefore be absolutely avoided during reactor operation.

In normal operation mode, when the desired power level is reached, the control rods then keep the total criticality very close to one. On average, every neutron produced during nuclear fission now splits exactly one atomic nucleus at a time. Since slight fluctuations in neutron activity can occur time and again, and since the amount of fission material decreases over time due to burn-up, the control rods must be continuously readjusted. This is monitored by the staff in the control room.

Without the help of the delayed neutrons, no slowly controlled, continuous chain reaction could be maintained, but only pulsed operation. This is only feasible in specially designed research reactors where special materials break the chain reaction when heating up. At the onset of the chain reaction, the material heats up strongly in fractions of a second, causing the chain reaction to collapse. Then the entire material cools down again and the cycle can start again from the beginning. In this way, very strong neutron pulses can be generated for certain research projects.

As recent research has shown, in prehistoric times there was apparently a "natural reactor" in the Oklo region in Gabon. This was possible because about 2 billion years ago the concentration of uranium-235 in natural uranium ore was higher than today. At that time, it was still at a few percent before it dropped to today's 0.7 percent because of the shorter half-life compared to uranium-238. With the degree of enrichment at that time – similarly high as in today's nuclear reactors – a low-level pulsed chain reaction was possible in rock with a high uranium content as long as sufficient water flowed in. The water acted as a moderator before it evaporated again after heating up through the chain reaction. The Oklo natural reactor seems to have been active for over half a million years, albeit at a very low power level. In total, researchers in the Oklo region have been able to prove the existence of more than a dozen of such pulsed natural reactors. The uranium ore in these places has a slightly lower uranium-235 content due the burn-up in ancient times.

To shut down a reactor, the control rods are moved back in, which stops the chain reaction. This can also be done very quickly during an emergency shutdown by shooting special emergency rods into the reactor with high pressure. The chain reaction also stops if the moderator is missing. This can happen if the water in the reactor is lost through a leak or if it becomes steam due to overheating. The neutrons are then no longer slowed down sufficiently and lose most of their ability to split atomic nuclei. However, this is only a last resort physical emergency system, since in the absence of water there is a risk that the fuel rods will melt because they are no longer properly cooled.

Nuclear reactors can therefore be shut down quickly, but only restarted slowly, because the delayed neutrons allow only small changes in power per minute. Frequent use of the control rods also leads to an uneven burn-up of the fuel rods and reduces the economic efficiency. For this reason, nuclear power plants can only be operated as base load power plants with at most small power fluctuations. They are not suitable as quickly controllable peak load power plants such as gas power plants. Now, modern control technology has opened up new possibilities here too, so that some nuclear power plant operators consider greater variability to be possible. However, this is always at the expense of a uniform burning of the fuel rods and thus of economic efficiency.

After a nuclear power plant is shut down, the chain reaction is interrupted, but the highly radioactive fuel rods continue to produce a considerable amount of heat for a long time. This so-called *decay heat* has led to the melting of three reactor cores in Fukushima, as the fuel rods heated up more and more after the complete power failure of the cooling systems. The decay heat originates from the radioactive decay of the fission products. In particular, the short-lived fission products generate enormous heat during their brief lifetime. Since a mixture of short-, medium- and long-lived radioactive isotopes is present in the fuel rods, the decay heat is especially strong immediately after the reactor is shut down. Initially, it amounts to about 5 to 10% of the heat output during full operation. Within the first day, it drops to less than 1% and then decreases more slowly over months and years. Especially in the first

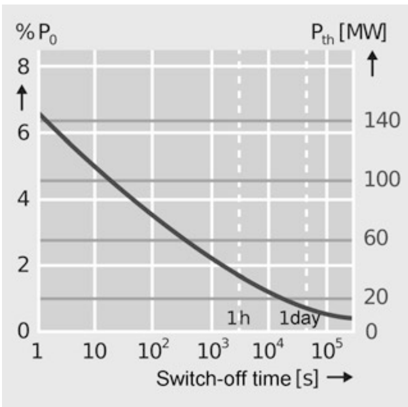

Fig. 5.7 Decay heat of a nuclear reactor with 1000 Megawatt electrical and 3500 Megawatt thermal power. The switch-off time is plotted logarithmically in seconds. On the left axis the heat output is indicated in percent of the nominal full output P_0, on the right axis the absolute heat output P_{th} in megawatts

weeks and months, the decay heat is still so great that the fuel rods have to be actively cooled. Burnt out fuel rods are therefore transferred to so-called *cooling ponds* after removal from the reactor. These are large water containers that simultaneously keep the fuel rods cool and shield their radioactive radiation. They are located inside the reactor buildings and are also called a *spent fuel pool* or *decay basin*.

Fuel rods are removed from the reactor after their life cycle of usually 3 years because most of their nuclear fuel has burned up. At the end of their life cycle, they contain so many highly radioactive fission products that they initially emit more than 100,000,000 times more radioactive radiation than unused fuel rods. Every unshielded person in their vicinity receives a lethal dose of radiation within a short time. After a few years of decay, their radiation is still dangerous and needs to be shielded, but they do not heat up so much that they need to be constantly cooled in water. They can then be transported in special, heavily shielded nuclear waste containers. To do this, the fuel rods are put into such containers under water, the water is then pumped out and the lids are sealed gas-tight.

High-level nuclear waste containers have a 0.5-meter-thick iron wall that very effectively shields the gamma radiation of the fission products in the spent fuel rods. Directly on the surface of such a container, the radiation dose

Fig. 5.8 Brand new, empty CASTOR high-level waste containers (CAsk for Storage and Transport Of Radioactive material), GNS production facility, Mülheim an der Ruhr

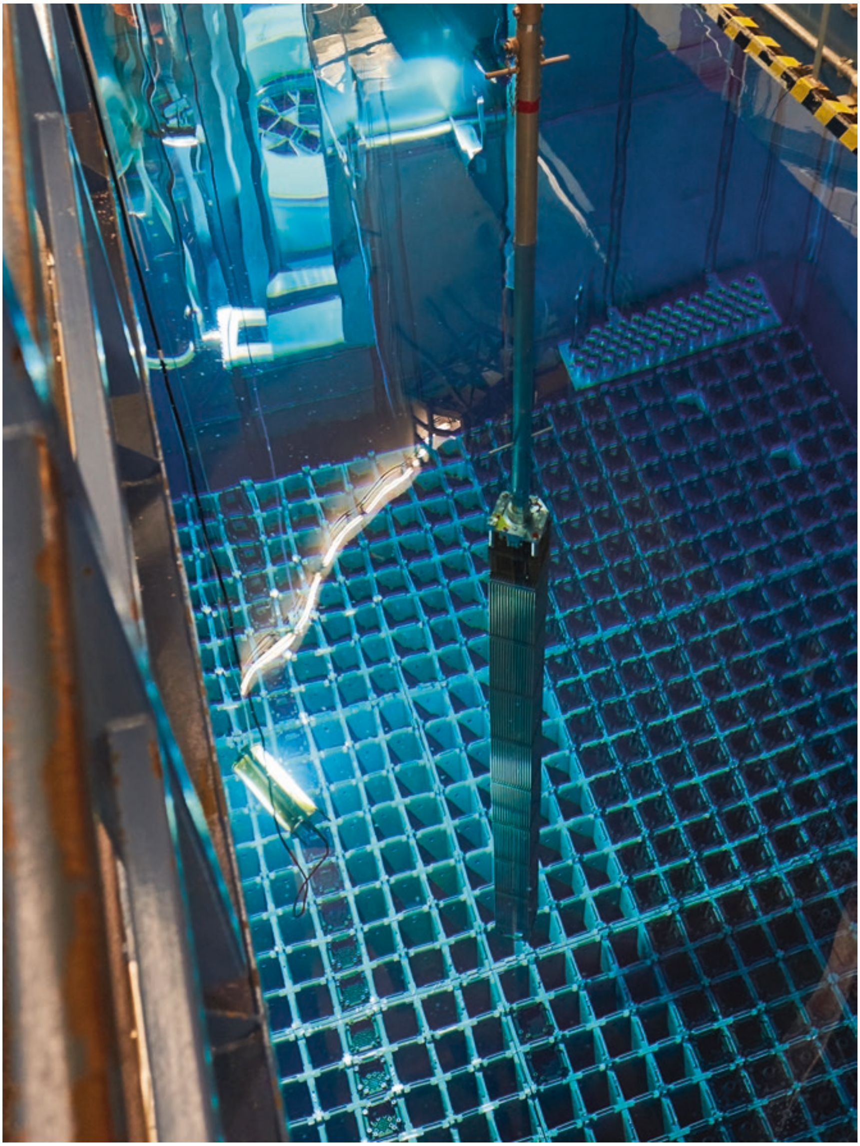

Fig. 5.9 Loading of a storage cask (round structure in the back) with used fuel elements, after they spent four to five years in the spent fuel pool in the front, Grohnde

must not exceed 2 mSv per hour. Workers in the nuclear industry are therefore not allowed to work directly on such casks for more than 10 hours per year, otherwise they would exceed the typically permitted annual dose of 20 mSv. At a distance of 1 meter, the usual safety distance, the dose must not exceed 0.1 millisievert per hour. This corresponds to the natural annual radiation dose within 20 hours. Such limits also define the maximum filling of nuclear waste containers with spent fuel rods. In such casks fuel rods are transported to interim storage sites or reprocessing plants.

6

Reactor Types and Safety

Nuclear reactors used for electric energy production are usually huge constructions. Research reactors are still big machines, but much smaller than power reactors. In order to provide a stable operation and guarantee a maximum amount of security, many different constructive and organizational features have been developed. While the general reliability of nuclear installations is very high, so are the hazards that may occur when things go wrong. This chapter depicts the various technology; the accidents will be discussed later in Chap. 10 on radioactive incidents and disasters.

The classification of nuclear reactors can be somewhat confusing at first, as it depends on the perspective. A physicist might classify reactors as those that use either thermal or fast neutrons, fuel rods or balls or liquid fuel, natural or enriched uranium or MOX fuel, or that have breeding capacity or not. An engineer might distinguish between reactor types with high or low coolant temperature, single or multiple cooling circuit, saturated or overheated steam. The operating company has to choose between cheap or expensive types, more or less safe, more or less reliable in terms of load capacity, lower or higher cooling water requirements and how to integrate such a power plant into an existing electricity grid. We will concentrate here on the physical and safety aspects, as these are more general and vital for the understanding of nuclear technology. Readers interested in more technical details will find these in some of the books presented in the literature list.

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_6

Power Reactors

There is a range of reactor types that differ with respect to the moderator material, the selected geometry of the fuel rods and the structure of the reactor core. Boiling water and pressurized water reactors have become the standard reactor type in most countries. Among the few exceptions are some British and Canadian models and reactors of the Russian RBMK type. The latter were designed by the former Soviet Union and include the reactors at Chernobyl. Older nuclear reactors with low to medium power typically have an electrical output of several hundred megawatts. Bigger and more modern plants reach values above 1 gigawatt. The most powerful ones today have a thermal reactor power up to 4.5 gigawatts and a corresponding electrical power of around 1.7 gigawatts.

Boiling water and pressurized water reactors use normal water as both the coolant and the moderator. These two reactor types are therefore also called *light water reactors*. So-called heavy water reactors do not use normal water, but water with an increased percentage of deuterium, the heavier sister isotope of normal hydrogen. The double use of water as coolant and moderator has the advantage that in case of loss of coolant (for example due to a leak in the pressure vessel) or in case of complete failure of the power supply and subsequent evaporation of the cooling water, the chain reaction breaks down – since the water can no longer fulfil its task as moderator – so that only the decay heat heats up the reactor. This is an automatic physical safety system which also functions when control over the reactor has been completely lost and when – either due to technical defects, unforeseen accidents or a terrorist attack – not even the control rods can be operated. However, the decay heat can still cause a core meltdown, as happened in Fukushima. However, in boiling water and pressurized water reactors, a sudden explosive heating as in the Chernobyl reactor (moderated with graphite and not with water) is not possible. We will discuss the differences in the design of the corresponding reactor types and the sequence of events of the two most catastrophic reactor accidents further below.

Boiling water reactors, in contrast to pressurized water reactors, have only a single water cycle. Pressurized water reactors, on the other hand, have two separate water circuits, which are connected to each other via a heat exchanger. In boiling water reactors, the water flows through the reactor core with the fuel rods and heats up to over 280 degrees Celsius. There it is under a pressure of about 70 bar, i.e. 70 times atmospheric pressure. When heated, the water evaporates, hence the name "boiling water reactor." The water vapor is led to

Fig. 6.1 Nuclear power plant Grohnde in operation

Fig. 6.2 Cooling tower in power operation, Grohnde

a turbine, which can convert about one third of the released heat energy into electricity. The water is then cooled by river or sea water using a heat exchanger and pumped back into the reactor, where the cycle starts all over again. The smoke that sometimes rises from the cooling towers of nuclear power plants is nothing more than the steam from this external water, which is evaporated when the turbine cycle water is cooled. Since nuclear power plants require large amounts of cooling water, they are generally located by rivers or the sea.

In boiling water reactors, the cooling water also drives the turbine. It absorbs small amounts of radioactive substances through contact with the fuel rods and the activated materials of the reactor core. In these setups, the turbine hall is therefore also part of the radioactive control area. Although the radiation there is very low compared to that in the actual reactor, it must be prevented from escaping by suitable protective measures. Over time, this also leads to radioactive contamination of the turbine and the corresponding pipes, which is why their surfaces must be decontaminated, such as by sandblasting, when they are replaced or dismantled. Boiling water reactors also tend to have a higher corrosion rate due to the formation of bubbles on the fuel rods. This reactor type has been developed mainly in the USA and Sweden.

In *pressurized water reactors*, the cooling water circuit (or primary circuit) is decoupled from the turbine circuit (or secondary circuit) in the reactor. The slightly contaminated water of the cooling water circuit is under very high pressure of over 150 bar, more than twice as much as in boiling water reactors. Due to this high pressure, it does not boil even at the temperatures reached of 325 degrees Celsius. The primary circuit transfers its heat energy via a heat exchanger to the secondary circuit, where, as in boiling water reactors, pressures of around 70 bar and temperatures of around 280 degrees Celsius prevail. This steam again drives the high- and low-pressure turbines, which are interconnected and situated in the turbine hall. The advantage of this design is that all radioactive substances remain in the reactor and in the primary circuit. The turbine hall is therefore not a radioactive control area (Fig. 6.3).

Pressurized water reactors were originally developed for use in nuclear submarines and warships, as here the secondary cycle could be used to drive the ship directly via steam turbines and without the lossy detour of electricity production. Similar to boiling water reactors, pressurized water reactors can convert about one third of the heat produced into electrical energy. The remaining facilities, including the cooling of the water in the secondary circuit by river or sea water or the cooling ponds for spent fuel rods, are largely similar for both types. This reactor type has been developed mainly in the USA, France, Germany and Japan.

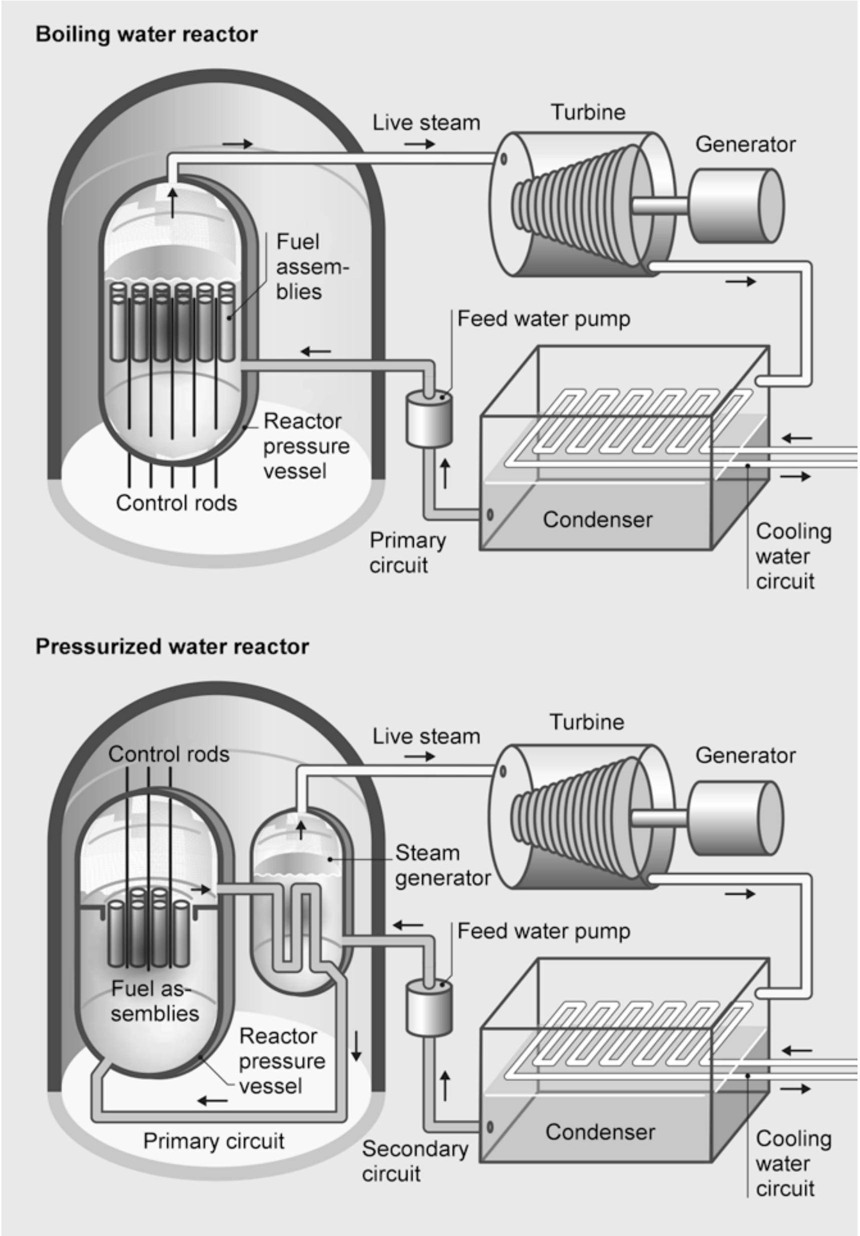

Fig. 6.3 Schematics of a boiling water reactor and a pressurized water reactor. The main difference is that in pressurized water reactors, due to the higher pressure, there is no water vapor in the reactor core, but it is produced only in the secondary circuit via a steam generator

Apart from boiling water and pressurized water reactors, which use water as both coolant and as moderator, there are other types of reactors. Since carbon is also a very good moderator, in some reactor types, such as the Soviet RBMK type or the experimental pebble-bed reactor, graphite is used instead of water for moderation. In these *graphite-moderated reactor types*, the problem arises that if the power output increases – whatever the cause – the evaporation of the cooling water does not automatically lead to a termination of the chain reaction. Other physical or technical precautions must then be taken to prevent explosive heating. Graphite also has the disadvantage that it is flammable. In Chernobyl, the large amount of burning graphite transported many radioactive substances into such high layers of air that they could be transported by the wind over very long distances.

A subtype of such reactors are graphite-moderated reactors wherein instead of water, they use carbon dioxide as cooling gas and can use natural uranium as fuel. Great Britain had developed such a reactor, the Magnox, in the 1950s, as had France with the UNGG (Uranium Naturel Graphite Gaz). These plants could be used to generate electricity as well as weapons-grade plutonium. These first-generation reactors, which have since been decommissioned, were followed in Great Britain by the AGR (Advanced Gas-cooled Reactor), a medium-power reactor type that is still the backbone of nuclear energy in the United Kingdom today. Nearly all other countries rely on boiling water and pressurized water reactors.

Some special types of reactors use gases like helium or liquid metals like sodium instead of water as coolant. However, liquid sodium in particular poses a great danger in the event of an accident. It must not be allowed to become too cold anywhere, otherwise it will solidify; it must also not be released, as it is highly reactive and difficult to extinguish once it starts burning. It burns both in air and in water. Thanks to their higher in-built security, boiling water and pressurized water reactors have so far become the commercial workhorses of the nuclear industry.

So-called *high-temperature reactors*, such as the pebble-bed reactors, can achieve higher temperatures and thus higher efficiency in electrical power. They use uranium enclosed in graphite balls, about the size of tennis balls. The graphite serves as a moderator, and helium as the cooling gas. Due to special physical effects at high temperatures, such reactors can achieve a similar automatic safety as water-moderated reactors despite using graphite as the moderator. Because of the high temperatures of up to 750 degrees Celsius, ceramic materials are used in the reactor core. High-temperature reactors should in theory be safer and more efficient than conventional reactors. However, the enormous demands on the materials and the difficult preparation of the fuel have not been mastered. Prototypes had to struggle with a much higher contamination of the reactor vessel than expected, so that these reactor types must be considered an economic failure.

Another option in nuclear power generation would be to use the element thorium, which is much more abundant on earth than uranium. *Thorium-fuelled reactors* should produce less radioactive waste and be safer than conventional reactors. Natural thorium consists nearly completely of the isotope thorium-232, which can be transmutated to uranium-233 via neutron capture in a breeding reaction – very similar to the breeding reaction of plutonium-239 from uranium-238. Uranium-233, which does not occur in natural uranium ore, is also easily fissile, similar to the standard nuclear fuel uranium-235. However, thorium-fuelled reactors are not yet sufficiently mature, and research is still underway. Furthermore, some scientists have expressed concerns that thorium reactors could increase the risk of proliferation of weapons-grade material. India, which has little uranium but large thorium resources, as well as China and the United States, are undertaking research and development projects with thorium-fuelled reactors.

A special reactor type is the *heavy water reactor*. This type, which has mainly been developed in Canada as the CANDU (CANada Deuterium Uranium) reactor, uses heavy water as moderator. In heavy water, the hydrogen in H_2O is not the usual light hydrogen isotope protium, but rather deuterium, which is one neutron heavier. Heavy water is expensive and has to be produced in a complex, energy-intensive process. But thanks to the special properties of heavy water, which absorbs less neutrons than normal water, this type of reactor can be operated with unenriched, natural uranium. It is therefore particularly suitable for countries that have access to uranium but do not have the centrifuge technology to enrich uranium-235. The possible exchange of fuel assemblies during operation also poses a proliferation risk, as weapons-grade plutonium can easily be produced with such reactors. Heavy water as reactor fuel also played a role in World War II, as both the Allies and the Germans were interested in the heavy water of the Norwegian specialists from Norsk Hydro, which led to one of the most daring espionage and sabotage commando operations of World War II.

Another special type of reactor is the so-called *breeder reactor*. These reactors generate electricity as they produce more fissile material than they consume. This is possible because they mainly consume uranium-235, but produce plutonium-239 from uranium-238, which is otherwise irrelevant for energy production, via the breeding reaction. This plutonium can then be used as MOX fuel in other power plants. Even though other nuclear power plants also produce a certain amount of plutonium, this ratio is much smaller

Fig. 6.4 Decommissioned heavy water research reactor FRJ 2 at Forschungszentrum Jülich of the DIDO type

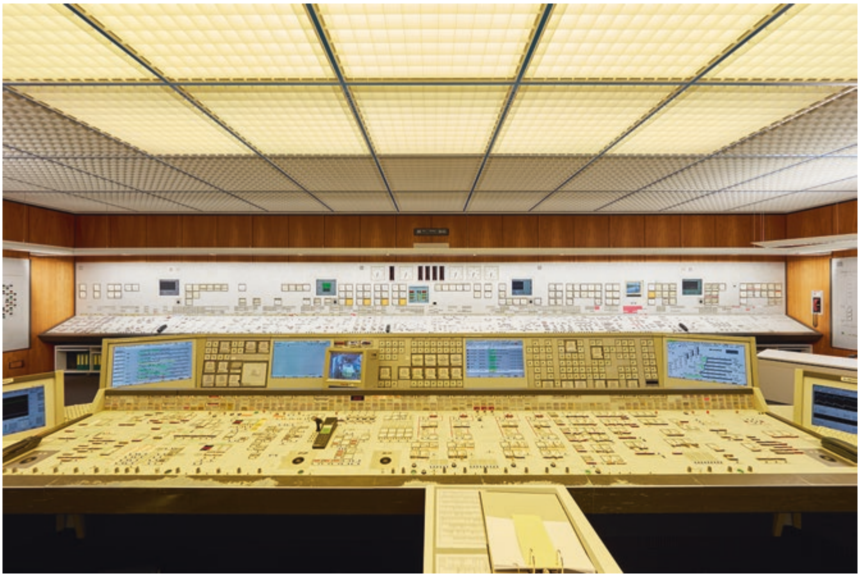

Fig. 6.5 Control room of the Grafenrheinfeld nuclear power plant

than the amount of uranium-235 consumed. Breeder reactors, on the other hand, are optimized to produce as much fissile material as possible. This theoretically increases the amount of energy that can be obtained from a certain amount of uranium ore by a factor of about 60. In practice, however, these values are still a long way off.

An important type of breeder reactor is the so-called *fast breeder*, because it does not need a moderator to split atomic nuclei due to its special design. These reactors use fast neutrons to maintain the chain reaction. (The name of these reactors comes from these fast neutrons, not because they breed particularly fast.) This is only possible with very high neutron fluxes, because fast neutrons react more reluctantly with nuclei than thermal neutrons that have been slowed down by a moderator. Fast neutrons, when they split a nucleus, generate a slightly higher number of new neutrons in comparison to normal reactors that use thermal neutrons. Breeder reactors use liquid sodium or similar materials as a coolant because sodium absorbs less neutrons than water and also does not slow them down. It is absolutely essential that fast breeders have a very fast and reliable safety shutdown, as they do not have the automatic stabilization mechanisms of water-moderated reactors.

For these reasons there are only a few breeder reactors worldwide, mainly in Russia, which is the world leader in this technology. Currently, there are two such breeder reactors in operation, the BN-600 and the BN-800. They can breed 30% more fissionable material than they consume. But actually, since 2012 the BN-600 has been operating in “burner mode,” consuming plutonium from Russian nuclear weapons instead of generating more of this element. The difference between “breeder mode” and “burner mode” consists in the reactor arrangement: in the first mode, it has a uranium-238 blanket around the core to capture neutrons, and in the second, steel reflectors to redirect the neutrons back into the reactor core.

The economically exploitable uranium reserves will be exhausted one day. Estimates vary widely, ranging from several dozen to several hundred or thousand years. Despite its much greater risks compared to conventional reactor models, breeder technology has the potential to stretch the existing reserves many times, which is why many proponents of nuclear technology regard it as an important future technology. But it also comes with a certain price, because the generated plutonium has to be separated in a reprocessing facility. (Further down, in Chap. 11 on Partitioning and Transmutation, we will have a deeper look into reprocessing technology.)

Nuclear power plants can be roughly differentiated by generation. Safety, power output and fuel efficiency increase from generation to generation. The first generation includes the early nuclear reactors, which were developed from the 1950s onwards. The majority of the nuclear power plants in operation today belong to the second generation and were mostly completed in the 1970s and 1980s.

The third generation includes modern types of power plants built from the 1990s until today. These include in particular the EPR (European Pressurized

Water Reactor), a Franco-German development that combines the most important features of both countries' series. Experts also refer to the EPR as a "Generation 3+" reactor due to its enhanced safety features, which are considered as very high. Apart from a sophisticated earthquake damping, these features include catalytic recombiners to reduce a possibly dangerous hydrogen content in case of a meltdown. The EPR also features a highly secured containment with efficient filters and a so-called core catcher that is designed to collect and cool the hot reactor material even in case of a large meltdown. A few reactors of this type are already in operation or under construction (Fig. 6.6).

The same applies to the new American AP1000 (Advanced Passive) series, also a pressurized water reactor, which has a special passive safety cooling system. In case of emergency, when passive cooling is activated, a tank above the reactor lets water flow down to the top of the reactor where it evaporates. This system also works in case of a station blackout. Thanks to the intelligent design, this reactor type also needs significantly less pumps, cables and valves compared to earlier models. This also means that less things can malfunction, decreasing the complexity and increasing the security of the whole facility.

With the "Akademik Lomonosov," Russia has put a small floating nuclear power plant into operation that can supply remote regions with electricity and also serve as a desalination plant for seawater. However, its output is

Fig. 6.6 Olkiluoto nuclear power station. Units 1 and 2 in the right and center are older boiling water reactors, Unit 3 on the left is a modern EPR type

significantly lower than that of large power plants, and construction costs ran over estimates by several times. More such floating power stations are planned, also to power offshore oil and gas field development. Historically, the American MH-1A was the first floating nuclear power plant. The ship had a pressurized water reactor with an electrical power of 10 megawatts. After the first criticality in 1967, it was towed to the Panama Canal Zone where it supplied electricity for several years.

Some countries are also developing small modular reactors (SMR), typically in the range between several dozen and a few hundred megawatts. These provide not only more economic plannability, but also other positive aspects: thanks to theirs small size and modularity, they can be built almost completely in a controlled factory setting and installed module by module. This increases the general construction quality and efficiency – something that has shown up as a big problem in some larger power plant constructions. Due to their smaller size, they can also rely better on passive safety systems. Additionally, it would be possible to build such reactors underground and thus increase both the safety of the installation against outside influences and vice versa. On the other hand, a multitude of small reactors would also be harder to control and secure.

SMRs also have other disadvantages. Usually, the price per unit of electrical generating capacity declines with increasing size. This is the main reason why modern nuclear power plants are as big as they are. When electrical output is reduced from 1 gigawatt to 100 megawatts, for instance, the material requirements used per megawatt more than double. The same counts for supervising personnel. It has been suggested to let one operator control up to three modules, but this raises serious questions about sufficient staff in the case of an accident or attack. Also, a secure containment for every single SMR would be prohibitively expensive. Thus, several modular reactors would be installed in one containment per project. This somewhat speaks against the flexibility of SMRs. But some aspects also speak in favour of SMRs. They can be built faster and integrated more flexibly in a changing electrical grid. Since renewables are growing fast and the high investment costs and long construction times of large nuclear power plants make planning difficult, SMRs could provide a way of combining the fluctuating renewables with base load thermal power plants. We will have a deeper look in Chap. 7 on the "Current status of the nuclear industry".

A promising concept is accelerator-driven systems (ADS), also called hybrid reactors. These reactors always run in the subcritical range and are therefore inherently safe. The neutrons necessary to maintain the chain reaction come from a special spallation source, which is driven by an external particle

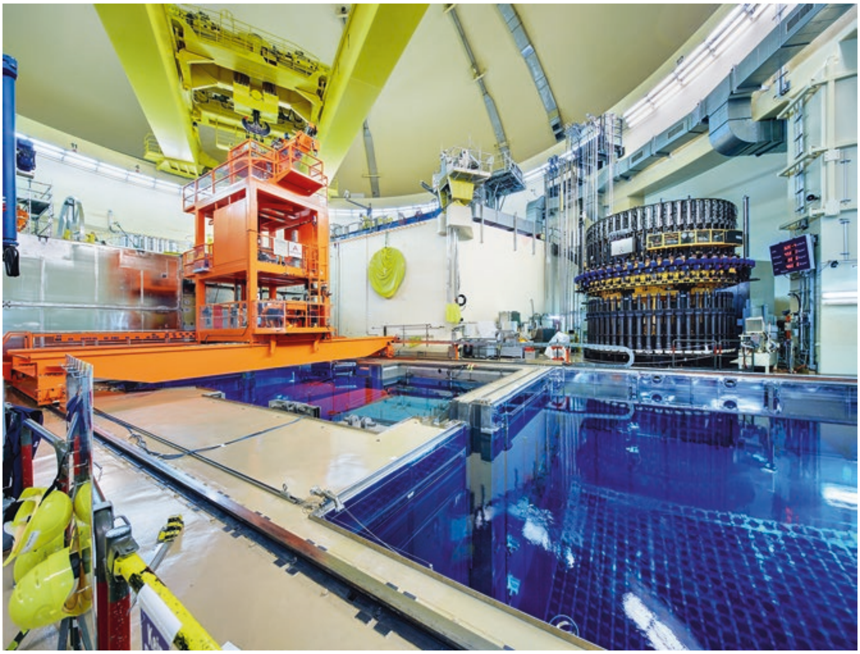

Fig. 6.7 Pressurized water reactor during revision, nuclear power plant Isar. Spent fuel pool (front right), behind it the bolt tensioning device with reactor vessel bolts. Reactor pool (left) with loading machine above it, service pool (middle). During normal operation, only the spent fuel pool on the right side is flooded, during revision also the others pools

accelerator. Since the problem of controlling the neutron number inside the reactor is solved by an external device and the reactor itself is subcritical, such facilities cannot undergo a power excursion. Accelerator-driven systems could be well suited for the transmutation of long-lived radionuclides in nuclear waste.

Researchers are currently also working on completely new reactor concepts of the fourth generation, which, thanks to modern materials, offer even greater safety and a number of other desirable properties. In particular, they should produce less radioactive waste, have a lower proliferation risk and offer the possibility of burning plutonium from nuclear weapons. Thanks to very high operating temperatures, some of these reactors could even produce hydrogen directly, which would be interesting for a low CO_2 energy economy. These concepts include reactor types such as the traveling-wave reactor, the molten salt reactor or the gas-cooled fast reactor. Such reactor types could breed fissionable material and then consume it as it builds up. This would make the nuclear fuel chain simpler and alleviate the nuclear waste problem.

Fig. 6.8 Boiling water reactor during revision, nuclear power plant Gundremmingen

However, it is not clear which of these concepts will be realized. The development costs of new reactor types are high. There is a saying in the nuclear industry that all too often, the dreams of a nuclear physicist are an engineer's nightmares. In the past, many ideas that looked interesting on paper have proved to be expensive failures.

Research Reactors

Apart from commercial power reactors, there are also many different types of research or experimental reactors that produce special isotopes for medical, scientific and industrial applications. Super-low-flux or "zero power" reactors with minimal power output – such as once the Chicago Pile-1 – are used for educational purposes, reactor personnel training and certain physics experiments. Some high-flux research reactors, on the other hand, are very strong neutron sources, which scientists use to do fundamental physics experiments and to elucidate the properties of materials, the structure of biochemical compounds or chemical reaction dynamics. But even such research reactors have much lower power and generate accordingly less radioactive waste than nuclear power plants. Some research reactors also operate in pulsed mode, which is unsuitable for power reactors.

Neutron research has little presence in mainstream media; however, it is a fundamental pillar of modern material science. Since neutrons, as their name implies, are electrically neutral, they easily penetrate different types of matter. At the same time, they carry a magnetic moment which can interact with the magnetic properties inside solid-state bodies. Therefore, neutrons are perfectly suited to research the structure of materials in a manner that is otherwise impossible. Neutron rays make things visible that regular light cannot display and to which X-rays are "blind." The latter, on the other hand, feature advantages in areas where neutron radiation shows weaknesses. It is the combination of these methods that offers modern science unforeseen possibilities.

The properties of neutrons are not just exploited for imaging. Neutron capture allows targeted material transmutation. While the neutron capture of uranium-238 in nuclear reactors produces unwanted plutonium, one can use neutron radiation on specifically chosen targets and thus produce radioisotopes for medical diagnostics and therapy or for scientific and industrial purposes.

Fig. 6.9 Research reactor at the Institute of Nuclear Chemistry of the Johannes Gutenberg University Mainz. This TRIGA Mark II swimming pool reactor is one of 66 TRIGAs worldwide and was officially commissioned by Otto Hahn in 1967. The control room is located at the top back

Fig. 6.10 Experimental Hall of the now decommissioned BER II research reactor in Berlin

But as practical as neutrons might be, and for as many applications they might be suitable, they do have one great disadvantage: neutrons have a degree of penetration capacity that makes it difficult to control them. And they are not available off-the-shelf. Free neutrons are unstable; they decay with a half-life of approximately 15 minutes into a proton, an electron and an electron-antineutrino. Surprisingly, the exact lifetime of neutrons is still subject to scientific debate: depending on the measuring method, the values vary significantly. The properties that make neutrons so valuable also makes their handling so difficult.

Neutrons must be generated where they are to be worked with. This is done by releasing them from their "cage" and shattering the atomic nucleus in which they are enclosed. Since heavy atomic nuclei like uranium have a notable excess of neutrons as compared to protons, they are particularly well suited for neutron production. There are two basic methods. In the first, scientists use the fission of uranium or plutonium nuclei in a chain reaction – as in normal power reactors, but with special geometrical features. In the second, one can also use a particle accelerator to shoot a high-energy proton ray at a target substance and shatter its nuclei into smaller pieces. This method is called *spallation* and has the advantage that no nuclear reactor must be maintained and that the energy of the reaction can be regulated very selectively. Currently, the *European Spallation Source* (ESS) is being built in Lund, Sweden. This research center is such a "shattering" machine and is to become one of the leading neutron research centres worldwide.

Until now, neutron research has mainly taken place in reactors, such as the Institut Laue-Langevin in Grenoble, France, which provides the currently strongest neutron source worldwide with its high-flux research reactor HFR.

One particularity of high-flux research reactors compared to nuclear power stations is that they also need a certain power to produce a sufficient number of neutrons. But in this context, the total power output is not important, which is much lower (usually less than 1%) than that of nuclear power plants. Instead, research reactors aim at the highest possible neutron density in the reactor core. Therefore, the reactor core must be very compact and feature a high reaction rate. This is usually achieved by using highly enriched uranium and a sophisticated geometrical setup of the reactor core. Sometimes the enrichment is so high that it is considered "military grade" and suited for the production of atomic bombs.

If, for example, the Institut Laue-Langevin in Grenoble needs a few more kilograms of new fuel with an enrichment of 97%, the delivery is not publicly announced. Rather, the gendarmerie closes the relevant access streets to the city on the foothills of the Alpes in a cloak-and-dagger operation, and the entire delivery takes place under the highest safety measures. If terrorists wanted to obtain nuclear material that, compared to plutonium, is more easily brought to explosion, such a delivery would be the perfect target. But well-coordinated police operations are not the only possibility to avoid this risk of proliferation. For some years already, nuclear physicists have striven to run research reactors with lower enriched material, which comes with a loss of neutron density. The goal is to compensate for these losses by packaging the nuclear fuel rods in the reactor core more densely, amongst other measures.

Research reactors are usually water-cooled, whereby the water simultaneously serves as a moderator and as a protective shield against radiation. Most of these reactors are pool-type reactors ("swimming pool reactors"). The reactor core is located in a several meters-deep, open water basin. This construction method is not suited for electricity-producing nuclear reactors because here, the water must be under very high pressure to achieve a good degree of thermal efficiency. In research reactors, the power is too low to heat up the water enough to generate much steam. Everything is built around the idea to generate as many neutrons as possible in a small volume without creating interfering effects like bubbles or steam.

The open water basin allows direct views of the Cherenkov radiation, which, depending on the intensity, can appear a glaring blue. It also facilitates access to experiments and makes research and education easier. Material samples, can, for example, be easily transported near the reactor core to be exposed to radiation. In the early years of neutron research, staff at the research reactor in Munich even used the so-called "fishing line" method, which proved to be surprisingly simple and successful. After the irradiation, the material just had to be left to decay for an hour until the neutron-induced radioactivity had decreased sufficiently. Then, the samples were ready to be examined in the laboratory.

Today, more accurate methods are used to radiograph materials with neutrons or expose them to radiation. With thin-walled steel pipes, the neutrons are led out of the reactor core to the experiment stations. Here, the steel pipes are always arranged slightly asymmetrically and do not point directly in the direction of the reactor core, as besides the neutrons, the reactor core also releases immensely strong gamma rays that must be shielded off so that they do not run along the steel pipes.

Research reactors run with significantly less power than large nuclear power plants. But in order to supply enough neutrons for the experiments, the larger ones do reach up to several dozen megawatts. The art of building such facilities is to allow the transportation of as many neutrons as possible with the appropriate energy from the place of generation in the reactor core to the experiment stations. Since neutrons are very penetrating, they are difficult to direct and manipulate. Elaborately constructed steel pipes made of carefully selected and treated materials lead at least a part of them to their intended destination. Research reactors are also subject to constant optimisation efforts. Over the past decades, this has led to significant improvements of the neutron ray quality for imaging without having to increase the reactors' power performance.

The neutrons run through the steel pipes to the experiment stations – more than thirty at the Institut Laue-Langevin, for example. The energy of the neutrons can be regulated across a certain energy range. When they leave the reactor core, they have already had many collisions with atomic nuclei in the water basin and are therefore adapted to the thermal energy of the water. In order to get neutrons with higher or lower energy, nuclear physicists resort to a trick: for higher neutron energies they install a large, thermally insulated graphite plate inside the reactor basin at the opening of a steel pipe. Merely by being bombarded with highly energetic neutrons, the plate heats up to 2500 degrees Celsius and passes the energy onto those neutrons that penetrate the graphite plate and enter the steel pipe. Neutrons can also be slowed down to very low energies by installing a duct with deep-frozen deuterium in front of a steel pipe.

Various tricks and helium-cooled deuterium can be employed to fully slow down and then store neutrons in a magnetic vessel. Such experiments with "ultra-cold" neutrons mainly serve the purpose of researching their fundamental physical properties. Neutrons are no elementary particles but rather composite particles that consist of three quarks held together by gluons. And that is exactly why they are very suitable for precision experiments to search for hints of hitherto unknown laws of nature – for example fundamental symmetries that correlate with the laws of nature, which, for a neutron, can become noticeable at its dipole moment. If the neutron had not only a magnetic but also an electric dipole moment, this would help to answer the question why our cosmos consists of matter rather than antimatter, and why, during the Big Bang, the amount of antimatter released does not equal the amount of matter released, but a little less.

However, most experiments at neutron sources are conducted to radiograph very different things. Since the wavelength of neutrons is in the range of typical inter-atomic distances, neutrons are an excellent means to find out more about the secrets of the nanoworld. In addition, their energy corresponds to the typical excitation energies in solid state bodies. This means that neutrons can be used to not only measure the structure but also the behaviour of materials. The research with neutrons therefore comprises almost all fields of material science research. Neutrons allow for irreplaceable insights not only into physics and chemistry, but also into crystallography, biology, geosciences and engineering sciences, all the way to palaeontology, archaeology and art history.

One of the major benefits of this approach is that research with neutrons is a non-destructive method. Therefore, scientists are able to radiograph archaeological artefacts or artwork without the fear of damaging these objects. Engineers can determine the residual stress of mechanically stressed parts deep in their interior. In this manner, highly stressed parts such as the turbine blades of aircraft engines can be examined thoroughly. But also new types of batteries, solar cells or other technologies, which are relevant for renewable energy technology, reveal their insides in neutron light. Many insights about modern battery types have been gained when researchers examined the loading and unloading processes with neutrons.

Modern material science is no longer conceivable without neutrons. Neutron imaging covers a large parameter range in the space-time diagram; it cannot be replaced by any other method. Neutron scattering makes structures visible from the picometer to the micrometer scale – practically the entire range "around nano." In addition, neutron scattering makes structural changes on time scales of picoseconds up to microseconds visible. New methods allow researchers to expand this range to larger structures and longer time periods.

This field encompasses many important physical and chemical processes in various materials, such as diffusion, tunnel processes, phonons, magnons and numerous exotic phenomena, which are used today in laboratories to work on the electronics of the future. In this context, one of the neutron's physical properties proves to be particularly practical: it carries a magnetic dipole moment with which scientists can examine the magnetic structure, the magnetic excitations and the electronic fluctuations in solid state bodies. This also provides important findings about correlated electron systems and nanomagnetic structures.

Such research provides scientists with information about magnetic materials for novel data storages, about possible high-temperature superconductors or about exotic materials with hitherto poorly understood topological properties. In 2016, the Nobel Prize in Physics was awarded for work in the field of topological materials. The corresponding theory is complex, as are the materials. Little can be predicted. All the more important are reliable imaging methods with which the manifold electromagnetic structures in the interior of these peculiar solid state bodies can be determined as precisely as possible. Over the last years, this research field has grown exponentially around the world.

Furthermore, neutrons can easily be used under difficult experimental conditions: even at extreme pressures, temperatures or electromagnetic fields, they deliver reliable data. In diamond anvil cells, for example, the pressure deep inside the earth can be simulated to better understand our planet's behaviour. Since the pressure at the centre of these cells is far too high to examine the samples, reliable imaging methods – such as that which neutrons can provide – are necessary.

Living (or at least biological) matter can also be examined with neutrons. Structural and molecular biologists exploit the properties of neutrons to screen sensitive biological samples or to determine the structure of important proteins, membranes and macromolecular complexes. This can lead to insights that allow the production of novel drugs.

Safety and Emergency Systems

Nuclear power plants are significantly more complex than other large power plants and, due to their highly radioactive inventory, pose a much larger threat to their surroundings. Therefore, they are equipped with comprehensive safety and emergency systems with multiple redundancies to avoid catastrophes or at least the release of radioactivity even if a serious accident occurs. A whole hierarchy of safety and emergency systems is in place to prevent the release of radioactivity even in the event of incidents, or, if possible, to prevent serious incidents from occurring in the first place.

The design of nuclear reactors is based on the principle of "defense-in-depth." The basis of this principle is that possible human error or plant failure must be compensated by several independent safety levels. The same applies analogously to long-term storage of nuclear waste.

The systems designed to manage disturbances start in the interior of the reactor with an automated fast shutdown of the reactor, followed by emergency power supply and containment, all the way to smoke dischargers on the outside of the plant that can rapidly envelope the reactor buildings in dense fog in order to ward off possible aircraft attacks. Research reactors also possess some of these safety systems. But due to their smaller size, lower content of fissile material, lack of high-pressure systems and much lower heat, they do not require the same amount of security measures.

As a safety philosophy in modern nuclear power plants, it has become standard that all relevant systems are designed with multiple *redundancies*. Each system therefore exists in up to four versions. So if one cooling water pump fails, three others should be able to jump into the breach. The probability that all four systems fail at the same time is of course very low, but not zero. However, since it cannot be ruled out that a whole series of redundant systems may fail due to technical or operating errors, additional attention is paid to *spatial separation* and *diversity* of the systems, i.e. different technical systems are used to handle the same task. A distinction is made between safety systems, which on the one hand are intended to stabilize the reactor in case of operational irregularities, and precautions, which on the other hand are intended to prevent contamination of the reactor building or the surrounding area in case of an incident.

There are different systems for stabilizing the reactor. In boiling water and pressurized water reactors, the most important physical emergency system is realized by the fact that the cooling water is simultaneously the moderator. Thus, the chain reaction is automatically stopped if the cooling system fails. However, this can only prevent overheating by a runaway power excursion, as in the case of Chernobyl, but not core meltdown, as in the accidents at Three Mile Island and Fukushima.

A fundamental safety system is the *fast shutdown*, should unforeseen malfunctions or damage occur. The technical term for this is "reactor trip" or "scram," which Fermi jokingly referred to as "Safety Cut Rope Axe Man," as was in fact deployed in the very first reactor.

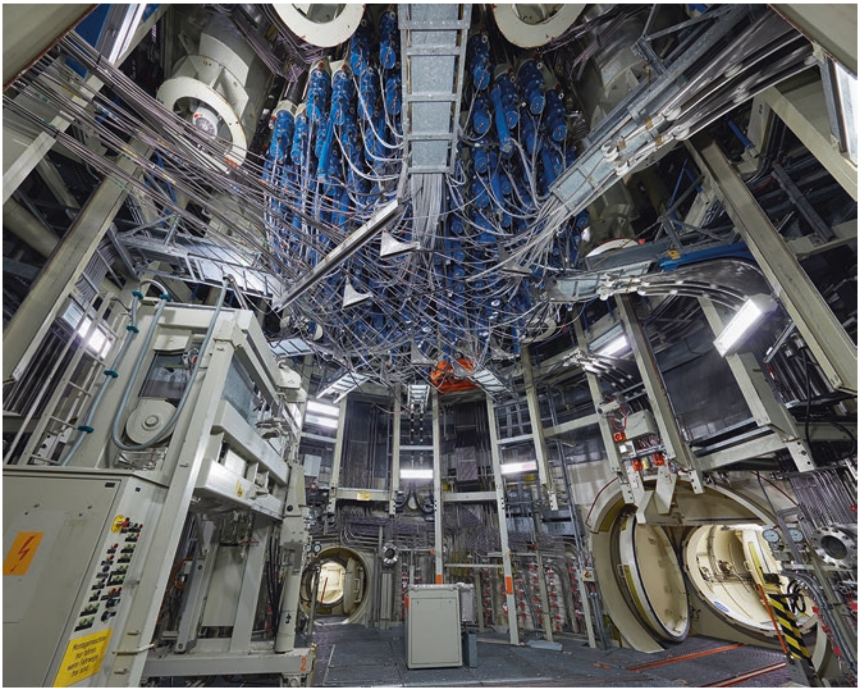

Fig. 6.11 Control rod drive room with electric motors (blue), directly below the reactor vessel, at the nuclear power plant Krümmel. In boiling water reactors, the control rods are adjusted from below

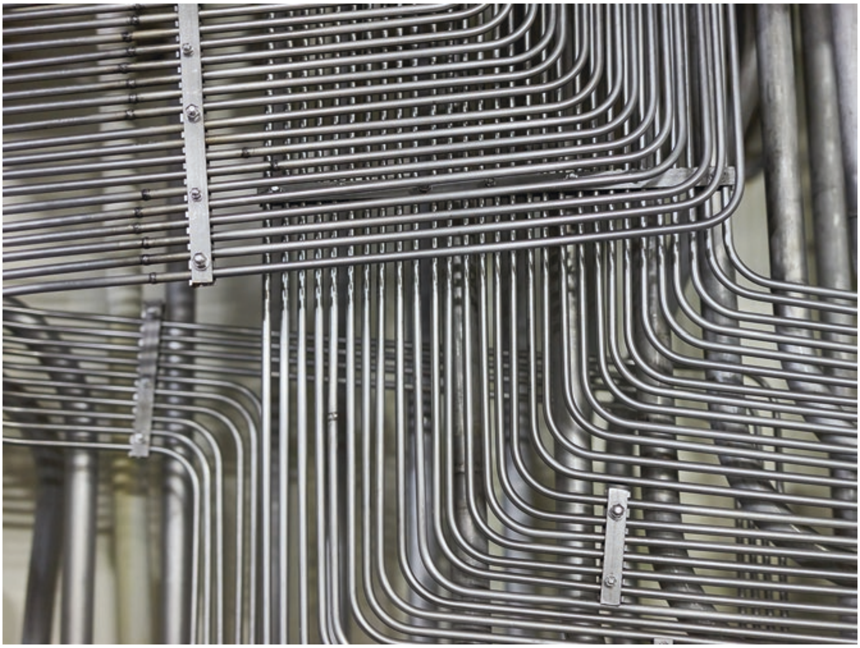

Fig. 6.12 Control rod drive room, Krümmel. Every safety relevant pipe or cable exists in multiple redundancies, leading to a huge number of components

A fast shutdown is achieved by special control rods that can be shot with high pressure into the reactor core, and, if necessary, by introducing strongly neutron-absorbing substances such as boric acid into the cooling water. Water is required for cooling the fuel rods and to prevent a core meltdown, but it should not act as a moderator when a shutdown is necessary. Thus, during an emergency the water is mixed with a neutron absorber like boron, which suppresses the chain reaction and prevents it from flaring up again.

The cooling water pumps need a constant power supply. Even after shutting down the reactor, the still strong decay heat must be removed. As soon as the reactor is shut down and no longer produces electricity itself, the pumps depend on an external power supply. Since the supply via the power grid can fail due to natural disasters, accidents, sabotage, etc., an *emergency power supply* such as large diesel generators is therefore an important protection against the dreaded "station blackout" – the total failure of the power supply.

A failure of the cooling system can lead to a *core meltdown* (see Fig. 6.13). During this process, the fuel rods overheat so much that the fuel rod cladding melts and releases the uranium tablets inside, as well as the highly radioactive fission products. In order to prevent this, the reactor must be supplied with sufficient cooling water as quickly as possible in the event of a temporary failure of the cooling system (due to pump failure, power failure, etc.) or in the event of water loss. Several large independent pump and emergency power systems are available for this purpose. If this is not possible, the fuel rods can partially or even completely melt within a short time and the molten mass can accumulate at the bottom of the reactor vessel. This is extremely dangerous because in this case the geometrical arrangement of the fuel rods and the control rods is lost.

Firstly, such a melted mass is difficult to cool. Secondly, so much fissile material can accumulate at the bottom of the reactor vessel that – if moderator material is still present – the chain reaction can start again. The enormous heat generation can then cause the hot and highly radioactive mass to eat its way through the reactor vessel and even through the floor of the building up to a few dozen meters into the ground and contaminate the groundwater, among other things.

Fig. 6.13 (continued) of a large part of the fuel rods, massive release of radioactive materials in the reactor pressure vessel and via the pipes and possible leaks also into the containment. The core melt collects in the lower part of the pressure vessel. Phase 4: Melting of the completely destroyed reactor core through the reactor pressure vessel and, in the worst case, through the containment and the concrete foundations with a corresponding massive release of radioactivity. The extent to which the wider environment is contaminated depends on the transport routes for the volatile or semi-volatile radionuclides

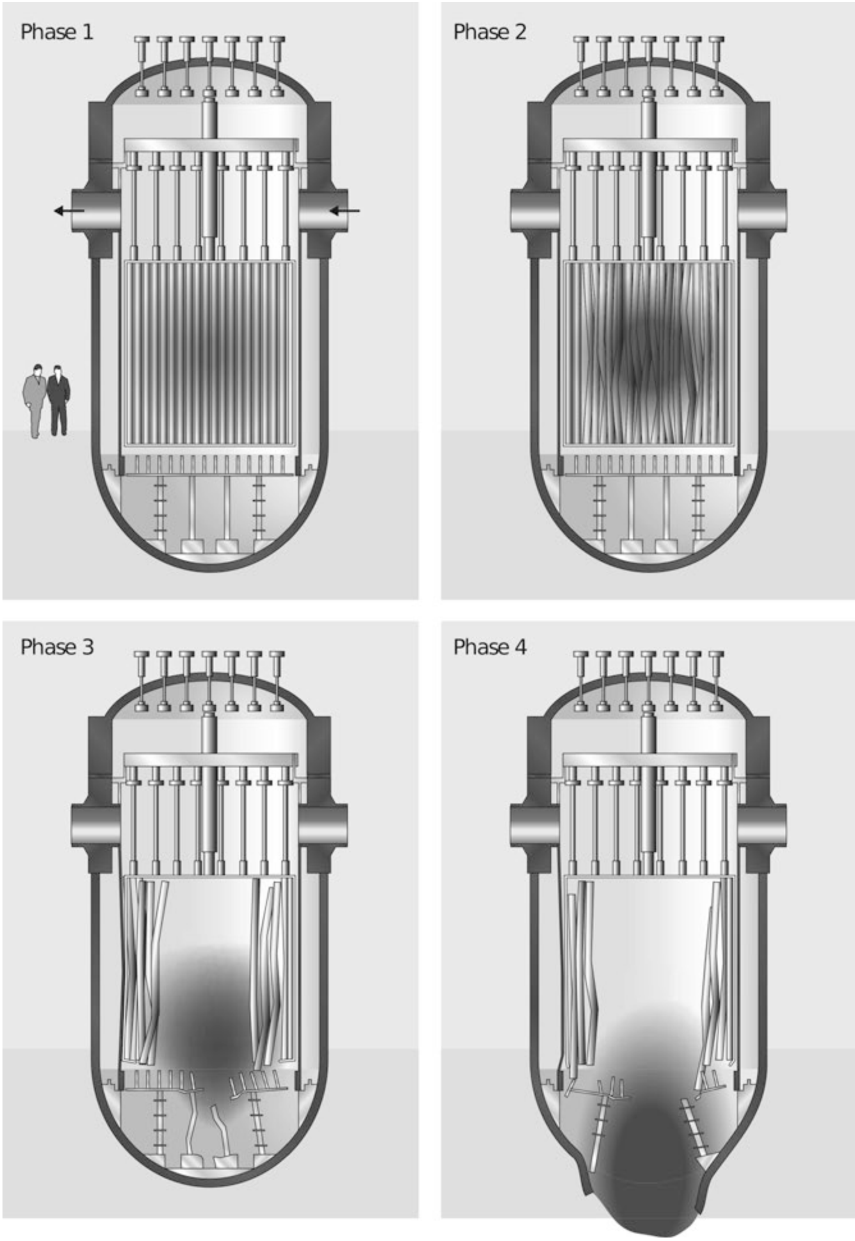

Fig. 6.13 Core meltdown in increasingly serious stages. The destroyed fuel assemblies form a closed mass and, in the worst case, can melt through the massive steel wall of the reactor pressure vessel. Phase 1: Local overheating, rapid countermeasures required. Phase 2: Severe overheating, deformation of the fuel rods, loss of geometry and controllability via control rods, use of boric acid required to interrupt the chain reaction. Beginning discharge of fission products from the fuel rods. Phase 3: Melting

To prevent this, boric acid can be fed into the reactor via an emergency feed system. The element boron is an excellent neutron absorber, which is why it is also used for the control rods. Boric acid prevents the chain reaction from restarting (also called re-criticality). But even if this restart does not occur, the fission products still generate a great deal of heat, especially in the first hours and days, but to a lesser extent also over months and years.

The danger that the core melt eats its way through the thick steel wall of the reactor pressure vessel is considerably smaller if a restart of the chain reaction is prevented. The risk also decreases over the course of days and weeks, because the short-lived, highly radioactive fission products have then already increasingly decayed and the heat output of the decay heat decreases accordingly.

To ensure the highest possible level of safety, the uranium with its fission products should remain firmly enclosed in the gas-impermeable cladding of the fuel rods. These usually consist of a special, high-strength zirconium alloy that allows only neutrons to pass through. The other barriers are then the reactor pressure vessel, the containment and the outer reinforced concrete shell of the reactor building.

In order to prevent the release of radioactivity – and also because of the high pressures in boiling water and pressurized water reactors – the *reactor pressure vessel* is made of steel about 20 to 25 centimeters thick. It is, apart from the fuel rods, the first and most stable barrier against the escape of radioactivity. Its dimensions are usually a good 10 meters high and 5 meters in diameter. The reactor pressure vessel is surrounded by a reinforced concrete cylinder a good 2 meters thick, which shields radiation and is therefore called *biological shield*.

This is surrounded by the *containment*, which consists of a several centimeters-thick steel wall. It is used to confine radioactive substances if the reactor pressure vessel or the pipes leading to it should leak, i.e. due to a core meltdown or material-related leakage. The containment is sealed off from the outside world by airlocks and is under slight negative pressure so that radioactive substances, should they be released during operation, remain in the containment and are not released into the environment. The containment can be entered through personnel or material airlocks.

The *outer reinforced concrete shell* of the reactor building is up to 2 meters thick. It serves not only to confine radioactive substances but also to ward off external dangers. Crashes of larger airliners or targeted terrorist attacks with armor-piercing weapons are difficult to neutralize. But the newer models should withstand even such impacts.

If the cooling fails and the reactor overheats significantly to over 1200 degrees Celsius the water in the reactor can react with the shells of the fuel

Fig. 6.14 Personnel airlock to the containment of the Grafenrheinfeld nuclear power plant. The old telephone on the left-hand side has meanwhile been replaced by a more modern one

rods, producing large amounts of hydrogen. This happens because the otherwise very stable zirconium cladding of the fuel rods can react chemically with water steam at such high temperatures. Together with the oxygen in the air, the hydrogen forms the highly reactive *oxyhydrogen gas*. This is why nuclear power plants should also have systems that can remove hydrogen. Or, the oxygen around the reactor is replaced by nitrogen, which does not allow an oxyhydrogen explosion.

The destruction of the reactor buildings in Fukushima was caused by such oxyhydrogen gas explosions as a result of core meltdowns. Passive catalytic recombiners remove hydrogen by recombining it with oxygen to water – without burning or explosion – until the hydrogen levels reach low enough levels. Such recombiners do not need external power supply and also work when a station blackout occurs. They consist of around 100 metal sheets with a coating of palladium and platinum, on whose surface hydrogen reacts with oxygen. In this way, the recombiners can prevent the proportion of hydrogen in the reactor building from rising above the dangerous 4%, at which there is a risk of an oxyhydrogen explosion. After some time, however, the plates have to be replaced because they lose their effectiveness.

Fig. 6.15 Personnel airlock, access to the containment from the reactor side, at nuclear power plant Isar. When one stays inside the containment, totally isolated from the outside, surrounded by nothing else but sophisticated technology, one easily gets the sensation of being in some kind of spaceship

As we will see in the later discussion of nuclear accidents, it can take some time before the water is lost or evaporated in case of cooling failure. But even a long time after shutdown, the decay heat in the range of megawatts is enough to heat up the fuel rods to very high temperatures. When they fall dry and heat up to 1200 degrees Celsius, the commencing reaction of zirconium alloy with water steam is strongly exothermic and produces even more heat than the decay heat. This leads to a partial or full meltdown of the reactor core and causes even the highly heat-resistant uranium pellets inside the fuel rods to melt.

To gain time and make even severe accidents better controlled, research programs are underway to increase the durability of fuel rods. There are tests with chromium-plated fuel rods, which have a higher resistance against water vapour and can delay a meltdown scenario. This would earn the operators precious time to conduct countermeasures.

In the future, *accident-tolerant fuel* (ATF) will be one of the most important new developments in reactor safety. Drawing from lessons learned during the multiple meltdowns of the Fukushima reactors, there are new research programs to replace the neutron-transparent zirconium alloy with other materials. This provides more safety than just coating. One candidate is iron-chrome alloys. Since they are less transparent to neutrons, the reactor steering would need to be adjusted to compensate. But they do not react with water steam like zirconium alloy and would thus be an important safety improvement. After rigorous tests, they could become standard in the nuclear industry in a couple of years. And later in the future, even fuel rods made of silicon carbide could be used. This material is highly heat resistant, but also brittle. To make fuel rods out of it, it would be necessary to develop a coiled composite material that combines physical and heat resistance.

If a meltdown occurs and the melted core eats itself through the pressure vessel, only the thick concrete foundations stand between the highly radioactive material and the ground, with a severe, large-scale contamination of the groundwater looming. The hot material can melt itself even through a five-meter-thick concrete foundation in only a couple of days. This also sets free large amounts of hydrogen and carbon dioxide, which increase the danger of an oxyhydrogen explosion. They can also lead to a breach of the containment due to high pressure levels. Smaller modern reactor designs circumvent this problem by constraining the size of the reactor core up to the point that even in the case of a meltdown, the reactor can be cooled from the outside well enough that the melted core does not eat itself through the reactor pressure vessel.

With larger reactors, this does not work. To prevent the radioactive substances from melting through the bottom of the reactor building during a core meltdown, nuclear engineers have developed the concept of a *core catcher*. This is a large basin made of a high-strength and heat-resistant concrete-ceramic mixture located below the reactor pressure vessel. In the worst case of a core meltdown, the core catcher is designed to collect and spread out the non-gaseous radioactive substances in a controlled manner until they have cooled down and decayed enough to be disposed of. Core catchers are a new development and are already being used in some reactor types. But since they require some space below the reactor pressure vessel, older reactors cannot be refitted with them.

When a meltdown occurs, the pressure inside the containment can rise sharply, endangering the integrity of the containment. To prevent an uncontrolled burst, there are bursting discs that only open when a certain pressure is reached. To ensure that they do not release too much highly radioactive material into the environment, they direct the gases over a system of several filter stages, with liquid and metallic filters. This "filtered venting" is another method to make even severe accidents more manageable.

Summing up these points, the safety of nuclear power plants is ensured by the following measures. Firstly, in the case of an incident, it must be possible to interrupt the chain reaction quickly and reliably by means of control or emergency rods or, if necessary, by introducing boric acid. Secondly, the cooling of the fuel rods must be ensured so that their structural integrity is maintained. If these two points are not ensured, the release of radioactivity and severe accidents up to a core meltdown may occur. The reactor pressure vessel as well as the outer protective shell of the containment must then limit the amount of escaping radioactive material as good as possible in order to exclude a hazard to the surrounding region. The functioning of the emergency systems depends on a working power supply, which must be secured by multiple emergency power systems. Only some of the newer and smaller reactor types are designed in such a way that they can provide passive cooling without external power. They do this by, for example, large water basins installed above the reactor level.

Nuclear reactors cannot explode like atomic bombs. Firstly, they do not have uranium-235 in the required enrichment. Secondly, the difficulty in building atomic bombs is to compress the required material long enough in a very confined space until the neutrons have fissioned a large part of the fissile material in a very short time. This can only be achieved with highly enriched fissile material and the aid of explosives that are fired with great accuracy and suitable casing material. This is a decisive technological hurdle in the construction of nuclear weapons. In nuclear reactors, these conditions are not met.

The INES Scale: Within and outside the Safety Margins

When things go wrong, very different scenarios can unfold. Modern nuclear power plants have much higher security standards than some of the old models. But even if the residual risk is low, there can always be fatal combinations of technical defects and human error that trigger an unforeseeable accident.

The INES scale (International Nuclear and Radiological Event Scale) is an indicator of the severity of nuclear incidents and accidents. This scale was developed by the International Atomic Energy Agency (IAEA), which is committed to promoting the peaceful use of nuclear energy. The IAEA's work includes increasing the safety of nuclear power plants as well as monitoring the Nuclear Non-Proliferation Treaty and preventing the illicit spreading of nuclear weapons and material. The INES scale ranges from 0 (insignificant deviation) to 7 (major accident). One can argue if "catastrophic disaster" would be a better name for accidents of level 7, since this describes complete failure of the reactor with a massive release of radioactivity, like in Chernobyl or Fukushima. The INES scale is logarithmic, just like the Richter scale for earthquakes. One step on the scale thus means a tenfold increase in safety significance. Accidents can become dangerous for the population from category 5, for the personnel of nuclear facilities accidents from category 3. So far, Chernobyl and Fukushima are the only two category 7 accidents.

Thanks to their many safety systems, nuclear power plants are built to withstand major malfunctions without releasing more radioactivity to the environment than allowed. Reactor safety experts use the term "MCA" (Maximum Credible Accident) to describe such malfunctions. Often, the term "DBE" (Design Basis Event) is also used.

These are not the worst accidents imaginable, but the most serious events that can be controlled according to the state of science and technology with which that plant has been designed. The exact definition of an MCA therefore always depends on what regulatory authorities consider an acceptable risk for the population. An "event beyond MCA" or "ultimate MCA" is accordingly an accident whose controllability is no longer given by the design of the plant and which goes beyond the limits given by its safety and emergency systems.

An "ultimate MCA" is therefore also called a "beyond-design-basis event." Thus, all incidents which release more radioactivity than approved have to be called "ultimate MCA," even if the radioactivity released is low. This corresponds to events on the INES scale introduced for nuclear incidents from level 5, but sometimes only serious and major accidents (INES level 6 and 7) are classified as ultimate MCA. So while a moderately severe accident might just be controllable, with only small amounts of radioactivity released, a major accident must be expected to result in a comprehensive failure of the safety systems, since the plant was not designed to cope with such a scenario.

Table 6.1 The International Nuclear Accident Scale (INES)

Category	Meaning	Examples
7	**Major accident** Severe release of radioactivity, widespread impact on health and environment	Chernobyl (1986) and Fukushima (2011)
6	**Serious accident** Significant release of radioactivity, full deployment of disaster control	Kyshtym (1957)
5	**Accident with wider consequences** Limited release of radioactivity, artial deployment of disaster control, severe damage to equipment, several radiation deaths	Windscale/Sellafield (1957), Harrisburg/Three Mile Island (1979), and Goiana (1987)
4	**Accident with local consequences** Radiation exposure of the population at the level of natural radiation exposure, heavy exposure of personnel, at least one radiation death	Fermi 1, Monroe (1966), Lucens (1969), Saint-Laurent (1969, 1980), and Tokaimura (1999)
3	**Serious incident** Slight radiation exposure of the population, severe radiation exposure of personnel	Windscale/Sellafield (2005)
2	**Incident** Inadmissible radiation exposure of personnel	Gundremmingen (1977)
1	**Anomaly** Deviation from permissible operation	
0	**Deviation below scale** Event with no or little safety significance	

Training and Testing

The types of nuclear power plants and research reactors in existence are manifold, and just as manifold are the training facilities, simulation power plants and pilot facilities used to test new technologies, materials and processes. Nuclear power plants are usually one of a kind. Even if they belong to a series of similar plants, they are adapted to their local requirements and built by various subcontractors. For this reason, the *training control rooms*, at which employees can train mastering an emergency, are unique. The training control rooms are also used to let managerial personnel prove their knowledge.

It has indeed happened that an Atomic Energy Authority has denied a person a management position in a power plant because he or she did not succeed in getting a simulated emergency under control in such a training control room. Such practise-oriented exams include the task of returning a reactor to safe condition within 30 to 60 minutes. Behind the scenes of these training control rooms, computers simulate the behaviour of a real control room as close to reality as possible. However, the training facilities are completely independent of the actual reactor and serve training purposes only.

The control rooms of different types of power plants are imitated true to detail in simulation centres. Here, power plant employees can participate in technical training classes, but the scope also comprises pre-testing of modified power plant setups. The large simulation centre of KSG/GfS (power plant simulator association/association for simulator training) in Essen, Germany, also has a large glass model of a reactor, providing the opportunity to study various thermo-hydraulic effects of operating processes as well as possible hazardous incidents.

One step closer to reality are *simulation power plants*. Here, no nuclear fission takes place, but these facilities still contain important components such as reactor pressure vessels, primary circuits, steam generators and the like. Most of these facilities are miniature versions of actual power plants, offering the opportunity to conduct important safety tests. Technicians can test

Fig. 6.16 D45 simulator control room at the reactor simulator center in Essen

Fig. 6.17 Educational glass model of a two-loop pressurized water reactor at the reactor simulator center in Essen. With this worldwide unique model, heated by electrical rods, the water flow can be studied under different working conditions

Fig. 6.18 Training reactor (AKR-2) at the Technical University of Dresden, a so-called zero power reactor with a maximum output of 2 watts

temperature profiles, behaviour under loss of pressure, control options during power outage and many other occurrences. Since the nuclear fuel rods do not contain any fissile material but are heated electrically, all tests can be conducted without the risk of releasing radioactivity.

The so-called "incident testing facility for primary circuits" is a full-height copy of the primary circuit of a typical pressurised-water reactor. It allows studying the behaviour of its critical components even if several safety systems fail simultaneously. This delivers valuable knowledge of the thermal-hydraulic behaviour and it is of great importance for the development of modern nuclear power plants. Other test facilities represent the primary circuit of typical reactors at a miniature scale. This enables measurements to determine the coolant flow and different scenarios of coolant mixing. It also allows to study different accident scenarios, as in the case of leakages.

In contrast to simulation power plants, *pilot plants* have a fully working nuclear core. Such small-scale nuclear power plants serve to test new technologies. Due to their small size, they are cheaper to build and easier to control. They have a reduced power output, typically in the range of tens of megawatts. Pilot plants are not designed for economic profitability but rather to deliver valuable experience for the construction of larger plants and for the establishment of new reactor types.

Probabilistic Safety Assessment and Residual Risk

The key responsibility of every nuclear safety commissions is to ensure that any potential risks stemming from the operation of nuclear power plants are taken into account. Such a *probabilistic safety assessment* (PSA) is a necessary licensing requirement that has to be passed before the official bodies allow the operation of a newly built nuclear power plant.

Prior experiences with similar reactors or pilot plants help to estimate the probability with which certain systems might fail. Apart from normal operation, crucial components of the plant also have to withstand abnormal operating conditions. These include severe weather conditions, seismic activity like earthquakes, tsunamis or flooding, or strong heat and pressure that can occur as a result of an accident in the facility. Other possibilities might include a terrorist attack, physical or cyber-sabotage. A secure nuclear power plant should resist all these conditions without releasing dangerous amounts of radioactivity. The approach to design a plant in this way is therefore called *deterministic safety analysis*.

However, as analyses of reactor accidents in the first decades of nuclear power has shown, such a deterministic safety analysis tends to underestimate the effects of unlikely events that might add up to create major problems. Therefore, from the 1980s on, researchers have developed complex tools for probabilistic safety assessment to account for such risks and to identify the possibly fatal combinations of malfunctions of the safety systems. This helps to identify possible weak points and develop effective countermeasures. Such a PSA can include several levels. In the first stage, every malfunction that might lead to a reactor meltdown is analyzed. In the second stage, the response of the containment is under scrutiny and the likelihood and magnitude of potential releases of radioactivity are assessed.

But perfectly secure technology does not exist, especially in a huge and complex system like a nuclear power plant. One speaks of *residual risk*, which remains even if all safety measures have been taken. We will see further down, in Chap. 10 on radioactive incidents and catastrophes, what kind of misjudgements have led to the biggest nuclear accidents in history, and how difficult it is to take the human factor into account.

7

Economic, Ecological and Political Aspects of Nuclear Energy

Nuclear power plants belong to the largest and technically most complex class of industrial buildings. The development of a new type can take years and cost billions of dollars or euros. It is therefore not surprising that there are only a few basic types that are built with certain variants by a few specialised companies. At the same time, each of these huge projects is adapted to the local requirements so that practically every nuclear power plant is a unique building. Even though this makes economic sense, it does make quality control and the accompanying risk estimation more difficult.

Nuclear power plants have a number of advantages over other types of power plants. They reliably supply large amounts of energy as base load power plants. And, viewed over their entire life cycle (including construction, uranium extraction, operation and decommissioning), they emit far fewer substances that are harmful to the climate and the environment than the fossil fuels coal, oil and gas. Although there is some controversy about the numbers, the emissions of carbon dioxide, nitrogen oxides and sulfur dioxide per kilowatt hour generated are well below those of fossil fuels and, depending on the technologies used, slightly above those of renewable energies.

The Nuclear Industry and the Fuel Chain

Nuclear power plants are only one (albeit the central) part of a complex industry. The provision of nuclear fuel begins with the extraction of uranium from ore deposits. The uranium ore is ground and the uranium is extracted and converted into so-called yellow cake, the basic material of the nuclear industry.

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_7

To enrich the isotope uranium-235, which is responsible for nuclear fission, the yellow cake is converted into gas form. Then, gas diffusion facilities or extremely fast-rotating gas centrifuges increase the content of uranium-235. Finally, the enriched gas is solidified again and tablets of uranium dioxide are produced. These pellets are used in fuel assembly fabrication plants to manufacture the fuel rods and join them to fuel assemblies. We discuss the treatment of uranium ore and the enrichment methods in more detail in Chap. 8 in "Extraction and processing."

When used in a nuclear power plant, the content of fissile uranium-235 inside the fuel assemblies decreases from the 3 to 5% enrichment down to slightly above the 0.7% found in nature. In addition, each fuel assembly produces about 16 kilograms of highly radioactive fission products and a good 4 kilograms of plutonium.

What happens to the fuel assemblies after use depends on political and economic considerations. One popular concept envisages that the spent fuel rods are to be sent directly to final storage. However, it is also possible to recover the uranium-235 remaining in the fuel assemblies as well as the plutonium and the fission products in reprocessing plants. This is only doable under high safety efforts. The highly dangerous substances produced must not be released to the environment under any circumstances; the gaseous fission products in particular have a very high hazard potential. There is also the danger that a critical mass of uranium or plutonium is formed during such a process, which then triggers a chain reaction and produces extremely strong radiation. The fission products as well as the heavy transuranium elements can be separated and sent for interim or final storage. During the technically highly complex reprocessing, accidents have repeatedly occurred in the past in which employees were injured or killed or radioactivity was released into the environment.

Due to a number of new construction projects for nuclear power plants, especially in China, India and Russia, the consumption of uranium will continue to increase and with it probably also the world market price. Consumption today significantly exceeds the production volume. This shortage is compensated by the reprocessing of fuel rods, by reserves and by material resulting from the disarmament of nuclear weapons. In the longer term, this could lead to increasing international focus on reprocessing plants and breeding technology, in which fissile plutonium-239 is produced from the otherwise useless uranium-238. However, this is accompanied by the risk of vulnerability of nuclear facilities, operational risks and proliferation.

However, even with reprocessing and separation of various types of radioactive material, the fission products and the transuranium elements are still

Fig. 7.1 Tailings. Casks of depleted uranium hexafluoride on the storage site of the Urenco uranium separation plant

intended for final disposal. The large quantities of plutonium produced are considered to be of particular concern. After a while capturing neutrons, reactor plutonium also contains heavier isotopes like plutonium-240, plutonium-241 on so on, which are not suitable for nuclear bombs, but these isotopes are still highly dangerous in terms of their radiation.

Due to the fluctuating world market prices for uranium, unconventional sources of uranium are increasingly being explored. This includes the extraction of uranium from the ashes of coal-fired power plants. Natural rocks and also coal always contain a certain amount of uranium and thorium. Some of them are blown through the chimneys with the smoke when the coal is burned. For this reason, coal-fired power plants emit similar amounts of radioactivity during normal operation as nuclear power plants. In the remaining ash, however, the uranium content is much more concentrated because uranium is a very heavy element and is less easily carried along with the air stream than others. The concentration of uranium in the coal plant ash is sometimes comparable to that of uranium mines and therefore is commercially interesting.

While most of the radioactive substances remain in the coal ash and in modern filters, a certain amount of uranium or thorium and its lighter and more volatile decay products (such as radon, polonium and lead isotopes) ends up in the flue gases of power plants. Depending on the opinion of the scientists and the type of coal used, the modernity of the filter systems and the predominant wind direction, the radioactive contamination of the surrounding area of coal-fired power plants is sometimes measurably increased, but normally not to a dangerous extent. On average, the radioactive emissions from coal-fired and nuclear power plants are normally well below natural radioactivity levels. Other emissions from coal plants are much more dangerous. Apart from climate gases, to which coal plants are the biggest single contributor, particulate pollution is a major source of concern. In addition, substances like arsenic, mercury and acid gases are set free. According to some studies, this could cost up to a million lives per year globally.

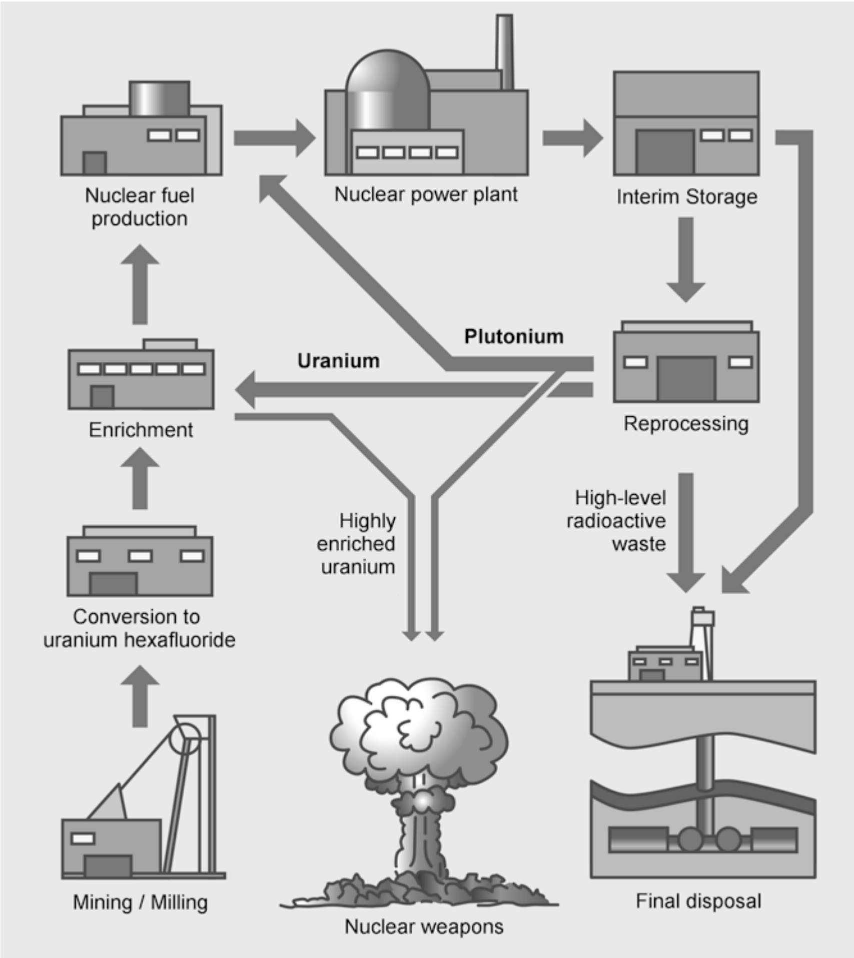

Fig. 7.2 The nuclear fuel chain including the planned final disposal. Countries with an interest in nuclear weapons must either master the high-grade enrichment of uranium-235 or the separation of as pure as possible plutonium-239 during reprocessing. Because of the proliferation risks and costs, reprocessing is increasingly being abandoned today by normal power plant operators

Construction and Decommissioning of Nuclear Power Plants

The construction time of the first nuclear reactors within the scope of the Manhattan Project was a matter of months. The better performance and safety a reactor was to provide, the more elaborate the construction became. The first reactor serving civil purposes, the Soviet AM-1 ("Atom Mirny," "peaceful atom") in Obninsk, went online in 1954 after three years of construction. It delivered its five-megawatt performance for almost 50 years without greater incidents. The Soviet research reactor F-1, the communist counterpart to the Chicago Pile-1, was in service even longer. It ran from 1946 to 2016 at the Moscow Kurchatov Institute, where most of the Soviet reactor lines were designed.

In the 1970s and 1980s, the typical construction time of new nuclear power plants was around six years. However, some of these power plants were the subject of altercations between anti-nuclear protesters and the police as well as juridical arguments that sometimes delayed the construction and commissioning by years.

Fig. 7.3 Construction of block 3 at the Angra nuclear power plant. Reactor building (center), turbine building (right), auxiliary hall (left)

Fig. 7.4 Dismantling preparations for the multi-purpose heavy water research reactor at Karlsruhe

In the meantime, construction times have in some cases increased significantly due to increased safety requirements, more complex technology and more elaborate certification processes. Many projects suffer from years-long delays and corresponding cost increase. Often, the time between approval and commissioning is more than ten years. During this time, energy prices can change – especially with the rapid development of renewable energies – and these variations are hard to predict. This makes long-term calculations difficult for the operators. Another aspect is lost engineering know-how, which must be redeveloped after many years without new nuclear power plant constructions.

Not just the construction, but also the dismantling of nuclear facilities is a highly complex affair. Before a nuclear power plant is decommissioned, the approval procedures and the planning of the dismantling process can take several years. The work itself often spans several decades, thus exceeding the building time considerably.

There are several methods to decommission a nuclear power plant. The idea is to either immediately dismantle or safely enclose the facilities. The advantage of immediate dismantling is that qualified personnel are still present who know the ins and outs of the facility. But the radioactivity levels are higher than in the case of safe enclosure. In the latter case, the entire facility is sealed off from the environment for years or decades before the actual disassembly begins. The US Nuclear Regulatory Commission calls this procedure SAFSTORE (Safe Storage). The de-fuelled plant is monitored for up to 60 years before the dismantling begins.

Contrary to many other types of buildings, a nuclear power plant is demolished from the inside out according to the radioactive contamination of the different building parts. Upon decommissioning, during the so-called post-closure phase, first the burnt, highly radioactive nuclear fuel assemblies are put into a spent fuel pool for approximately four years until the decay heat has decreased sufficiently to allow packing them into dry casks. These casks can then be put into air-cooled interim storage facilities before they can be transported to final storage.

The next step is the dismantling of the inner areas, especially the reactor vessel and the contaminated parts of the cooling loop. To do this, the workers need special systems, such as a high-pressure decontamination system, a drying system, an effluent treatment system as well as presses and saws. These are used to shred, clean and decontaminate meter-thick pipework, cables and other materials. Locks and air filters retain radioactive dust particles. Heavily contaminated building parts that should not even be touched with protective

Fig. 7.5 Dismantling of the Stendal nuclear power plant, inner parts

Fig. 7.6 Flooded basement of the emergency diesel building, Stendal. At the back the rest of the reactor building can be seen

Fig. 7.7 Dismantling of the reactor building, Stendal

clothing can be treated via remote control. The accruing low to medium radioactive materials are packed into suitable containers and put into interim storage as well.

When the radioactive control area has been cored, the next items to dismantle are the inner and the outer structures, and finally the solid building envelope. This includes chiselling the layers of paint of the walls and taking apart, cleaning and sandblasting most of the components. Huge band saws are used to cut parts such as turbine rotors into manageable pieces of around one ton each. Many chemical and mechanical surface processing activities are carried out in "active workshops." The major share of this material radiates very little or practically not at all. After the measurement values of the residual radioactivity have been approved, the building rubble is no longer subject to laws pertaining to nuclear material and can be burned or fed into recycling processes, or it ends up as landfill. The cost for nuclear power plant decommissioning can run up to the billions. At the end, the site gains "greenfield" status, which involves the complete removal of all systems and buildings, or it is used for other purposes.

Current Status of the Nuclear Industry

As of September 2020, altogether 409 nuclear power plants are in operation. They deliver about 390,000 megawatts, which is a good 10% of the worldwide electricity demand – down from a record high of 17.6% in 1996. 31 plants are in long-term outage, usually to increase security levels. Around 50 more nuclear power plants are currently being built, the majority of which are in Asia – especially in China, but also in Russia, India, South Korea, Japan, Bangladesh and Taiwan. In the Middle East, the United Arab Emirates and Pakistan are driving the construction of nuclear power plants. Several new power plants are also under construction in the USA, Great Britain and several countries in Eastern Europe. 190 plants have already been closed. More than 90 construction projects have been abandoned for various reasons. The mean age of the operating nuclear power plants is slightly above 30 years. Commonly, lifetimes between 40 to 60 operating years are reached. There are also plans to extend plant lifetimes up to 80 years.

The reason for the high number of current construction projects is that many of the power plants built during the boom period of the 1970s are reaching the end of their economic operating life. Combined with a steep global increase in electricity demand – numbers could more than double in

Fig. 7.8 Reactor room of the Gösgen nuclear power plant during annual revision. The large block in the upper left is a steam generator, the orange structure in the back is a loading machine, the silver pipe in the top left is a live steam pipeline

the 2020s – and the need to build carbon-free power plants, nuclear power is an interesting option for many countries.

Worldwide, there are plans for the construction of more than 100 new nuclear power plants, even though many of these projects are still subject to questions about financing and feasibility. For this reason, the actual number of plants that will enter construction phase will probably be somewhat lower than that. There are some serious economic obstacles. For one, the price for renewable energies has dropped significantly, and will probably drop further. Secondly, the costs to build reactors have risen due to increased safety demands. For this reason, many of the planned projects are under reserve of economic viability. In some cases, it might have been geopolitical rather than economic or environmental factors – higher energy-political autarchy, central controllability and a possible link to nuclear technology for military use – that geared the decision toward nuclear technology.

But even if renewable energies have become cheaper than conventional thermal power plants, there are still important reasons to maintain a fleet of large thermal power plants – usually nuclear, coal-fired or gas-fired. Security in energy production is one. Especially in winter, when sometimes there is no sunshine for days and wind speeds are low, electricity production by renewables sinks drastically. This can affect large regions and could lead to a lack of available power and corresponding blackouts as well. Thermal plants can power up to balance out energy fluctuations.

Another reason is the stability of the electricity grid. The amount of electrical power it can transport over large distances is limited not only by the grid capacity, but also by other constraints such as frequency stability, redispatch capabilities, reactive power and other system services.

Large plants contribute to the stability of the whole grid. When the share of renewables in total electricity production increases to a high percentage, the cost of these system services also rises, because unlike large thermal power plants, wind and solar power cannot be powered up or down at will. This explains the growing interest in small modular reactors, as they allow for a more flexible and adaptable stabilization of the energy grid – even if the raw cost per megawatt does not always seem favourable at first sight.

Another option is gas-fired plants, which use natural gas or also biogas or synthetic gas. Natural gas is less polluting than coal, and such power plants can be constructed faster than nuclear plants. For this reason, gas will replace coal in many cases and gas-fired power plants will play an important role in the electrical grid. But in the long run, to reduce carbon emissions, a transition to biogas, climatically neutral synthetic gas or green hydrogen will be necessary. This could lead to capacity problems to produce enough of the needed carbon-emissions-free gas and will also increase the price tag of gas-fired electricity generation. This and the decline of the fracking industry in the USA, as well as growing environmental concerns about shale gas, also explain the increasing interest in small modular reactors.

Ecological Footprint and Life-Cycle Assessment

Today, solar power generated by photovoltaics is already the cheapest means of generating electricity – at least as long as the sun shines. But, hitherto, this type of energy can only be stored at significantly higher cost. Many research facilities are currently working on possibilities to store solar energy in various media, like molten salt or ceramic compounds, to be able to produce electricity when it is dark. It will be interesting to see how these solar thermal technologies, which might become powerful competitors for nuclear power plant builders, will develop. In terms of electricity generation, nuclear energy and renewable energies share the advantage of not emitting climate-damaging gases during operation. However, they do generate some amount of carbon dioxide if their entire life-cycle is considered.

Roughly calculated, from construction to decommissioning, nuclear power plants release less than a tenth of the carbon dioxide per generated kilowatt hour compared to fossil power plants. The majority of the ecological footprint of a power plant – except for nuclear waste – stems from the enormous amounts of concrete (several 100,000 cubic meters) and steel (several 10,000 cubic meters) that are used for the construction of large power plants and that must be disassembled later. Adding to this is the laborious extraction of uranium and the energy-intensive enrichment. We will address these topics further in Chap. 8 on uranium mining.

In literature on life-cycle assessment, data on the ecological footprint of nuclear power plants varies greatly. Scientific meta-studies indicate a range of four to more than 200 grams of carbon dioxide per kilowatt hour. However, a value of around ten to twenty grams of carbon dioxide per kilowatt hour seems a realistic number for modern types of nuclear power plants. This is somewhat less than photovoltaics, slightly less than wind power and a bit more than hydropower, which has the lowest greenhouse gas emissions of all electricity producing facilities.

The energy return on investment (EROI) figures for nuclear energy also fluctuate considerably. This figure describes the ratio of the energy available in a quantity of fuel to the effort required for its use. A broad-based meta-study has shown a pessimistic EROI for nuclear energy of only 5. This means that calculated from power plant construction to uranium extraction to final disposal, five times the amount of energy used for construction etc. is produced by the power plant. But some sources, that view mining, construction, enrichment, decommissioning and waste storage more favourably, cite more than ten times higher EROIs for nuclear energy. Breeder technology can enhance this value, but at certain costs. Solar energy and oil have an EROI of about 10, wind energy even 18, and biofuels also only 5.

Yet, with all these calculations there remains a high uncertainty factor concerning the processing of uranium ore which today is based on fossil energy. If the uranium content in rocks decreases too much due to increasing exploitation, the expenditure for extraction will increase significantly and the carbon dioxide balance will worsen. It is also to be expected that the life-cycle assessment of photovoltaic and solar thermal plants will become more favourable in the future, since much research is being done on these still young technologies.

Open and Hidden Costs

Nuclear power plants, if they run long enough, provide very cheap electricity despite their high initial investment costs, which is why nuclear power is economically interesting for energy suppliers and energy-intensive heavy industry. They require comparatively little manpower and can achieve a capacity factor of 80 to 95%, which is the highest in the energy industry. Except for the annual revision and change of fuel assemblies, nuclear power plants often run the whole year through without interruption.

Fuel costs are also comparatively low. Compared to fossil power plants, the production of fuel rods for nuclear power plants only amounts to about 15% of the total costs. For this reason, the productive lifetime, which typically is around 40 years, is a decisive factor for the profitability of nuclear power plants. With modernization and good maintenance, operators often plan to extend the lifetimes up to 60 or even 80 years. This sometimes requires backfitting measures, as the security standards have risen over the years, especially after the Fukushima disaster. Such backfitting measures can include filters for certain radioactive substances, cooling systems, valves, instrumentation, additional grid connections etc. and can add up to the point where further operation is no longer economically feasible.

Yet, various factors are not included in the price of nuclear power. Firstly, one must consider the insurance costs. No nuclear power plant in the world

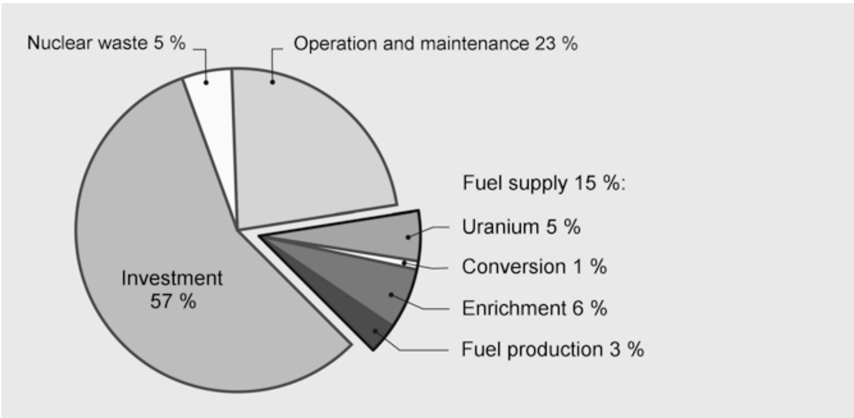

Fig. 7.9 The cost structure of electricity from nuclear energy. The high share of investment costs and the low share of fuel costs are striking in comparison to fossil fuels. Consequently, the lifetime is a decisive factor for the profitability of nuclear power plants. The calculated costs for nuclear waste are so far only estimates resulting from the originally planned final storage concepts and may turn out to be very optimistic

Fig. 7.10 Cooling tower, lamella level, during revision at the nuclear power plant Gundremmingen

is insured against a catastrophic accident. This is for the simple reason that no insurer in the world is willing to take out such insurance. It is not possible to clearly calculate the probability of such an incident occurring – as has been mentioned, even if a nuclear power plant belongs to a series, it is a unique construction and catastrophe tests are not reasonably feasible. Nor are the gigantic damage sums affordable by any insurance company. (For the concept of residual risk and its ethical implications, see below). Society as a whole is liable for catastrophes – even if the profits usually end up in only a small number of pockets.

Secondly, many scientific and technical feasibility studies have been pre-financed by the taxpayer. This is common practice for practically all new technologies that have economic and strategic relevance. For some countries with nuclear ambitions, the corresponding research is also of military strategic interest.

The civil research program in nuclear physics as well as in fusion and plasma research has many interfaces with military applications and also serves to acquire and maintain personnel experienced in nuclear technology. The funds provided to date for the expansion of renewable energies, for example, amount to only a fraction of what was once paid for the establishment of nuclear energy. Renewable energies, however, have so far a lower geostrategic

Fig. 7.11 Interim storage facility with storage machine at La Hague. Under each cover is a several meters-deep shaft for moulds with vitrified high-level radioactive waste

relevance than nuclear energy and, due to their decentralized structure, a less organized lobby. Also, fossil fuels and especially coal have received huge subsidies over the decades – often with the geostrategic aim of guaranteeing a certain level of resource independence.

Thirdly, as long as the disposal problem remains unsolved, the costs of long-term storage or possible reprocessing or transmutation of nuclear waste are not foreseeable at all. Although there are reserves in the billions that are earmarked for the financing of disposal, many billions have been put into exploratory mining for final deposits over several decades, some of which had to be given up due to unexpected problems. Little has been achieved so far and many questions are open.

In the author's view, this indicates that new solutions should instead be investigated. In addition, new ways of political decision-making and a deeper ethical understanding of our responsibilities toward future generations are urgently needed in order to find acceptable solutions for this technically, politically and ethically complex subject area; more on this, however, in the final Chap. 11 on disposal.

Taking all these points into account, the profitability of nuclear power would be significantly reduced. Point 1 in particular is an otherwise unusual exception. Point 2 is a typical technological subsidy, but the sums involved are quite large compared to other technologies. Point 3, on the other hand, represents a certain special case. Fossil-fired power plants, for example, do not participate at all or only to a small extent in the true costs of their emissions. Future generations would perhaps like to retrospectively impose massive fossil fuel taxes on the generations living today in order to pay for future environmental damage and climate change. But at least in the case of carbon dioxide emissions, the basic effects are clear and at least the magnitude of the damage can be estimated. Carbon dioxide, once in the air, has a long-term effect on the climate that affects all people. Highly radioactive substances must not be allowed to enter the biosphere in the first place, and extremely long-term consequences are hardly predictable.

The exemption of the energy companies from these costs makes the operation of nuclear power plants economically calculable in the first place and thus makes sense from a private economic point of view. The exemption of these costs is therefore to be understood as an offer from political bodies to the energy companies against the background of the geostrategically intended entry into nuclear technology. However, the calculation is far from complete as to whether other technologies might not be more profitable in macroeconomic terms. The true costs of the nuclear industry could rise significantly in view of the lack of disposal concepts. However, although fossil fuels have for a long time been the economically most relevant benchmark, they are also not subject to sustainable cost accounting with regard to their environmental impact. Common goods such as stable climate, clean air, drinkable water and an environment that is not too polluted are always at risk of being damaged by individual interests, which is why strict regulations are needed to protect them. Although some steps have been made thanks to the international climate agreements, today, humankind is still a long way from pricing the principle of sustainability into its global economy.

Apart from financial aspects, there are also moral obligations of the individual to the community and those of the community to the individual to consider. These obligations consist not least in finding a social consensus on energy production and consumption, on dealing with risks and on the consequences of our actions for future generations. Considering the way we deal with these problems and the way we assert our interests on the political stage, in the media and on the streets, it is clear that even modern democracies still have considerable potential for development.

Part III

Social Conflict Areas of Nuclear Energy

Through the use of nuclear energy, we are confronted with several problem areas. These are summarized in this part under the four main aspects of uranium mining, proliferation, radioactive incidents and disasters, and disposal. Each of these main subjects contains in turn numerous sub-items, which naturally cannot be discussed here in all details. Nevertheless, these points can be regarded as the most important problem areas of the entire nuclear technology.

The four subjects are all linked to economic and technological considerations, individual profit-seeking, political and geostrategic calculations and not least to military applicability. They raise ethical questions concerning social organization and the balance of interests and risks within and between societies, as well as between present and future generations.

8

Uranium Mining

Uranium is the basic material of the nuclear age, just as coal and oil were the fuel of the Industrial Age. The special properties of the two main isotopes of this element – one can be split, the other be used to breed plutonium – make access to this substance vital for any country that wants to belong to the club of nuclear nations. Uranium, however, is not equally distributed over the world.

Occurrence and Quantities

The earth's crust contains on average only 0.0003% uranium. Depending on the local concentration, this amount of uranium provides about half of the natural radioactivity, especially via the decay product radon, which – as a radioactive noble gas – can escape from the rock. In certain geological formations, uranium occurs in much higher concentrations.

There are very different types of uranium deposits. Uranium is abundant in some silicate rocks such as zircon and monazite, but uranium-specific minerals are also found. The most important of these uranium minerals are uraninite (also called pitchblende) and coffinite. Economically, uranium ores with a uranium content of 0.03% to 0.5% are usually mined today. Some mines with very special geological conditions even have uranium concentrations of up to 20%. However, these are rare exceptions. Often uranium is also extracted as a by-product of gold or copper mines.

Uranium production is spread over only a few countries worldwide. The main producers are Kazakhstan, Canada, Australia, Niger, Namibia, Russia,

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_8

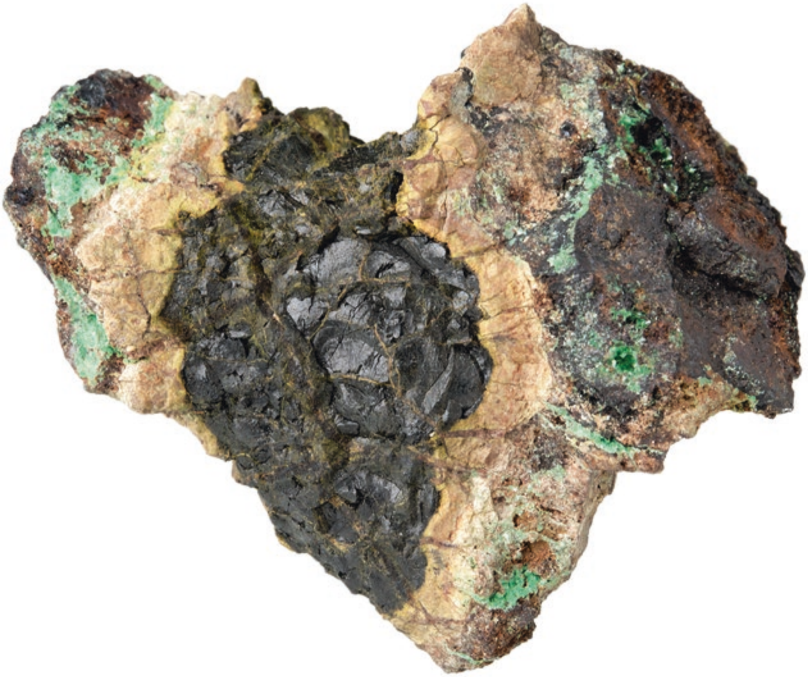

Fig. 8.1 Uraninite (or pitchblende) with sections of uranopilite (yellow) and torbernite (green). This piece of rock marks the very beginning of the nuclear age. Uranium was discovered in 1789 by the renowned chemist Martin Heinrich Klaproth, who also discovered a number of other elements. The image shows one of the samples from the Ore Mountains used by Klaproth for the discovery of the element. It is now in the collection of the Natural History Museum in Berlin. Credit: Hwa Ja Götz, Natural History Museum Berlin

Uzbekistan, the United States and China. Many former mines, especially in the USA and Europe, are considered exhausted. With modern extraction processes, however, they could be partially developed again.

Since the world market price for uranium fluctuated somewhat in recent years, and extraction methods are being developed, even low-grade uranium deposits are being analyzed for exploitation again. The world production is often lower than the consumption; the missing quantities are compensated by stocks, reprocessing of spent fuel rods and uranium sourced from the disarmament of nuclear weapons. This highly enriched weapons-grade uranium is depleted again to be used in reactors.

The demand for uranium is expected to continue to grow as the number of nuclear reactors increases. For this reason, potential uranium deposits are increasingly being prospected, or decommissioned mines are being examined to determine whether recommissioning would be profitable. In light of the fact that the known uranium deposits can only secure the supply for a few more decades, unconventional processes are now also being tested, such as the extraction of uranium from the ashes of lignite- (coal-) fired power plants. The ashes of coal with a particularly high uranium content can have a higher uranium content than some uranium ores. Seawater, too, is a uranium reservoir; large amounts of uranium are dissolved in it, but in very low concentrations. The extraction of uranium from seawater would only be profitable if the world market price were to increase several times over. This process is also being tested with regard to its industrial feasibility.

However, due to the fact that uranium mining accounts for only a very small percentage of electricity costs – about 5% – even expensive mining methods are likely to be profitable in the future. Uranium is still much less prospected worldwide than fossil fuels. The reserves known today could probably be stretched by several decades, perhaps even centuries. Should seawater extraction one day turn out to be practicable and economical, the uranium reserves will probably be sufficient for hundreds to thousands of years – at least if consumption does not also increase significantly.

Extraction and Processing

Uranium is mined in three different ways: underground, open pit and by a chemical process known as “in-situ leaching,” in which the uranium is flushed out of the rock by sulphuric acid. Production wells are then drilled into the center of the ore body to extract the uranium-bearing solution from the rock.

The advantage of underground mining is that uranium-bearing ore veins can be mined in a very targeted manner, which reduces the amount of overburden and landscape consumption. The disadvantage is that uraniferous rock always contains a lot of the radioactive noble gas radon, which can accumulate in mines to high concentrations. It must be removed by suitable ventilation systems.

Surface mining is also suitable for lower concentrated uranium deposits due to the possibility of moving large masses of rock. In the process, corresponding quantities of overburden are produced. With the chemical process of in-situ leaching this can be avoided. But when using this method, larger quantities of sulphuric acid get into the rock, which can pose a danger to the groundwater, above all because not only uranium but also other heavy metals are dissolved from the rock.

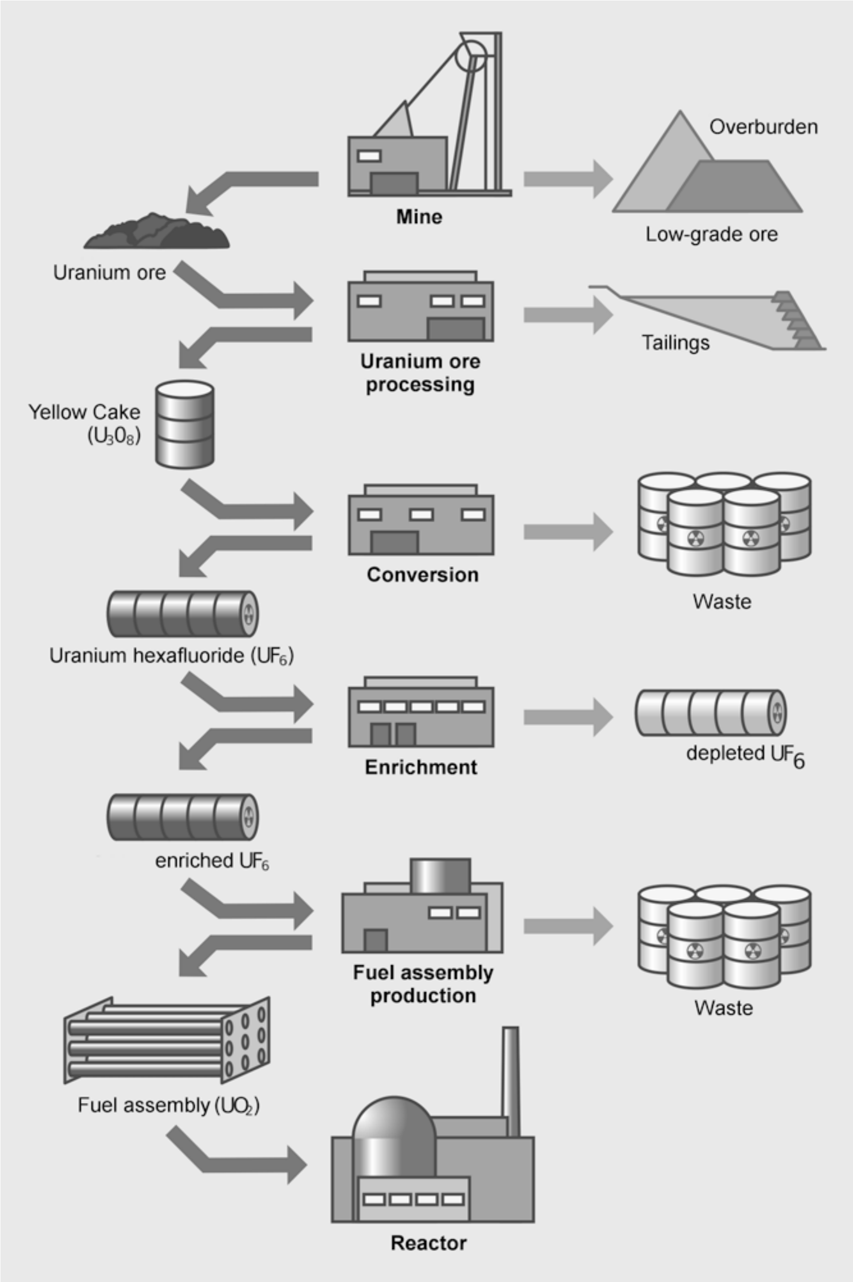

Fig. 8.2 Detailed illustration of the production of nuclear fuel from uranium ore

The usable uranium ore is delivered to a mill, where it is first crushed and finely ground. After milling, the uranium is chemically dissolved from the rock. Sulphuric acid is usually used for this. With the help of ammonia, the uranium is now precipitated from the acidic solution and then dried. The yellowish uranium powder with a good 70% uranium content is called *yellow cake* and is the basic material of the nuclear industry. About 1 kilogram of yellow cake can be produced from roughly 2 tons of ore by washing it out with acid. The exact amount depends strongly on the uranium concentration in the ore. This processing leaves larger residues of toxic waste, the so-called tailings. Even though most of the uranium has been separated, there is always a certain amount left in the tailings, together with the decay products of the uranium, which are also radioactive. The tailings must therefore be stored safely over a long period of time, which is normally done in special large basins. The tailings contain not only the radioactive decay products of the uranium rock, but also heavy metals mobilized by the breaking up of the rock and flushing out with solvents, as well as residues of the solvents.

The yellow cake is then chemically converted into gaseous uranium hexafluoride. In this form, it is suitable for enrichment to the required concentration in light water reactors, so that instead of the natural 0.7% content of uranium-235, now it is a good 3 to 5%. At an enrichment level of a few percent, which is sufficient for commercial operation in boiling and pressurized water reactors, we speak of low enriched uranium (LEU). There is some ambiguity with the definition. Officially, anything under 20% enrichment is called LEU, while anything higher is classified as highly enriched uranium or HEU. Weapons-grade enrichment is anything with more than an 80% share of uranium-235. For practical purposes, many experts also speak of moderately enriched uranium (MEU), which corresponds to an enrichment between 5 and 80%, as used in compact ship reactors and some research reactors. Since some research reactors run with very high enrichments, which poses proliferation risks, especially from terrorism, there are strong efforts to convert research reactors from the use of HEU to MEU.

There are different technical solutions for *enrichment*. As a large-scale commercial technology, gas centrifuges have now prevailed over the earlier diffusion process because gas centrifuges use less energy and are more flexible to handle. This is a technically very elaborate process. The reason for this is that uranium-235 and uranium-238 are chemically identical, making it impossible to separate them by chemical means. They differ only very slightly in their weight, so that a multi-stage process is required to increase the enrichment step by step.

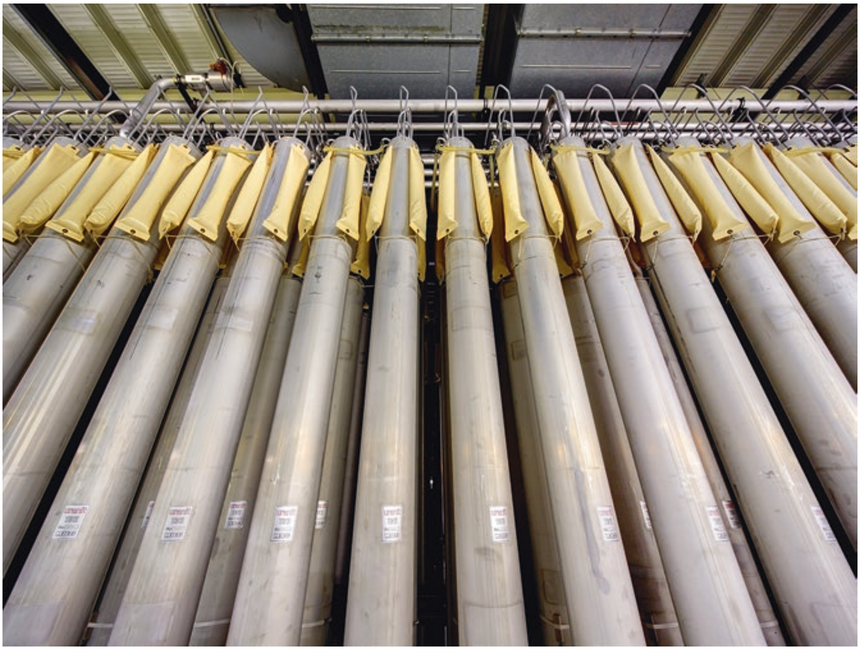

Fig. 8.3 Centrifuge cascade at the Urenco uranium separation plant in Gronau

Fig. 8.4 Containers with 3% enriched uranium, Advanced Nuclear Fuels, Lingen. This is uranium oxide for sintering to fuel pellets, converted from uranium hexafluoride

Fig. 8.5 Freshly sintered fuel pellets, Advanced Nuclear Fuels, Lingen. These pellets come out of the sintering furnace and are then pushed into fuel rods

In *diffusion separation*, the uranium hexafluoride is forced through a porous membrane under pressure. The molecules containing uranium-235 are somewhat lighter and therefore diffuse through the membrane a little bit faster. The separation factor per stage is low. More than 1000 stages connected in series result in a so-called separation cascade, which provides enriched uranium. However, this process is relatively energy-intensive.

Much more efficient is the isotope separation with *gas centrifuges*. These centrifuges are elongated cylinders made of aluminum, steel or composite materials that rotate extremely fast, typically at several tens of thousands of revolutions per minute. Due to the difference in mass between uranium-235 and uranium-238, the gas molecules experience slightly different centrifugal forces. Thus, each centrifuge causes a slight shift in the isotope ratio. Whole cascades of hundreds of centrifuges can be interconnected to produce either large amounts of low enriched uranium for power plant operation or small amounts of high enriched uranium. To ensure that the centrifuges are not used for the production of weapons-grade material, international control institutions like the IAEA need to check such installations by regular inspections. Interestingly, the modern design of gas centrifuges was developed in the Soviet Union, with the help of many German and Austrian scientists and engineers who were conscripted after World War II.

Fig. 8.6 Fuel assembly production with frameworks for pressurized water reactors. The guiding channels for the control rods are already installed, the fuel rods will later be placed in the empty slots. Advanced Nuclear Fuels, Lingen

After enrichment, the production process is not finished yet. The enriched uranium is first converted into solid uranium dioxide and then formed into small pellets. These are inserted into fuel rods, which are finally put together into fuel assemblies that can be placed in reactors.

Hazards in Uranium Mining

Mining in uranium-bearing rock is associated with special dangers. Compared to the other problem areas of the nuclear industry, they appear less obvious, because they mostly occur out of the sight of the media of developed countries. The main hazards consist of the radiotoxicity of radon, the radio- and chemical toxicity of the tailings as well as the landscape consumption and business practices of some mining companies. The latter point is a particular problem in developing countries or in sparsely populated areas. It is not limited to uranium mining, but applies to all types of insufficiently regulated and controlled raw material extraction.

The first danger is the inhalation of the radioactive noble gas radon-222, which is the immediate decay product of radium-226, which again belongs to

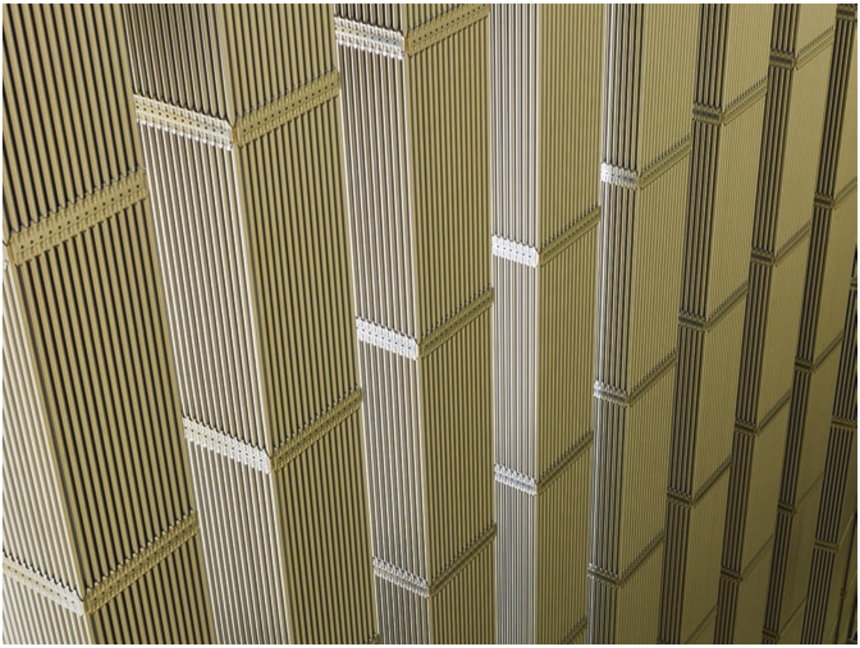

Fig. 8.7 Fresh fuel elements, Grohnde. The cladding of the fuel rods is made of Zircaloy, a special zirconium alloy which is highly permeable to neutrons but also corrosion resistant and safely encloses the radioactive contents

the decay chain of uranium-238. Although it only has a half-life of 3.8 days and therefore cannot travel long distances in the air, it is released from the rock and can accumulate in poorly ventilated rooms and especially in mine galleries. Its decay products are also radioactive and can be deposited in the lungs. As a highly active alpha emitter, it can cause severe damage to lung tissue and eventually lead to lung cancer. (See the decay series of uranium-238 in Fig. 3.5. The dangerous radon has the element symbol Rn-222.)

Already in the Middle Ages, a frequent cause of the death of miners was the so-called "Schneeberg disease," named after the village Schneeberg in the Saxonian Ore Mountains. The rocks there contain a high proportion of uranium. As a result of this, the miners, who were actually mining for silver, cobalt and bismuth, were unknowingly exposed to very high doses of radiation from radon. Only at the beginning of the 20th century was the reason for the high rate of lung cancer found. This problem occurred worldwide in uranium mines, especially in the period after World War II, when the winning powers needed large amounts of uranium for weapons production.

The East German uranium deposits in the Ore Mountains, for example, were of great strategic importance to the Soviet Union and represented the most important source of its early bomb material. The Soviet leadership paid little attention to the health of the miners in this workers' and peasants' state. The aim was to scrape together material for the first Soviet atomic bombs as quickly as possible to make up for the geostrategic deficit with the United States. Therefore, basic safety precautions were disregarded. Before these mines were largely exploited, the communist German Democratic Republic was the third largest uranium producer in the world. Probably thousands of cases of lung cancer can be attributed to these mining activities.

Nowadays, good ventilation with fresh air is installed to ensure that no dangerous concentrations of radon can occur in such mines. However, there are many other dangers that result from the special nature of uranium mining and the associated consumption of landscape. These include the pollution of the environment with heavy metals and toxic effluents such as sulphuric acid, which can threaten the groundwater. The nature of these threats is comparable to other types of mining and is highly dependent on the existence of and compliance with environmental standards.

Fig. 8.8 Tailings storage site with casks of depleted uranium hexafluoride, Urenco

Fig. 8.9 Tailings of a large uranium mine in Australia. Credit: Strahlendes Klima e.V., aerial view from the film *Uranium – is it a country?*, documentary about the origin of uranium, www.strahlendesklima.de

The total area of uranium mining sites is not large compared to other raw materials. Furthermore, uranium mining is in the hands of only a few large corporations, which is why there are less uncontrolled activities than in gold mining, for example.

The particular problem with uranium mining, however, is that not only uranium, but also all its decay products (including radioactive isotopes of radium, radon, polonium and lead) and other heavy metals (such as arsenic or cadmium) are extracted from the rock by grinding and chemical separation, thereby making these substances mobile.

Large quantities of crushed toxic material lie on the tailings dumps, which must be secured for long periods. Strong winds can spread this material as dust into the environment. Toxic substances can contaminate the groundwater. The large amount of water used in uranium mining in water-poor areas also poses a major problem, as the often very poor farmers in these areas cannot compete with international mining corporations. Outgassing radon can accumulate in residential areas nearby. To reduce the radiation and to avoid dust formation, tailings are often surrounded with dams and then flooded with water. These dams in turn can soften and burst.

The Church Rock Disaster

It is not well known that the largest release of radioactive material in the history of the USA was one such dam burst. At Church Rock in New Mexico in 1979, almost 400,000 tons of contaminated water and over 1000 tons of tailings were released into the Rio Puerco, which served as a drinking water reservoir for various indigenous villages of Navajo, Hopi and Pueblo Indians. This led to a contamination which exceeded the permissible limits for radioactivity several thousand times over and rendered the river unusable as a drinking water reservoir for many years. However, poverty and water shortages often left farmers in this region no choice but to let their animals graze and drink from the river.

In that region, there have been around 20 uranium mines over the years. Even before that dam accident, many of the employed indigenous workers did their job under precarious conditions, often without masks, gloves or other security precautions. Many did not even speak English. The Navajo language had no term for the concept of radioactivity. For this reason, already before the dam break, there had been a high occurrence of lung, kidney and liver diseases as well as cancer cases.

The breaching of the dam announced itself months in advance. Already in 1977, technicians had discovered small cracks in the dam and warned of the consequences. The ground on which the dam was built was not geologically stable. However, the operating company United Nuclear decided not to reinforce the dam, although the cracks were getting larger and larger. Instead, the company hoped that the scorching sun of New Mexico would evaporate the waste water. But on July 16, 1979, with a loud bang, the dam finally burst and a yellowish, foul-smelling broth poured over the landscape. After the dam break, the local health situation deteriorated. Not only indigenous people, but also Hispanic and white Americans were affected. After rather superficial cleanup work and a short shutdown, United Nuclear was allowed to resume its mining activities.

It is a sign of scandalous business practices, public indifference and far-reaching political corruption that even for this incident, which took place on US territory and affected its citizens, hardly any reliable epidemiological figures are available, although the extent of the accident is known and the proportion of cancer and kidney disease among the affected inhabitants is significantly higher than the American national average. Some environmental organizations classify this accident as the third biggest civilian accident of the nuclear age, just after Chernobyl and Fukushima and comparable to Kyshtym.

Only a few years ago – decades after the incident – a major epidemiological study was finally initiated on pregnant Navajo women and their children.

If not just the release of radioactivity but also the number of people seriously harmed is taken into account, due to inadequate civil protection and lack of public interest, the consequences of this accident may even surpass the Fukushima accident. This remains to be judged by future studies. If one takes public negligence of basic radiation protection measures into account, the Church Rock disaster as well as the hazardous working conditions of the East German uranium miners probably deserve to be ranked among the most severe radiological incidents in nuclear history. But especially in the early years of the nuclear age, nobody really cared about the effects of radiation on the miners' health. In uranium mines worldwide, be it in Colorado, Canada, the Congo or South Africa, safety levels were low and the working conditions were often highly irresponsible. And there is even less news of the living conditions of people in other, more remote regions of the world where uranium and other raw materials of our highly technical civilization are mined.

The fact that indigenous people were affected by this accident is by no means a coincidence. It may sound surprising at first that 70% of the uranium mining sites currently providing the raw material for a high-tech industry are located in the territory of indigenous peoples. However, the principles of the market economy and the human drive for profit naturally favor mining on land that costs less and where, due to poverty, people are more willing to take on risky ventures with high profit margins. Unfortunately, this is often associated with additional problems of low social control, a lack of publicness, economic entanglements of local authorities and companies, and the associated opportunities for corruption and lack of monitoring of safety standards.

It is also often observed that the promised profits do not remain with the local people – only the environmental damage. Or, in the case of resettlement, the promised compensation is not paid or only partially paid. Niger is a prominent example. It is one of the poorest countries in the world, but rich in uranium. Uranium exports, especially to France, account for over 60% of exports and are the most important source of foreign exchange. Water consumption and contamination caused by uranium mining have led to problems in this central African country. But many people do not profit at all from the exploitation of its natural resources.

These are common side effects in the post-colonial commodity business. In uranium mining they are aggravated by the radiotoxicity of the overburden, which makes more comprehensive safety measures necessary than for instance at iron ore or copper mines. The repair of damage to the landscape caused by uranium mining is sometimes considered as expensive as the extraction of

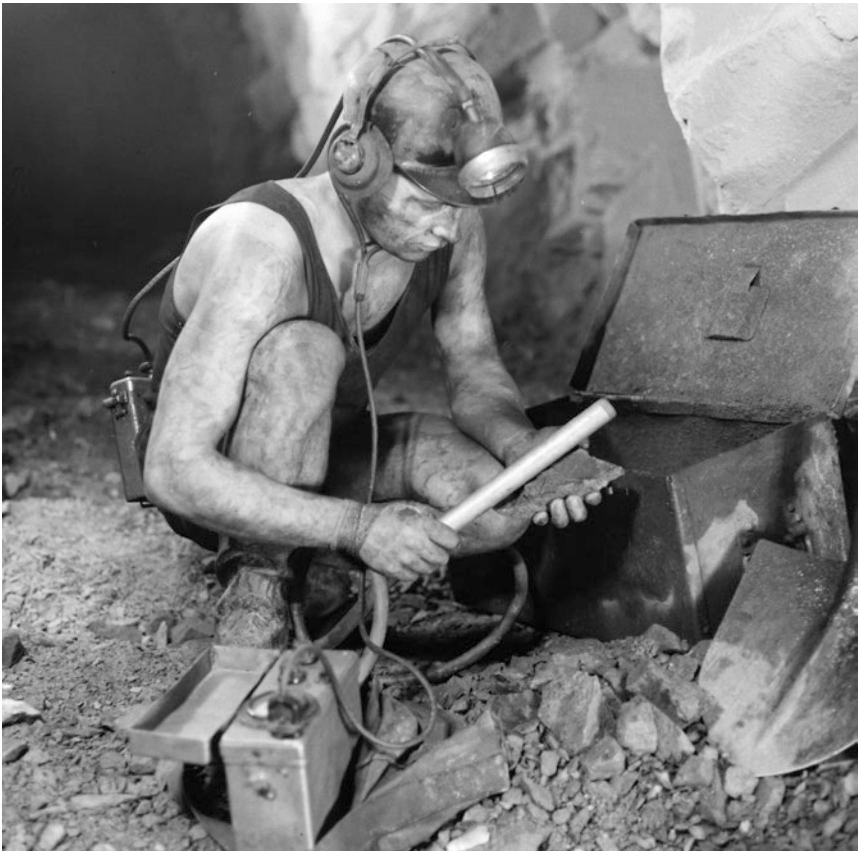

Fig. 8.10 Miner in the Ore Mountains, radiometrically sorting uranium ores around 1960. Credit: Wismut GmbH

uranium itself, which is one reason why it is repeatedly neglected. In the event of non-compliance with safety and environmental standards, the operating companies have so far had little to fear, either legally or through consumer behavior due to the low level of public interest. While it has become common practice for uranium mining companies to pay into remediation funds in order to reduce the financial burden on the taxpayer for landscape remediation, these funds have often proved to be far from sufficient.

For all these reasons, several indigenous groups in various countries have started to publicly oppose the development of new uranium deposits and the opening of new mines on their land or around national parks. For some of them, such invasive mining and interference with nature is also a violation of religious traditions and taboos. The First Nations in Canada as well as Aboriginal communities in Australia have spoken out time and again against uranium mines.

This shows that the understanding of nature of some indigenous peoples, whose self-image is closely tied to nature, is fundamentally different from the more technocratic perspective of highly modern societies. Both types of societies may attribute the label "civilized" to each other in a different degree.

9

Proliferation

Proliferation is the spread of weapons of mass destruction and their carrier systems. In a narrow sense, this refers to the weapons themselves or the corresponding materials and knowledge for their construction. In a broader sense, especially in the case of nuclear proliferation, it also refers to any technology that could be useful for the construction of nuclear weapons. This includes special centrifuge technologies as well as certain types of reactors, which are particularly suitable for the production of weapons-grade material, up to and including rocket technology. Due to the enormous destructive power of nuclear weapons and their geostrategic significance, nuclear proliferation is the most sensitive area of international arms control, which is subject to special monitoring and regulation. The most important instrument for this is the *Treaty on the Non-Proliferation of Nuclear Weapons,* or Non-Proliferation Treaty for short, which entered into force in 1970.

The Non-Proliferation Treaty states that, with the exception of the five official nuclear powers and permanent members of the United Nations Security Council – China, France, Great Britain, Russia (then Soviet Union) and the USA – all other signatories are prohibited from possessing nuclear weapons. Without a binding deadline, the Non-Proliferation Treaty also calls on the official nuclear powers to achieve general and complete disarmament under international control. Furthermore, the Non-Proliferation Treaty grants all member states the right to a civil nuclear program. The Non-Proliferation Treaty can be terminated by all signatories with three months' notice. It has been signed by all UN member states with the exception of the de facto nuclear powers India, Israel, North Korea and Pakistan. The International Atomic Energy Agency has no or only limited access to control the nuclear

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_9

facilities of these countries. South Africa has destroyed the few nuclear weapons it had developed in a secret program during the apartheid era and then joined the Non-Proliferation Treaty.

Apart from the cases of national nuclear weapons programs discussed here, nuclear bombs lost and never found again in plane crashes or submarine accidents, as well as radioactive substances that have disappeared or been stolen – such as numerous Soviet isotope batteries – are also a danger of proliferation. They could be used by terrorist groups to build a dirty bomb and for blackmail purposes. Controls on nuclear materials have become much stricter since the collapse of the Soviet Union, but not even in reprocessing plants can the disappearance of dangerous materials be documented sufficiently sharply, let alone prosecuted.

The Balance of Terror

The logic of the Cold War, in which the ideologically and geopolitically controversial blocs in West and East were armed to the teeth, can be expressed in simple words: Whoever shoots first, dies second. Or to put it another way: Even a state that conducts a successful first strike against its opponent, causes millions of victims and destroys practically all of its opponent's nuclear weapons must fear that at least some nuclear bombs will survive the attack and destroy its own cities. So, once both sides had built up a sufficiently large stockpile of nuclear weapons, neither side could win a nuclear war anymore – at least, if victory is understood to be more than just the killing of a larger amount of enemy civilians than one's own civilians. And even this logic has been pushed to an absurd point by the multiple overkill capacity of the huge nuclear stockpiles of both superpowers (Fig. 9.1).

To maintain the balance of terror, one must possess nuclear weapons that can be used in indefensible retaliation, even in the event of a large-scale surprise attack by the enemy. This strategic situation is called *mutually assured destruction* (MAD). It was first fulfilled by long-range bomber fleets, wherein a large number of aircraft was in the air around the clock, as in the operation "Chrome Dome." After several serious accidents of bombers with full nuclear weapon loads, like in Palomares, Spain and Thule, Greenland, these tasks fell to the nuclear intercontinental ballistic missiles, which are either bunkered in high-strength underground silos or kept in mobile concealed launchers. In addition, nuclear second-strike capability is guaranteed by strategic nuclear submarines that can carry up to two dozen missiles, each of which can carry several warheads. A single strategic nuclear submarine thus houses a gigantic

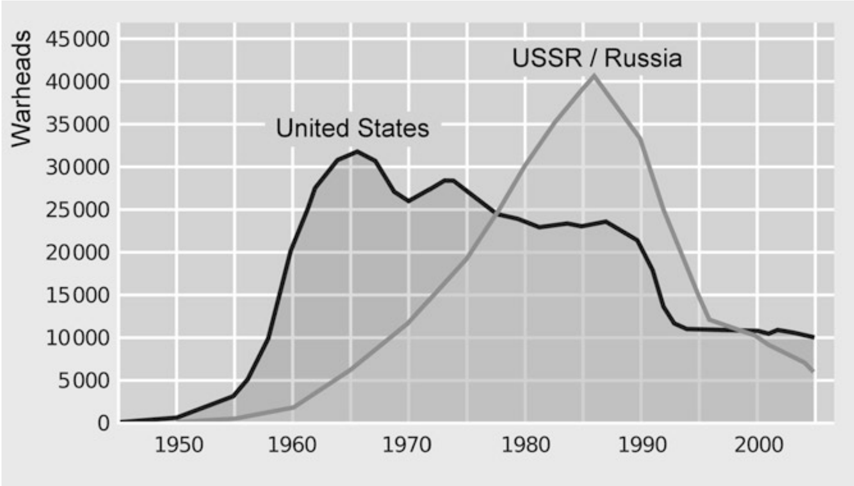

Fig. 9.1 The nuclear weapons stockpile of the two superpowers. Correlated are the gigantic economic burdens of nuclear armament during the Cold War

destruction capacity many times more than all ammunition of World War II combined. Modern nuclear submarines can launch their ballistic missiles in a submerged position and remain underwater for months thanks to their nuclear propulsion. Small and reliable ship reactors – especially for submarines and aircraft carriers – played a decisive role in the arms race of the Cold War. Since nuclear submarines can thus sneak undetected close to the enemy coast, they offer not only a second-strike but also a first-strike capacity, forcing the enemy to take extensive precautions.

As long as the possession of nuclear weapons was limited to the two major blocs of the Cold War, the bipolar balance of terror could theoretically be grasped more easily than in a multipolar world, as it is becoming more apparent in the 21st century. Today a similar stalemate exists between the adversaries India and Pakistan, but it is exacerbated by the unresolved dispute over the Kashmir region and the mutual accusations of supporting terrorist or separatist groups.

The Non-Proliferation Treaty is often criticized for merely cementing the geostrategic status of the winning powers of World War II by prohibiting other nations from possessing nuclear weapons. In view of the destructive potential of nuclear weapons, however, this constellation has the advantage that firstly, control over nuclear weapons is easier to secure against misuse and terrorism since fewer nations have access to them. Secondly – and this has been proven both theoretically and historically – there is a geostrategic incentive for neighbors and regional counterparts of nuclear-armed states to also arm themselves with nuclear weapons, which can lead to ever-increasing proliferation. Thirdly, the risk of a falsely initiated nuclear war, for example, through the misinterpretation of missile launches as a nuclear attack, increases with the number of nuclear powers. And fourthly, the cold, uncompromising logic of mutual annihilation is weakened and the world political situation becomes much more unmanageable and incalculable when many small or medium-sized states each hold only a small arsenal of nuclear weapons. The temptation to use a nuclear first strike to eliminate an opponent's nuclear weapons potential may then still lead to international condemnation, but it is not as unlikely as the confrontation of large blocs.

In game theory, the balance of terror is a situation in which, due to the gigantic losses in the event of an escalation, there are great incentives to reduce the probability of such a situation occurring. However, the greater the number of unknown variables, the more difficult it becomes to understand and calculate such a situation. Particularly during the Cold War, extensive strategic research was conducted on the use of nuclear weapons and to develop a suitable nuclear doctrine. Nuclear weapons are primarily suited as a means of deterrence, as a last resort in the case of an enemy attack. In particular, any state that uses nuclear weapons offensively would have to reckon with massive international condemnation. However, strategies diverge with regard to the question of whether nuclear weapons should be used only in response to a nuclear attack or also in response to a conventional attack. The NATO doctrine, for example, provided for nuclear escalation even in the case of a purely conventional attack by the numerically superior forces of the Warsaw Pact. While at the beginning of the Cold War the immediate maximum nuclear escalation in case of war was foreseen, this doctrine was later changed to a gradual escalation. Depending on the individual situation, the nuclear doctrines of the great powers still differ today.

The quintessence of all these theoretical considerations is quite simply that the existence of nuclear weapons reduces the risk of war and acts geopolitically as a stabilizing factor due to their deterrent character, yet at the same time it increases the possible damaging effects of war to an apocalyptic level.

Global Distribution of Nuclear Weapons

The development of the Cold War was such that after the end of World War II, the Soviet Union worked at full speed on nuclear weapons because it did not want to fall behind the USA strategically. As early as 1949 – years earlier than US strategists had suspected – the Soviet Union detonated its first nuclear bomb. At that time, the USA already possessed well over 100 atomic bombs, which compensated for its numerical inferiority in conventional weapons. In 1952 the USA then ignited the first thermonuclear hydrogen bomb, whose explosive power of about 10 megatons was about 800 times as powerful as the Hiroshima bomb. The Soviet Union was already able to catch up in 1953. By the end of the 1950s, the USA already possessed over 12,000 nuclear warheads, the Soviet Union over 1,000. The arms race accelerated further and further: a total of over 100,000 nuclear warheads were produced during the Cold War! The total number of available nuclear weapons reached its peak in 1986 with almost 70,000.

Thanks to various disarmament treaties, the majority of these nuclear weapons have since been disarmed. Today there are around 13,000 nuclear warheads left worldwide, of which more than half are in military stockpiles, while the rest are awaiting dismantlement. Nearly 4,000 warheads are deployed with operational forces, a substantial part of these on high alert, ready for use on very short notice. The arsenals of the two nuclear superpowers account for over 90% of all nuclear weapons. The official nuclear powers China, France and England each possess a few hundred warheads, the other nuclear powers between a few dozen to more than one hundred.

Especially in the USA and even more so in Russia, the gigantic complex of the nuclear arms industry is responsible for serious damage to the environment and health, abetted by the conditions of military secrecy and a lack of state and social controls. In the long term, this has damaged the acceptance of nuclear armament and the nuclear industry among the population. Because of the heavy contamination during the early above-ground tests, the governments later switched to detonating nuclear weapons underground.

Today, the major nuclear powers have the technology and sufficient experience to detonate nuclear weapons as a virtual simulation on supercomputers. Thanks to modern information technology, real atomic bomb tests are no longer necessary to modernize the arsenal.

To achieve this capability, France conducted a series of nuclear bomb test on islands in the Pacific in late 1995 and early 1996, many years after the other great powers did their last tests. These highly controversial, globally criticized tests provided its government with the final necessary data for its own nuclear bomb simulations. The US government had offered simulation technology, but the French government insisted on developing its own simulations, even against remarkably harsh public reactions.

An evaluation of nuclear armament during the Cold War and beyond is a difficult task.

On the one hand, the very existence of nuclear stockpiles is a threat to humankind; on the other hand, nuclear weapons have stabilized conflicts and maybe prevented conventional wars. When even the rich and powerful have nothing left to win in a nuclear war except infirmity and ruin, there is one less reason to wage war. Then the concept of mutually assured destruction is a guarantor of peace; this is how the strategists on both sides of the Iron Curtain precisely foresaw it in the Cold War. And indeed, for almost half a century this balance of terror has brought a Cold Peace to a divided Europe and led to more than one proxy war in other parts of the world. But at what price? In the 40 years between the beginning of the Cold War and the fall of the Berlin Wall, the world has repeatedly stood on the brink of nuclear war, whose internal logic is as escalating as any other war. There even is the concept of "brinkmanship," which is characterized by pushing events to the edge of serious escalation and thus gaining advantage over a more cautious adversary. This strategy can be studied in detail in the Cuban Missile Crisis between the USA and the Soviet Union.

The absurdity of the internal logic of the Cold War becomes obvious when one looks at the numbers for multiple overkill, i.e. the possibility of wiping out the enemy several times over by nuclear fire. Through large-scale contamination and a possible nuclear winter, this would massively affect the whole world and not only the warring nations. Einstein once remarked that he was not sure which weapons would be used to fight the Third World War, but that in the Fourth World War they would fight with sticks and stones.

Functionality of Nuclear Weapons

To build a nuclear weapon, it is necessary to first bring the fissile material to a critical mass and secondly to keep it compressed in a sufficiently dense form long enough for the incipient chain reaction to split a large part of the fissile material. The first step can take place in any appropriately equipped laboratory with access to enriched material; it leads to a chain reaction with enormous release of radiation and also heat. During the development of nuclear weapons, some technicians have died after a few days as a result of high doses of radiation during negligently triggered chain reactions. The radiation doses were in the range of several sieverts within a very short time (see also Table 3.1).

Such a chain reaction heats the fissile material very quickly, causing its volume to expand, which in turn slows down the chain reaction. Nuclear fission, the emission of neutrons and the next generations of nuclear fissions take place extremely quickly. For this reason, the fissile material must remain compressed long enough to ignite an atomic bomb so that the neutrons can fission as much of the material as possible. Only then is a high energy yield, and thus a high explosive power, possible. Since in a chain reaction the neutrons are released at an approximately exponentially increasing rate, the vast majority of atomic nuclei are only fissioned in the last moments of the chain reaction by the last generations of neutrons.

To compress the fissile material so precisely in time and space that these last, decisive neutron generations can cause a big nuclear explosion is a technically very demanding task. Fortunately, it can only be realized in large national research programs and not in the training camps of terror groups. Thus, although the principle of building nuclear bombs is known worldwide, there are only a few nations that have developed the technical competence and the necessary facilities to build such weapons. This is also the point at which international arms control comes into force to prevent proliferation. After all, any modern industrialized country with enough money and time is capable of developing nuclear weapons if only the political will exists.

There are two different design types of nuclear weapons. In both, subcritical masses are shot at each other, resulting in a supercritical mass. In the first, the *gun design*, two subcritical masses are fired at each other. This rather simple and heavy design type is only suitable for uranium bombs and was first used – untested – in Hiroshima. Of 64 kilograms of highly enriched uranium, approximately 650 grams, i.e. one hundredth of the fissile material, were fissioned within millionths of a second, which corresponded to an energy release of over 12,000 tons of conventional explosives. This type of construction is not suitable for plutonium, as plutonium has a much higher spontaneous

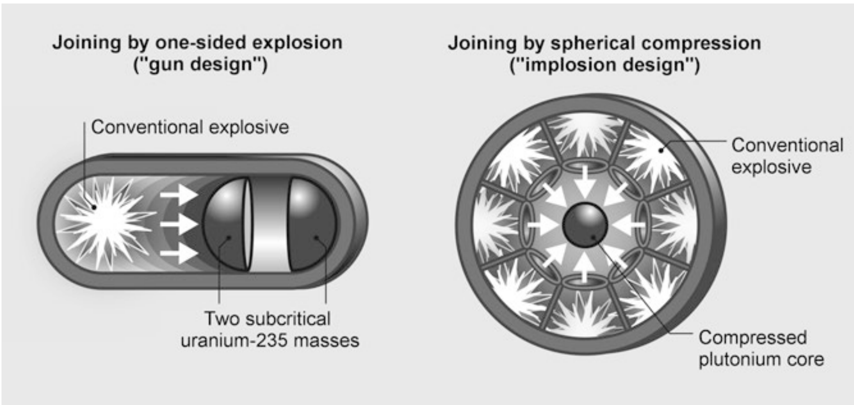

Fig. 9.2 The gun and implosion design to achieve a supercritical mass in the construction of atomic bombs

fission rate than uranium, which would lead to a premature ignition and comparatively harmless "fizzle" explosion.

Greater explosive power and a more compact design can be achieved with the second arrangement, in which a hollow sphere of fissile material is made to implode by means of external explosive lenses. This *implosion design* is suitable for plutonium and uranium or for mixtures of both. It allows the use of larger quantities of fissile material in a lighter design. In addition, due to the compression caused by the implosion, the critical mass is reduced, so less fissile material is required. Although this design is technically much more sophisticated, both in terms of materials and the high-precision ignition mechanism, its more compact and lighter construction makes it particularly interesting for countries that prefer missiles and cruise missiles to heavy bombers as their preferred launch vehicles. This corresponds to the usual geostrategic use as a difficult or even impossible to defend retaliatory weapon for deterrence.

This design has therefore become customary. It is also advantageous in terms of safety, because in the event of an improper ignition (due to material defects, sabotage, external explosion, etc.), the hollow sphere is not symmetrically compressed and consequently no chain reaction and thus no nuclear explosion is triggered, though radioactive material is spread in the environment as with dirty bombs. In more modern nuclear weapons, an asymmetrical construction of the detonator, which is triggered by precisely timed firing commands that only come with the order to deploy, provides additional protection against terrorist misuse.

Compared to uranium-235, plutonium-239 has a significantly lower critical mass, which makes a more compact and lighter bomb design possible. Today, at an average level of nuclear engineering capability, it is estimated that about 20 kilograms of highly enriched uranium, or a good 3 kilograms of plutonium, are needed to build a bomb with an explosive power comparable to that of the Hiroshima bomb. Uranium and plutonium bombs can be additionally enhanced by adding a few grams of tritium (the so-called "superheavy hydrogen") as a "booster," because this tritium undergoes fusion and provides additional neutrons. These bomb types have an upper limit for their explosive power, which nevertheless is incredibly high. Only thermonuclear hydrogen bombs in which nuclear fusion is ignited by means of an atomic detonation can achieve far stronger destructive power.

The construction and testing of nuclear weapons have led to massive contamination in many regions. Due to strategic priorities, the control of military armament factories is often less strict than that of civilian factories, so that large quantities of radioactive substances have been released during production time and again. The large number of over 2000 nuclear bomb tests conducted by all nuclear weapons powers to date has also led to the contamination of extensive areas. But there is some difference between tests high in the atmosphere, on the ground, in water or deep underground.

In atmospheric tests, the majority of the fission products are torn along with the rising fireball high into the stratosphere, where they remain for a long time, so that the majority of the short-lived radionuclides also decay up there. However, the remaining fallout contaminates a large area. Even dirtier are bombs detonated on the ground, because the neutrons they radiate can activate material in the ground nearby, creating radioactive isotopes, and spread these substances over a large area. Underwater tests have also led to strong contamination of the vicinity. Rather few underwater tests have been conducted by the nuclear powers, mainly to learn how to use nuclear depth bombs and torpedoes against enemy ships and submarines. Although it turned out that warships are quite well protected against such blasts if they are not too close to the explosion, the heavy contamination can expose the crew of ships in the area to dangerous doses of radiation.

The hundreds of nuclear bomb tests aboveground in the 1950s and 1960s led to a significant increase in environmental radioactivity. To limit further contamination, the Soviet Union, the US and Great Britain agreed to sign the Partial Test Ban Treaty in 1963 (also called Limited Test Ban Treaty). This declared that nuclear bombs were only to be tested deep underground where the radioactive substances remain trapped. However, accidents have happened in which the explosive power of the bombs was so high that the detonation created breaches in the ground, through which large amounts of radioactivity have escaped.

Regarding contamination by nuclear weapons, it must also be considered that there is much less nuclear material in a single atomic bomb than in the fuel rods of a nuclear power plant. The maximum contamination is therefore much lower, however, the explosion spreads all kinds of dangerous substances over a large area, not simply the highly volatile ones. And the highly active, short-lived radioactive isotopes are immediately spread into the environment.

Military Requirements for Nuclear Material

In contrast to nuclear reactors, in which a degree of enrichment of a few percent uranium-235 – or several percent plutonium-239 as an admixture in MOX fuel assemblies – is sufficient to initiate a continuous chain reaction, nuclear weapons require the highest possible purity of these isotopes. Only then can the critical mass be reached in such a way that the decisive moment for ignition is exactly reached. Early or late ignition leads to a significant drop in explosive power. Although such a bomb can still be devastating compared to conventional explosives, it is much less devastating than a precisely detonated atomic bomb. Material contaminated with other isotopes also has the disadvantage that the critical mass then increases sharply, which would make the bomb much heavier.

To build nuclear weapons, the enrichment level of uranium-235 should be over 80%, compared to 0.7% in natural uranium. This high degree of enrichment is also necessary because without moderator materials (which are useful in reactor operation but not suitable for bomb construction), no critical mass or only a very large critical mass could be achieved. This is because the fast, unmoderated neutrons released during nuclear fission do not react frequently enough with uranium-235 at lower enrichment levels and would not allow a chain reaction. A sufficient amount of such highly enriched uranium can only be obtained in large, purpose-built factories, today usually with gas centrifuges.

Since a state that has access to uranium can only produce weapons-grade material with the help of modern enrichment or reactor technology, this is another important aspect of proliferation control. The operation of a nuclear reactor is not in principle necessary to build a uranium bomb. However, it is helpful in that it can both serve as a civilian cover for a nuclear weapons program and provide scientists with important data on the reaction dynamics of chain reactions.

The situation is somewhat different with plutonium, which must first be bred in a nuclear reactor, as it does not occur naturally. During the breeding process in a reactor, plutonium-239 is produced from uranium-238 by neutron capture. The plutonium can then be extracted from the fuel rods. However, if it remains in the fuel rods for a longer period of time, part of it reacts with the neutrons constantly buzzing around in the reactor and turns into plutonium-240, which can then be further transformed into plutonium-241 or even heavier isotopes. These heavier isotopes are not suitable for bomb-making, as they can cause early ignition that is difficult to control. To build a plutonium bomb, one needs the purest possible plutonium-239. Of course, it somewhat depends on the knowledge and abilities of the weapon-builders how pure the plutonium exactly has to be. Or, in the confident words of a plutonium expert from Los Alamos: "We can build a weapon out of any plutonium."

Since plutonium-239 and plutonium-240 differ only minimally in weight, isotope separation as between uranium-235 and uranium-238 is not practical. The only way to obtain plutonium-239 that is as pure as possible is to remove the fuel rods after a short burning period, i.e. with a burn-up of only a few weeks or months in the reactor, to extract the plutonium in a reprocessing plant and to equip the reactor with new fuel rods. Plutonium from civilian power plants operating at high burn-up is hardly suitable for weapons. Weapons plutonium is therefore obtained in special types of nuclear reactors.

Depleted Uranium Ammunition

As a waste product, both the civil and military enrichment processes produce a larger amount of depleted uranium, which has a lower proportion of uranium-235 than natural uranium. Since uranium has an extremely high density and large unused quantities of depleted uranium are available from enrichment plants, this depleted uranium is used both in aircraft or yacht construction as a balance weight (in jacketed form) and in the manufacture of particularly powerful armor-piercing ammunition (so-called depleted uranium or DU ammunition). The latter is a very controversial secondary use, as the ammunition shatters into small radiotoxic particles that can also be inhaled by civilians.

The advantage of uranium ammunition lies in the enormous density of this element. As a result, it achieves a huge impact, making it ideal for use against armored vehicles. Added to this is the effect that the uranium dust ignites. Often a single projectile is enough to destroy a tank. NATO has used tens of thousands of such projectiles in the wars in former Yugaslavia as well as in Kuwait, Iraq and Syria. While such ammunition represents a good opportunity for the uranium industry to reduce its stockpiles of largely useless depleted uranium, the health consequences are rather poorly known. The main problem is that the uranium is finely atomized on impact, making it much easier to absorb. The uranium can be whirled up by wind or, over time, washed into the groundwater and increase background radiation levels. Although studies on this problem are still incomplete, independent groups of physicians demand a ban of this type of ammunition.

The Relationship Between Civil and Military Nuclear Technology

Normally, civil and military nuclear programs are strictly separated. Both because of the different modes of operation and because of questions of security and secrecy, a military program must be shielded from external influences and espionage. From a technological point of view, however, there are large overlaps, including both the training of nuclear-savvy personnel and the operation of certain types of reactors. Some reactor types like the heavy water reactors are very well suited for the production of weapons-grade plutonium. The extraction of heavy water is very energy-intensive and expensive. However, depending on the design of such reactors, since they work at low pressures, the fuel rods can be exchanged during operation, so that the reactor does not have to be shut down for fuel exchange. This increases the load capacity on the one hand and on the other hand allows for a continuous production of weapons-grade plutonium. Such a fuel rod exchange during operation is also possible with the RBMK reactor, as it was used in Chernobyl. It was also possible with early French and British reactor types.

To avoid this type of proliferation, boiling water and pressurized water reactors are used almost exclusively for civil energy production worldwide. They offer the safety advantage that they have to be shut down completely for fuel change, which usually happens once a year. A more frequent shutdown at the rate of a few weeks could be immediately detected by the changed electricity production and would be a strong indication for the international control authorities that possibly weapons-grade plutonium is to be produced there. Frequent shutdowns would also be quite expensive.

In the usual commercial nuclear reactors with high burn-up, the annually exchanged fuel rods are so heavily contaminated with different plutonium isotopes that they can at best be used very poorly in nuclear weapons and greatly reduce their efficiency and controllability. The separation of plutonium and other substances from fuel assemblies takes place in reprocessing plants. Reprocessing plants are therefore another important interface between civil and military nuclear technology that has "dual-use" capability.

The same applies to enrichment technology, which can only be dispensed with if heavy water reactors operated with natural uranium are used. Centrifuges, for example, can either be connected to enrichment cascades in such a way that they produce large amounts of low-enriched uranium for reactor operation or small amounts of high-enriched uranium for weapons production.

Therefore, the operation of civilian nuclear power plants – or at least research reactors – and the establishment of the entire nuclear industrial complex is an almost indispensable prerequisite for any country wishing to upgrade its military nuclear capability. Although it is also conceivable in principle that a country could procure nuclear weapons from another country without running its own nuclear program, it would then be completely dependent on trusting this partner country, which is very risky, especially in view of such a sensitive technology. All the nuclear powers operate a civilian nuclear

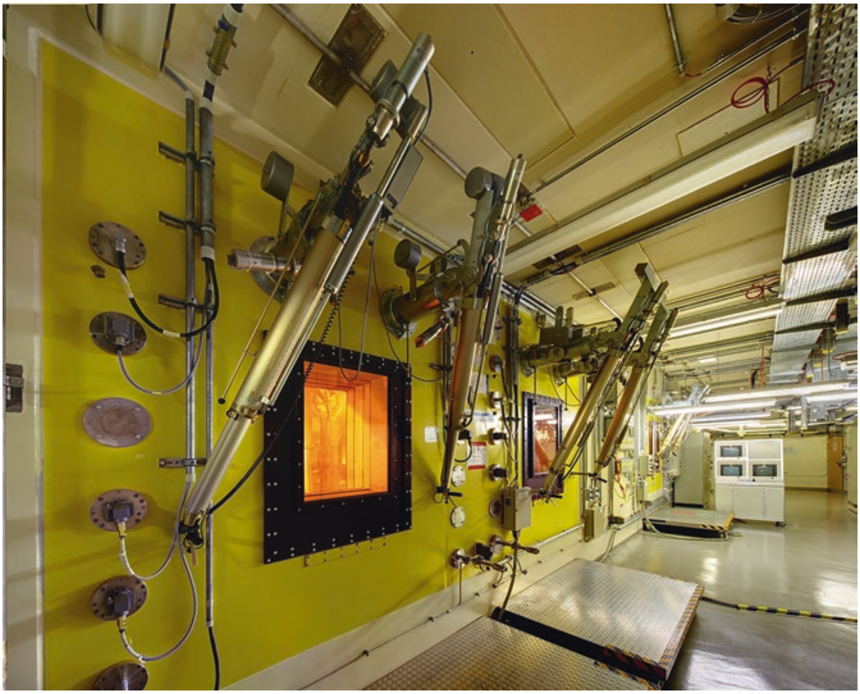

Fig. 9.3 Hot cell of the vitrification facility at the Karlsruhe reprocessing pilot plant for processing liquid high-level radioactive waste. Such hot cells have a 120-centimeter-thick lead glass pane that effectively shields radiation. Generally, hot cells allow extraction of different materials from burnt fuel rods or irradiated substances

program. In this way, technical and scientific talents can be recruited and trained, and additionally, a civilian nuclear program is a good cover for all activities required for a military program. This includes the procurement of centrifuges, reactor materials, uranium etc. on the world market. In the shadow of a civilian program, many armament activities can be concealed from the international community. Furthermore, a civil nuclear industry provides important knowledge about radioactive materials and the dynamics of chain reactions. Mastery of civil technology is thus a preliminary stage on the road to becoming a military nuclear power.

Interestingly, while today any connections between civil and military branches of nuclear industry are usually kept concealed, in the early days of nuclear power they were publically emphasized by governments. In this way, the costly construction of reprocessing plants etc. that were necessary for building nuclear bombs could be justified as being practical for the entry into the age of nuclear power anyway. This made the military projects look cheaper than they actually were.

Fig. 9.4 Analysis laboratory in the La Hague reprocessing plant. During reprocessing, samples are taken and analyzed via remote control with a plasma torch at a temperature of 10,000 degrees Celsius to determine which elements they contain

Civil Nuclear Bombs

In a related vein to the above relationship between civil and military dual-use technologies, several concepts have been put forward for how to use the enormous explosive power of nuclear bombs for civilian purposes. One utopian idea was to propel huge spaceships with the help of small atomic bombs that were detonated in pulses behind the ship. This study, called "Project Orion," proved to be unrealistic and was finally abandoned after the Partial Test Ban Treaty of 1963 came into force, as this treaty banned atmospheric explosions as well as those in space.

The American "Project Plowshare," started at the end of the 1950s, was a much more concrete program. Dozens of underground explosions were conducted to study excavation, earth removal, seismic measurements, geological exploration or even isotope production. A couple of tests were done with very powerful bombs and created craters up to 100 meters deep. Some officials proposed using nuclear bomb to widen the Panama Canal, cutting lanes for highways through mountains or blasting large caverns into rock for gas or petroleum storage. The actual idea behind the project, though, was to accustom the global society to atomic bombs and in this way to create a better acceptance for the necessity of atomic bomb tests. However, the program was discontinued at the end of the 1970s, as the contamination problems proved too big and public opinion become more and more critical of their use.

Less known but many times larger, with over 200 explosions, was the Soviet counterpart program "Nuclear Explosions for the National Economy." One success of the program was detonating an underground nuclear warhead to extinguish a large fire in a natural gas field in a desert area of Uzbekistan. The fire had been raging out of control for three years. Conventional firefighting methods had failed. But in 1966, the underground nuclear explosion cut off the fire from its gas supply and saved vast amounts of natural gas from going up in flames. Only months later, a second nuclear explosion stopped a blowout in another nearby gas field. Apart from these detonations, the Soviet civil nuclear explosions program had similar aims and problems to the American Project Plowshare. It lasted from the 1960s until 1988, when Mikhail Gorbachev halted it to promote nuclear disarmament negotiations.

Known Cases of Proliferation

While some countries have developed nuclear weapons singlehandedly, others have shortened this path and massively cut costs by purchasing the relevant technology from other nations or through hidden channels. These include above all nuclear espionage, which the Soviet Union operated very effectively against the West. What is striking about the history of nuclear espionage, especially at the beginning of the Cold War, is that for some spies, financial aspects played an almost insignificant role compared to the ideological or idealistic motivation that not one single nation in the world should possess such a powerful weapon – but also another nation that represented a different social system.

Both nuclear superpowers conducted hundreds of nuclear tests in the atmosphere, underwater and underground, often creating large-scale contamination. Altogether, around 2100 nuclear weapon tests of all types have been conducted worldwide, from nuclear grenades with rather low yield up to massive thermonuclear devices like the Soviet "Tsar Bomba." This 58 megaton bomb – the mightiest devices ever detonated – was so ludicrously powerful that not even a useful military application was conceivable.

The main test areas, the Nevada Test Site in the US, and its Soviet counterparts, the Semipalatinsk Test Site in Kazakhstan and the Arctic Archipelago Novaya Zemlya, are among the most heavily contaminated places on earth. In the early years, it was also common for all nuclear powers to let soldiers walk around ground zero after an explosion. This has led to numerous cases of cancer. Only after decades have veterans received compensations.

England received strong technical support from the United States in the early postwar years because the US highly desired a trustworthy European nuclear power as an antipole to the Soviet Union. Moreover, British scientists had played a major role in the development of the Manhattan Project. As a result, Great Britain was already one of the nuclear powers in 1952. France and China, on the other hand, developed their nuclear armament program independently and have been among the nuclear powers since the early 1960s. Britain tested its first nuclear bombs in Australia. The later decontamination efforts have been criticized as a cheap solution that would not be adopted on "white man's land" and that the clean-up would rather have been a "cover-up." Moreover, there had been little care for the Aboriginal communities in the area. After a dozen tests in Australia, Britain continued to test its bombs in the Pacific and also in the US at the Nevada Test Site, where a large number of American devices were detonated. The tests continued until 1991, when President George H. W. Bush – to the surprise of both the British and American military – decided to halt all nuclear tests. The Cold War had ended.

France was one of the pioneers of nuclear physics until the German occupation in World War II. After regaining its independence, France tried to return to its former strength, but suffered from late-colonial overstretching. In the Indochina War, during the decisive defeat of Dien Bien Phu in 1954, negotiations between France and the USA took place to possibly turn the tide by using the USA's nuclear weapons. However, the Americans, who wanted to strengthen the civilian use of nuclear energy with the "Atoms for Peace" program and at the same time expand their own global influence, ultimately decided against it, as in their worldwide power struggle with the Soviet Union, they could not afford to undermine their credibility in the Third World and lose decisive sympathies to the Soviet Union just for the sake of promoting late-colonial interests. The same was true of the Israeli-English-French occupation of the Suez Canal in 1956, in which – rarely enough and unexpectedly for the warring parties – the United States and the Soviet Union jointly demanded a withdrawal of the three aggressors. This was probably the decisive factor in the French government's decision to develop its own nuclear weapons in order to achieve greater geostrategic independence in the future. Despite an appeal by the UN General Assembly with a two-thirds majority in November 1959 to refrain from nuclear weapons testing, France detonated its first nuclear bomb in the (still French-controlled) Algerian desert in 1960, which led to sharp protests by many African and Asian states. This was only two years before Algerian independence, after which France continued its nuclear bomb tests on Pacific islands. With a total of around 200 tests conducted, France is in third place behind the USA and Russia/Soviet Union in terms of number of tests.

China entered the club of nuclear powers in 1964 – later than planned, after the Soviet Union withdrew its initially offered help in building nuclear weapons. Despite their ideological proximity, the People's Republic and the Soviet Union had become estranged in the 1950s and 1960s, partly due to border conflicts and ideological disputes. In creating its nuclear force, China had benefited greatly from the exchange of nuclear and missile scientists, both with the Soviet Union and with Western countries. With the development of its own nuclear bombs, the People's Republic of China not only sought to secure itself against the other major powers, but also to become the sole representative of the Chinese nation in the United Nations. This was because the United States had denied the People's Republic of China membership in the United Nations and had instead recognized the National Chinese Republic in Taiwan as the sole Chinese representative. The People's Republic of China took over this role in 1971, not least thanks to being a nuclear power with corresponding geopolitical weight.

Some NATO states – Belgium, Germany, Italy, the Netherlands and Turkey – kept or still keep American nuclear weapons on their air bases in the framework of so-called nuclear sharing. This is in conflict with the declared zero nuclear weapons policy of these countries and the spirit of the Non-Proliferation Treaty. The country closest to developing nuclear weapons, if it wished to do so, is Japan. While it has a pacifist constitution and a strong anti-nuclear-weapons movement, it also has all necessary ingredients for the construction of an atomic bomb: enrichment facilities, a reprocessing plant, sufficient stockpiles of nuclear material and experts. Should the United States decide to withdraw its nuclear umbrella, Japan is expected to be able to join the club of nuclear powers in about a year's time or less.

At present, only four countries have not joined or have withdrawn their ratification of the Non-Proliferation Treaty, which allows only the five permanent members of the UN Security Council to possess nuclear weapons. These four countries are India, Israel, North Korea and Pakistan.

It is feared that Iran also has a secret nuclear weapons program and will be one of the nuclear powers in the not too distant future, which would make the geostrategic balance in the Gulf region more difficult. Like Japan, Iran is regarded as having a fast *breakout capacity*, which means that it could build a nuclear bomb in only several months after deciding to do so. Other states in the region, from Egypt over Turkey to Saudi Arabia, could then feel compelled to strive for nuclear weapons in order to regain the strategic balance. The experience of the Cold War between West and East and the tensions on the Indian subcontinent give rise to fear that some countries could feel blackmailed without access to nuclear weapons of their own. Saudi Arabia in particular has good contacts with Pakistan; it may have been involved in financing Pakistan's nuclear program. In addition, several states in the region have been accused in the past of running secret nuclear programs even though they had signed the Non-Proliferation Treaty; these include Libya, Syria and Iraq. The growing interest in nuclear energy in and around the Gulf Region must also be seen in light of these developments. No important player wants to fall behind too much in nuclear technology.

Other countries that ran secret nuclear programs without having developed completed nuclear weapons were Argentina and Brazil during the time of their military dictatorships. Both countries completely wound up their military nuclear programs after democratization in the 1980s and joined the Tlatelolco Treaty, which declared all of Latin America and the Caribbean a nuclear-weapon-free zone.

Israel began a nuclear program as early as the 1950s. Especially for a small country without strategic depth and without allied neighbors in a hostile environment, the possession of nuclear bombs can be a desirable deterrent. However, the United States, as Israel's ally, feared a nuclear arms race in the region and therefore rejected Israel's nuclear program and its desire for nuclear technology. The French government, which pursued common strategic interests in the region – as was evident during the Suez crisis in 1956 – nevertheless decided to supply a research reactor, with the help of which the Israeli government has since been operating an officially non-existent nuclear program in the Negev desert, the strategic value of which has always been that its existence is in fact known by other countries. It is even possible to see the research reactor near Dimona when taking a public bus through the Negev Desert.

India has its own uranium deposits, but for a long time it had no access to modern enrichment technology. The nuclear superpowers were reluctant to supply India with such technology because they feared nuclear armament on the Indian subcontinent. Apart from the tensions with Pakistan and the resulting wars, it was especially the defeat in the 1962 border war with China and the first Chinese nuclear weapons test in 1964 that prompted the Indian government to develop its own nuclear weapons. Ten years later, India possessed a plutonium bomb that was roughly equivalent to the explosive power of the Hiroshima bomb.

As with the nuclear armament of all other unofficial nuclear powers, here the proliferation of Western technology was decisive. Since India was not to receive any enrichment facilities, and because unenriched natural uranium can only be brought to a chain reaction in special reactors, the Canadian government supplied India with such a reactor – the heavy water reactor. To be on the safe side, Canada requested from India credible assurance that this nuclear technology would be used exclusively for peaceful purposes. India conducted its first nuclear bomb test, named "Smiling Buddha," in 1974, which the government correspondingly called "peaceful" – in the same sense of geoengineering as Project Plowshare. It was only then that the now seriously outraged Canadian government decided to stop any further nuclear development cooperation with India. Heavy water reactors are excellently suited for the production of weapons-grade plutonium.

In 1998, the Indian armed forces, and shortly afterwards the Pakistani armed forces, ignited nuclear bombs for test purposes, not least for domestic political reasons. Since then, the arms race on the Indian subcontinent has intensified. Arms programs costing many billions of US dollars are a burden on the budgets of both countries. This conflict is made particularly explosive by the fact that both countries are in close proximity and have medium-range carrier systems, meaning such weapons may only take a few minutes to reach the metropolises of the neighboring country and that there is practically no advance warning time.

Pakistan felt forced by the Indian nuclear bomb to also arm itself with nuclear weapons in order to be able to assert itself against its larger neighbor. As the then Foreign Minister, Zulfikhar Ali Bhutto, declared even before India's first nuclear weapons tests: if India were to develop a nuclear bomb, Pakistan would do the same "even if we have to eat grass and leaves or stay hungry." Given the living conditions of many people on the Indian subcontinent and the funds that go into nuclear armament, this striking image is not entirely inaccurate.

First, Pakistan tried to buy a plutonium reprocessing plant from France, which France initially seemed willing to do. Under pressure from the US government, however, France then cancelled the planned sale, compelling Pakistan to adopt a different strategy. After the failed negotiations with France, Pakistan's atomic bomb was then essentially developed by Pakistani scientists who had worked in nuclear laboratories and enrichment plants in Belgium and the Netherlands. These researchers were granted access to high-level technology suitable for weapons production by Western states and companies. In addition to the necessary know-how and secret construction plans, they brought with them contacts to Western companies that were inclined to sidestep nuclear export regulations.

Pakistan's nuclear program began in the early 1970s, but the first bomb was not detonated until 1998 as a direct response to the recent Indian nuclear weapons tests. Since then, Pakistan has demonstrably violated proliferation regulations on several occasions. In the 1980s and 1990s, the head of Pakistan's nuclear program not only supplied centrifuge technology to Iran, but also complete construction plans to Libya and North Korea; according to official announcements, this was done without the knowledge of the Pakistani government. In return, Pakistan probably received plans from North Korea for the construction of long-range missiles.

France has the world's highest share of nuclear-generated electricity of all the major industrial nations. Nuclear power has the dominant position in electricity generation at about 75%. This percentage is going to decrease somewhat, as renewable energies are to receive a greater share of the energy mix. The French government, which has traditionally maintained very close contacts with the nuclear industry, has also often been very receptive to the idea of selling nuclear technology, even to politically dubious regions. Not least with Iraq and Libya, there were agreements on the sale of nuclear reactors. The Iraqi nuclear reactor, still under construction in 1981, was destroyed by the Israeli air force in a secret operation shortly before its completion, which was strongly condemned by the United Nations. At a later date, the destruction of a reactor already in operation could have triggered a nuclear catastrophe. In case of war, nuclear reactors turn into potentially huge dirty bombs. Libya is one of the few countries that initially pursued a nuclear armament program in secret, but then ended and disclosed it under international pressure.

North Korea joined the Nuclear Non-Proliferation Treaty in 1985 under pressure from the Soviet Union, and had later concluded an agreement with South Korea that provided for a Korean peninsula free of nuclear weapons.

This also prohibited foreign powers from storing nuclear weapons. At that time, North Korea's civilian nuclear program was operated with graphite-moderated reactors of the Russian type, which are basically suitable for the production of weapons-grade plutonium. The American government declared itself willing to supply light water reactors instead if North Korea granted the inspectors of the International Atomic Energy Agency IAEA unhindered access to its facilities. Annual oil deliveries were also agreed to in order to alleviate North Korea's energy problems. But this period of careful rapprochement was followed by mutual provocations between North Korea and the United States, including missile tests by North Korea and, from 2001, the classification of North Korea as a "rogue state" by the United States, whose government should be replaced. American officials stated that under no circumstances would they intend to force a regime change by military means. But of course, the half-life of such assertions was sometimes rather brief in regions richer in raw materials. In 2003 North Korea withdrew from the Nuclear Non-Proliferation Treaty.

In 2006, thanks to Pakistan's construction plans, North Korea finally succeeded in detonating its own nuclear bombs, initially with a weak effect and later with optimized power. North Korea possesses modern delivery systems, and the South Korean capital Seoul is very close to the common border and would be virtually indefensible against a nuclear attack. North Korea's termination of the Non-Proliferation Treaty also reveals one of the essential weaknesses of this treaty, namely the possibility of first developing a civilian nuclear program under the umbrella of the treaty, in order to then implement the acquired knowledge militarily after termination.

The situation today is somewhat sobering. Hopes that the end of the Cold War would bring about as a kind of peace dividend the more or less complete disappearance of the world's nuclear weapons stockpile have not been fulfilled. The 1963 Partial Nuclear Test Ban Treaty is still in force today, but China and France have not joined it. This treaty prohibits all nuclear weapon tests except underground. The Comprehensive Nuclear Test Ban Treaty, which bans all nuclear weapons testing, was adopted by the United Nations in 1996, but has not yet come into force. One reason for this is that countries like China, India, Iran, Israel, North Korea, Pakistan and the USA have not yet ratified the treaty. The situation is similarly difficult with the treaties on launcher systems and missile defence. Even if the political confrontation between the great powers has become less ideologically charged than during the Cold War, no one wants to give up the cherished possibility of nuclear power projection.

10

Radioactive Incidents and Disasters

Kyshtym

In the afternoon of September 29, 1957, a giant explosion roared through a secret city in the Urals, throwing radioactive material high up in the sky. This release of large quantities of radioactive substances occurred at the Mayak Combine and was later classified as a "serious accident" on the second highest level 6 of the INES scale. This accident is still the only one of this category today and is only surpassed by the catastrophic reactor accidents of Chernobyl and Fukushima. As the first Soviet production facility for fissile material, the Mayak Production Association was one of the most important nuclear facilities in the Soviet Union and extended over 90 square kilometers. It is located in the Southern Urals in the Chelyabinsk region of present-day Russia, 15 kilometers east of the small town of Kyshtym, and borders on the closed city of Ozyorsk. Due to the secrecy customary during the Cold War, the nuclear center as well as the residential town of the scientists Ozyorsk were secret cities that were not allowed to appear on maps and were surrounded by a restricted area. Ozyorsk was first called Chelyabinsk-40, later Chelyabinsk-65. Nearby was a gulag in which up to 20,000 people were imprisoned until 1960, some of whom were also forced to work for the Mayak facilities. The Kyshtym accident was a state secret during the Cold War and became known to the world public only after 1990, which explains why it is not better known.

The accident of Kyshtym did not occur in a reactor, but in a steel tank for radioactive residues from fuel assemblies, as they accrue during reprocessing. Highly irresponsible handling of radioactive material in military facilities could be seen not only in the Soviet Union, but in a similar (though not as

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_10

pronounced form) with the other nuclear powers at the beginning of the Cold War. It is a prime example of noncompliance with basic health and safety standards in projects under military secrecy. The numerous cases in which not only soldiers but also civilians were harmed by the avoidable release of radioactivity cannot be listed here. Many of these cases happened due to sloppiness in weapons production or by radioactive fallout during atomic bomb tests.

On the site of the Mayak Production Association, there were a total of ten nuclear reactors of different types, of which only two are still in operation today, with one reactor under construction. The two still active reactors produce among other things special isotopes for medical, industrial, scientific and military applications. The production of weapons-grade material was stopped in 1987. The plant also serves for reprocessing and production of fuel for nuclear power plants and submarines. In 1948, the first nuclear reactor was put into operation; in the same year, a radiochemical plant was opened for reprocessing the weapons-grade plutonium bred in the reactor.

For some time, the light to medium radioactive waste water from the reactor operation and treatment was channelled into artificially created waters as a final storage for liquid radioactive waste. However, large quantities of radioactive substances also reached the nearby river Techa, exposing many workers and residents to high levels of radiation. Attempts were made to limit nuclear contamination by damming the water flow to the Karachay Lake, which had no outflow and thus became some kind of natural final storage. The most dangerous and most radiating residues of reprocessing were collected in large steel tanks.

Due to the highly radioactive isotopes, a large amount of decay heat was generated in these tanks. These tanks were embedded in the ground, and constant cooling was necessary. By 1956, the cooling pipes in one of these tanks, which had a capacity of almost 300 cubic meters, had already started to leak. Due to the lack of cooling, the radioactive liquid inside slowly dried out and crystallized into highly explosive acetate and nitrate salts. A spark from a control device then exploded this huge tank, which contained about 100 tons of radioactive substances in a massive detonation. Even though this detonation was purely chemical and not nuclear, the amount of explosive material was so great that even a few kilometers away, window panes burst and radioactive substances were blown up to 1 kilometer into the sky. Eyewitnesses reported even from hundreds of kilometers away that on this day, the night sky was glowing bluish, possibly due to the ionizing radiation. The Soviet authorities explained this phenomenon to the population as sheet lightning or northern lights.

This explosion released large amounts of caesium-137 and strontium-90. The total activity of the radioactive material was in the same order of magnitude as that of Chernobyl. However, it was not released over such a wide area. About 90% of the material came down again on the site of the combine. Houses, streets and cars had to be decontaminated for over half a year. Fortunately, the nearby residential towns were largely spared from the fallout. However, the remaining contents of the steel tank were carried high into the air by the explosion and carried away with the constant northeast wind. An elongated area up to 300 kilometers long and 50 kilometers wide, the so-called East Urals Radioactive Trace, was contaminated. A total of 270,000 inhabitants were exposed to increased radiation doses. Over 10,000 inhabitants of the worst-affected areas were evacuated at a leisurely pace over the next few years; their villages, with the exception of the churches, were razed to the ground by bulldozers so that the inhabitants could not return (Fig. 10.1).

The number of victims of this disaster is not clear. The figures are certainly much lower than those of Chernobyl, but reliable studies are only now being undertaken. In 1967, the highly contaminated Lake Karachay dried up for the most part after a period of drought, which caused radioactive dust to be

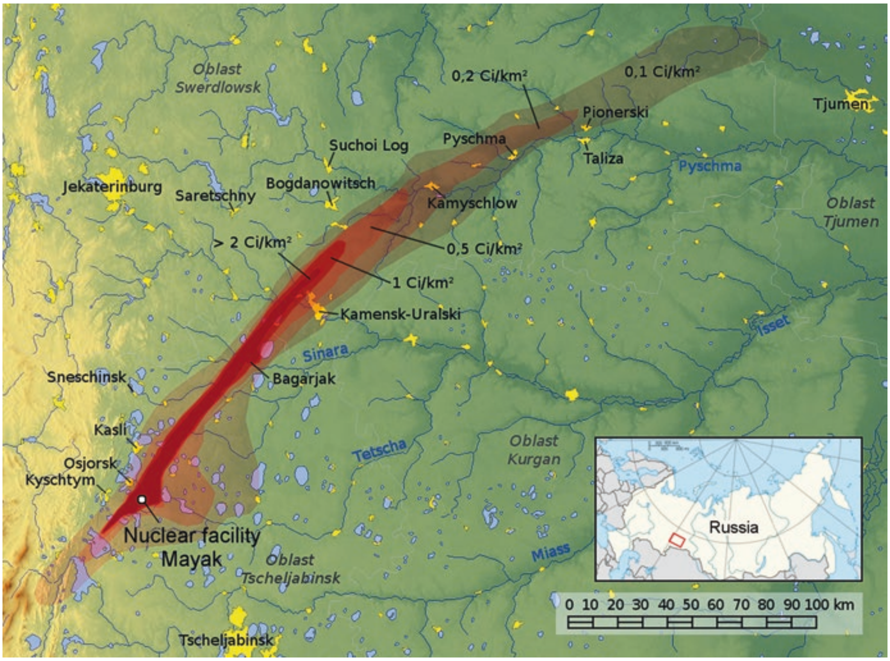

Fig. 10.1 The so-called East Urals Radioactive Trace of the areas contaminated by the Kyshtym accident. (The unit Ci = Curie is an old unit for the activity: 1 Curie equals 37 gigabecquerel)

stirred up in a storm and exposed several hundred thousand people to increased radiation. Today, Lake Karachay is the most severely contaminated region in the world and a strictly prohibited area. In the 1980s it was filled with concrete to fix the sediments. The driver cabs of the trucks were lined with solid lead to protect them from radiation. Even in the 1990s, staying on its banks for just one hour would have been enough to absorb a lethal dose of radiation. It is feared that the water of this lake could reach the Techa River via the groundwater and further from there into the Ob river and the Arctic Sea.

Three Mile Island, Windscale and Similar Incidents

On March 28, 1979, a core meltdown occurred at the Three Mile Island nuclear power plant in Unit 2. This was classified as a "accident with wider consequences" on the third highest level 5 of the INES scale. The Three Mile Island nuclear power plant consisted of two pressurized water reactors with a capacity between 800 and 900 megawatts. It is located near the city of Harrisburg in the eastern US state of Pennsylvania on the island of the same name, Three Mile Island, in the Susquehanna River. The meltdown of Three Mile Island is the best known, but not the biggest civilian radioactive catastrophe in the history of the USA. That title goes to the dam burst of the uranium mine at Church Rock.

During the Three Mile Island reactor meltdown, the destruction of the reactor building was fortunately avoided, meaning the highly radioactive material remained inside the containment and only small amounts of radiation were released despite the extensive destruction of the reactor core. This reactor accident could have become much more serious under certain circumstances, as the operating crew had to partially operate in blind flight due to a lack of measuring instruments. The Three Mile Island accident has been excellently investigated and documented, thus, it proved to be important for understanding, preventing and controlling future nuclear meltdowns.

The Three Mile Island accident began when a valve to the main feed pumps of the secondary circuit closed at 4:36 a.m. The reason for this is believed to be that a water hose was incorrectly connected to the compressed air supply, which led to a malfunction of the control system. The fact that the water and compressed air supply had the same connections at all and were also badly marked was later classified as a design fault. When the valve was closed, the main feed pumps immediately shut down, and as a result the steam generators that cooled the reactor failed. To reduce heat generation, the reactor was quickly shut down by pushing the control rods into the reactor core. This ended the chain reaction, but the decay heat still amounted to a good 100 megawatts, with a slowly decreasing trend. The emergency cooling system was then supposed to start according to regulations; the pumps began to run but did not transport any water. Barely two days before the accident, during a test of the emergency cooling system, the relevant valves had been closed, and it had been forgotten that they should be opened again.

Due to the lack of cooling, both the temperature and the pressure in the reactor rose steeply within seconds until a pressure relief valve opened that released steam from the primary circuit – only slightly radioactively contaminated until then – into a tank. The overpressure valve was only supposed to remain open for a few seconds and then close, but it blocked and remained open, which was not noticed by the operating crew due to the lack of a corresponding display. Had they been aware of this, countermeasures could easily have been taken and the incident could have ended without major consequences. But the water continued to flow into the tank until the pressure there became so high that finally a pressure protection broke open and the cooling water drained into the containment. After 8 minutes, the operators noticed the closed valves of the emergency cooling system and opened them. However, due to a missing level indicator in the primary circuit, they assumed incorrect cooling water quantities in the reactor. But the reactor was constantly losing cooling water due to the blocked, open overpressure valve. In addition, pumps had to be switched off due to pressure changes.

A good two hours after the beginning of the incident, which had now become an accident, the fuel rods in the upper third of the reactor fell dry; the decay heat caused them to heat up enormously to many hundreds of degrees Celsius. The zirconium cladding reacted with the steam; this reaction heated the fuel rods to over 2000 degrees Celsius, until they broke open and released their highly radioactive contents. This mixed with the cooling water and contaminated the containment. Later, one would notice that the fuel rods had melted to over 30% and were damaged to a good 70%. This corresponds to a core meltdown of phase 3 from Fig. 6.13.

During the burning of the zirconium cladding, more than a ton of hydrogen was produced, which finally triggered an oxyhydrogen gas explosion that was not too severe. Fortunately, it was too weak to damage the integrity of the containment. After some time, the operators succeeded in deducing the reason for the incident and initiated appropriate countermeasures. The core meltdown was stopped by supplying water to the primary circuit; 16 hours after the occurrence of the accident, the pumps of the primary circuit were restarted. The temperatures stabilized. Radioactive gas was released into the environment to relieve the pressure. The safety of the operators and the population was not acutely endangered, as practically all the radioactive inventory remained locked up in the containment. This was a confirmation of the Western safety philosophy of multiple barriers. The interior of Block 2 was largely destroyed; the decontamination work took over a decade and cost a good billion US dollars. The dismantling has not yet been completed and will continue for many years to come.

In the days following the accident, evacuation was recommended to pregnant women and infants within a five-mile radius of the power plant. The radius was later extended to 20 miles. A total of 140,000 people, less than half of the region's residents, left the area for several days to weeks. The population was largely dissatisfied with the government's information policy. Officials later announced that due to the low release of radioactivity, only about one additional case of cancer would be expected; some independent scientists assume slightly higher numbers.

The cause of the accident was identified as poor instrumentation of the nuclear power plant, combined with inadequate equipment in the control room and errors of the operating crew. The training of the operators and the official nuclear supervisory and regulatory authorities were also sharply criticized, which led to the creation of the Institute of Nuclear Power Operations. This institute has since been responsible for improving safety guidelines in the nuclear industry, from which it is also financed. As a result of the accident, the public in the USA became much more sceptical about nuclear power. Nevertheless, the slump in the number of newly built nuclear power plants and stagnation in the number of existing nuclear power plants did not occur until a decade later with the Chernobyl disaster.

An incident comparable to Three Mile Island, but which released considerably more radioactivity and was also classified as an "accident with wider consequences" at level 5 of the INES scale, was a fire at the British nuclear reactor at Windscale (now Sellafield) in 1957. This was the worst ever accident in the history of British nuclear power. Here, a radioactively contaminated cloud was released, which then contaminated the surrounding region. The cause for this accident was that in one of the reactors the moderator graphite had started to burn. It heated up to around 1300 degrees Celsius, carrying radioactive isotopes out through the chimneys. Only after days and by an improvised and dangerous operation could the fire be extinguished. Luckily, most of the radioactive material was carried toward the sea. But some radioactive iodine rained down on pastures, from where it found its way into dairy products. These had to be poured away for 6 weeks. But government officials did not inform the public properly, because they did not want bad press for their nuclear program. The reactors at Windscale produced the plutonium for the first British nuclear bombs.

Different reports and model calculations assume different numbers of victims. No significant health effects were found among the workers involved in the clean-up operations. Some authors suspect a total of several dozen to over 200 deaths in the long term, mainly from lung cancer. The contamination would have probably been much worse, had the physicist and Nobel Laureate John Cockcroft not insisted on installing scrubbers as air filters in the chimneys. Many technicians had regarded this as superfluous and even spoke of it as an expensive folly.

The nuclear power plant in Saint-Laurent suffered the two worst nuclear accidents so far in France. First in 1969, during loading of a gas-cooled graphite reactor of the UNGG type (Uranium Naturel Graphite Gaz), the reactor core was damaged. This stopped the cooling of a fuel assembly, which started to melt. 50 kilograms of uranium were set free. The accident could be contained; the population was not even informed. Then in 1980, in the other reactor of the same type, one fuel assembly melt, which led to a contamination of the site. The reactor installations had to be decontaminated, which took more than two years, before the reactor could resume operation. Both partial meltdown accidents are classified as INES level 4.

The most serious reactor accident in the Federal Republic of Germany occurred on January 13, 1977 in Block A of the Gundremmingen nuclear power plant. This reactor, built in 1966 and thus the oldest German power reactor, suffered an economic total loss in this accident and has been in the process of dismantling since 1983. On that day in January, very humid and cold air currents caused severe hoarfrost formation on two power lines connecting the power plant to the power grid. This caused short circuits, which in turn caused the reactor to power down to a low level sufficient to generate its own energy and keep all pumps and installations running; in this case, not even the emergency diesel engines would have been necessary.

Due to control errors, the operators had to carry out a quick shutdown, which succeeded without any problems. However, faulty steering caused the permissible pressure in the reactor vessel to be exceeded, so that finally safety washers burst and radioactive steam and several hundred cubic meters of hot, radioactively contaminated water flowed into the containment, causing a 3-meter-high flood. Water and steam were subsequently released into the environment in a controlled manner. Since the main structures were still intact, the initial plan was to put the power plant back into operation. Subsequent investigations led to significantly increased safety requirements. These and the necessary repairs could no longer be implemented economically, so Block A was shut down. Already two years before that accident, two workers were killed when hot, radioactive steam escaped from the primary circuit.

Over the decades, there have been a number of meltdown accidents that luckily did not lead to a major contamination of the surroundings. In 1966, a malfunction in the sodium cooling system caused the meltdown of some fuel assemblies at the Fermi 1 prototype fast breeder reactor in Monroe, Michigan, USA. This reactor used sodium instead of water as a coolant. A fragment blocked a cooling pipe, which led to overheating of the reactor core, with two out of 105 fuel assemblies melting during the accident. But the contamination could be kept inside the containment vessel. This accident was classified as INES level 4.

One fuel element melted and a steam explosion occurred in the Lucens reactor in the Canton of Vaud, Switzerland, in 1969. This experimental reactor was situated in a rock cavern. Due to loss of coolant, the reactor had overheated. Thanks to the cavern acting like a containment, no radioactive contamination occurred outside. This accident was also classified as INES level 4.

There were also intentional core meltdowns. In the 1950s, the USA conducted a series of experiments as part of the BORAX program to test the overheating of small experimental reactors. To do this, they steered these small reactors into a prompt criticality state – physically the same as in the case of Chernobyl. Although the core meltdown was more severe than expected, the data later helped to better estimate the safety margins of nuclear power plants. The area surrounding the reactors had to be decontaminated.

In 1961, the SL-1 (Stationary Low-Power Reactor Number 1), an experimental reactor of the US Army, also went into a prompt criticality state – this time unplanned. This led to a steam explosion and a core meltdown, killing three workers.

Also the Soviet submarine K-431 suffered a prompt criticality accident. In 1985, during a refuelling operation at the Chazhma Bay naval facility near Vladivostok, the reactor lid was being replaced. However, the lid was not put in the correct position and had to be lifted another time, with the control rods attached. Because of incorrect handling, the lid with the control rods was lifted too high, which led to the starboard reactor reaching prompt criticality and causing a steam explosion. This destroyed the machine enclosures, ruptured the pressure hull and aft bulkhead and threw the fuelling shack's roof 70 meters farther in the water. The ensuing fire took four hours to extinguish. Thanks to the fuel assemblies being entirely new without spent fuel, the radioactive contamination was comparatively small. But ten naval personnel were killed, probably by the explosion and not by radiation.

Beyond accidents with reactors, incidents with radioactive substances or in nuclear facilities have occurred time and again. In the Brazilian city of Goiania, a medical device for radiation therapy was stolen during a break-in at a decommissioned clinic in 1987. The unsuspecting thieves and a scrap dealer fatally opened the device and distributed the radioactive material among friends and acquaintances. They had no idea that the fascinatingly bluish glowing material contained highly radioactive caesium-137. Hundreds of people were contaminated, some of them severely. Four people received very high doses and died within a few weeks, and several other deaths are also associated with it. The radioactive material had been carried over several residential districts, and entire streets and squares were contaminated. Of 85 contaminated houses, 41 had to be evacuated for safety reasons. Seven buildings were completely demolished for decontamination. In many gardens and public parks, the top layer of earth had to be partially removed. The IAEA classified this incident on the INES scale level 5 – at that time the most serious civil radiological incident apart from reactor accidents, as the disaster of Kyshtym was not yet known in the West.

Similar cases were also reported in other countries. In 2000, in Samut Prakan, Thailand, a medical irradiation device with cobalt-60 fell into the hands of scrap collectors who broke open the device in order to recycle its individual parts, despite the warnings attached to the device. Some parts of the scrap yard were heavily contaminated. Directly at the open radiation source, the radiation doses were as high as at the damaged reactor at Chernobyl. Three people died from the high radiation. More than a thousand people received increased radiation exposure before the authorities could find the cause of the problem and decontaminate the site.

Some accidents have also occurred when working with fissile material. A 6.2-kilogram plutonium core, known as the “demon core,” even caused two serious accidents at the Los Alamos National Laboratory. During criticality experiments in 1945 and 1946, researchers tried to get as close as possible to the criticality limit to study neutron dynamics. The researchers were well aware of the danger of such experiments, which is why one of the experiments was even called “tickling the dragon’s tail.” In both cases, small handling mistakes caused a neutron reflector to increase the criticality of the plutonium sphere, which itself was slightly subcritical, to a supercritical level. Thus, a chain reaction started and released lethal doses of radiation. In both cases, the researcher who was closest to the plutonium sphere received a lethal radiation dose and died after a few days. In the second accident, an assistant standing next to the researcher suffered severe injuries and permanent damage. Presumably further deaths of researchers in the vicinity are also attributable to these incidents. As tragic as these accidents were, they also illustrate that a nuclear explosion cannot be brought about too easily. In both cases, the chain reaction quickly broke down by itself due to thermal expansion.

The worst nuclear accident in Japan before the Fukushima reactor accident was also such a criticality incident. It happened in 1999 in the fuel assembly factory of the Japan Nuclear Fuel Conversion Company in the coastal city of Tokaimura. Here, workers had handled uranium enriched to 18.8% in a chemical cleaning process. Certain containers were allowed to be filled with a maximum of 2.4 kilograms of uranium during this process. To save time and money, however, the workers filled this container with 16.6 kilograms of uranium. The critical mass – in this case around five kilograms – was exceeded, and an uncontrolled chain reaction started. This led to a blue flash and a loud bang. Unfortunately, the workers had not been informed about the special criticality hazards. The chain reaction continued for about 20 hours before other workers – in short term assignments – succeeded in stopping it by, among other things, injecting boric acid. Residents living close to the factory were evacuated, and more than 300,000 residents of the surrounding region were told via loudspeaker not to leave their homes. The two most severely affected workers received fatal doses of between 6 and 20 sieverts and died after a few weeks. Fortunately, the surrounding area was not seriously contaminated. This accident ranks on the INES level 4.

Nuclear energy is a good choice for use in space, as it can store and provide a great deal of energy in a small space. For this reason, radioisotope generators are frequently used for satellites and especially for missions in the depth of our solar system. These devices use the decay of a highly radioactive isotope to generate heat, which is then converted into electricity by a thermoelectric generator. In this way, one is independent of solar panels and can generate electricity even far out in space where solar radiation is weak. Practically all space probes that fly into the outer solar system, as well as the Mars rover Curiosity, have such radioisotope generators on board. This has led to some protests, as environmental groups have repeatedly complained against the use of such generators, fearing widespread contamination if a rocket launch goes wrong. However, the radioactive material in such generators is usually well encapsulated and less problematic than spent fuel rods. The Soviet Union also used such radioisotope generators to generate electricity in remote stations, especially for military radio facilities. Some of these generators were very large and contained over 100 kilograms of radioactive material. In connection with the collapse of the Soviet Union, however, some of these generators were lost and there were several accidents, among others by scrap metal collectors, where people were exposed to radiation.

It is little known that also nuclear reactors circle above our heads. The Soviet Union launched more than 30 nuclear-powered satellites into space between the 1960s and the 1980s – mainly RORSAT radar satellites, which require considerable power for their active radar. They fly in a low orbit to observe ships, so they cannot use solar panels. This would cause too much air resistance and the satellites would sink too fast. The highly questionable idea of the designers was that at the end of operating time, the reactor would be fired into a higher orbit. There, it would decay for several hundred years before plummeting back to earth with significantly reduced radioactivity. However, some of these satellites have already experienced problems shortly after launch. The satellite Kosmos 954 underwent problems only a few months after the launch. The operators could no longer control its course, and the reactor could not be fired to a higher altitude. The satellite finally crashed in Canada, with parts burning up in the atmosphere. However, some parts, including highly radioactive parts, were scattered over an area of 124,000 square kilometers. A joint Canadian-American team searched this area and found some of them. Another satellite, Kosmos 1402, suffered the same fate in 1983. It crashed over the South Atlantic and sank there. The reactor and its contents probably burned up in the atmosphere.

Generally, on both sides of the Iron Curtain, military facilities in particular were responsible for extensive contamination. In addition to the aforementioned incident at Mayak, there were numerous secret "nuclear cities" in the Soviet Union where consideration for the environment and future generations was not the main focus of attention. But in the hot arms race of the Cold War, the USA also too often put speed before security. Since the Manhattan Project, the Hanford Site in Washington State has been a center for the production of weapons-grade plutonium. Hanford is considered the most severely contaminated region west of the Iron Curtain. Along the Columbia River there were a number of nuclear reactors, nine in all, which were intended to breed plutonium. In addition, there were five reprocessing plants and 900 other buildings for workshops and laboratories, structurally very similar to Mayak. Hanford supplied around two-thirds of the plutonium that was used in the over 60,000 nuclear warheads built for the US nuclear forces. Many of the early safety measures were inadequate, resulting in severe contamination of the river and soil. Corroded underground tanks allowed large quantities of highly radioactive materials to seep into the earth, which also polluted the groundwater. Decontamination work – the largest in the USA, with a price tag of over 100 billion dollars and thousands of employees – has been underway for around 20 years and will continue for decades.

But contamination has also occurred at other sites of the nuclear weapons program, such as the Rocky Flats Plant in Colorado. Among other things, important components for hydrogen bombs were manufactured there, which were then delivered to the Pantex Plant near Denver for final assembly. Over the years there have been several incidents at Rocky Flats, the most serious in 1957. Plutonium can ignite spontaneously in air. This happened in a glove box, which caused several other such boxes to catch fire, along with the Plexiglas pane and eventually the plant's air filters. The fire lasted for almost four hours. When the air filters were burned through, the building's fans blew the unfiltered plutonium dust out of the exhaust chimneys. It took a while before they were finally shut down. This led to significant contamination of the surrounding area. Another fire of the same kind occurred in 1969, this time burning even more plutonium. Luckily, the air filters did not burn through, as in the meantime they had been replaced by non-combustible material. Also in the late 1960s, however, there was a major contamination of plutonium from leaking barrels. When these were removed, the contaminated soil was stirred up. Storms then spread radioactive dust in the surrounding area – a similar scenario to that at Lake Karachay, although with less radioactivity. Here, too, the area was asphalted for safety reasons. Later, it was decontaminated.

The test areas for nuclear weapons will be reminders of the Cold War for centuries to come. The more than 2000 nuclear tests that have taken place since the end of World War II have contaminated large areas. In the USA, the Nevada Test Site, which was used from 1951 to 1962, is particularly affected. 86 aboveground and 14 underground nuclear tests have released a significant amount of radioactive material into the atmosphere. The fallout from nuclear weapons contains hundreds of different radionuclides. The wind spread these substances over other areas in the USA, which is why the USA and also the other western nations later moved such tests mainly to the Pacific. This affected above all the Marshall Islands with the Bikini Atoll, Christmas Islands, Johnston Atoll and Mururoa Atoll.

The situation was similar on the other side of the Iron Curtain. The Semipalatinsk Test Site in northeastern Kazakhstan was the Soviet equivalent of the Nevada Test Site. From 1949 through 1962, 88 atmospheric tests and 30 surface tests were conducted there. But the biggest Soviet bombs, including the 58-megaton "Tsar Bomba," the most powerful nuclear weapon ever detonated, were tested on the Novaya Zemlya Test Site. To put this in perspective, all explosives used in World War II – the two nuclear bombs included – added up to only around three megatons. (In fact, the Tsar Bomba was so powerful that although it served as an effective political demonstration, it was militarily useless.) Novaya Zemlya is a windswept, remote arctic island. It served as the main Soviet test site from 1955 to 1990. It is heavily contaminated, not only by nuclear weapon fallout but also by dumped nuclear reactors, sunken nuclear submarines and other nuclear waste.

Chernobyl

The reactor accident on April 26, 1986, in Chernobyl is still by far the gravest radioactive accident in the history of nuclear energy. On the INES scale for nuclear events it is classified at the highest level 7 as a "major accident." The Vladimir Ilyich Lenin Nuclear Power Plant in Chernobyl consisted of four large nuclear reactors of the Soviet RBMK type with 1000 megawatts of electrical power each, built in pairs so that two reactors each shared buildings and service structures. Two further reactors were under construction. The Chernobyl nuclear power plant is located in today's Ukraine, 3 kilometers south of the town Pripyat, 130 kilometers north of Kiev and 20 kilometers south of the Belarusian border. An artificial reservoir on the eponymous Pripyat River supplied the cooling water for the reactors. Pripyat was not just another industrial city in the Soviet Union. It was regarded as a model city with a high standard of living, thanks to the nuclear power station. At the time it had a population of almost 50,000. Now, it is a ghost town.

Block 4 of the nuclear power plant was just commissioned in 1984 and was considered safe by Western reactor experts, among others, even if some special features of the RBMK design would not have received certification in Western countries. RBMK translates to "High Power Channel-type Reactor;" this reactor design was developed at the Moscow Kurchatov Institute, where most of the Soviet reactor lines were designed. Desirable features of the RBMK reactors are the modular design and the general structural simplicity, which allow a comparatively uncomplicated construction even in remote regions and the possibility of changing fuel rods during operation (as in some heavy water reactors), leading to longer operating times and, in theory, the possibility of producing weapons-grade plutonium. Disadvantages include the absence of a containment, a slow emergency shutdown system and the two fatal characteristics – firstly, to allow a self-reinforcing chain reaction at low power levels, and secondly, that the reactor core was designed with large amounts of combustible graphite as moderator material.

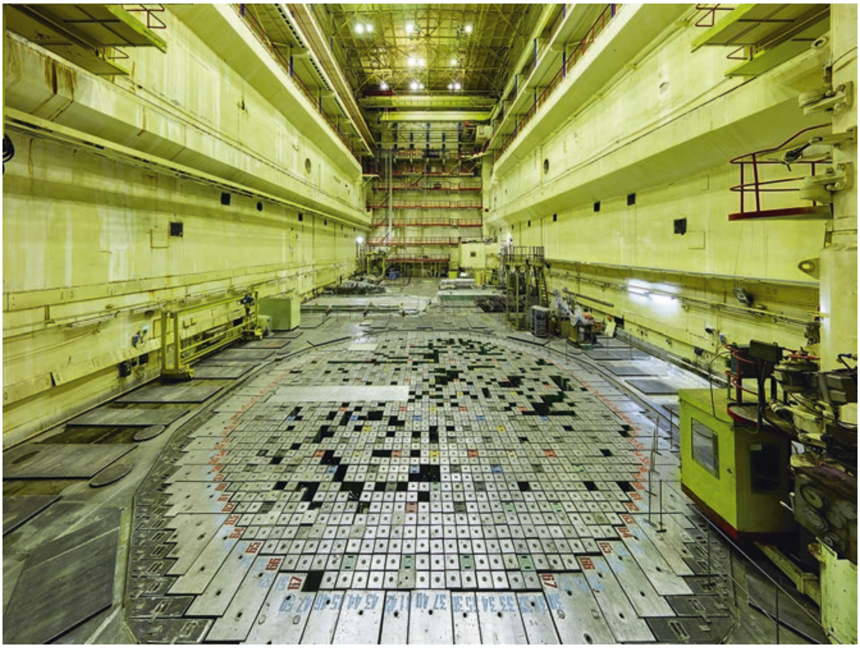

Fig. 10.2 Reactor block 3 at Chernobyl, of the same RBMK type as the neighboring, destroyed block 4. The shiny metallic grid is the biological shield. Under it are the pressure tubes with the fuel elements. With the sophisticated loading machine on the right, the fuel elements can be changed individually during operation. The individual "pixels" are massive concrete covers. Today, several pieces are removed. The colour shows the function (control rods, fuel rods, etc.)

Initial Situation

The ironic tragedy of the Chernobyl reactor accident lies in the fact that, of all things, the catastrophic accident was triggered by an experiment that was meant to increase operational safety. During this experiment, the operating team repeatedly disregarded important operating regulations and overrode safety systems due to severe time pressure and the conviction that they had a very good understanding of the reactor and could control it even far outside the regular operating conditions. Together with the principal safety risks of the RBMK type, this led to the worst reactor accident ever.

The idea of the experiment was to test whether, in the event of a power failure and a drop in steam pressure, the turbine generator could be used as a flywheel to act as a temporary power supply. Normally, the large turbines rotate at about 3000 rpm and take about 15 minutes to come to a standstill after a shutdown. With the help of special voltage regulators coupled to the pump motors responsible for cooling the reactor, these turbines would still provide sufficient power for just under a minute. This would bridge the time until the emergency power diesels would start and could take over the further power supply.

The failure of the overall power supply is one of the most dangerous scenarios for the safety of nuclear power plants, since a failure of the cooling system can lead to a core meltdown. The test was therefore significant to increase the overall safety of this reactor type and could have provided valuable findings for a transition from normal to emergency power supply in a way that was as controlled and as safe as possible. However, it was poorly planned and examined; its execution was inadequate and did not meet the specifications. The operating team was among the best in Eastern Europe, and they had a corresponding confidence in their abilities. The Chernobyl plant was considered a flagship power plant, one of the most important contributors to stable power supply with only very short interruptions.

Sequence of the Accident

Reactor number 4 was due for annual inspection. Since the reactor had to be shut down anyway, the safety experiment was to be carried out in the night from April 25 to 26, 1986. For this purpose, the reactor was to be powered down from full load to 25% load. This corresponded to about 750 megawatts of thermal power. Such a reactor with 1000 megawatts of electrical power has a heat output of a good 3000 megawatts. Only a third of the heat can be converted into electricity; the rest has to be discharged as waste heat to outside waters.

The experiment that night began with a delay, as due to an increased demand for electricity, the reactor was to remain connected to the power grid longer than originally planned. For this reason, it ran for several more hours at 50% power. This increased the time pressure on the operating crew and led to a shift change of the operators. As planned for the experiment, an emergency cooling system had already been switched off, but this was actually forbidden in grid operation. This probably had no influence on the course of the accident, but it shows how little attention was paid to safety regulations.

The technician in charge then made a mistake when he steered the control rods to further reduce the reactor power down to 25%. That caused the reactor power to drop much more than planned; it finally settled at only 30 megawatts thermal power instead of the targeted 750 megawatts. This was the only major unintentional operating error in the entire disaster. All other errors were deliberate digressions from safety guidelines and violations of operating regulations.

As a result of the sharp reduction in power and the longer operation at reduced output, something had now taken place that experts call "xenon poisoning." Xenon-135 is one of the many fission products in nuclear fission; however, unlike the other fission products, it has a significant influence on the dynamics of the chain reaction because it is a very good neutron absorber. Up to 2% of all neutrons are captured by xenon-135, causing this xenon isotope to transmute into something else. About half of the xenon-135 is converted by such neutron capture during operation of the reactor, while the other half decays due to its relatively short half-life of only 9 hours. A rapid power reduction increases the concentration of xenon-135 in the reactor core, because it is no longer split by neutrons. At the same time, it acts as a strong brake on the chain reaction. In order to increase the power of the reactor despite the high xenon concentration, the neutron-absorbing control rods had to be moved out quite far. The only alternative would have been to wait a few half-lives until the xenon had decayed naturally. Due to the substantial burn-up before annual revision, the control rods were already pulled out relatively far.

It was finally possible to power the reactor up again and stabilize it at 7% of nominal power, which was well below the 25% intended for the test. Due to the low heat output, further control rods had to be completely extended. In order to carry out the experiment, the automatic control rod steering system was switched off, which was a further violation of fundamental safety guidelines. With less than 15 control rods still in the reactor, the experiment was far outside the operating regulations, which requested at least twice as many as a safety minimum. This was a dangerously unstable operating mode, since the RBMK reactor type can develop rapid, self-reinforcing power changes at such a low power levels and with the given parameters (like high burn-up in the fuel rods before a revision, few control rods in the reactor core, etc.). According to the operating regulations, under such conditions the reactor was not allowed to be operated at all below 20% of its nominal power.

At 1:23:04 am on April 26, 1986, the experiment was started and the steam connection to the turbines was interrupted. In order to be able to run the experiment a second time without losing time in case of a failure in the first run, the automatic protective shutdown was bypassed, which was another violation of the safety guidelines. The following events happened too fast to leave much time for further mistakes.

At 1:23:31, the operators suddenly observed an unexpected increase in reactor power. An unsuccessful attempt was made to limit this increase by means of 12 automatic control rods. The increasing number of neutrons lowered the amount of xenon-135 nuclei more and more, which increased criticality; the same effect was caused by the formation of steam bubbles, which reduced the slightly neutron-absorbing effect of the cooling water. Both effects intensified each other.

Technically, the reactor had about 200 control rods, but now only few were in operation. Thus, the water became an important factor in neutron dynamics. Water is only a light neutron absorber, but its relative influence on the neutron dynamic compared to the few fuel rods increased under these conditions. Due to the low power, initially there were only a few steam bubbles. But when the chain reaction became stronger, the water started to boil more strongly. And when it boils, its density decreases and it thus absorbs less neutrons. An increase in reactor power therefore led to a self-reinforcing effect: more neutrons, more power, more steam, more neutrons – a fatal feedback loop, which experts call "positive void coefficient" (void for bubbles) and which should be avoided at all costs in reactor design.

Only few seconds later, the output increased rapidly, which is why the shift supervisor manually activated the emergency shutdown at 1:23:40 a.m. However, since most of the control rods were fully extended, it took too long to drive them back in. During this time, the neutron density in the reactor core had already risen sharply.

The lower end of the control rods was not made of neutron-absorbing boron, but of graphite. Driving the control rods in simultaneously therefore even increased the reactivity of the reactor for a few fatal seconds, because the graphite end of the control rods displaced the slightly neutron-absorbing cooling water and acted as a reaction-enhancing moderator for a short time instead of slowing down the chain reaction.

The reactor now entered a so-called "prompt criticality" state, which (except as an extremely short-term pulse in specially designed research reactors) must be strictly avoided during reactor operation. The neutrons directly released during nuclear fission could now trigger a self-reinforcing chain reaction without the aid of the delayed neutrons, as happens – albeit on a much more dramatic scale and under different conditions – in an atomic bomb explosion. In boiling water and pressurized water reactors, such a power excursion would be terminated very quickly by massive boiling of the water; because then the moderator would be missing, the neutrons would no longer be slowed down and they would therefore lose much of their ability to cause nuclear fissions. With the graphite-moderated RBMK type, however, this inherent physical emergency brake is not present.

The chain reaction in the reactor core of unit 4 shot up massively within seconds and could no longer be slowed down by the control rods. At 1:23:43, the reactor power already exceeded the nominal full load and then exploded exponentially – a "runaway excursion." The power meter stopped at 30 gigawatts of thermal power output, ten times the nominal full load, but the chain reaction still got stronger and stronger. As simulations later showed, only one second later it was more than 100 times full power! This released an energy equivalent to about 50 tons of the explosive TNT. That amount of heat could not be dissipated; the reactor core overheated enormously and deformed. The power output collapsed briefly and reached a second peak. Pressure tubes burst, the control rods blocked, and the zirconium cladding of the fuel rods reacted with the water vapor at the enormous temperatures, producing hydrogen, which combined with atmospheric oxygen to form explosive oxyhydrogen gas.

At 1:23:48 a.m., two heavy explosions concussed the reactor building; blowing away the upper reactor shield, which weighed over 1000 tons, and the thin roof of the reactor building, which only served as weather protection. The first explosion was a steam explosion, caused by the immense vapor pressure of the water, which was heated to over 3000 degrees Celsius. It hurled the shielding cover high into the air. This explosion ruptured fuel channels and severed most of the coolant lines that fed the reactor core. Thus, the remaining coolant evaporated to steam and escaped the reactor. This further boosted the reactor power.

Only seconds later, an even more powerful explosion occurred, distributing glowing, highly radioactive fragments of the reactor core onto the roof of the reactor and turbine buildings and in the entire surrounding area. While the exact nature of this explosion is debated among experts, probably oxyhydrogen gas had ignited, which had been generated by the extremely overheated fuel rods or maybe also by the red-hot graphite. This explosion shattered the damaged reactor core and finally terminated the runaway chain reaction.

Around the reactor building, over 30 fires broke out. An employee who watched the reactor from the outside shortly after the explosion reported that he saw a "very beautiful," laser-like ray of bluish light, caused by the extremely strong ionizing radiation.

At 1:30 a.m., the fire department on duty was on site and was later also supported by their colleagues from Pripyat and Chernobyl. At 5:00 a.m., all fires on and around the reactor and turbine buildings had been extinguished, except for the burning graphite core. Many of the firefighters later paid with their lives for their heroic efforts in this apocalyptic scenario. Surprisingly, the neighboring Block 3 of the nuclear power plant remained in operation until

Fig. 10.3 Control room of block 3 in Chernobyl, which was operational until 2000. The control room of block 4 once looked more or less identical

5:00 a.m.; the other two blocks, 1 and 2, remained in operation until the next day.

The reactor building did not have a safety containment like Western nuclear power plants, so the reactor core was exposed and the glowing graphite together with the molten fuel rods enclosed in it now burned continuously in open air for days, with a column of hot radioactive smoke rising steeply upwards. It was later estimated that the amount of burnt graphite was around 250 tons. The Soviet authorities devised an emergency plan. In 1800 helicopter flights, over 5000 tons of material were thrown into the reactor in the following days to get the fire and the chain reaction under control. Many of the pilots only got a lead cushion to sit on as radiation protection. Boron compounds were used to interrupt the chain reaction; dolomite, which develops carbon dioxide, to stop the fire and cool the graphite; lead, because it melts into the cracks in the reactor and thus not only shields the radiation but also prevents the release of fission products; sand and clay as a protective layer and effective filter for radioactive dust. From May 6, 1986, the rescue teams could breathe a short sigh of relief; the situation was far enough under control that little more radioactivity was released.

Fig. 10.4 Control room of block 4 in Chernobyl. Behind the new wall there is a corridor

Fig. 10.5 Details of the control room of block 4 with reactor core panel. The fatal emergency button was on the control table on the lower left

But not everything was good just yet. A good 130 tons of hot radioactive material formed a lava-like mass in the lower part of the reactor building. To prevent it from eating its way through the reactor building and contaminating the groundwater, a cooling system was installed. Coal miners built a coolable concrete slab under the reactor foundation within only 2 months. The drinking water supply for over 3 million people would otherwise have been at risk. It is assumed that 6 to 7 tons of radioactive material were released into the environment during the major fire; just under a ton of this material remained on the power plant site; about 4 tons were deposited within 20 kilometers; the rest was carried into higher air layers up to above 1500 meters and transported by the wind further away – even to Central and Western Europe. By the end of 1986, the damaged reactor was surrounded by a concrete shell several meters thick, called the "sarcophagus."

Consequences

In the nearby city of Pripyat, the next day the radiation dose rose to 10 millisieverts per hour, 50,000 times the natural dose. The city was completely evacuated within hours. In the following days, 115,000 inhabitants of the restricted area within a 30-kilometer radius around the reactor were also evacuated, as well as over 200,000 people from other areas in the following years, depending on local radiation exposure.

A large-scale clean-up and decontamination operation was started. Up to 800,000 so-called liquidators, composed of military units, forced recruits and volunteers, including residents of the evacuated areas, cleared radioactive waste and debris in the following days, months and years to make the contaminated areas and buildings accessible again and allow the operations of the three other reactor units to resume. They built the necessary infrastructure as well as the sarcophagus, or "Shelter Structure," around the destroyed reactor – a massive concrete and steel structure which should lock away the whole radioactive inventory.

The regulations were such that it was accepted for each liquidator to receive a maximum radiation dose of 250 millisieverts (around 100 times the natural annual dose) in the first year, 100 millisieverts in the second year and 50 millisieverts in the third year. Initially, this dose was reached in and around the affected buildings within a few minutes. In later years as decontamination progressed and the highly active short-lived isotopes decayed, it was reached usually after days or weeks. However, some liquidators were probably exposed to higher radiation doses than the official ones.

Directly after the accident, the strongest radiation was on the roofs of the reactor complex. Since German and Japanese robots failed there due to the high radiation doses, the liquidators, also called "biorobots," were not allowed to stay there even for one minute. They donned improvised protection gear, a heavy lead vest and breathing protection, ran up to the roof in this outfit to throw a shovel full of radioactive waste back into the reactor and then ran off again as quickly as possible.

In the first days after the reactor accident, the Soviet leadership tried to keep it secret. Only when Western experts measured a radioactive cloud over Sweden did the extent of the disaster become internationally known.

The contamination of the surrounding areas is extremely variable; depending on wind direction and precipitation. Some areas, such as the Gomel region 100 kilometers to the north, are much more severely affected than other, much closer areas. The restricted areas are therefore distributed outside the 30-kilometer zone like a patchwork carpet (Fig. 10.6).

Only a few older people have now been allowed to return to the 30-kilometer zone; radiation exposure there has fallen in many places to a high level, but at least for older people it is considered bearable. However, during strong winds, there is a risk of radioactive dust being whirled up that can be inhaled. In addition, the danger of strontium contamination of drinking water will remain for hundreds of years.

All in all, around 5000 square kilometers in Belarus and the Ukraine are likely to remain uninhabitable for at least 100 years until the activity of the caesium, which is mainly responsible for the contamination, has significantly subsided. Together with plutonium, caesium remains in the uppermost soil layers for decades. To date, there is no affordable method for removing the extremely long-lived plutonium.

Shortly after the old sarcophagus or "Shelter Structure" was finished, Soviet experts guessed it would only last a few decades. Inside are large amounts of highly radioactive material, as only a part of the total nuclear inventory had been blown into the air by the fire. There are still around 200 tons of the molten reactor core present, as well as 30 tons of highly contaminated dust and 16 tons of uranium and plutonium. Since the old sarcophagus showed cracks and started to leak, a new sarcophagus, called the "New Safe Confinement," was added in 2017 to cover the old one. This huge steel structure is the largest movable land structure ever made. It took 15 days to push it over the old sarcophagus by a hydraulic mechanism. The New Safe Confinement is supposed to last for at least one hundred years and costs around 2 billion dollars. The complete disposal of the reactor remnants will cost many times more. The new sarcophagus has all the necessary

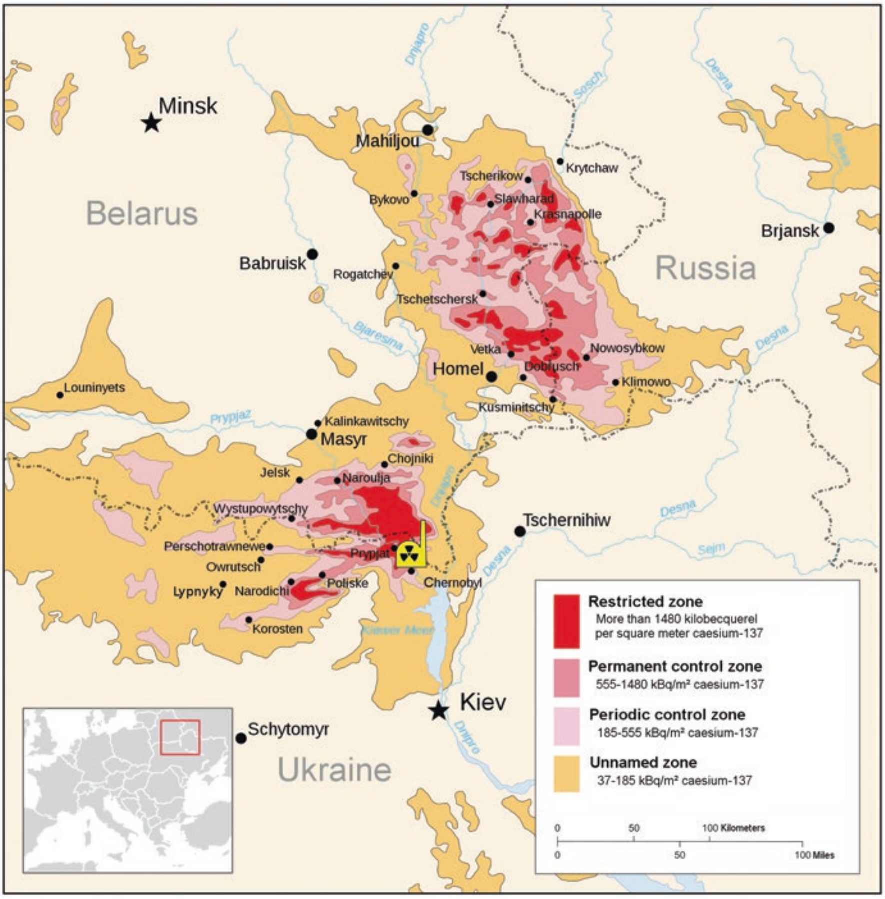

Fig. 10.6 Local distribution of the radioactive contamination in Ukraine, Belarus and Russia as a result of the Chernobyl reactor accident, broken down by restricted zone, permanent control zone and periodic control zone. Note the patchwork of very different levels of contamination depending on wind direction and precipitation in the days and weeks following the disaster

infrastructure to dismantle the destroyed reactor. This operation will last decades.

In Western and Central Europe, radioactive fallout, especially in the Alpine region, had led to a clearly measurable increase in radioactive contamination, especially by the highly volatile caesium. Even today, forest berries, mushrooms and red deer are still significantly contaminated in some areas. It should be noted, however, that in the case of radioactivity the legal limits and monitoring are very strict and that a slight exceeding of the limits does not necessarily mean that these foods are in principle unfit for consumption – especially if they are not consumed on a permanent basis. On average, the exposure in

Fig. 10.7 New Safe Confinement encasing Chernobyl reactor block 4. Block 3 is on the right

Central and Western Europe from the Chernobyl reactor catastrophe today is less than one hundredth of the natural radiation exposure.

The data on the health effects of the radiation on the liquidators as well as on the affected population around Chernobyl are highly controversial. There is therefore disagreement among experts as to how many cancer cases are attributable to radiation exposure from the reactor disaster. This is due to different assumptions, firstly regarding the amount of radiation absorbed, secondly regarding the biological effectiveness and thirdly to insufficient population statistics and epidemiological data. It also has to be taken into account that the latency period for the manifestation of cancer or hereditary damage can extend over decades.

In spite of all the controversy about how many people fell victim to this catastrophe, it is also a question of methodology – on which there is no agreement – whether only the statistically clearly detectable radiation victims are officially counted as such (which can lead to an underestimation of their number), or whether certain extrapolations are made even into statistically undecidable areas with small doses and large populations (which can lead to an overestimation of the number of victims).

The people most severely affected were those employed directly on the night of the accident, especially the firefighters. 237 of the approximately 400 involved persons developed symptoms of acute radiation sickness. Three died directly from debris, shock and burns, 28 died of radiation sickness within a week and an estimated 19 to 100 more died in the coming years, although the cause of death for these is not always clearly attributable to radiation exposure. The liquidators working on the roofs and the helicopter crews were also exposed to very high doses of radiation.

Some authors suspect that already several hundred or thousand liquidators could have died of radiation sickness, and even more became seriously ill or incapacitated for work. According to some official sources, the number of deaths is estimated at just 50; some authors, however, estimate considerably more than 10,000 radiation-related deaths. The extremely divergent figures cannot be evaluated here. There are still too few reliable figures that could support these statements. Comprehensive epidemiological studies are currently being conducted.

The figures for victims among the civilian population are similarly divergent. The clearest evidence is the dramatic increase in thyroid cancer, especially among children and adolescents. The highly radioactive iodine-131 was released in large quantities during the catastrophe and absorbed in high doses by the surrounding population, mainly through dairy products. When this isotope gets into the soil with rain, it is taken up by plants and then ingested by cattle. It has a strong damaging effect on the thyroid gland. Several thousand cases of thyroid cancer, which otherwise occurs rather rarely, have been counted in the following years and decades in the region around Chernobyl. Fortunately, although thyroid cancer is a malignant tumor, it is one of the best treatable types of cancer with a death rate of only about 1%. Therefore, despite the dramatic increase in thyroid cancer, not many deaths have been reported.

For other cancers, such as leukaemia and breast cancer, the situation looks more difficult, as their cause can hardly be deduced from the statistics of the total population. The IAEA expects a total of 4000 deaths from all types of cancer. Some authors take a more pessimistic view of radiation exposure and suspect that in the decades following Chernobyl, a total of several tens of thousands of cancer cases should be attributed to radiation exposure from the reactor accident. In view of the approximately 30 million cancer cases, summed over a large area, that can be expected naturally, this corresponds to only a very small, statistically hardly detectable increase in the cancer rate. Other authors estimate the expected numbers to be lower. Compared to other cancer risk factors such obesity, smoking and alcohol or substance abuse, the health risks posed by the radiation caused by Chernobyl are certainly much lower for the population as a whole. But there is a difference between cultivating one's own vice and being exposed to a risk one has not chosen. In Germany, for example, depending on the study, between 0 and up to over 1000 cancer cases are expected to be caused by Chernobyl. The air pollution from coal-fired power plants with almost 60 presumed deaths per year can serve as a comparison.

In the Ukraine and Belarus, there has been a sharp increase in the suicide rate in the affected regions, as well as a significant rise in depression, anxiety symptoms and stress-related illnesses. These mental illnesses have increased much more significantly than the cancer rate and are therefore described by some authors as the most serious consequence of the reactor accident when calculating the effects of the catastrophe for a larger population. It is difficult to separate these traumas from the psychological and material burdens of the collapse of the Soviet Union, including the drastic deterioration of the social and economic order and medical care. But similar symptoms of mental suffering have also been observed in other regions of the world in cases of radioactive contamination. It seems that radioactivity, precisely because we humans have no sensory organ for it, represents an invisible danger and thus a special psychological burden that is difficult to cope with. The suicide rate among the hundreds of thousands of liquidators is one and a half times higher than in the general population. In some regions affected by radiation, it is even up to three times higher.

As a consequence of the reactor accident, the Soviet government commission has drawn some far-reaching, unusually self-critical conclusions. The design weaknesses of the RBMK reactor and the operating errors were named as being due to institutional and organizational deficits of the Soviet nuclear industry. Above all, a safety culture that put expediency before quality was criticized. This is the only way to explain the repeated violations of fundamental safety guidelines under time pressure and the inadequate design and implementation of the fatal experiment. The most dangerous features of the RBMK design were changed in the other reactors of the same type by comprehensive improvements in the years to come. The other reactor blocks of Chernobyl were put back into operation but were then gradually shut down until the year 2000.

As drastic as the Chernobyl reactor accident was, the rescue measures were praised by experts around the world as excellently coordinated in view of the severity of the accident.

While the fight against the catastrophe and its consequences has often been described as heroic, it also laid bare the structural problems inside the Soviet society. The Chernobyl accident further eroded the believe of the inhabitants in the communist party. Just a few years later, the Soviet Union was history. The reactor catastrophe was not the cause, but certainly an important catalyst in these historical developments.

After all, the accident was not solely caused by operating errors. The design deficiencies of this reactor type – above all the positive void coefficient, the insufficient shutdown measures and the reaction-enhancing shutdown effect with fully extended control rods – were well known at the time. Some Soviet experts had expressed criticism of these points and made detailed suggestions for improvement. However, these were not implemented for cost reasons. As early as 1975, there had been a local reactivity accident in the RBMK reactor of the Leningrad-1 nuclear power plant near Sosnovi Bor. Here, several fuel elements melted, in a small precursor to the Chernobyl accident. And in 1983, the positive shutdown effect with fully extended control rods was observed at both the Ignalina nuclear power plant and Unit 4 at Chernobyl. In the same year, Victor Sidorenko, later scientific director of the RBMK program at the Kurchatov Institute, pointed out this effect and its dangers, especially when the reactor power was low.

It was clear long before the accident that the neutron-physical behavior of this reactor type was not fully understood and that its control system had not been adapted to these dangers. These are omissions of the technical-scientific and also the political leadership, who later wanted to distract from its own omissions by pointing at the errors of the operators. Professor Valery Legasov, head of the commission of inquiry into the reactor accident and a member of the Academy of Sciences, commented that this accident was the culmination of decades of mismanagement in his country. He took his own life on the second anniversary of the reactor disaster. The inhabitants of the affected regions in the Ukraine and Belarus will have to struggle with the consequences of this accident for generations to come.

Fukushima

The Japanese nuclear power plant Fukushima-Daiichi was first hit by an extremely strong earthquake on March 11, 2011, and then a large tsunami flooded the outside facilities, including the emergency power supply. This led to the second most serious reactor accident to date, in which several of the six reactor blocks including a cooling pond got out of control and released massive amounts of radioactivity. On the INES scale, this accident is classified as a "major accident" at the highest level 7, just like Chernobyl.

The Fukushima-Daiichi nuclear power plant is located 250 kilometers northeast of Tokyo in the central-eastern prefecture of Fukushima directly on the Pacific Ocean, from which it drew its cooling water. With a total electrical output of all blocks of 4500 megawatts, it was one of the most powerful power plants in Japan. It is owned by the operating company Tepco – Tokyo Electric Power Company. The nuclear reactors of Fukushima-Daiichi were among the older plants in Japan. Block 1 was already scheduled to be shut down at the beginning of 2011, but the Japanese nuclear regulatory authority had extended its operating life shortly before.

Blocks 1 to 4 were completely wrecked in the accident; blocks 5 and 6 survived the disaster without major damage but remain shut down. The damaged reactors belonged to the medium power class with 430 megawatts (Block 1) and 760 megawatts (Blocks 2 to 4). Blocks 4 to 6 were not in operation at the time of the earthquake due to maintenance work, but an oxyhydrogen gas explosion and fire destroyed the reactor building of Block 4.

The situation at the time of the accident looked like this: units 1 to 3 were in operation with partially filled cooling ponds, reactor 4 was not equipped with nuclear fuel rods but had a cooling pond filled to the limit of what was permissible, while Units 5 and 6 were already equipped but not yet in operation with cooling ponds that were not completely full. Since the fuel rods in the cooling ponds still develop a lot of decay heat, these too must be permanently cooled.

All reactors at Fukushima-Daiichi are boiling water reactors. They are based on the American plans of General Electric, which were intended for inland operation and not for the coastline. Multiple warnings from engineers and members of parliament that the nuclear power plant would probably not be able to withstand a strong earthquake and a tsunami were ignored by the operating company and the supervisory authorities. In addition, in all the damaged reactors, the cooling ponds – in which the spent and still highly radioactive fuel assemblies are stored – are located in the upper part of the buildings outside the containment, without any special protection. This was a decisive structural safety risk. Likewise, a 5.7-meter protective wall against tsunamis, which in the end was completely inadequate, was only completed in 2007. From the construction time in 1970 until that date, the power plant was only protected against waves of 3.1 meters in height. The fatal tsunami that hit large parts of the coastal regions of northeast Japan and, together with the earthquake, was responsible for around 20,000 deaths, reached a height of about 14 meters in Fukushima. The reactor buildings are only 10 meters above sea level, and important infrastructure such as the diesel tanks are even lower.

Due to the earthquake and the tsunami, more than 200,000 people had to be evacuated and over 100,000 buildings were completely destroyed. Some seaside towns were razed by the deadly water masses. Such huge tsunamis are rare, but in Japan, even much larger tsunamis have been recorded. In the last 500 years, 16 tsunamis with a height of more than 10 meters have been documented in Japan. Since Japan is located in one of the most seismically active regions of the world, the so-called "Pacific ring of fire," the building regulations for earthquake-proof buildings are extremely strict and used as a model worldwide. The dangers posed by the much rarer major tsunamis, on the other hand, had tragically been clearly underestimated, both in coastal cities (with the exception of the small town of Fudai with its 3000 inhabitants and its large dam) and in the construction of nuclear power plants. With regard to the Fukushima-Daiichi nuclear power plant, one has to speak of a serious misconstruction, since at least the emergency power diesels should have been built at a safe height or in secured bunkers.

Natural Catastrophe and Series of Accidents

On March 11, 2011 at 14:46, the northeast of Japan was shaken by one of the most severe earthquakes in the history of mankind. With a magnitude of 9.0 on the Richter scale and a duration of 2 minutes, it is the most severe earthquake since records began in Japan – six times stronger than the largest earthquake ever measured. Its strength was more than 25% beyond the specifications of what the robust reactor design was developed for.

The nuclear disaster itself was not caused by the earthquake, but by the tsunami that followed it. The epicenter of the quake was located 130 kilometers east of the nearby coastal city of Sendai at a depth of 20 to 30 kilometers below sea level in the Pacific Ocean; this triggered a large tsunami. Due to the strong earthquake, all nuclear power plants in the region were automatically shut down. Important infrastructure, in particular the power grid, broke down as a result of the earthquake; this included the power supply to the Fukushima-Daiichi nuclear power plant. The diesel emergency power generators started up as planned. Several aftershocks followed, some of which were still very strong, but by far not as strong as the main quake.

Around 3:40 p.m., the tsunami hit the coast in several waves and flooded over the protective wall of the nuclear power plant. The outside facilities were destroyed or rendered inoperable – especially the running emergency diesel generators, which were housed with poor protection in the lower levels of the powerhouses. The diesel tanks for the emergency power supply were washed away; the emergency battery supply was not intended for a longer, continuous operation and was also inundated. This resulted in a total failure of the power supply (the dreaded “station blackout”) and thus also of the cooling system. Attempts were then made to remedy the situation with the help of generator vehicles, but due to the destroyed infrastructure and too short cables, this was not successful. The population within a radius of initially 2, then 3 kilometers around the nuclear power plant was evacuated as a precaution. In the whole north of Japan there were widespread power failures.

The thermal output generated by the decay heat in a nuclear reactor directly after an emergency shutdown is still almost 10% of the nominal power, after one day still 1% and after 5 days still 0.5% of the nominal power. Thus, the reactors and also the cooling ponds – especially the one full to the brim at Block 4 – still needed constant cooling. This worked only for a short time and then failed. In the following hours, the reactor cores heated up more and more.

In order to compensate for the dangerous pressure increase in reactor 1, radioactively contaminated steam had to be released at 6:40 a.m. on the following morning of March 12. The evacuation zone was extended to 10 kilometers and now affected 45,000 people.

Since the control system had failed without electricity, the technicians had to open the valves by hand. Due to the increasing radiation doses, the few remaining workers wore protective clothing and oxygen tanks; they had to make their way through the dark corridors to the valves. They managed to open them by a quarter. Suddenly, at 3:36 p.m., there was a powerful oxyhydrogen explosion in Block 1, which completely destroyed the upper technical area of the reactor building. However, the lower, heavily reinforced containment with the nuclear reactor remained largely intact. If the workers had not managed to open the valves, the containment might have burst and the radioactive contamination would have been much worse. The evacuation zone was increased to 20 kilometers, affecting 140,000 people. The engineers and technicians made every effort to set up emergency cooling in all blocks and cooling ponds, but due to the extensive destruction, this was possible to an insufficient degree or not at all.

In the morning of March 13, the cooling system of Block 3 failed. The Prime Minister described the triple disaster of earthquake, tsunami and reactor accident as the worst crisis since World War II.

One day later, Block 3 was also destroyed by a severe oxyhydrogen explosion. Here, too, the reactor vessel remained intact. Only one day later, an explosion also occurred in Block 2, but less powerful than in the other blocks. However, as it turned out later, the containment in Block 2 was damaged, allowing large quantities of radioactively contaminated water to escape. On the reactor site, very high radiation doses were measured in places above ground – high enough to cause acute radiation sickness within only one hour. During some radiation leakages, the dose was so high that the remaining personnel had to be temporarily evacuated from the site. Even at some locations 30 kilometers away, up to where the evacuation zone had now been extended, very high radiation doses of up to 100 millisieverts per day were measured for a short time, due to a radioactive cloud passing through. A fire broke out in Block 4; the upper part of the building was also destroyed by an oxyhydrogen explosion – probably from gas that streamed in through connecting pipes from Block 3. The control rooms could only be entered for a short time due to the high radiation and were of limited use in this situation, with only emergency lighting and failed instruments.

The oxyhydrogen explosions were caused by the three core meltdowns in the reactor blocks 1, 2 and 3. After the failure of the cooling system, the fuel rods heat up so much due to the decay heat of the highly radioactive fission products that even without a chain reaction, up to over 1200 degrees Celsius were reached. At these temperatures, the zirconium cladding of the fuel rods reacts with the water steam and produces oxyhydrogen gas. In sufficiently large quantities, this gas can ignite and cause a massive shock wave. Probably the core meltdowns had occurred shortly after the cooling system failed, even though the operating company and the government only admitted this later after first appeasing the public. In units 1 to 3, the fuel rods were probably not sufficiently covered with water for several hours.

On March 14, Tepco considered withdrawing all remaining employees because of the radiation hazard and leaving the Fukushima-Daiichi nuclear power plant to itself. This would have made the disaster much worse and caused the meltdowns to get completely out of control. The Prime Minister refused. Thus, an emergency crew of 50 employees was left on site; they were revered by the media as the “Fukushima 50.” But they were not alone. They received support from 130 other helpers from the fire brigade, other companies and the armed forces.

Over the next few days, the rescue teams tried to use helicopters and water cannons to cool the reactors and cooling ponds from the outside. The cooling ponds, especially the one filled to capacity of Block 4 with its high thermal output, were a special danger, since the cooling ponds – in contrast to the fuel assemblies inside the nuclear reactors – were not sealed from the environment by a thick steel shell. These fuel rods would be openly exposed after the evaporation of the water. Therefore, they could be subject to a kind of nuclear meltdown in the open air, similar to Chernobyl.

In addition, the containments and the pump systems connected to them were leaking in some places, resulting in the release of highly radioactive water contaminated with fission products. The cooling had already been carried out provisionally with seawater for days, as the regional infrastructure had collapsed due to the earthquake and tsunami, and so had the drinking water supply. This emergency cooling had led to the formation of a salt layer by evaporating sea water, which would make further cooling even more difficult. Several dozen tons of salt accumulated in each reactor. In addition, tens of thousands of tons of radioactively contaminated water now accumulated in the lower floors of the reactor buildings. But finally, after a few days, technicians managed to establish a power connection to a nearby high-voltage line and get the still operational systems back on track, especially the cooling systems and lighting.

In the coming weeks and months, intensive work was carried out to install a functioning fresh water supply and a water filtration system for decontamination. By the beginning of April, over 10,000 tons of slightly radioactively contaminated water had been dumped in the Pacific Ocean. It was finally possible to stabilize the reactors and the cooling ponds of the damaged blocks 1 to 4 and to limit the emission of radioactivity. Blocks 5 and 6 now had stable cooling. Radioactive material was bound on the reactor site by synthetic resin spray; this had proved as a successful emergency measure in Chernobyl. Wherever possible, corrosion-inhibiting substances as well as water containing boron were introduced into the reactor vessels to prevent a chain reaction from flaring up again. Neutron radiation had been measured in between, an indicator that a chain reaction had restarted at some point, creating more radioactive substances and heating up the already hot and heavily damaged fuel rods. Special attention was paid to reactor 3 because it was equipped with MOX fuel assemblies. These contain particularly large amounts of dangerous plutonium, though all other fuel rods with significant burn-up also contain a certain amount of plutonium.

Consequences

One important difference to the Chernobyl accident is that in Fukushima there was no long-lasting graphite fire to transport large amounts of radioactivity to high altitudes. Thus, there were fortunately no mechanisms that could lead to a similarly heavy contamination of distant regions. In addition, the wind drove a large part of the radioactive material that had escaped seawards into the Pacific Ocean, where it was greatly diluted. In particular, the short-lived fission products released at the beginning of a catastrophe are highly radioactive emitters. But this time, the population was mostly spared from these effects.

The situation in the sea was further aggravated by the discharge of large quantities of radioactively contaminated water that could not be stored on site. For this reason, a fishing ban was imposed in the region. The radiation exposure was noticeably reduced in the course of the coming years. The total amount of radiation released was estimated to be about 10 to 20% of that at Chernobyl. Accordingly, the heavily contaminated areas were around 10% compared to Chernobyl. Around 80% of the released radioactivity ended up in the Pacific Ocean.

Given that this time not one, but four reactors or cooling ponds had been severely damaged, this is a clear indication that the multiple barrier security concept of the reactor core with reactor pressure vessel, containment and reactor building – as has become established in Western reactor designs – is at least capable of preventing the very worst.

Nevertheless, a broad strip towards the northwest from the power plant, which extends far beyond the 30-kilometer zone, is particularly affected by radioactive radiation. The municipality Iitate, 40 kilometers to the northwest of Fukushima-Daiichi, had to be evacuated and is one of the most severely hit regions by radiation. Similar to the lessons learned at Chernobyl, one can see here that local contaminations can vary strongly depending on wind direction and precipitation when a radioactive cloud is released. All inhabitants had to leave their homes by end of May 2011. In 2017, thanks to decreased levels of radiation, the government allowed inhabitants to return to their homes – with the exception of a few places with remaining high levels of radiation. But most people refused.

Similar to the sarcophagus in Chernobyl, in 2011 the damaged reactors were enclosed by a stable steel framework, replaced by a more robust structure in 2016. It will take several years until the radiation of the short- to medium-lifetime isotopes has decayed to such an extent that the dismantling of the reactors can begin. Due to advanced Japanese robot technology, these attempts will be of great interest to those responsible in Chernobyl and to radiation protection experts worldwide. So far, even many radiation-hardened robots have "died" inside the reactor buildings. These robots were built to withstand 70 sievert per hour, but extremely high values up to 530 sievert per hour have been measured in Unit 2.

One major problem of the decontamination work was the outflow of large quantities of contaminated water from the damaged reactor buildings, hundreds of tons daily. After the water was first allowed to spill into the ocean, tanks and water treatment systems were set up to filter the radioactive isotopes as well as possible. Technicians constructed an underground frozen soil barrier, the so-called "ice wall," to stop groundwater from flowing into the reactor buildings and mixing with the highly radioactive water inside. But this structure could only curtail, not halt, the flow of water into and out of the reactor buildings. At least, the melted reactor cores remained inside. Decontamination of the affected areas around the plants and decommissioning of the plants themselves will take several decades.

Reliable data on the number of dead and injured as a result of radiation damage will need to be researched for several more years. However, it is clear that the extremely high doses caused by the open fire of the reactor core in Chernobyl did not occur in Fukushima. Nevertheless, several dozen workers were exposed to greatly increased radiation doses. Two people at the power plant were killed by the earthquake and tsunami, one by a heart attack, and several were injured by the oxyhydrogen explosions. Two workers without suitable protective boots suffered skin burns on their feet and legs from the beta radiation of highly contaminated water. According to official sources, there were no cases of acute radiation sickness, which would speak for the prudence and expertise of the plant team. Therefore, there were hardly any cases of heavy exposure of half a sievert or more. The radiation dose for emergency situations had been increased by the government from 100 to 250 millisieverts, which, if the full dose is reached, results in a radiation-related cancer risk of 2.5%.

Thanks to the much slower unfolding of the catastrophe compared to Chernobyl, the evacuation of the civilian population happened early, and monitoring of food radioactivity was good. For this reason, radiation experts estimate that except for some cases of thyroid cancer, no statistically measurable increase of cancer cases should occur in the general population. Studies by organisations like UNSCEAR have confirmed this. A study by Stanford scientists that used the LNT model estimated the number of radiation-related deaths by cancer around 130, with high uncertainties. Other researchers arrive at higher numbers, up to above 1000 deaths worldwide. But even if this occurs, these numbers will be invisible in the statistics, as the naturally occurring number of cases over decades is orders of magnitude higher.

The zone of 20 km radius around the nuclear power plant has been declared a permanent exclusion zone, and there is flexible regulation for areas up to 30 km away. In Fukushima, like in Chernobyl, long-term contamination with caesium is now the most serious problem after the initially high level of radioactive iodine, which decays after a few months. The economic consequences for the region, which has already been severely affected by the natural disaster, can hardly be estimated; the social and psychological consequences through evacuation, loss of jobs, loss of confidence in the regional food industry, etc. are difficult to assess and require long-term social studies. In a study by the World Health Organization (WHO), 15% of 60,000 displaced persons that were interviewed on their situation reported anxiety disorders, feelings of guilt or depression. This is five times higher than usual. Some people are still fighting for compensations.

Japan, which is poor in raw materials and has traditionally had a pro-nuclear power government, is facing the task of developing a new social consensus on its energy policy. The country had entered World War II precisely because of its difficult raw materials situation. Its brutal attempt to establish a colonial regime in Eastern Asia had ended with the trauma of the atomic bombs dropped on Hiroshima and Nagasaki. After the war, the will to make use of civilian nuclear technology, which is resource-saving and guarantees self-sufficiency, became one of public consensus and had a strong impact on popular culture. For decades, the Japanese view of nuclear energy has been shaped by the desire to curb the power of atomic nuclei and make it available to society. The "excessive confidence" in the controllability of nuclear technology has been criticized in Japan in retrospect. It manifested in an institutional and entrepreneurial carelessness and led to a catastrophe that necessitates a reassessment and reorientation of energy policy.

After the Fukushima accident, all 54 nuclear reactors in Japan were shut down for inspections and to enhance safety. In 2012, Japan for the first time in 42 years was without nuclear energy. Since nuclear power provided 30% of the country's electrical power, it then had to rely more on coal and gas plants, leading to a significant increase in electricity prices. This again increased the mortality of poorer people during the cold winter period by several hundred people. It also made meeting the greenhouse gas emissions allowed by the Paris agreement more difficult. In 2015, the first nuclear reactor was restarted. Since then, a couple of reactors have restarted operation, but the majority remains shut down. Since the approval procedures have become stricter, their restart is often uncertain. Worldwide, nuclear power plant operators have conducted stress tests to find out weaknesses of their reactors. The increased safety standards have also raised the costs of building and refitting nuclear power plants.

The tragedy of the Fukushima reactor catastrophe is that the safety risks were well known and repeatedly expressed by experts, but the operating company or government agencies did not take them to heart. It would not have required major investments to ensure a safe emergency power supply. A higher protective wall or a structurally safer arrangement of the emergency power generators and the tanks – maybe simply on reinforced concrete stilts or securely bunkered – could have prevented the accident or at least significantly reduced it, even though the reactors were not designed to withstand such a strong earthquake, but only a somewhat less powerful one. This shows that the basic safety philosophy behind the design of nuclear power plants, namely to make all necessary safety installations as redundant and diverse as possible, was not given sufficient consideration. It is not enough to have several emergency power generators (each of which, in the sense of redundancy, produces sufficient electricity) if all these generators can fail simultaneously due to a common cause. A seriously diverse safety philosophy would be to have several physically separated and safely bunkered emergency diesel generators – maybe from different manufacturers – with diesel fuel in physically separated tanks and changing inspectors. The same applies to all highly safety-relevant systems such as emergency power supply, cooling water pumps, etc. Such a safety standard is not yet common everywhere. Given the profit margins of nuclear power providers, it would probably be affordable.

Interestingly and little known, Fukushima-Daiichi was not the only nuclear power plant that suffered from flooding in 2011. Fort Calhoun Nuclear Generating Station is located in the US state of Nebraska on the Missouri River, a branch of the Mississippi River. After heavy rainfall and a dam burst, a severe Mississippi River flood occurred in June 2011 that lasted for weeks and washed around the nuclear power plant. The plant was protected from flooding only by sandbags and a large, inflatable tube around the plant. The latter, however, had been damaged by a vehicle. The transformers, which provided the connection to the power grid, were washed around by the water masses, so that now the safely bunkered emergency diesels had to ensure the power for the cooling water pumps.

Fortunately, this was accomplished without any problems. Although water entered some buildings through a few leaking doors and connections, it did not damage any safety-relevant equipment. The flood, which lasted a total of 80 days, therefore did not cause any serious problems.

Since nuclear power plants are generally located near large bodies of water due to their large cooling water requirements, nuclear power plant operators around the world reviewed in detail their flood precautions after Fukushima and this incident. And even a good decade earlier, in December 1999, there was a similar flooding scenario at the Blayais nuclear power plant in France. A hurricane had initially caused disruptions in the power grid, which led to the automatic shutdown of two of the four reactors. Then, the storm pushed water from the Gironde River over the dikes onto the power plant site, flooding some underground areas of two units – including parts of the cooling and emergency cooling systems and other safety equipment. Fortunately, two of three cooling circuits remained functional, so there was no danger of a core meltdown. However, this example shows that the danger of unusual flooding was known even before Fukushima and was discussed among reactor safety experts.

Beyond Japan's borders, the Fukushima reactor accident has highlighted the fallibility of human planning and the enormous risk posed by inadequately implemented basic safety concepts. It demonstrated to the world that even Western nuclear technology is not safe from a huge disaster when everything goes wrong, and when human negligence and unforeseen natural forces collide in a fatal way. As the multiple catastrophe in Fukushima has shown, in such cases the tiny residual risk can turn into an inevitable disaster scenario that can only be contained by the selfless courage and determination of competent individuals. Very soon after the accident, Germany decided to phase out nuclear power and instead extend the operating life of its coal plants. In the following years, Belgium, Spain, Switzerland and South Korea also decided to phase out nuclear energy completely in the medium term and instead rely on renewable energies.

Despite all the hazards to those affected, thanks to the fact that most of the radioactive inventory remained trapped inside the reactor blocks and to the coincidence that the offshore wind carried most of the released radioactivity towards the Pacific Ocean, far fewer victims are expected than after the Chernobyl disaster. Also, early evacuation helped to minimize radiation exposure to the population. Final figures regarding the costs of this multiple reactor accident will not be available for a long time to come. No cases of radiation-induced fatalities can yet be associated with the disaster. But since the radiation risk of small doses is not clear, it will be difficult to assess the true effects of this accident. The cases of social and mental distress and resulting illnesses that always come with such catastrophes are often not considered in official studies and may – like in Chernobyl –be the most severe consequences of this accident.

Aspects of the Operational Safety of Nuclear Power Plants

As all minor and major nuclear accidents have shown, the safety of nuclear facilities not only depends on reliable technology, but also very much on the people working in this demanding sector. This concerns above all the nuclear power plants themselves, as well as the fuel assembly factories and reprocessing plants. Politicians and industry representatives have repeatedly emphasized that all modern nuclear power plants are safe and equipped according to the latest technical standards. This serves to reassure a skeptical public. Nevertheless, some points have been criticized times and again over the years by renowned nuclear safety experts, not least after the Fukushima accident. These points include optimisations both of a technical and organizational nature and are meant to bring about significant improvements in the safety of nuclear power plants. Some of them are not even particularly expensive; they only demand the concession that the real existing nuclear power plants, which usually have a few years on the clock and run with decades-old technology, can be improved in terms of safety.

It is necessary to check whether all causes of possible accidents, however difficult they may be to conceive, have really been analyzed, and whether the fundamental safety-relevant systems can be secured against multiple failures that seem extremely unlikely or almost impossible. Some examples: If a power plant does not already have a safe enclosure, then how would it be possible to ward off an airplane crash or terrorist attacks with armor-piercing weapons? The answer could be a sufficiently high and thick concrete wall around the power plant. It would not even need to have a roof and could therefore be constructed rather cheaply, since commercial aircraft cannot be nosedived in a controlled way even by suicide squads.

Such analyses now include the consideration of natural disasters that are extremely unlikely. This is a bitter lesson from Fukushima. Even under extreme circumstances, such catastrophes must not lead to a beyond-design-basis disaster. For this reason, both the emergency power supply and the cooling systems should be self-sufficient and spatially separated, possibly in multiple versions. After Fukushima, it has become a de facto industry standard to have much larger battery banks to be able to bridge more time until regular power supply can be provided by grid connection or emergency diesels. Now, they should be sufficient for up to one day. Also, the diesel supply schemes have been enhanced. Instead of delivering enough power for three days, some plants now have reserves for up to seven days or longer.

Other risk factors can be found in the control technology. Modern control technology is digital, which means that it has a high degree of functionality. However, it can only handle situations for which its program code was written. Even with all due caution, an infestation with computer viruses and other malicious code, perhaps even a targeted sabotage, can never be completely ruled out. Crucial digital infrastructure is usually not connected to the internet, but such a scenario remains a possibility. In the event of serious computer

Fig. 10.8 Insulated steam pipes in the turbine building of the Gösgen nuclear power plant

problems or similar situations, like in the case of sensor or control malfunctions, it could therefore be desirable to have completely independent, hardwired, analogue basic control technology that can be used to implement the rescue functions "shut down reactor" and "switch on after-cooling." Finland has installed such a "hardwired backup system" in its new EPR reactor at Olkiluoto.

From an organizational point of view, safety could be increased by creating a team of specialists trained to deal with serious incidents. Such a team of highly qualified experts must be able to deal with unusual deviations from normal operation, if necessary by taking creative measures. Creativity is frowned upon in regular operation; deviations from the established procedure are not intended. This is highly desirable, as reliability and thoughtfulness are the highest virtues in power plant operation. As an employee in a nuclear power plant once said, after a few years of work there, one is hardly suitable for other branches of industry. Right from the start, you get used to doing things very slowly, carefully and thoughtfully in order not to make any mistakes and to always keep an eye on the consequences. However, during an emergency, sometimes more courageous decisions are needed.

During the Three Mile Island accident, the operators were too afraid of filling too much water into the pressure vessel – something they were rightly taught during their training to be highly dangerous. They therefore recognized the signs much too late that more water was needed. In Chernobyl, the operators were not well enough aware of the highly dangerous partial load range in which they were operating the reactor. In Fukushima, the entire plant was not designed to operate in a region prone to earthquakes and tsunamis; with the chaos that followed, it took too long to admit how bad the situation already was.

After Fukushima, the worldwide nuclear community has started to rethink fundamental aspects of reactor safety. Up to that point, the prevailing philosophy was to define strict rules for reactor construction and then to hold tightly to these rules. The lesson from Fukushima was that this is not enough. The plant fulfilled all regulations. But the regulations were bad and did not include the small, yet existing probability of a major tsunami. Even the strictest regulation can neglect certain unforeseen events. For this reason, the fundamental safety philosophy now also includes the idea that even if the worst happens and a meltdown is imminent, the situation should be as controllable as possible. More flexibility under the most severe conditions is necessary.

Since both serious human error and extraordinary coincidences can never be completely ruled out, an emergency team should therefore be on hand to coordinate rescue operations and, in the worst case, to limit damage. For example, helicopter-transportable generators and high-pressure pumps could be kept in sufficient numbers for catastrophes if a major terrorist attack or a natural disaster destroys important equipment on site and quick remedial action must be taken before a reactor overheats. France has already introduced such emergency helicopter teams. Other countries rely on heavy trucks with mobile equipment. Accordingly, the nuclear power plants need to provide appropriate external connections for water and electricity. These have been refitted in many plants over the last decade. In Fukushima, this would probably have prevented the disaster. Another question is whether nuclear power plants should be turned into militarily secured restricted areas or whether military security should rather be kept secret.

A further organizational and social aspect concerns the entanglement of politics and energy industry. Just as between the executive and the judiciary, conflicts of interest between controlling authorities and energy companies should be avoided as far as possible. In Japanese, the transfer of deserving officials from the civil service to lucrative positions in the private sector is known as "amakudari" (literally "descending from heaven"), in English as "revolving doors," in French as "pantouflage," and in German as "cousins' economy." Such an amalgamation does not serve the security interests of a country, nor those of the energy company.

What applies to nuclear power plants applies to all other nuclear facilities. It is largely unknown to the public that such large quantities of highly radioactive material are stored in interim storage facilities and reprocessing plants that, in the event of an airplane crash, a war or a terrorist attack on such facilities, the same release of radioactivity can be expected as in a catastrophic reactor accident. Since nowadays nobody knows where to put the nuclear waste and since the public often has a negative attitude towards the transport of nuclear waste, large amounts of nuclear waste are stored directly at the nuclear power plants or are located in the cooling ponds. These could often be better protected.

The Human Factor, Residual Risks and Ethical Conflicts of Nuclear Energy

Residual risk refers to the insight that in complex systems, despite the best possible security systems, it is never possible to exclude all dangers. Nuclear power plants are among the most complex systems ever conceived and built. The basic principles of operation described in this book can only represent a small fraction of the relevant technology, where thousands of wires, power cables, measuring devices, pipes, connections, pumps, valves, etc. form a complex whole in which every single weld seam can be relevant to safety. A single person can never fully understand such a system.

Accordingly, the residual risk of all safety systems failing and a major accident occurring in a nuclear power plant can never be specified exactly. We learn from experience, most of all from mistakes. This also applies to our knowledge of error estimation. Although experts try to indicate the residual risk for the operation of nuclear power plants as objectively as possible, it is true that all calculations of the residual risk are always made by humans and that only factors known to these people can be included in such calculations. Even if the calculations are performed correctly, strange chains of events and rare interactions can still be overlooked.

Depending on the type of nuclear reactor, a beyond-design-basis accident is expected every 10,000 to 100,000 years or so, based on theoretical residual risk estimates. These figures are obtained by multiplying the very low probabilities of failure of safety-relevant components and thus arrive at extremely low probabilities due to the multiple design of these components. With a good 400 reactors worldwide, these theoretical considerations result in a core meltdown or similarly grave accident every 25 to 250 years. Obviously, due to human error in planning, testing and operation, the real figures are significantly higher. The question then remains whether a meltdown will remain contained, as in the case of Three Mile Island and similar accidents, or whether the surrounding area will be contaminated, as in Chernobyl and Fukushima.

And even the best theoretical considerations can never take into account very weird chains of events like those that occurred in the near-disaster at the Browns Ferry nuclear power plant in Alabama in 1975. In this nuclear power plant, the operating crew had developed a peculiar practice of testing for leaks in cable penetrations that affected the negative pressure in the containment. They did this with the help of a candle whose flame was deflected by the airflow if there was a leak. But one day, a team of technicians got too close to the combustible foam of the cable sheathing (which was later replaced by non-combustible foam due to the events that occurred) and caused a severe cable fire that could spread unhindered because the sprinkler system was switched off at that time. This fire paralyzed much of the power plant's instrumentation by short circuits. Even though the instrumentation was largely out of order, the operators were able – with great effort and a little bit of luck – to perform an emergency shutdown, switch on aftercooling and prevent a core meltdown. Investigations later revealed that not only the handling of open fire, but also the use of flammable foam and the whole way of wiring was contrary to basic safety regulations.

In nuclear power plants, the greatest possible fault tolerance must therefore be taken into account throughout the entire chain of possible events, from planning, construction and operation to maintenance and inspection, both in terms of technical and human error. In the opinion of many scientists, reliability predictions about complex systems are only possible with large errors; exact figures are only possible for individual systems at most. The interaction between human and machine is usually not even considered. The analysis of all major nuclear disasters shows that it is always humans who make mistakes, either in planning, construction, operation or monitoring. However, the human factor can hardly be quantified. The crux of the whole story is that if more technical safety is achieved at great expense, the concentration and diligence of the engineers and technicians could possibly decline as a result of social dynamics, precisely because they think they are on the safe side. The Chernobyl operators were highly respected and thus overestimated their own ability to control their reactor outside of instruction manual regulations.

Safety culture is difficult to prescribe. It must be laboriously practiced again and again. The regulatory and control authorities are also affected by this.

Several independent audit bodies with the same rights and duties do not correspond to the usual way the hierarchical apparatus of government agencies works, but they could be an asset when it comes to security issues – at least if the human factor does not thwart this due to a conflict of competence and a mutual blockade.

All that makes up a human being – ambition and comfort, courage and fear, creativity and innovative power, short-sightedness and fallibility, striving for power, recognition and profit as well as modesty and selflessness – can be found in the most diverse forms when looking at the historical development of the nuclear age. All these human factors are unpredictable, but they must never be ignored in a social evaluation of nuclear energy and its future development. This applies not least to the assessment of the residual risk in the operation of nuclear facilities. At this point, technicians, scientists and engineers are not the only people involved: society also needs to participate in such a discussion.

Nuclear energy is one of the pillars of energy supply in many highly developed industrial countries, in democracies as well as in more authoritarian societies. However, the once enthusiastic assessment has turned out to be exaggerated, and the evaluation of the risks involved has turned out to be too optimistic. The extraordinarily difficult dilemma of finding a sober view of nuclear energy is that there are several interrelated, socially relevant problem areas that are as complex as the construction of nuclear power plants themselves.

Thus, in order to provide a balanced and objective analysis of the situation – after all, this book is intended to stimulate reflection and discussion, not to present ready-made solutions – both positive and negative aspects should be mentioned. Since waste disposal and the associated risks are discussed in the following chapter, the discussion here is limited to the possibility of serious and catastrophic accidents.

Today, nuclear power plants cannot yet be built in such a way that catastrophic accidents can be ruled out in principle for reasons of nuclear physics. Such inherently safe nuclear power plants, which are nevertheless affected by the problem of waste disposal, are currently in the development phase. While the most modern reactor types, of which several are under construction or already finished, feature formerly unreached security levels, there are always thinkable chains of improbable events (airplane crashes, terrorism, unforeseen natural catastrophes etc.) which can lead to major accidents. During the operation of a nuclear power plant, there is always a very low risk connected with a very high level of damage in the event of a disaster. Coal-fired power generation, which is an indispensable part of the energy supply of most countries, produces air pollution that regularly causes a small number of people to die.

Many more people die from alcohol and tobacco, but they have deliberately taken this risk.

In the case of nuclear power plants, most people are unable to assess either the residual risk or the degree of personal danger. In normal operation, nuclear power plants are an extraordinarily clean technology, apart from the problem of disposal. In the event of a disaster, they can contaminate large areas of land in the long term. On the other hand, mining, and especially opencast lignite mining, is a landscape-destroying and sometimes also culture-destroying activity. Regenerative energies, too, can cause extensive interference in existing landscapes.

A question that has to be renegotiated again and again in societies is what risks one is prepared to take, who bears the disadvantages and who profits from the advantages. The specific problem with nuclear energy is that the vast majority of the population has no opportunity to verify the information provided by the government and large energy companies. Not everyone enjoys reading books on nuclear energy. Thus, these people depend on fragile trust in such institutions. The way in which government institutions worldwide have repeatedly asserted the interests of big industry has not necessarily fostered this trust. In the case of nuclear energy, weighing up the individual and societal benefits and risks is fraught with major gains and losses.

Some opponents of nuclear power, for example, cite numbers of victims as a result of nuclear catastrophes that are many times higher than the scientifically verifiable figures. Although it cannot be ruled out that a certain number of radiation-related deaths occurs above the statistically verifiable ones, there is no reason to completely distrust official findings. If things were as bad as some people fear, then the visible statistics would be very different. The large public organizations that are concerned with radiation protection and with the corresponding statistics by and large work with a scientific integrity that could only be wished for in many other areas. There are some blind spots, not least with respect to uranium mining and military nuclear facilities, but generally, radiation protection measures are well coordinated.

Another aspect that is difficult to quantify but which is also highly relevant is the psychological effects. It is a natural human reaction to be afraid of the unknown, even though the stress that this fear causes may be more dangerous to health than what triggers this fear. Most smokers would probably be surprised to learn to how much more radioactive radiation they expose themselves to through cigarette smoke, even if the increased risk of lung cancer is still mainly caused by chemical toxicity. The individual and economic effects of anxiety can be enormous. The psychologically induced health effects of the population around Chernobyl and Fukushima – combined from the loss of home and workspace, fear of being contaminated, the feeling of helplessness and the inability to understand and cope with the invisible danger of radiation – are greatly underestimated by the rational-technological viewpoint of scientifically minded supporters of nuclear energy. Nobody can quantify the kind of mental torture that many pregnant women experienced after the Chernobyl accident, when they were haunted by nightmares of giving birth to monsters.

Instead, all too often the residual risk is dismissed as hypothetical and the controllability of even the most serious accidents is taken for granted. Minor incidents that were at least potentially dangerous are often portrayed in a trivialized manner so as not to unsettle the population. This explains many peoples' lack of trust in the announcements of companies and institutions.

However, if a major accident does occur and the residual risk changes from a hypothetical number to a real disaster scenario, the lives of many people are radically changed. For the rescue workers on site, such a disaster can be accompanied by a noticeable increase in their cancer risk or, in rare cases, even radiation death. For many people from the surrounding regions, it usually means a slight increase in the cancer risk, possibly the loss of their home and associated trauma.

In such a scenario, a democratically constituted society cannot apply the same pressure to its citizens as an authoritarian dictatorship might. One must then be grateful for every person who puts his or her life or health at risk. It is a fact of experience that in liberal as well as in authoritarian societies, there are always people – especially in certain professions, such as firefighters – who show heroic personal commitment in emergency situations. But it is not possible to rely on the assumption that in all catastrophes, there will always be enough volunteers willing to risk their lives or their health for the public at large.

Forced helpers are not usually treated as heroes. Most of the liquidators of Chernobyl were sent home with a few rubles and a handshake. The medals that were given to them can now be bought cheaply at the region's flea markets. Such a path is not open to more democratic societies; they are therefore much less resistant to such a catastrophe. Considering the circumstances that

1. nuclear energy and its risks cannot be understood by a large part of the population, neither in its mode of operation nor in its effects, that
2. as a result, these people cannot adequately represent their interests vis-à-vis industry and politics, that
3. due to this uninformedness, profits and risks are unevenly distributed, that
4. the operation of nuclear power plants can have serious consequences, though with very low probability, and that

5. personal courage, which cannot always be institutionalized or forced, is required to contain disasters,

the question can be asked as to whether nuclear energy is a technology suitable for a democratic society and what conditions should be met in terms of the distribution of risks and benefits so that it can be classified as such. While the modern standards are certainly higher than in the past, these questions have to be asked time and again in order to further increase safety levels.

It is also not always clear in what way a society as a whole has to bear responsibility and take precautions for people who are harmed by accidents. This is particularly true since, in the case of radioactive contamination, mental stress is exacerbated by the feeling of imperceptible and simultaneously abstract and concrete danger. These and similar questions can of course be put to other controversial technologies.

In the public debate, there is some deficit in the interdisciplinary discussion of these topics. And this is aggravated by the unfortunate division between natural and engineering sciences on the one hand and humanities and social sciences on the other. For while natural scientists and engineers are not trained to think critically about the consequences of new technologies and its impact on people, philosophers and sociologists often lack the scientific understanding of the many connections that exist in a complex field like nuclear energy. This book should be seen as an invitation to engage in a joint discussion on these topics. In France, students of nuclear engineering and students of philosophy were highly inspired by and praised a joint workshop that thematized the problems of nuclear energy. Unfortunately, such interdisciplinary encounters are still far too rare.

11

Disposal

The responsible handling of the radiating legacies of nuclear energy is one of the major unsolved problems of today's energy industry. In contrast with the use of fossil fuels and the associated climatic changes, there is no immediate urgency to solve these problems. Yet, the total amount of material that will emit dangerous radiation for periods of time beyond all human imagination is so large that no satisfactory solution has been found so far – anywhere in the world. And worse, today's decision-making procedures in the search for a repository often neglect the human factor in particular, which could prove to be a huge mistake.

The problem of nuclear waste disposal does not pose such an acute threat as proliferation or possible reactor accidents. But intellectually and ethically, it is the most difficult of all. It will continue to occupy many generations after us, potentially affecting an enormous number of people. And unfortunately, the relevant decision-makers in politics and business are often too fixated on solutions that can be planned in the short term, which is why long-term, social-ethical conflicts of interest are only taken into account inadequately or not at all. Most philosophers and social theorists lack the expertise in nuclear physics and radiology needed to recognize the gigantic scope of this problem. A responsible civil society is needed here.

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6_11

Types and Quantities of Nuclear Waste

There are three types of radioactive residues in the nuclear industry: low-level, intermediate-level and high-level radioactive materials. A further distinction is made between heat-generating and non-heat-generating waste. This last distinction is, however, more relevant for technical problems of storage and less for the fundamental issues as discussed here. This is because the more heat waste generates, the more spacious and less dense it has to be stored and the longer it has to remain in interim storage facilities until its decay heat has decreased to a tolerable level. High-level waste can generate up to 20 kilowatts of thermal energy per cubic meter. This enormous amount of heat has to be dissipated away so that it cannot damage the integrity of the casks containing burnt fuel assemblies.

Low-level radioactive waste includes solidified liquid waste, cleaning cloths and work clothing. This class poses the least problem due to the low level of contamination, but the quantities of material involved are quite large.

Intermediate-level radioactive waste includes activated parts of fuel assembly casings and reactor parts, structural parts from reprocessing, resins from water purification and waste from medical and industrial applications. These wastes already place higher demands on proper storage. In some cases, they have to be well shielded and stored safely over a long period of centuries to millennia. In terms of their damage potential, however, they are exceeded many times over by the high-level radioactive waste.

High-level radioactive waste is responsible for the vast majority of radioactivity, even if it is the smallest amount. It consists mainly of two types of radioactive materials: first, the extremely radioactive fission products with half-lives of up to 100 years, and second, the transuranium elements, which are often much longer-lived and therefore also have a lower activity and heat generation. A few fission products have half-lives similar to those of the long-lived transuranium elements.

After burning and some time in a cooling pond, a fuel rod still contains about 93% uranium, which has only weak radioactivity. The proportion of fissile U-235 has dropped from a few percent back to below 1%, but can be enriched again with the help of centrifuges if reprocessing is carried out. Of the remaining 7% material in the fuel rods, there are now:

- 5.2% stable fission products (mostly daughter nuclides of already decayed, very short-lived radionuclides)
- 1.1% plutonium

Fig. 11.1 Milling machine during excavation works in a chamber in Schacht Konrad, a former iron ore mine turned into a final repository for low- to intermediate-level radioactive waste

- 0.2% short-lived fission products (such as caesium-137 and strontium-90)
- 0.32% long-lived fission products
- 0.2% transuranium elements

One ton of nuclear fuel, after three to four years in the reactor, contains 930 kilograms of uranium – 99% of which is uranium-238 – and around 11 kilograms of plutonium. In addition, it contains nearly one kilogram of americium, 800 grams of neptunium-237, 100 grams of curium and 55 kilograms of fission products, 3.2 kilograms of which are extremely long-lived. The exact numbers depend not only on the burn-up, but also on the reactor type. Not only the plutonium, but also the long-lived fission products and the transuranics cause many long-term problems. Their half-lives are often longer than those of plutonium (24,000 years for Pu-239), and they are all highly radiotoxic. Neptunium-237 has a half-life of over two million years, while americium-243 has a half-life of over 7000 years. Americium-241 decays much faster. Its half-life is 432 years. But its decay produces, among other things, the long-lived neptunium-237. Such decay chains lead to the effect that some dangerous isotopes are not present at the beginning, but build up over years or millennia.

Among the fission products, there are seven very long-lived isotopes: technetium-99, tin-50 and selenium-79 with a half-life of around 200,000 to 300,000 years, and zirconium-93, caesium-135, palladium-107 and iodine-129 with half-lives from 1.5 to over 15 million years. As these isotopes are lighter than the transuranium elements and form different chemical compounds, they are also more mobile in the ground and can be transported more easily in a geological repository.

The transuranics consist of very heavy elements called "minor actinides" after their position in the periodic table of the elements. These minor actinides include isotopes of neptunium, americium, curium, berkelium and californium. Especially isotopes of neptunium and curium cause problems here, because they are partly very long-lived and also strong alpha emitters. But all these heavy elements undergo several alpha decays in their decay chains, usually with high energies.

If it were possible to separate the more short-lived fission products with a very high degree of purity from the long-lived waste, these fission products would have to be stored for a good 1000 years or a little longer before they have largely decayed and no longer pose a significant danger. The transuranium radionuclides and long-lived fission products, on the other

Fig. 11.2 Interim storage facility for high-level radioactive waste at Grohnde. The casks are six meters high and radiate heat like ovens in the cool hall. Access to the ground level is highly restricted and only possible when wearing a special neutron dosimeter

Fig. 11.3 Interim storage facility north for decommissioned parts at the nuclear power plant Greifswald. Steam generators (grey), high-pressure parts and several reactor pressure vessels (center)

hand – including the weapon material plutonium-239 – must be stored for several hundred thousand years!

Today's final storage concepts consider a storage period of one million years to be necessary. After about 300,000 years, at least plutonium-239 has mostly decayed, which reduces the danger of proliferation. Considering the fact that nobody today can make any predictions over such periods of time, which are longer than the phylogeny of Homo sapiens on planet earth, a few dozen millennia might not make a difference. One million years ago, our ancestor Homo erectus still roamed the plains, with its most advanced technology being the use of fire.

Although the very long-lived radionuclides initially account for less than 1% of radioactivity, since they are much longer-lived, they survive the short-lived fission products many times over. In the first 1000 years, therefore, the greatest activity stems from the short-lived fission products. For the coming million years, the radiation comes almost exclusively from the transuranium elements as well as from the few very long-lived fission products.

The quantities involved are, in a medium-sized nuclear energy country, several ten to one hundred thousand cubic meters of low- and intermediate-level radioactive waste. About one tenth of this is high-level radioactive waste. Worldwide, around 12,000 tons of high-level radioactive waste are produced annually. The accumulated worldwide amount of high-level waste is around 300,000 tons. For comparison: a typical nuclear power plant of 1 gigawatt electrical power produces around 27 tons of used fuel every year, while a coal plant of similar power output generates 400,000 tons of ash.

Some of the resulting radionuclides have half-lives of well over one million years. Accordingly, they have lower activity. The planned safe storage time of one million years is the result of a calculation that takes the remaining radioactivity after this time into account. It is assumed that radioactive waste should be stored safely away from the biosphere at least until its activity is no longer higher than that of typical uranium deposits. This is, of course, an arbitrary decision of today's generations that future generations may see differently.

These radioactive materials do not occur in nature, since radionuclides with such half-lives decayed long ago, some time after the formation of earth. According to the current state of the art, the separation of fission products and transuranium elements involves a highly sophisticated technical effort in reprocessing plants. Reprocessing plants can extract unused uranium-235 and the breeding product plutonium-239 from spent fuel rods. Besides these elements, many other radionuclides can be separated from used fuel rods. This is done to extract rare radionuclides for use in science, medicine and industry. Uranium-235 and plutonium-239 can be reintegrated into fresh fuel rods, while the other radionuclides must be stored safely. However, reprocessed uranium is more expensive than uranium that comes directly from uranium mining. Thus, the operation of reprocessing plants serves the extraction of plutonium and is motivated mainly by military technology. Still, the expensive recovery of uranium also allows stocks to be stretched.

Due to the reprocessing of fuel rods, such large amounts of plutonium have accumulated in the meantime, that nobody knows how to use it. As long as the world market price for uranium does not rise steeply, the use in MOX fuel rods is uneconomical and mainly serves the consumption of plutonium to reduce the enormous stocks. Although the vast majority of stockpiles do not consist of weapons-grade plutonium, impure reactor plutonium is in principle suitable for the construction of a weaker atomic bomb, which could still cause considerable damage. Fearing that plutonium could be stolen for terrorist purposes, some of the expensively separated plutonium even has been remixed with highly radioactive fission products. In this way, it is unfit for such purposes and lethally radiating. For these reasons, there is an increasing international trend not to reprocess fuel rods and to avoid this expensive, dangerous and potentially contaminating route.

In any case, MOX fuel rods usually contain only a certain percentage of plutonium compared to uranium and therefore cannot cause a significant stretching of uranium reserves. In addition, MOX fuel produces a lower percentage of delayed neutrons, so the chain reaction gets more difficult to control. Without changes to the reactor, light-water reactors can only substitute around 30 to 40% of U-235 by Pu-239. There are, however, reactor concepts such as certain breeder reactors, including the so-called traveling-wave reactor, that are able to extract a multiple amount of energy from the uranium via the detour of breeding plutonium.

Due to the economic and radiation protection problems associated with reprocessing, most of the spent fuel assemblies used in civil nuclear technology today are therefore packed in high-level radioactive waste containers with all their fission products and transuranium elements and then transported for storage. There are various different container systems for such dry cask storage. Each canister can hold up to several fuel assemblies, depending on the type of assembly. The containers are filled with inert gas to reduce corrosion and then sealed by welding or bolts.

Because of the heat generated by highly radioactive waste, this waste is gradually treated in such a way that the freshly spent fuel assemblies are first cooled underwater in the cooling ponds of the nuclear power plants for several years until the short-lived, extremely active fission products have vanished. Then they are placed in interim storage facilities for several decades, in which air circulation is sufficient for cooling. During this time, the medium-lived, still highly active fission products lose a large part of their activity. Only then can these containers be stored permanently without external cooling. Temperatures inside the casks can still exceed 300 degrees Celsius in some cases, but on the surface they must be below 100 degrees Celsius in order to be stored in rock – as currently planned. This temperature limit is important, because above it these containers could cause water in the surrounding rocks to evaporate, strongly increasing corrosion and deterioration of the containers and driving unwanted chemical reactions.

Dangers from Nuclear Waste

Due to the generation of heat and radiation as well as the danger of theft or attack by terrorist groups, radioactive waste transports with high-level radioactive material have to be well protected. Should a terrorist group succeed in carrying out a successful attack with armor-piercing explosives on such containers, massive radiation of the surrounding area would have to be expected. The accident in Kyshtym shows what problems could ensue in such a scenario.

Despite nuclear transports not being very popular in some regions, a single centralized or a few decentralized interim storage facilities are easier to protect and cheaper to maintain than if – as is currently the case in many countries – radioactive waste simply remains in large quantities at the nuclear power plants for lack of a good disposal concept. This practice is neither a permanent nor a particularly safe solution. However, many people fear that the nuclear waste, once temporarily stored, will remain there for much longer than the decades of aboveground storage that are necessary anyway.

Transports of low- and intermediate-level radioactive waste require less elaborate protection and shielding. But even this waste has to be stored for a long time, as it may contain some dangerous isotopes. The exact limit between low- and intermediate-level radioactive waste is somewhat arbitrary and varies from country to country; it is determined by health policy and economic considerations. Apart from the fact that their activity and heat generation is much lower, they are also much less problematic than high-level waste because they do not contain many extremely long-lived isotopes or bomb-suitable material.

Nuclear waste can be handled in very different ways. In the early days of the nuclear industry, the principle of dilution in the environment was followed. As long as only very small amounts of radioactive material reach the biosphere in a thinly distributed form, this would lead to a radiation exposure that is only a fraction of natural radioactivity. Even back then, this was a bad idea and irresponsible politics. It is always better – and more expensive – to store dangerous material in safe containers than to spread it into the environment.

Today, the production of highly radioactive material during the operation of large nuclear power plants is so large that dilution in the environment is no longer an option anyway. If in an average industrialized country the radioactive waste from its nuclear power plants were evenly distributed over the area, the result would be a multiple increase in natural radiation (and, depending on the initial storage period, up to well over a hundred times) with a correspondingly high number of fatalities. In addition, certain substances accumulate in the food chain and can become highly concentrated.

Fig. 11.4 Decontamination works in the active workshop at the decommissioned Greifswald nuclear power plant

Responsible handling of radioactive waste can therefore only consist of isolating the material as completely as possible from the biosphere. According to the current assumptions about radiation protection (compare the discussion of the LNT model in Chap. 3), a slight increase in natural radioactivity could lead to cancer with a small statistical probability. Now, human activities are always carried out under uncertainty, and other technologies unfortunately claim their victims as well. A minimal release of radioactive substances can never be ruled out. But it should be the declared goal of a responsible nuclear industry to avoid radioactive emissions as far as possible.

A particularly controversial – not to say scandalous – method of disposal was the dumping of radioactive waste at sea, which was banned by the International Maritime Organization only in 1994. Up to this point, over 100,000 tons of radioactive waste had been dumped into the sea! According to official data, this was low- and intermediate-level radioactive waste. But critics assume that some highly radioactive waste was also mixed in. The British nuclear industry is responsible for over 80% of this dumping, mainly

Fig. 11.5 Interim storage facility north at Greifswald, for low- and intermediate-level radioactive waste

in the Northeast Atlantic. Switzerland also contributed a not-inconsiderable amount. Smaller quantities came from Germany, France, Belgium and the Netherlands. Between 1946 and 1970, the USA also sank over 90,000 containers of radioactive waste off its coasts.

Investigations have shown that the dumped barrels have now largely dissolved in seawater, together with their contents. The disposal concept at that time: "Dilution is the solution." That this is nonsense – for example, because radioactive substances can also accumulate again in the food chain – can also be seen from the fact that this dumping was carried out in secret. It would probably have been carried on for a long time if Greenpeace hadn't drawn media attention to this disposal practice in the 1980s with some spectacular actions.

Due to an odd regulation, the dumping of liquid radioactive waste into seawater is still permitted. It is practiced in Europe by the La Hague and Sellafield reprocessing plants, so that large quantities of slightly radioactive waste water are still discharged into European waters. Worse still, in Russia and the former Soviet Union, the "deep well injection" method still exists, in which liquid radioactive materials are pressed directly into deeper rock with powerful pumps. Even in several hundred meters' depth, porous sandstone and limestone formations can take up these fluids like sponges. On a smaller scale and with less radioactive material, this procedure had also been used in the USA in the 1970s. None of these practices are sustainable or worthy of imitation.

Utopian Disposal Concepts

In view of the incredibly long-term problems with nuclear waste, some very ingenious proposals for solutions have been made, which in the end have turned out to be impractical or nonsensical. Since the reserves of the energy companies may not be sufficient for the disposal of nuclear waste, the economies engaged in nuclear power could face great expenses or permanent burdens. The profits of energy companies from nuclear power could be significantly reduced if the disposal costs were taken into account. Perhaps nuclear power would even become highly unprofitable; in view of the lack of disposal concepts, this is by no means impossible. If governments are taking over the disposal costs as well as the development costs of nuclear power, this can only be understood as an offer from the political sphere to the energy companies to make the geostrategically desired entry into nuclear technology economically viable in the first place.

For this reason, there are a number of suggestions on how to deal with this problem as cheaply or quickly as possible. In order to remove nuclear waste permanently from the earth, it could be shot out of earth's orbit into the sun – or maybe only at the moon – with rockets. The costs for this, however, would be enormous and would be many times higher than the price of electricity generation. In addition, rockets would have to be launched every day worldwide, each with a payload of several tons. A failed rocket launch – as it happens from time to time – could result in contamination comparable to a serious or major reactor accident. This type of disposal is therefore neither economical nor environmentally friendly.

It was also proposed to dump the nuclear waste in the deep-sea trenches because it was assumed that the deep water there has practically no exchange with the rest of the ocean water. This turned out to be wrong; the exchange period with the surface water is around 750 years. The containers would likely soon dissolve and the oceans would be contaminated to a considerable extent within the next 1000 years.

Another proposal was to let the nuclear waste melt into the ice of the Antarctic, where it would remain buried in the ice for thousands of years. Beyond the fact that Antarctica is a protected ecosystem, as internationally agreed in the Antarctic Treaty, this method of disposal is also problematic. It is not known how quickly heat-generating containers migrate with the ice drift. In addition, global warming could accelerate the ice drift so that in much less than 100,000 years, nuclear waste could find itself at the edge of the ice shelf in Antarctic waters and could then lead to high concentrations of long-lived radioactive substances.

One not uninteresting idea is to dispose of the nuclear waste by drilling deep into the liquid mantle of the earth. Depending on local geology, the earth's mantle begins at a depth of 7 to 70 kilometers below the surface. If volcanic regions were avoided, the nuclear waste could be permanently sealed off from the biosphere and remain far below the earth's surface, in contrast to the final storage sites envisaged today, which are only a few hundred meters deep. With today's technology, however, it is just possible to reach the upper viscous range, and even then only with enormous difficulties and costs.

Another idea was to dispose the high-level waste at subduction zones, where the material is slowly transported into the earth mantle. But this would come with difficult long-term issues. Subduction zones are often seismically active. Earthquakes could open pathways for radioactive material, and volcanoes might spit out radioactive waste that has been recycled deep below our feet, even after many millennia. Numerous technical and safety issues would have to be clarified here. These concepts would require a great deal of basic research into the strength of underground convection and the transport of materials in the earth's mantle. Also, the high costs of such a disposal still stand in the way of such futuristic concepts. But they might prove – sometime in the future – as plausible alternatives.

Partitioning and Transmutation

A much more mature proposal, but one that is not yet feasible on the necessary scale with current technology, is so-called transmutation. Intensive research is already being conducted on this topic today. There is increasing international interest in it, as it provides some desirable possibilities.

The basic idea of *transmutation* is to transform the dangerous and long-lived isotopes into more short-lived or stable isotopes by irradiation with neutrons or high-energy particles. Fast neutrons can split practically any heavy nucleus or excite it strongly, causing it to "steam off" neutrons and protons, making it a lighter and more short-lived isotope. Many of the long-lived radionuclides that pose a biohazard are much more easily destroyed by fast rather than by slow neutrons – typically one to two orders of magnitude faster.

In addition to transmutation machines, special reprocessing plants are required to separate the short-lived fission products reliably and with high purity from the long-lived radionuclides, which then can be introduced into the transmutation reactor. The separation of the different radionuclides as the first step in a transmutation process is called *partitioning*. The whole process is therefore also called "partitioning and transmutation."

In this way, the disposal problem could be significantly reduced. If, for example, all radionuclides with half-lives of more than 100 years could be converted into those with less than 100 years, then nuclear waste would only have to be stored for about 1000 to 2000 years until the problem with the radiating waste has completely dissolved into heat. Although such a period of time is still long, it is much more manageable and easier to plan than the unimaginable hundreds of thousands of years envisaged for direct final disposal.

There are different ways to do transmutation. On the one hand, researchers try to split atomic nuclei in large particle accelerators with the help of high-energy particles. With today's technology, this method is not only very expensive but also very energy-intensive. With the help of particle accelerators, at best a few grams per day could be converted. But particle accelerators can be specified very precisely to their desired performance. Even if no economic solution to the disposal problem is in sight in the near future, they have great potential for future technologies, possibly even for energy generation. Many years of development work will still be necessary for this to happen.

The second concept foresees using special types of reactors, the so-called transmutation reactors. This technology is already somewhat more advanced and promises faster results, but it is also still in its infancy. Since slow neutrons attach themselves preferentially to atomic nuclei and thus increase the proportion of heavy transuranium elements instead of decreasing it, transmutation reactors are based on the idea of using fast, high-energy neutrons. These fast neutrons are able to split more heavy atomic nuclei than they produce. However, since unmoderated fast neutrons – compared to slow, moderated neutrons – are also much less likely to cause nuclear fission and keep the chain reaction going, such reactors would also have to be built much larger than typical nuclear reactors today.

In principle, such reactors are also suitable for power generation. However, for political reasons and because the focus today is still on technology development, this aspect is often not mentioned. This is because these reactors also release energy during the demolition of heavy atomic nuclei.

If they are cleverly designed, transmutation reactors, unlike some fast breeder reactors, are capable of reducing the amount of long-lived

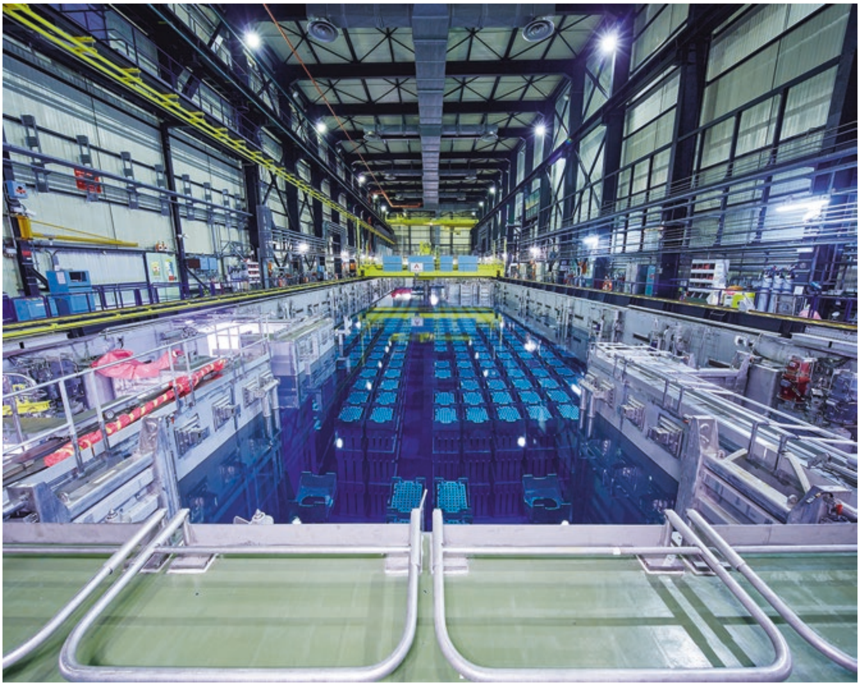

Fig. 11.6 Storage basin at the reprocessing plant La Hague. Spent fuel elements from nuclear power plants await reprocessing

Fig. 11.7 Hot cell, one of three vitrification facilities for high-level radioactive waste, La Hague

radionuclides. Similar to fast breeder reactors, transmutation reactors usually operate at very high temperatures with liquid metal as coolant, which poses certain safety risks. Using water as a coolant is not possible because water moderates and slows down the neutrons. Therefore, only non-moderating materials may be used in the reactor core.

Instead of cooling with liquid metal, there is also the concept of gas cooling. Other proposals envisage the development of a high-temperature reactor fired with thorium instead of uranium, which should be particularly suitable for the conversion of transuranium elements. Some modern concepts for normal nuclear reactors (e.g. the molten salt reactor) also envisage using fast neutrons to produce as few transuranium elements as possible. These are still in an early stage of development.

The two concepts – particle accelerator and fast neutron reactor – can also be combined with a particle accelerator-driven transmutation reactor, in which both the operational safety and the desired fission properties could be significantly optimized. Such a facility is currently being planned in Mol, Belgium. It is called MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) and is scheduled to go into operation around 2035. China is also working on such a reactor.

Technological hurdles currently include the exact understanding of the nuclear-physical processes in such a reactor, as well as the required material properties. Due to the temperatures reached and the strong neutron bombardment, the material is subjected to high stress. The particle accelerator also has to meet demanding specifications. It must deliver a strong proton beam and run extremely reliably, since even short interruptions in the particle beam can lead to long delays in reactor operation. There are also ideas to use laser beams to accelerate the protons, but laser accelerators are still in a very early phase of development.

Accelerator-driven reactors can be operated subcritically, so that a Chernobyl-like accident can be strictly ruled out. This is a very important point, since reactors with fast neutrons have much smaller safety margins than light water reactors, where a power excursion brakes itself again by the formation of steam bubbles.

But where do the necessary neutrons for the chain reaction come from if criticality is not reached? This is where the accelerator comes into play in machines like MYRRHA, which is why such facilities are also known as accelerator-driven systems (ADS). The accelerator shoots a strong beam of high-energy protons at almost the speed of light through a long tube onto a target made of lead or similarly heavy atomic nuclei in the middle of the reactor. Upon impact, many of these atomic nuclei burst and release high-energy neutrons and protons. This large number of fast particles now causes further nuclear reactions in the rest of the reactor. Because a constant supply of externally produced neutrons is available, the reactor itself can easily be designed to be subcritical and to have a neutron multiplication factor of about 0.95. Each neutron produced by the proton beam thus leads to 20 nuclear fissions on average. The reactor core itself contains not only uranium and plutonium, but also fuel rods with long-lived atomic waste, which after some time is largely fissioned into smaller and shorter-lived nuclides.

MYRRHA, which uses a lead-bismuth mixture as coolant, is still a prototype model and will cost around 1.6 billion euros. Future commercial transmutation reactors are likely to be even larger and are not expected to be available until the second half of this century. One such reactor should then be sufficient to irradiate the long-lived nuclear waste of about ten nuclear reactors. However, a single irradiation round will not be sufficient: After being bombarded by fast neutrons in the reactor, about 90% of the transuranium elements are destroyed. But, in order to eliminate the long-lived nuclear waste as residue-free as possible, at least 99.99% of it should be destroyed. Therefore, these substances would have to undergo at least four rounds of irradiation in a transmutation reactor. After each round, the fuel rods would have to be split up in a reprocessing plant, the contents chemically separated and the long-lived substances returned to the transmutation reactor. The whole procedure is complex and expensive, but so far it is the most promising method of destroying the extremely long-lived nuclear waste.

Such transmutation reactors could be integrated into an existing nuclear power industry or could also be the last nuclear reactors in operation to dispose of the nuclear waste of a previous generation of nuclear power plants. Of course, even then, safe storage facilities for radioactive waste are still needed. The short-lived fission products in particular emit very strong radiation. But their radiation goes down sharply after a few years or centuries, so that there is no need for geological repositories.

In short, transmutation opens a possibility to transform the problem of final storage from a geological to a historical problem. After all, the goal of final disposal is to protect future humans from nuclear waste at least until its radioactivity has decayed to approximately the radioactivity of uranium ore. With the help of transmutation, this would be the case after 700 to 1000 years – instead of over a million years for untreated nuclear waste (Fig. 11.8).

But there is also a disadvantage in transmutation. Although the heavy transuranium elements can be fissioned well, the long-lived fission products have a smaller cross section for neutrons – they are therefore much more difficult to destroy. Additionally, the fission products are not heavy metals and

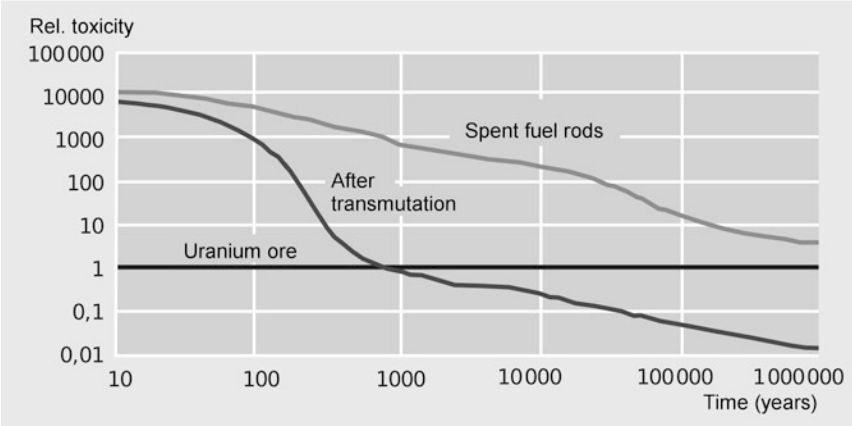

Fig. 11.8 Temporal development of the radio-toxicity of spent fuel assemblies with and without transmutation in double logarithmic representation. The reference point is the radioactivity of uranium ore and a separation efficiency of the short-lived from the long-lived isotopes of 99.9%, i.e. well above the separation efficiency that is technically common today. Acceptable radio-toxicities could be achieved in this future scenario with transmutation after about 700 years

are much more mobile in the ground. They could therefore reach the surface more quickly and cause increased radioactivity there. At the same time, they are produced during the fission of heavy nuclei. Some critics of transmutation therefore note that although this method can be used to destroy the long-lived transuranium elements, it is much more difficult and takes more time to destroy the long-lived fission products. However, the two biggest biohazards, technetium-99 (which has the highest share of radioactivity among long-lived fission products and can be very mobile in the ground) and iodine-129 (also mobile and easily absorbed by the human thyroid gland) can be transmutated, albeit slowly. If, for example, it were possible to design such a facility in a way that the long-lived fission products are also destroyed, this important counterargument could be dispelled. This will become more apparent in the future.

Both the construction of transmutation reactors and the partitioning technology still require a lot of research and development. Currently, the reprocessing of nuclear fuels is based on the so-called *PUREX process*, which originally dates back to the 1940s. PUREX stands for "Plutonium-Uranium Recovery by Extraction" and was originally intended for the production of weapon-grade plutonium from fuel rods with low burn-up. The large civilian reprocessing plants also use this process and are therefore monitored by the IAEA to ensure that no hazardous material is diverted. Highly active nuclear waste is treated in so-called "hot cells." These are gas-tight, thickly shielded rooms in which all necessary work can be carried out by remote handling. A very thick viewing window made of lead glass serves as a shield against penetrating gamma radiation.

For isotope separation, the fuel rods are cut to pieces and the burnt nuclear fuel with all its components is dissolved with hot nitric acid. The extraction agent used is a phosphoric acid ester, usually diluted with kerosene. If the two liquids are mixed well together in a countercurrent process, uranium and plutonium form chemical compounds that remain in one of the two liquids, while the fission products remain in the other. Then both liquids can be separated and the desired substances can be extracted. Since one pass only achieves a certain purity, several stages are required.

All other long-lived radionuclides remain in the second solution. These substances are usually vitrified or chemically bound in ceramics so that they remain as fixed as possible in a repository. The necessary storage time of nuclear waste cannot be reduced by reprocessing alone. But the amount of waste is significantly reduced, since uranium and plutonium make up the majority of spent fuel assemblies. 97% of the material can therefore be recycled and used in MOX elements, for example. To date, the major nuclear energy nations have had about one third of all spent fuel assemblies reprocessed. However, the costs of uranium amount only to few percent of nuclear power. Reprocessing is much more expensive. Reprocessing spent nuclear fuel is also used to extract some rare and very expensive isotopes for scientific, medical or industrial purposes.

Even though the PUREX process has been refined over the years, it does not allow a highly selective extraction of materials heavier than plutonium. This is because americium and curium in particular behave chemically very similar to some fission products. Today, typically around 1% or slightly less long-lived radionuclides remain with the short-lived fission products during reprocessing. This proportion would also have to be significantly reduced before the desired medium-term storage of around 1000 years can really be achieved. Otherwise, although radioactivity will be reduced by a factor of 100 after this period compared to direct final storage, it will still be strong enough to require long-term storage over hundreds of thousands of years. Only an extremely pure separation of the fission products in combination with transmutation reactors makes sense if partitioning and transmutation are to work.

Highly specialized chemicals are required for efficient partitioning, some of which are very complex and expensive to synthesize. In addition, the high radioactivity of spent nuclear fuel not only poses a danger to humans but also makes reprocessing much more difficult. This is because it increases corrosion within the protected facilities, and additionally, the radiation can break down the chemical complexes needed for extraction (so-called “radiolysis”). A lot of basic radiochemical research is needed here, since for satisfactory results, the transmutation targets need to have very high purity. This problem has already been described as a playground for chemists, but a challenge for engineers. In the future, apart from methods using solvents, electrometallurgical processing techniques (“pyroprocessing”) or other novel techniques may prove to be efficient.

There are also proposals to use extremely high-energy laser beams to transmute certain isotopes. This might only work for some isotopes and could be very expensive, since the irradiated amounts of material in such experiments are tiny compared to transmutation reactors. In view of the rapid development of laser technology, however, this method could perhaps become an interesting alternative in a few decades to treat certain radionuclides in a selective manner. However, such experiments require very pure material and are thus dependent on modern partitioning techniques.

Many researchers regard transmutation as the best and ethically least questionable technology for solving or reducing the problem of nuclear waste. The costs of establishing a complete transmutation-based nuclear waste economy cannot be estimated at present and will amount to many billions. Many concepts still exist only on paper or in computer memory and will have to be tested in large international research projects for their practical suitability and safety. Several dozen such reactors would have to be built worldwide to transmute the quantities of nuclear waste that have already been produced and will be produced in the future.

It is not yet clear whether partitioning and transmutation will prove to be practicable or which transmutation path will prove to be the most effective or economical. Maybe even a combination of different technologies could prove advantageous, in which first a reactor with or without energy generation splits the majority of the transuranium elements, while in a second step an energy-consuming particle accelerator does the remaining precision work and removes most of the remaining long-lived isotopes. In the coming years, humankind will have to switch to regenerative energies anyway, as fossil fuels have a negative influence on the climate. They cannot be completely replaced by nuclear energy. Surplus energy from regenerative sources – which are getting less expensive every day – could then be very cheap during times of strong wind or strong solar radiation and could be used to reduce the costs of transmutation.

Even though there is still a lot of research work to be done and money to be raised before this technology becomes a serious disposal option, it has much potential to transform the extremely long-term nuclear waste problem into a less questionable medium-term one. Another question is whether and where the construction of transmutation reactors and the associated reprocessing plants will be possible, as this will be subject to public mood and political will. After all, the right to vote extends only to the currently living generations.

The Concept of Final Disposal

Due to current political and economic considerations, mainly the principle of direct final disposal is being pursued in the civil nuclear industry. Low-level waste can be stored near the surface, while longer-lived medium-level and all high-level waste should be stored further underground. There are already several storage facilities for low-level and intermediate-level waste in operation worldwide, but only a few for high-level waste. These include Russian deep boreholes, the American Waste Isolation Pilot Plant and one storage facility each in the Ukraine and Belarus for nuclear waste from the Chernobyl accident.

There are different approaches to final storage. So far, none of these approaches has proven to be the best proposal. There are different views both on the type of rock in which the repository is to be built and on the question of whether the nuclear waste should be hermetically sealed as quickly as possible, or whether it is better to ensure retrievability over a longer period of time. In addition, rock formations of the same type differ depending on local geological conditions. Some nations using nuclear energy also do not have a suitable rock formation for a repository and therefore try to find a repository in multinational projects.

To prevent the radionuclides from entering the groundwater, a repository must be located under rock layers that are as watertight as possible and several hundred meters thick. But a repository must also not be located too deep, because the rock itself becomes warmer at depth. Together with the heat generated by the nuclear waste, the temperature on the surface of the containers should not rise too high and must remain below 100 degrees Celsius. Otherwise, water – which is always present in rock in small quantities – would evaporate, which could lead to microchannels in the rock and stimulate chemical processes that could increase corrosion, make the rock porous and open paths to the groundwater. This should be avoided at all costs. One therefore has to find a compromise: A depth of about 250 to 1000 meters is considered favorable. Furthermore, the thermal conductivity of the host rock determines how compactly a repository can be constructed.

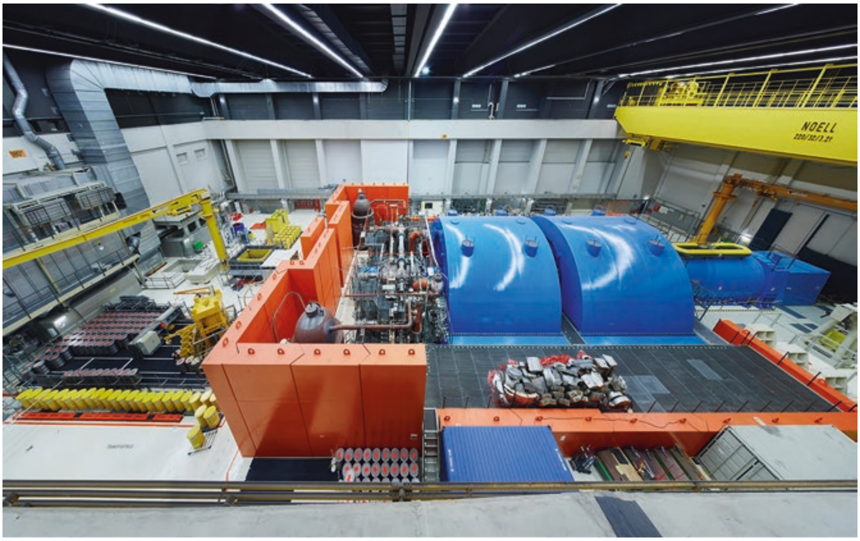

Fig. 11.9 Turbine hall of the boiling water reactor in Brunsbüttel during dismantling. Radiation protection wall (red), barrels of low- to intermediate-level radioactive waste (yellow), low pressure turbine rotors (blue), generator section (right). Between the red wall and the blue turbines is the high pressure turbine rotor, with its cover removed

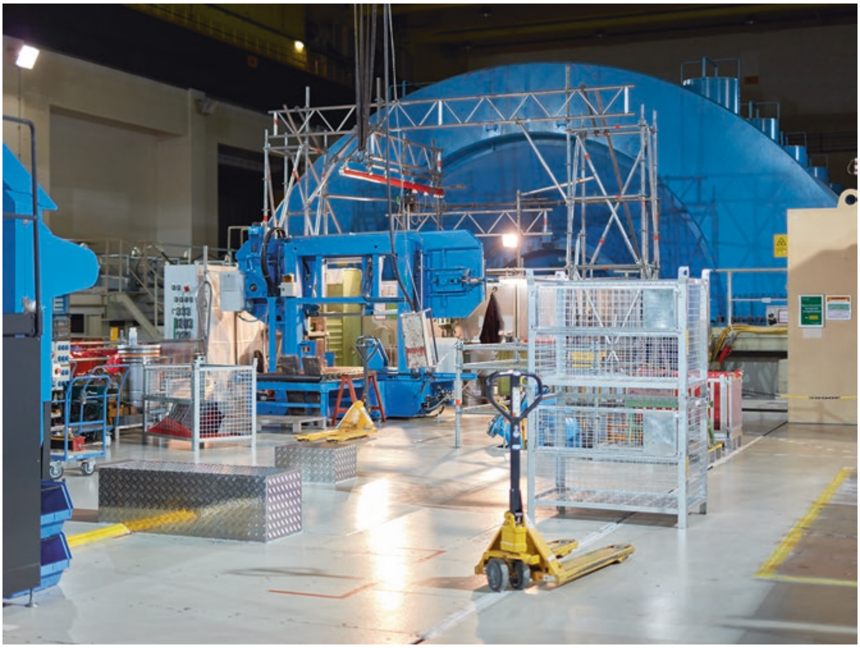

Fig. 11.10 Turbine hall in dismantling, nuclear power plant Krümmel

The containers and their enclosures (copper and bentonite, which absorbs water, are among the favorites) should be able to withstand the high pressures underground for as long as possible. If all goes well, the most radiating substances will be retained by these barriers for several thousand years until they have decayed. In the course of time, however, the containers together with the fuel rods corrode, and the contents will diffuse into the surrounding rock. From this point on, when large quantities of plutonium and other dangerous materials are still present, only the host rock serves as a protection. For this very reason, the focus in the search for a repository is on host rock that has remained unchanged and watertight at depth for over a million years.

Possible rocks formations for a repository are mainly salt, clay and crystalline rocks such as granite or gneiss. Salt and clay have the great advantage over crystalline rocks that they are virtually viscous under high pressure and close cavities by themselves. The thermal conductivity of salt is also better than that of clay. Clay is more difficult to work and is a poorer conductor of heat. Granite is very stable, but can have more crevices because it is not as ductile under pressure. According to the latest scientific findings, it is said to be porous even down to a depth of 15 kilometers, which could pose a major problem for final storage. The question can now be asked whether salt (as an essential raw material since time immemorial) and clay (for example as a possible oil deposit) will not be the preferred exploration targets of future generations.

A million years ago, there were no people who would have dug deeper into the earth. But if, for example, future generations create groundwater access to old salt formations, it is quite possible that the water will damage the integrity of the salt dome to such an extent that it will no longer provide a good containment for nuclear waste. None of the current search methods can rule out such a scenario.

At some sites, especially on the Finnish island of Olkiluoto, in Forsmark, Sweden, and in Bure, France, the construction of large nuclear waste repositories is already advancing. The host rock appears very stable and has already survived ice ages without structural damage. The majority of the population in Olkiluoto and Forsmark supports the respective project and also nuclear energy; many residents are employed at their local nuclear power plant. But it is of course completely unclear whether future generations will have the same judgement. In other countries, advanced repository exploration mines were abandoned after it became clear that the host rock did not have the desired properties. This was the case with Yucca Mountain, USA, and Gorleben, Germany.

The concept of final storage is as follows: First, the radioactive waste is reprocessed or the fuel assemblies are packed directly in safe containers. After several decades of decay in interim storage facilities, the highly radioactive waste is cold enough to be suitable for final storage. The waste containers in the underground repository are then placed at a sufficient distance from each other to avoid excessive heat generation; the spaces between them are filled. The containers themselves receive additional envelopes; according to current models, a thick copper shell should significantly slow down corrosion. The next protective layer consists in covering the containers in bentonite. This material is a mixture of various clay minerals, which is characterized by its ability to absorb a lot of water. This causes the material to swell and close any cracks. Bentonite has already proven itself many times over in cat litter, civil engineering and industrial applications.

To make the highly radioactive substances of reprocessing as non-water-soluble as possible, they are melted down in particularly durable glasses such as borosilicate glass or processed into ceramics. Spent fuel rods remain in the container as a whole. Depending on the water content of the host rock and the permeability of the other barriers, the steel containers dissolve over periods of several thousand to ten thousand years. This is due to unavoidable corrosion and the high mechanical forces deep underground. The next barrier consists of the crystal lattice of glasses or ceramics in which the radioactive substances are incorporated. These too dissolve at some point in the course of the millennia, so that the radioactive substances are then distributed in the host rock by diffusion. Even today, too little is known about the long-term effects of radioactive radiation on the crystal lattice of glasses to be able to accurately estimate their durability.

At the latest, after several thousand to ten thousand years of storage – or earlier, if there is sufficient access to water and corresponding corrosion – the repository transforms into a mixture of former host rock and the remaining, not yet decayed radioactive substances. If for any reason access to the groundwater should occur, large-scale contamination cannot be ruled out. The host rock of a repository must therefore provide the best possible protection against access to water, because it is the rock, not the containers, that provides long-term isolation from the biosphere. This is also known as the "multi-barrier concept:" first the container with its protective covers, then one or more layers of rock. Some radioactive atoms will always find their way up to the surfaces after many years. But if all goes well, the radioactive contamination of the surface and the groundwater should be several orders of magnitude below the natural radioactivity and should therefore be harmless. But of course, many things can happen over such long periods of time that we do not yet have in

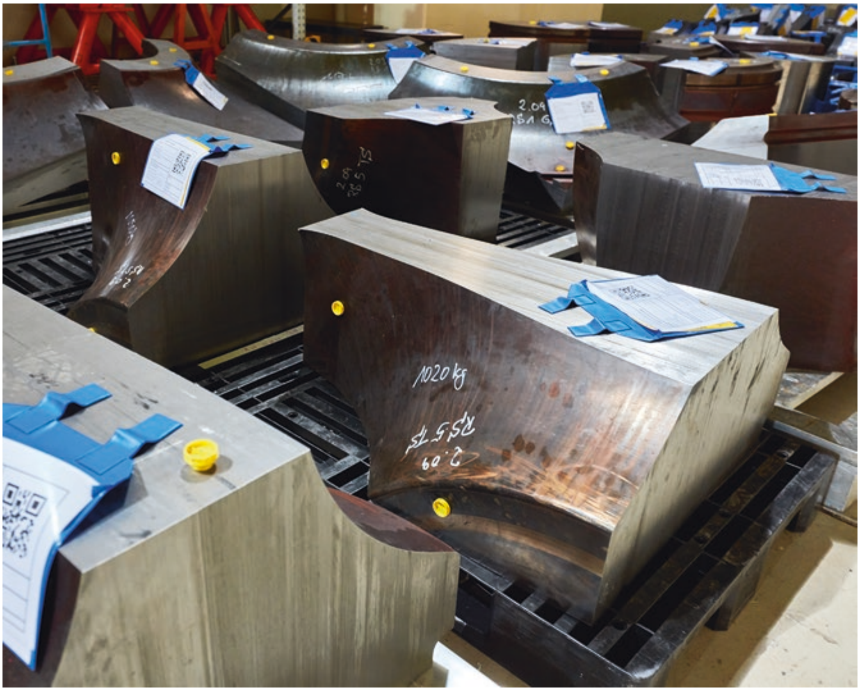

Fig. 11.11 Cut up turbine rotor parts awaiting release from nuclear regulatory control, nuclear power plant Krümmel

sight today. The large and small reactor catastrophes are illustrative of how neglecting seemingly minor effects can add up to a big problem.

For this reason, the long-term stability of the host rock is of utmost importance. Earthquake and volcanic areas must therefore be excluded from the outset, as must all other tectonically active rock formations. Today, the approach is to analyze which rocks have undergone as few changes as possible in the last million years and, in particular, which were not permeable to water. Among other things, millions of years-old gas and oil deposits can be found under clay rocks.

Salt also has the property of impermeability. However, critics of final storage argue that the crystal lattice of salt could be damaged by radioactive radiation. This process is called *radiolysis* and leads to the chemically highly reactive substances sodium and chlorine gas. It is particularly dangerous in the first few hundred years, when the radioactive radiation is still at its strongest. There are fears that these processes could locally damage the salt dome. It is difficult to simulate in the laboratory whether this is sufficient in the long term to cause damage over a larger volume.

In general, over the extremely long periods of time, it cannot be excluded that small quantities of long-lived radionuclides find their way into the biosphere through slow diffusion processes of perhaps a few millimeters per year. According to current model calculations, this should only minimally increase the natural radioactivity in the area of the repository. If water enters the repository, however, the situation can change dramatically, because the transport speed then increases many times over, which in the long term can contaminate groundwater and allow radioactive substances to enter the biosphere. A groundwater aquifer can cover an area of around 100 square kilometers or much more. Increased radioactivity would be expected in this region – both from the water supply and from the uptake of radionuclides in plants and animals. Adjacent areas could also receive slightly increased radioactivity from rivers. The mobile fission products iodine and selenium in particular could accumulate in fish. According to calculations with the help of the LNT model – which, however, is not proven to give reasonable statistics at the expected low doses – this alone could lead to thousands of deaths over the years. Other substances are more difficult to simulate, but could lead to similar or maybe even greater effects.

Another important question is whether a repository should be designed to be retrievable or non-retrievable. In France and the USA, for example, the concept of retrievability for at least 100 years is currently favored, while in Germany it was intended to quickly seal off nuclear waste from the environment by hermetically filling the tunnels. In the meantime, however, the worldwide trend seems to be moving towards retrievability – this includes Germany, not least because the biggest scandal in German nuclear history to date has to do with a leaking repository.

This mine, called Asse, is fortunately only a research mine for light and medium radioactive waste. However, it also contains small amounts of highly radioactive material. Asse is a former salt mine that has been used as a test repository since the end of the 1960s. Altogether, more than 120,000 containers with radioactive waste were deposited in a number of caverns. The geological unsuitability of the salt dome led to a severe water ingress, which is urgently to be avoided in repositories. The problem in Asse: Around 1900, a salt mine had taken up its operation that lasted several decades, causing the cap rock to leak and water to penetrate – currently several cubic meters per day. The corrosive brine has obviously already damaged nuclear waste containers, as contaminated brine was found in the mine. Retrievability was never intended in this repository. Many nuclear waste containers were therefore simply dumped into the caverns. Due to political pressure, the government has now decided to salvage all nuclear waste anyway. Many experts doubt that this makes sense, since the majority of the waste is only slightly radioactive, the retrieval operation will be very expensive and it could even increase the risk of a release of radioactive material. If retrieval had been planned from the outset, recovery would have been much cheaper. Asse is therefore an excellent example of how a repository should not be devised. One can only hope that a similar scenario will never occur in a repository for highly radioactive waste.

If a repository is designed to be retrievable, this means that for about 100 years, the tunnels will be easily accessible and the containers can be removed – maybe for transmutation or to be stored elsewhere. Another distinction can be made here between reversibility and retrievability. *Reversibility* means that during the operation of the repository, every step can be reversed. *Retrievability* means that the repository is designed in such a way that the radioactive waste can be retrieved even after the repository has been closed.

After a longer period of time, however, the underground passages become deformed by the forces in the rock, making it increasingly difficult to retrieve them after 300 to 500 years. A repository can also be set up in such a way that at least re-mining is possible. This would require the drilling of new galleries,

Fig. 11.12 Research mine for high-level radioactive waste, Gorleben

Fig. 11.13 Corridor in the research mine, Gorleben

which is very expensive, but can be done by mining techniques, provided that the waste containers are still intact. After about 1000 years, the heat development of the containers has greatly decreased, but the probability of the containers losing their integrity due to mechanical stress has also increased. This may make a salvage operation very costly. Today's plans envisage retrievability for about 100 to 200 years, because after that the difficulties increase considerably.

Another proposal is not to set up a mine at a depth of 250 to 1000 meters, but to drill very deep boreholes. With today's drilling technology – not least from the oil and gas business – it is possible to drill to depths of up to 5000 meters. In the lowest 2000 meters, one could fill in the nuclear waste containers – each at some distance from the next and each encased in bentonite or similar substances. The upper 3000 meters of these boreholes would be filled in. In this way, the nuclear waste is further away from the biosphere. And it also becomes more improbable that future civilizations inadvertently drill into the repository. However, the pressure and heat acting on the containers are much greater in these depths. The temperatures down there are around 150 degrees Celsius. The corrosion is therefore many times higher. Accordingly, retrievability is much more difficult.

Open Questions and Ethical Problems of Final Disposal

In view of the decades of difficult research into possible repositories and the many billions that this work above and belowground has cost in the meantime, the great difficulty of this undertaking becomes clear. Although the concepts are now more mature than in the past and a much more responsible approach to radioactivity has become standard than in the early years of nuclear energy, many problems are still unsolved and insufficiently researched. Some of the most important questions, which have so far barely appeared in the political discourse but which are highly relevant for experts, are interdisciplinary in character. Their nature is in part scientific-technical nature and in part ethical-philosophical.

It can be said at the outset that there is a much greater diversity of opinion on these questions among scientists than is usually communicated to the outside world by the institutes and organizations involved in repository research. There are very different views on the question of retrievability alone, where each option has strong arguments for and against it.

One could ask whether the term “final repository” is an understatement, and whether the term “infinite repository” would be more appropriate. The time periods involved are beyond the scope of human imagination. What in geological time periods is only the blink of an eye is an eternity on a human timescale.

Nuclear waste still radiates strongly enough for hundreds of thousands of years to represent a considerable health risk. Today’s final storage concepts are designed to ensure a geologically safe enclosure for around one million years – equivalent to several tens of thousands of generations of humans. Consider that the phylogeny of Homo sapiens is only about 300,000 years old and that early advanced civilizations such as ancient Egypt are only about a few thousand years old. The last ice age ended almost 12,000 years ago. Agriculture and animal husbandry are just over 10,000 years old, the pyramids 5000 years. We therefore have to make short-term decisions within two or three generations whose consequences will last several times longer than modern humans already exist! This is a tremendous moral responsibility where the smallest mistake can have vast effects. Our natural moral compass does not reach so far into the future, but is at best designed for one or two more generations (and often it does not even suffice for the present). When dealing with such problems, we must always face our best convictions with great skepticism and reckon with our own hubris.

Periods of perhaps a few thousand years can still be roughly surveyed, at least in terms of possible civilizational developments. For longer periods, we simply lack any feeling or judgement of our responsibility. These interrelationships have been insufficiently researched and, despite the inclusion of humanities expertise in the search for a final repository, are not planned as a research project. In fact, they should be at the very beginning of every search for a final repository – to avoid exactly the hubris that led to the major reactor catastrophes.

It is clear that with such long periods of time and such large quantities of highly radioactive material, a very large number of people could be affected if something goes wrong with our calculations and tests. Only with the greatest possible caution can we minimize the probability that such damage will affect an enormous number of people. Because of less political resistance, only sparsely populated areas for final repositories are now being investigated. But nobody can predict whether these areas will still be sparsely populated in tens of thousands of years. And this question is particularly important, since a small amount of radioactive waste will diffuse to the surface even under favorable conditions. Enrichment processes in the food chain or geological concentrations that are difficult to estimate today could exacerbate the problem.

It is also difficult to estimate how certain our geological and geochemical theories are. Although the natural sciences are advanced and fundamental upheavals within well-researched disciplines are not very likely to occur, it cannot be ruled out that at some point, previously unknown effects will accumulate which, in their sum, run counter to our plans. In addition, the earth's interior is still too poorly explored and understood for long-term geological forecasts to be theoretically validated – especially when future human influences come into play. Our forecasts are therefore nothing else than extrapolations from past rock history. It is not necessary to take into account the very unlikely residual risk of a major asteroid impact in the repository area to realize that things could well go differently than planned. The question of human intrusion is one of the big open question in repository research.

In fact, even many natural underground processes are not yet well understood. For a long time, science assumed that hardly any life can exist at great depth. However, as investigations in the Swedish underground laboratory Äspö have shown, even 500 meters belowground there are numerous microorganisms that form biofilms – above all bacteria and archaeae. These consist of thousands of species with different biochemical abilities. Researchers have already found 2000 different microorganisms and expect another 10,000 species or more. Some of these could help to fix the radioactive substances underground, while others could massively increase corrosion and the transport of substances. Among the microorganisms in this environment are numerous extremophilic species that not only cope well with high salt concentrations but also tolerate high doses of radioactive radiation. According to first results in this still very young field of research, elements such as uranium, plutonium and curium attach rather quickly on the surface of these microorganisms. This would significantly increase the mobility of these heavy metals, which are rather immobile when considering only geological influences. Moreover, such microorganisms can penetrate and then dissolve many different materials. There is hardly a poison on our planet that would not serve as food for some microorganisms. According to recent experiments, some microbes have also been able to migrate through bentonite.

Another question concerns the glasses in which particularly dangerous substances are enclosed, such as radioactive iodine isotopes. New research results have shown that radioactive radiation can probably damage the structure of these glasses over time more than expected. Accordingly, these substances could be released earlier and in greater quantities than planned.

In addition, the pure geochemistry is complicated. The very heavy elements in particular have unusual electron orbitals and can be present in different oxidation states. It is not yet clear which classes of substances can form under conditions deep in the earth and whether all compounds are poorly soluble in water and immobile. Both the experiments and the theoretical calculations are enormously complex. It is known that uranium can form water-soluble uranyl compounds. Although uranium does not radiate as strongly as the other substances in atomic waste, it is also a toxic heavy metal. Plutonium is another problem. Although it does not dissolve too well in water as a heavy metal, analyses in contaminated areas have discovered that within a few years, it had been transported over kilometers with the groundwater. It travelled, so to say, by hitchhiking and attaching itself to colloids – nanometer-sized particles of clay minerals, iron oxide or organic substances. This whole field of research is still much less explored than one would wish for when deciding on a final repository. For example, it has only recently been discovered that plutonium can also form a pentavalent stable chemical phase – a theoretically unexpected chance discovery that further increases the complexity of geochemical analyses.

Another problem is gases in the repository. Both chemical and biochemical reactions can release gases that can build up at high pressure. In addition to geological forces, such gases can have great effects, such as cracking the rock. It could well be that some microorganisms also have the opposite effect, because some bacteria consume gases such as hydrogen instead of producing them. Scientific studies are underway on all these problems. Reliable results will still take many years.

And even if all the geological and nuclear physics calculations are correct, the "human factor" must never be ignored. The current method of repository exploration involves searching for geological formations that were stable for at least a million years and, in particular, did not allow access between the deep repository layers and the groundwater. However, over the last million years, fewer people have lived on our planet than at present. And earlier generations did not build large cities as we do today, did not excavate such deep mines or extract raw materials from deep underground, which could damage the integrity of the repository cap rock. The concept of the "Anthropocene" as an epoch of manmade transformation of our planet has become widely accepted. Modern humankind already moves about as much rock on the earth's surface as do natural erosion and other processes. The year 2020 could also have marked the point when the mass of human-made items (mainly buildings, roads and machines) surpassed the living biomass. The human-made mass has about doubled every 20 years for the past 100 years.

However, the effects of manmade reshaping of the earth's layers do not appear in the search for repository host rocks: After all, this "human factor" cannot be predicted. It could prove fatal – for example, if future generations decide to build a salt mine in the cap rock of a repository, in ignorance of the deeper-lying nuclear waste, and water ingress occurs as a result. The former salt mine Asse should serve as a warning. In the repository concepts currently being pursued, the human factor only occurs to the extent that a potential human intrusion by drilling into the repository is to be minimized as far as possible – for example by encapsulating the radiating containers well. But the people of the future would not even have to dig directly into the repository or build a mine directly above it. If hydrocarbon production or larger carbon sequestration and energy storage projects take place nearby, this can create underground pressure gradients that can damage the repository rock.

The assumption behind today's repository search procedures is implicit: If future generations are able to drill holes as deep as we are, they should also be able to detect radionuclides. They would then stop their drilling in time and fill their boreholes because they should be able to recognize that they have come across a nuclear waste repository. This premise is itself loaded with so many premises that it can make you dizzy. After all, it did not need any knowledge of quantum physics to build the pyramids.

If future generations find out that either our choice of repository was far from optimal, or that it is much smarter to transmute nuclear waste using advanced methods and then dump it in the liquid mantle of earth – which

Fig. 11.14 Transport containers for high-level radioactive nuclear waste, reprocessing plant La Hague. The many small ribs dissipate the decay heat to the outside

may well be possible with future technology – they will have no great problems with an accessible and properly maintained repository, but they will have problems with a sealed and corroded one. The disadvantage of an accessible repository, however, is that terrorists could also find access to it more easily. While a terrorist who gains access to a still young and only partially corroded repository would not live too long, in a good 1000 years when most of the short-lived fission products have decayed, he or she will still have enough time to cause great disaster. Perhaps robotic technology will be so far developed in 100 years that humans will no longer need personal access to perform these actions.

A repository would therefore have to be very well guarded. One problem here is the costs. Over such enormous periods of time, even low personnel costs accumulate to gigantic sums. On the other hand, even if we close and secure all accesses to the repository, it is very likely that future generations will install extensive measuring equipment to ensure that they are not exposed to creeping contamination, simply out of concern for their health. These too are follow-up costs of final storage that are not taken into account in current calculations.

Fig. 11.15 Transport containers for high-level radioactive waste, La Hague

In fact, some repository operators wish that the location of a repository be forgotten as quickly as possible. Then, no one would worry anymore, and the danger of terrorism would decrease. But forgetting cannot be decreed. On the contrary, future generations can be expected to monitor any repository known to them closely. Humans are curious from birth – that is simply our nature. But then, it is also expected that many people may start to worry about their health unnecessarily. As all major reactor catastrophes have shown, the psychological consequences are even more serious than the radiological ones in the large population average. This also means that a purely geological determination of a favorable repository rock formation neglects what may be the most important factor – the human being with his or her worries and fears!

Of course, the knowledge of a repository can also be forgotten – for example, if major migration movements occur during an ice age or other climatic changes. A repository can also be forgotten and rediscovered several times. But a repository cannot be marked as such over very long periods of time. It must be assumed that many future generations will not know what lies buried under their feet. Imagine such a repository being drilled into near a large city. If our descendants have no knowledge of nuclear physics – and certain regressions in civilization and technology have occurred time and again in history – this could lead to a contamination of food and drinking water that would remain unrecognized for a long time. And even if the radionuclides are recognized as such and if the amount of radioactivity released is so low that this city would not need to be evacuated, a not too strong increase in the surrounding radioactivity could lead to a minimally increased cancer rate. If the LNT model is true, then there is no lowest value for radioactivity that would be without consequences. The radiological effect may be lost in the statistical noise, but taken over many generations, this could nevertheless lead to a considerable number of additional deaths. Maybe the LNT model is not perfectly right, but lower doses have a sub-linear effect. In that case, assessments with help of the LNT model would give unrealistically high numbers, while the true number of cases would be lower. But summed up over many years, that could still mean that many people could get sick or die.

There might also be less dramatic psychological and economic effects that may not cause acute problems. Maybe there will be some smaller towns at a little distance from the repository. But many small problems added up over immense periods of time are also an ethical problem – one that we simply ignore by using our definition of "acceptable background radiation." How many thousands of generations might live in fear of radiation from underground, even if this fear is not rational and medical-radiological unfounded? Living in the Anthropocene not only entails recognizing the influence we have on our planet, but also managing the influence we exert in such a way that future generations are burdened as little as possible.

One could well ask the question: If all generations of people were to behave as we do, would our planet not increasingly turn into a dumping ground for contaminated material over many generations? Fortunately, we ourselves do not have to struggle with the legacy of earlier generations to the same extent as future generations will have to deal with ours – if only because more and more people with ever greater technical capabilities are living on earth.

We cannot predict today how future generations will judge how we as their ancestors dealt with this problem. What we consider right and necessary today may be seen by future generations with different technical possibilities, ethical principles and needs as wrong and dangerous decisions.

Also in the face of climate change, it is clear that philosophy has so far dealt inadequately with the consequences of our lifestyle for future generations. The question of multigenerational justice is a central, but all too often neglected ethical question of our time. Our society as whole – and not least the academic disciplines in the humanities – is still highly focused on individual careers and not on the consequences of our actions. An important subdiscipline of a multigenerational environmental ethics should be nuclear ethics, which hopefully will one day be institutionally established at universities.

As these simple examples illustrate, the current search concept for a final repository still lacks scenario analyses, a broad discussion on responsible ethics with various actors in civil society and due consideration of the interests of future generations. Here, the unfortunate academic split between the humanities and philosophy on the one hand and the natural sciences and technology on the other becomes strikingly apparent. How do we deal with the consequences of our technological civilization in such a way that we behave fairly toward future generations? Why are billions spent on exploration mines and why are large national institutions for nuclear waste disposal being founded, while at the same time we still do not have university chairs for nuclear ethics?

There is not even agreement on whether final repositories should be kept as secret as possible or whether they should be marked in some way as a warning for future generations. The US government has conducted a major interdisciplinary research project to investigate whether it is at all possible to use universal symbols to warn distant generations against drilling into or living at a repository area. The preliminary result of these investigations is that human language is too complex, too strongly culture-bound, and too subject to change to guarantee a reliable warning over longer periods of time.

It may even be that future generations, perhaps because they have already used up most of the readily mineable uranium, will regard a repository as an economically viable resource. With advanced technology, the uranium and plutonium or other elements could be of economic interest. In this case, too, a well-documented and maintained repository would be of great advantage. If, on the one hand, the repository is kept secret, for example to avoid attracting terrorists, this could turn out to be a bad surprise. Maybe people there accidentally drill into the repository while searching for raw materials, thereby contaminating their groundwater over a large area. If a warning is to be issued, the question arises as to what this warning should look like and how it could be permanent. Almost fantastic suggestions have been made in this regard – for example, the establishment of a secret "nuclear priesthood" or genetically manipulated fluorescent cats. Why the latter should warn people by their presence is uncertain. Certainly, some may in fact start digging deep into the earth just because of this.

We cannot even estimate at what technological level mankind will be in tens of thousands of years and whether they will still understand our signs. The development of humankind so far suggests a somewhat fluctuating cultural evolution towards higher technical skill and social complexity. In our history, however, there have also been repeated regressions and dark ages. Even if it seems unlikely in a globalized world that one day in the distant future humanity will live on a technologically much lower level than we do in our time, this is not completely impossible. People at the technological level of the Middle Ages could in the worst case die in large numbers from contaminated groundwater without even remotely understanding what kind of pollution they were exposed to.

Other difficult questions concern liability and moral responsibility. How long will the energy companies or even the nations that currently operate nuclear power and earn money with it be able to exist and, above all, remain solvent enough to be liable for unforeseeable consequential damages in the future? How large must risk reserves be for generations of which we cannot even know how numerous they will be? Perhaps one day the world's population will shrink to such an extent that in future it will be possible for people to use certain areas as a waste dump area without any problems and to steer clear of them. Or, land will become so valuable in some regions that every square kilometer of contaminated land will be an incredible loss.

Another question in turn touches on the complex of legal succession of nation states. Which organizational structures will prevail in human societies in the future? Will nation states in 200 or 2000 years perhaps lose the significance they had in the last 300 years of human history? Who will then be the legal successor? Will there be a world government or will local authorities take their place? Is our society and the generations that have benefited from the provision of nuclear-generated electricity not obliged to make the hazardous waste produced by us as harmless as possible? Even if this involves enormous costs and major technological and scientific challenges; if it requires the input of many of the best minds that our universities produce; and if large-scale, concentrated research programs are required? Not to mention the political will to tell the voters the truth about the problem of waste disposal.

It could also be that even the politically easily instrumentalized term "final storage" makes a reasonable approach to nuclear waste disposal difficult. The concept of final storage implies that substances are stored in such a way that humankind can forget them and no longer need to worry about them. However, it is not in our knowledge, nor is it in our discretion, to predict whether future generations will be rightly or wrongly concerned about their safety, and whether they may be forced to finance expensive and elaborate decontamination programs or even close down entire areas of land for an extremely long period of time – be it due to ignorance and exaggerated fear or to greater caution and more developed ethics. Seen in this light, the term "final storage" can become a misleading one, since it applies our standards – or at least those of some experts and politicians of our time – to periods of time that are beyond human judgement.

Fig. 11.16 Schacht Konrad, low- to intermediate-level radioactive waste repository in construction. The settlement joints at the top will be pushed together by the rock pressure

Fig. 11.17 Construction of the final repository "Onkalo" on Olkiluoto island. Blasting of the tough gneiss rock is being prepared

Perhaps the term "final storage" is also too business-oriented. We are used to dealing with civilization waste in such a way that we have to dispose of it somewhere and quote some price for it. One tries to indicate costs for the consequences of a technology, but one cannot know them, and because one has to choose among various unclear possibilities, one chooses the option that seems most calculable in the short term, even if it involves enormous risks in the long term.

Perhaps it would be wiser to admit to ourselves that we do not have an acceptable solution to this problem at present and that perhaps the geostrategically desired operation of nuclear power plants would not be economically viable if all the economic costs of responsible waste disposal were taken into account. The avoidance of carbon dioxide emissions would still be a valid reason for operating nuclear power plants, but the competitiveness with regenerative energies would shift. In any case, we should also invest research funds in projects that not only deal with the final disposal envisaged so far, but also with alternative disposal concepts. These could include transmutation or other possibilities.

For all these reasons and unresolved questions, internationally, experts have turned away from the idea of final disposal without retrievability in recent years. Both the consideration of longer-term retrievability and intensified efforts in the field of transmutation indicate a welcome change in thinking and point to ways in which the disposal problem could be better dealt with than the questionable approaches of the Cold War era from the 1950s to 1980s. Not only the scientific-technical options but also the ethical implications should be pursued in an institutional framework. The question of the extent to which we restrict the options of future generations or even harm them through our behavior are essential ethical questions that should be at the beginning, not at the end, of a decision on how we deal with the legacies of our time.

We must not lose sight of the social dimension of technology. We should always keep in mind: Nuclear energy has been a geopolitical technology from the very beginning. Energy self-sufficiency, technological leadership and military options have always been its main arguments – openly stated or otherwise. This has a great advantage, but also some disadvantages. The advantage is that politicians are particularly interested in this technology and support it with sufficient financial resources so that there is also a certain number of suitably trained and competent people who can handle nuclear technology.

But there are also several disadvantages. Because of the large sums of money involved in nuclear power, every government is tempted to find the cheapest possible way of disposing of it. And because of the sceptical attitude of the population, hardly any politician tries to make the subject more public. This applies to democracies as well as to more authoritarian forms of government. Instead of an open political discussion involving various social actors, responsibility is often outsourced to committees of experts. This is not a bad idea at first, since calm discussions without too much public exposure are quite helpful for such debates. However, it can also block an open discussion: If, for example, representatives of research organizations are too dependent on politics anyway, or if such committees are set up from the outset with a fixed mandate, science loses one of its most important characteristics – the free exchange of opinions with an open outcome.

In addition, many scientists are reluctant to throw themselves into the hectic, simplistic and sometimes personally unpleasant waters of public debate. As a result, technical discussions on fundamental positions on final disposal, which can be quite controversial within the internal scientific community, hardly ever reach the public in their complexity.

Some scientists involved in repository research complain that there should be more free research and more international coordination. In fact, all governments of countries involved in nuclear energy are promoting research projects that point in the direction they want. What is missing is stronger institutional support for critical research projects and better international coordination. This reflects the discrepancy between nuclear energy as a national, geopolitical energy source on the one hand and on the other hand the human task of leaving our descendants a planet that is as worth living on as possible.

Pathways for a Responsible Storage and Treatment of Nuclear Waste

In this last section, we take the aspects presented so far some steps further into the future. Much more than the other sections, this one therefore reflects the personal assessment of the author. Although the content of this final section is somewhat speculative, it appears at least to the author to be much less speculative than some current final disposal plans and at the same time ethically less questionable.

The most important questions on this issue are what kind of responsibility we are prepared to bear ourselves, how we assess the limits of our knowledge and what kind of burdens we want to delegate to future generations. The choice of a responsible disposal concept then results from these points.

Taking responsibility for future generations can also mean trying to be wise enough to admit to ourselves that we do not currently have a good solution for a particular problem, but that we may have to work on a reasonable solution for a very long time.

Technology continues to develop. Of course, there can also be civilizational setbacks – this too must be expected. But since the Stone Age, we have seen an ever-increasing advance in the technical abilities of mankind. This does not mean, of course, that we automatically become morally better people because of this. But we no longer have the hygienic problems today with the trash and filth from which the cities of the Middle Ages suffered. For the people of the future, maybe we are the Middle Ages. In view of the eons over which we would burden and endanger our descendants, the necessary decades or even centuries of research work are an almost vanishing period.

First of all, there is a significant need for research if we want to gain a strong understanding of the possible events underground and the possible transport of dangerous substances. This includes a better understanding of possible chemical and geochemical reactions, especially of the heavy elements, as well as long-term effects that microorganisms can cause. All this should be tested in as many different geological scenarios as possible, at the same time taking human activities into consideration. These may involve direct drilling into the repository, mining activities or exploration in the area of the repository, or even the construction of a city including skyscrapers, leaky sewers and much more. All research on this topic is still quite young and should be pursued for many decades before decisions on a repository are made.

Ethical issues should also be examined much more thoroughly. In view of the uncertainty of all human activity, it should be a guiding ethical principle to guarantee future generations freedom of choice. We cannot know how future generations will think and judge and what technological possibilities they will have. Not only do scientific knowledge and technical skills change, but also values and worldviews can evolve. In non-totalitarian societies, it is not always possible to reach a consensus; neither is it always possible to agree on what is meant by responsibility towards future generations. Opinions on this can change – especially with regard to such highly sensitive decisions as the disposal of nuclear waste. Future generations should therefore at least be given the opportunity to reverse our decisions. If we make final, irreversible decisions, this means that we are incapacitating future generations. Generally speaking, this can be described as the principle of giving future generations as much autonomy as possible with regard to their way of life.

In today's concepts of citizen participation in the search for a final repository, there is the idea of representing future generations by "ombudspersons" – individuals who act as advocates of future generations and represent the interests of our descendants. This is an interesting possibility and helps to think the problem more from the end. However, if intergenerational justice is taken seriously, tens of thousands of ombudspersons would have to participate in such discussions for every person involved today – just one ombudsperson is certainly too few, partly because the interests of future generations may well differ. If the repository is still known but safe 10,000 years from now, psychological aspects are likely to play the most important role. At a much later date, things may look different.

A question that also arises when thinking about the problem from the end: Who are actually the potential victims of an unsafe repository? Over the past 100,000 years, humankind has migrated around the globe from Africa, changing skin color several times in the process, advancing from the equator to the arctic, retreating to warmer climes during the ice ages, and crossing oceans by the simplest means. By now, we are so mobile that intercontinental marriages are no longer special. So, if a nation uses nuclear energy, it will not necessarily be the descendants of that nation who have a problem with nuclear waste. Of course, the nations that profit from nuclear energy should also be financially responsible for its disposal. But the potentially damaged people can come from anywhere. In any case, this is an important argument for viewing the disposal of harmful substances as a problem of humankind and not as a purely national project.

We cannot estimate the risks of a repository over the required periods of time in the slightest. We have no chance to check whether our assumptions are too optimistic or rather pessimistic. The risk of an unforeseeable negative development could be 0.1% or 99.9%. It could mean one additional death over one million years or it could affect, damage or even kill 1000 or 1,000,000 or more people in total – and if "only" by psychological effects. At the present state of our knowledge, the factors contributing to this are not foreseeable, conceivable or predictable. Nor are the actions and views of future generations. The goal of a responsible policy should therefore be to provide future generations with better instruments for treating radioactive waste than those we have at our disposal today.

So what is the best solution? Very different answers are possible depending on which problem one considers the most urgent.

Those who consider the longevity of the radiating remnants and the associated unsolved ethical questions as the most serious problem will tend to store nuclear waste for a long time – perhaps for generations – in safe long-term interim storage facilities. During this time, in-depth research should be conducted on technologies such as novel transmutation processes or containment options, or at least a better understanding of the interaction between humans and deeper geological layers should be developed. Perhaps a combination of different transmutation methods and advanced partitioning techniques will prove to be a viable option. From a purely scientific-technological point of view, the development over the last 100 years alone is astonishing and gives hope for further innovations. 100 years ago there were neither lasers nor nuclear power plants, and nuclear physics was still in its infancy.

One who assumes that human societies have a short half-life and that revolutions and wars are the ugly, recurring companions of human civilization may want to put nuclear waste underground as quickly as possible. From this point of view, it is better to have a suboptimal final storage facility than extensive, permanent contamination, for example if an aboveground interim storage facility is blown up by war or terror.

Those who base their ethical convictions strictly on the polluter-pays principle and assume that a generation of people will have to solve the problems they cause themselves, will strive for the rapid construction of a final repository and not rely on future technologies that may never prove practicable. They will then possibly also focus on a repository without retrievability, because this can be better shielded against external influences than one that guarantees retrievability.

Those who want to offer future generations freedom of choice because they do not want to incapacitate them will on the contrary rely on retrievability.

Anyone who thinks that a society has to take full responsibility for its own legacies will look for a solution in a national context. This is the common international practice and makes sense insofar as today's global economic dependency relationships – as can be seen in uranium mining, but on a much more dramatic scale – give rise to fears that vast areas of the Third World could be contaminated, should there be a cheap export of nuclear waste to less developed countries.

Whoever considers the disposal of nuclear waste to be a task for the whole of humankind – since people will intermingle over the millennia anyway and since, after all, the institution of "nation state" is only a few centuries old and will perhaps no longer be of any relevance in the distant future – could come up with a completely different idea. Perhaps it would be better to find a single large "infinity site" for the nuclear long-term waste of all humankind. This site should be in a region that is as remote and as hostile to life as possible – a repository in a hopelessly dry desert area, far away from any human settlement, inhospitable and dust-dry even during extreme climatic changes such as an ice age, and at the same time geologically so boring that nobody will ever get the idea of drilling for raw materials there. And if somebody does, then hopefully such an ambitious civilization should be so advanced that at least it has mastered the basics of nuclear physics.

What speaks against such a solution is that, firstly, extensive nuclear waste transports would have to take place around the globe and, secondly, that many actors would no longer have much incentive to take the avoidance or safeguarding of nuclear waste too seriously. It is possible that transmutation may prove to be an inadequate alternative or only work on some isotopes, but highly efficient separation processes could eventually make it possible to achieve a sharp separation of the long-lived components in nuclear waste. These account for around 1% of all highly radioactive waste. That 1% that radiates danger over millions of years could be taken to a place far away from civilization, while the remaining, more short-lived 99% would be disposed of in repositories in the country of origin for about a thousand years. This currently still hypothetical solution appears, at least on paper, to be ethically more justifiable than the final storage of long-lived substances in potentially densely populated areas.

In view of the advances of the last centuries, it seems almost naive to believe that future generations will not develop better technologies than ours. No generation before us could have foreseen our technological status. Just 100 years ago, the idea of seriously wanting to fly to the moon would have sounded absurd. For several thousand years, the moon was regarded as a deity. An inaccessible repository could be perceived by future generations not only as an extraordinary burden but also as an insult to their problem-solving skills. Whatever waste and garbage the people of the Middle Ages produced and whatever hygienic problems they dealt with, is a walkover for today's disposal technologies.

If no progress can be achieved despite all efforts, future generations can still choose the path of final disposal without further treatment of the nuclear waste. They may also be forced to do so by war or conflicts, because interim storage facilities and nuclear power plants are major targets with gigantic damage potential in the event of war. The people living at that time would not obstruct further freedom of choice for future generations if they also make the final storage facilities retrievable.

To protect against natural disasters, terrorism, airplane accidents or bombing during war, highly dangerous substances are best stored underground in dry tunnels that are inaccessible to groundwater. In this way, even in the event of an accident, the release of radioactivity can be better contained. It would also be possible to store nuclear waste in a long-term, permanent storage facility rather than in a final storage facility for the time being. Like interim storage facilities, these would not be intended as final storage facilities, but would be better secured – possibly underground, but not as deep as a final storage facility. This would ensure a high level of environmental protection. In addition, they would be faster to set up and more accessible than final repositories, since the geological forces are much lower at a shallower depth. Such repositories may be called long-term interim storage facilities, permanent storage facilities or long-term storage facilities.

Of course, it must be taken into account that social changes can occur, including the possible collapse of control structures, the loss of technological knowledge and a lack of qualified personnel. Such a concept therefore requires a fundamental reorientation of the previous nuclear safety philosophy and the corresponding legal framework. The protection of such a facility also requires the permanent presence of security personnel and, if necessary, governmental emergency services.

Today's interim storage concepts are typically designed for storage periods of 40 to 100 years. Long-term interim storage could even extend to several hundred years. With such a long period over several generations, undesired degradation of the nuclear waste such as corrosions of the containers can of course occur. Such facilities should therefore provide the necessary means for maintenance, such as repackaging the fuel assemblies. For the treatment of highly active nuclear waste, so-called hot cells are necessary, as they are also in use in reprocessing plants. Over the course of decades or even centuries, numerous building maintenance or mining activities may also be necessary, for example when corridors need to be supported or rubble has to be cleared away.

Because of the possible danger of radiation, this should not be done by humans, but preferably by remote-controlled robots. All relevant occurrences and measurement results should be transparent and publicly available so that independent scientists and the public can inform themselves about proper storage. For robot-based maintenance, further developments in robot technology are needed to automate the relevant tasks such as welding, corrosion protection, mining, decontamination and transport to a reprocessing or maintenance facility. Such a long-term storage facility could be combined with a reprocessing plant and a transmutation reactor if a nation decides to go this way. However, if transmutation turns out to be impractical, too risky, unaffordable or socially undesirable, in a technically advanced future there might also be the possibility of sinking the nuclear waste deep into the liquid mantle of earth in very deep boreholes.

In order to avoid unnecessary transports with corresponding dangers from accidents or terrorism, it is desirable to accommodate the long-term storage and maintenance facilities and possibly also the reprocessing plant and the transmutation reactor on a large, appropriately secured site. The reactor could be dismantled together with the reprocessing plant after the burn-up of the last long-lived radionuclides and a corresponding decay period, if society so wishes or if continued operation is uneconomic. The long-lived transuranium elements left over from the last burnup period would then only make up a small fraction of the former amount and could perhaps be disposed of as completely as possible in an appropriate particle accelerator.

The costs for such disposal complexes and the necessary research and development could perhaps only be raised in a large international context and not on a national scale. The current structures of political decision-making may also have to be further developed in order to achieve the necessary transparency and acceptance of such a disposal concept among the population. It can be assumed that many people will find such or similar concepts positive in principle, but do not want to see them implemented in their region at any price. However, it could – after some years of international research work – turn out to be much more predictable and ethically acceptable than the current concepts. It could also be that transmutation will only prove to be safe and profitable, or at least technically feasible and affordable, in many decades' time. Only a mature, convincing and long-term waste management concept will have any chance of gaining acceptance over such periods of time. This could also include a binding obligation not to convert the long-term interim storage facility into an uncontrolled repository under any circumstances, as well as comprehensive compensation and precautionary plans in the event that contamination occurs, e.g. due to accidents. Such an approach will not be cheap, but most of the other options face unforeseeable costs in the future and ethical problems of unclear and potentially catastrophic proportions.

While most countries only consider a maximum time horizon of around 100 years for interim storage, the Netherlands have developed a remarkable concept that includes longer-term opportunities and that also takes socio-psychological components into account. The facility, called HABOG (Dutch abbreviation for High-Level Radioactive Waste Treatment and Storage Building), is a surface long-term interim storage facility designed for 100 years and planned in perspective for up to 300 years. The Dutch concept involves planning for the transfer of technical expertise and financial resources over several generations. This is important because the knowledge of how to construct and repair large and stable buildings will probably still be known centuries from now. However, the skills for constructing nuclear facilities and dealing with nuclear substances are so highly specialized that their preservation should be ensured. The HABOG concept also considers that the facility should be designed to be very robust and remain safe even in the event of temporary changes in state structures. In such times, the storage facility might be neglected and unmaintained for longer periods. What is unique about the Dutch concept is that in order to maintain public interest in the facility so that the nuclear waste is not forgotten, the facility is being given an artistic upgrade. The building is painted in a special color scheme to make it a kind of artwork in itself. Additionally, some parts of the building that do not contain highly radioactive waste will be used as a museum depot for historical art objects. This should help ensure that the storage facility and the problem of nuclear waste remain in the consciousness of society over the long term.

The insights gained from such long-term maintained nuclear waste repositories could also be applied to the handling of non-radioactive hazardous waste, such as waste containing arsenic, cyanide and mercury. These wastes, which are highly dangerous and will not decay by themselves one day, are today also disposed of deep underground. If the principle of sustainability is taken seriously, these substances should one day also be neutralised. In any case, a growing humanity cannot continue to bury all hazardous substances somewhere in the earth or discharge them into the oceans for hundreds of thousands of years without making life difficult for future generations.

Progress in the transmutation of long-lived radioactive substances is definitely desirable. In view of the extreme persistence of the disposal problem, it will probably not make sense to adapt the first operable transmutation reactor worldwide. We must rely on the imagination and creativity of future generations to ensure that their safety is not jeopardized. And if a transmutation path can only be established at significantly higher costs, our responsibility towards future generations should be worth the price. We will perhaps have to invest as much or even considerably more money to eliminate the legacies of the nuclear age than was spent on establishing this technology. Future generations will perhaps look back to the Cold War era shaking their heads, when humankind threatened each other with multiple extinction by nuclear fire. We should uphold the spirit of international cooperation in the elimination of the nuclear waste problem.

The following waste management concept attempts to meet these demands in the best possible way. Despite all its advantages, it can of course only be formulated as a noble goal – not to say a dream – at the current state of science and technology. However, it has the undeniable advantage that it would lead to partially satisfying results, even if not all its technological and economic hopes can be fulfilled.

Firstly, long-term underground storage facilities should be constructed, permanently maintained by robots and well secured – as a basic prerequisite for responsible and sustainable disposal. This is safer than the current practice of simply leaving large quantities of nuclear waste at the nuclear power plants. Secondly, the various types of transmutation technology and the partitioning of nuclear waste should be further researched in detail; corresponding large-scale international research projects are necessary for this purpose. Thirdly, the mentioned geochemical and microbiological reactions and interactions with human activities should be investigated in much more detail. And fourthly, other disposal concepts that still seem utopian, such as sinking containers into the earth's mantle, could one day prove to be reasonable alternatives. Corresponding basic research in this area should be conducted, maybe in many years, when the technology is more mature.

It may also make sense to set up national repositories for nuclear waste with shorter half-lives, but to store all long-lived radionuclides in a single repository worldwide. This region should be as dry, deserted, inhabitable, hostile, remote, raw-material-lacking and geologically uninteresting as possible. It should also not be connected to other aquifers. And it should retain these characteristics even if major climatic changes occur. Maybe there is no such place, but it could be worth looking for it. Then, even in the worst case, the number of people affected by this repository would remain within narrow limits.

The scientific-technical development gives good reason to hope that in the not too distant future, methods will be available and technologies affordable that we would today at best call a fantasy. At least, this corresponds to the historical development of the last centuries. So if enough progress is made in both robotics and transmutation research to ensure that, firstly, a long-term interim storage facility for highly radioactive waste can be operated safely and maintained over long periods of time and, secondly, that long-lived radionuclides can at some point be converted into short-lived ones with high efficiency, then the problem of final storage could indeed be massively mitigated.

Of course, even then it is not really possible to predict what might happen over time. No one knows the future. But if you look at the time periods over which we have to make responsible decisions, from the Middle Ages to the present day or even from the pyramids to today, it still seems much more assessable than the period that started with Homo erectus.

Glossary

Absorbed dose Measure of the strength of radioactive radiation. It indicates the amount of energy deposited by **ionizing radiation** in a piece of matter or tissue. Its unit is **Gray**. The absorbed dose is a physical unit; the biological effect of the same amount of energy can vary greatly depending on the type of radioactive radiation and the radiation sensitivity of the target tissue. (**activity**, **equivalent dose**)

Actinides A series of 15 heavy metallic **elements**, from atomic numbers 89 (actinium) to 103 (lawrencium). The most important actinides are uranium (atomic number 92) and plutonium (atomic number 94). These two elements are also called "major actinides." The so-called "minor actinides" are actually heavier than plutonium and are generated by a complex series of **neutron** capture and subsequent decays from uranium-238. These radioisotopes, including the elements americium, curium, berkelium and californium, are partly very long-lived and highly radioactive. Thus, they are of major concern for any long-term disposal concept of **radioactive waste**.

Activation The transformation of stable **nuclides** into radioactive nuclides (**radionuclides**) by the capture of **neutrons**. This cannot be avoided during reactor operation and leads to the generation of **radioactive waste** and also years of decay before decommissioning, until most of the strongly radiating activated substances have decayed. In research reactors, however, neutron bombardment is used specifically to produce radionuclides for medical and industrial applications.

Activity Measure of the strength of radioactive radiation. It indicates the number of radioactive decays per second. Its unit is **Becquerel**. It is a purely physical measure and tells nothing yet about the energy released and the biological effect. (**absorbed dose**, **equivalent dose**)

D. Eidemüller, *Nuclear Power Explained*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-72670-6

Alpha radiation Consists of high-energy helium nuclei of two **protons** and two **neutrons**. It hardly penetrates matter at all and is already shielded by a sheet of paper. Alpha emitters absorbed into the body can, however, be very harmful locally.

Atom Practically all matter is made up of molecules, which in turn are made up of atoms. Atoms consist of a shell of light, electrically negatively charged **electrons** and a much heavier, electrically positive nucleus. The atomic nucleus is tiny compared to the dimensions of the entire atom and yet contains almost all of its mass. It in turn consists of positively charged **protons** and neutral **neutrons**. The different numbers of protons and neutrons determine the type of atom and its stability. (**element**, **isotope**, **mass number**, **nucleon**, **nuclide**, **atomic number**, **periodic table**, **radioactivity**)

Atomic number Other term for **nuclear charge number**, equal to the number of **protons** in an atomic nucleus. Defines the **element**.

Becquerel Unit of the measured radiation **activity**.

Beta radiation Consists of high-energy **electrons** or **positrons**. It penetrates matter on the surface but can be shielded by thin aluminum sheeting.

Breeder reactor In breeder reactors, the difficult to fission uranium-238 is converted to plutonium-239 by neutron capture. Since uranium-238 is much more common than the easily fissile uranium-235, breeder reactors can theoretically stretch the stock of nuclear fuel many times over.

Chain reaction If exactly one of the neutrons released during a **nuclear fission** triggers another nuclear fission, a permanently stable chain reaction is possible. This is the operating mode of nuclear power plants. If on average less than one neutron triggers a new fission, the chain reaction dies off. If more than one nuclear fission is triggered, the reaction rate increases exponentially. This is the construction principle of nuclear weapons and can lead to a power excursion in **nuclear reactors**. To avoid this when increasing power, nuclear reactors only increase their **criticality** slightly above one with the help of delayed neutrons.

Containment Area within **nuclear power plants** that is shielded from the environment by air locks. It encloses the **reactor pressure vessel** and is responsible for retaining any radioactivity that may be released in the event of an accident as completely as possible, thus limiting the effects on the surrounding area (**contamination**) even in the event of serious reactor accidents.

Contamination Pollution of an area with radioactive substances (**radionuclides**). Depending on the level of contamination and the type of substances, this can lead to costly decontamination measures or even to the closure of areas and necessary resettlement.

Control rod Highly neutron absorbing rod for steering the **chain reaction** in a nuclear reactor.

Core meltdown Overheating of the reactor core of nuclear power plants due to failure of the cooling system; this leads to melting of the **fuel rods** and release of the highly radioactive **fission products** trapped in them.

Criticality Multiplication factor of **nuclear fission** from one generation of neutrons to the next. If the criticality is at least 1, a **chain reaction** is possible.

Critical mass Minimum amount of fissile material of a given substance necessary to maintain a **chain reaction**. The critical mass is defined by a spherical arrangement without the aid of other materials. By using neutron reflectors and **moderators**, the critical mass can be significantly influenced.

Decay heat Since after the end of a **chain reaction**, especially the short- and medium-lived **fission products** still generate large amounts of heat due to their radioactive decay, this decay heat can lead to a **core meltdown**, even after weeks. Spent **fuel rods** are therefore stored for years underwater in spent fuel pools and then in interim storage facilities for decades until the decay heat has lowered sufficiently. (**half-life**, **radioactivity**, **radionuclide**)

Decay series All **radionuclides** finally decay – sometimes over several intermediate steps and after a very long time – into stable atomic nuclei. The entire chain of steps up to a stable **nuclide** is called a decay series. The best known decay series is the so-called uranium-radium decay series, in which the uranium-238 present everywhere in rock finally decays via isotopes of radium, radon and polonium to stable lead.

Dose conversion factor Calculation factor for determining the radiologically effective **equivalent dose** from the physical quantities of radiation **activity** and **absorbed dose**. The dose conversion factors include the type of radiation, the type of absorption (external or internal) and the sensitivity of the tissue to **ionizing radiation**.

Electron Basic constituent of matter. Electrons are negatively charged and very light. Electrons make up the shells of **atoms** on which all chemical processes take place.

Electronvolt Unit of energy, not only for electrons. It corresponds to the kinetic energy of an electron that has been accelerated in an electric field in a vacuum and has passed through an electric potential of 1 Volt. Chemical reactions usually involve energies around the order of magnitude of 1 electronvolt, nuclear reactions often around 1 megaelectronvolt (million electronvolt).

Element Chemical elements form the basic units of all known chemical compounds. All kinds of atoms (**nuclides**) with the same proton number (**atomic number**, **nuclear charge number**) belong to the same chemical element. The different nuclides belonging to an element can differ in their **neutron number** and therefore also in their mass and stability (**radioactivity**, **radionuclide**). These are the different **isotopes** of an element.

Element synthesis The cosmic element synthesis is the production of different elements, mostly inside stars throughout the history of the universe. Initially, medium-heavy nuclei up to iron were created by **nuclear fusion** from light nuclei, then heavier elements up to uranium were created by neutron capture and radioactive decay (**activation**, **decay series**). This process is also called "chemical evolution" of the universe. Element synthesis is also carried out in a targeted manner – in small quantities – in research reactors or with special particle accelerators to produce certain nuclides for scientific, medical or industrial purposes (**transmutation**).

Equivalent dose Measure of the biological effectiveness of radioactive radiation. It is derived from the **absorbed dose** by using weighting factors (**dose conversion factor**) that take into account the specific radiation sensitivity of different tissue types as well as the different damaging effects of different types of radiation. Its unit is **Sievert**. The equivalent dose is the internationally recognized measure for assessing **radiation exposure** and **radiation damage**. (**activity**, **radioactivity**)

Fallout Radioactive **contamination** after **nuclear weapon** tests or civil accidents. The health hazard depends on the type and quantity of **radionuclides** released.

Fission products **Radionuclides** produced as daughter nuclei during **nuclear fission**, most of which have a significant surplus of neutrons and are therefore strong emitters of **beta radiation**. Due to their dangerous nature, they are usually left in the **fuel rods** unless they are separated from the uranium and plutonium in **reprocessing** plants.

Fuel assembly They contain the nuclear fuel for **nuclear power plants**, usually based on uranium or plutonium, but possibly also on thorium. Fuel assemblies for common **light water reactors** consist of several dozens to hundreds of **fuel rods**, which are assembled according to exact geometric specifications.

Fuel rod The fuel rods contain the nuclear fuel pellets. They have a high-strength and gas-tight cladding that absorbs as few neutrons as possible. The cladding, typically made of zirconium alloy, encloses the nuclear fuel and the highly radioactive fission products that are produced during the **chain reaction**. Fuel rods are assembled into **fuel assemblies** for use in nuclear power plants.

Gamma radiation Consists of very high-energy electromagnetic radiation. It is stronger than **X-rays** and much more penetrating than **alpha** or **beta radiation**. It can only be shielded by massive concrete walls or solid lead blocks. In **hot cells**, it is also shielded by meter-thick lead glass that serves as a viewing window.

Gray Unit of the measured radiation **absorbed dose**.

Half-life After the time period of one half-life, exactly half of a **radionuclide** has decayed. After two half-lives, only a quarter of the starting material is left, after ten half-lives, only just under a thousandth.

Heavy water reactor A less common type of reactor in which heavy water (instead of normal water as in **light water reactors**) serves as a **moderator**. Heavy water reactors can be operated with unenriched natural uranium and are suitable for the production of weapons-grade plutonium; therefore they pose a risk for **proliferation**.

Hot cell Strongly shielded, gas-tight room for remote handling and short-term storage of highly radioactive substances. Used in some nuclear medical facilities and in **reprocessing** plants.

Ionizing radiation Collective term for all types of high-energy radiation with the ability to kick **electrons** out of the shells of atoms and molecules and thus ionize these atoms. This can break chemical bonds and trigger chemical reactions. Radiation of any kind can have an ionizing effect, provided it has at least a few **electronvolts** of kinetic energy. **Radioactive radiation** also belongs to the category of ionizing radiation, just like **X-rays**. Depending on its strength, duration and the target tissue, ionizing radiation can cause **radiation damage**. (**equivalent dose**, **radioactivity**, **radiology**)

Isotopes The **nuclides** belonging to an element, i.e. all kinds of atoms that differ only in their **neutron number**.

Light water reactor Most common type of nuclear power plant for electricity production, where (in contrast to **heavy water reactors**) normal water is used as **moderator**, for cooling and turbine operation.

Mass number Total number of **neutrons** and **protons** in an atomic nucleus. It determines the atomic weight.

Moderator Any substance that is capable of slowing down **neutrons** without absorbing them. Slow neutrons are more likely to cause **nuclear fission**, so moderators are important in the construction of **nuclear power plants**. Water or graphite are the most common moderator substances.

Neutron Basic component of matter. Neutrons are electrically neutral. Neutrons and **protons** make up the nuclei of **atoms**.

Neutron number Number of neutrons in an atomic nucleus. It determines the **isotope**.

Nuclear charge number Other name for **atomic number**. Number of protons in an atomic nucleus. It defines the **element**.

Nuclear fission Conversion of an atomic nucleus into two daughter nuclei of roughly half its weight. It takes place mainly in very heavy nuclei and then releases a lot of energy. Nuclear fission can occur spontaneously in some radioactive nuclei, but this is quite rare. However, by bombarding some nuclei with **neutrons**, such as uranium-235 or plutonium-239, these can be very effectively induced to split. Since several neutrons are released from heavy atomic nuclei during nuclear fission, a **chain reaction** is possible.

Nuclear fusion The fusion of two light atomic nuclei into one heavier nucleus generates much energy. Nuclear fusion is responsible for the glowing of the stars and thus also the main energy source of our solar system.

Nuclear power plant Type of power plant in which the energy released by **nuclear fission** is used to produce electricity. The **fission products** as well as the radiation released generate huge amounts of heat in the reactor core. This heat energy is used directly or indirectly to boil water and drive large generator turbines with the steam. (**light water reactor**, **heavy water reactor**)

Nuclear weapon Weapon based on the principle of **chain reaction** of uranium or plutonium with devastating effects. The **isotopes** most suitable for the construction of nuclear weapons are highly enriched uranium-235 or plutonium-239.

Nuclear weapon, dirty Weapon with conventional explosives in which radioactive material is dispersed in the environment to cause **contamination**. Sometimes simply called a "dirty bomb." It is not a **nuclear weapon** in the true sense.

Nucleon Component of atomic nuclei, i.e. **neutrons** and **protons**.

Nuclide Certain type of **atom**, i.e. an atom with a certain number of protons and neutrons. The different **nuclides** of an element are called **isotopes**. Unstable nuclides are radioactive and are called **radionuclides**.

Nuclide map In nuclide maps, the known **nuclides** are shown according to their number of neutrons and protons. The color scheme usually emphasizes the stable nuclides as well as the decay types of the **radionuclides**. In addition, nuclide maps provide information on atomic masses, **half-lives** and decay energies.

Partitioning Step in the **reprocessing** of spent **fuel rods**, in which certain **radionuclides** are separated from each other with the highest possible purity to prepare them for possible **transmutation**.

Periodic table In the periodic table all **elements** are listed according to their **atomic number**. In contrast to **nuclide maps**, the periodic table does not distinguish between **isotopes**. The representation is instead based on the chemical regularities resulting from the shell structure of the electron shell. (**atom**)

Positron Electrically positively charged antiparticle of the **electron**, with which it can radiate to pure energy in the form of **gamma radiation**.

Proliferation Distribution of weapons of mass destruction or the technology necessary for their production. In the narrower sense, this includes the weapons themselves, especially **nuclear weapons**, in the broader sense also any technology that enables the production of these weapons or their use.

Proton Basic component of matter. Protons are positively charged electrically. Neutrons and protons make up the nuclei of **atoms**.

PUREX process (Plutonium-Uranium Recovery by EXtraction) Complex physico-chemical separation process used in **reprocessing** facilities to recover uranium and plutonium from spent **fuel rods**.

Radiation damage Generic term for early or late damage caused by **ionizing radiation**. Early damage occurs only at high doses, but then with certainty and within a short time. This includes radiation hangover in mild cases and radiation sickness in more severe cases. Late damage manifests itself above all in an increased risk of cancer or cardiovascular diseases, which can also take effect decades later. Often overlooked are also psychological problems in connection with **radiation exposure**.

Radiation exposure Effects of **ionizing radiation** on an organism. Radiation exposure is composed of natural and artificial radiation sources. Higher doses can lead to **radiation damage**.

Radiation protection All measures that protect against the effects of **ionizing radiation**. These include structural measures, shielding and filters in laboratories, hospitals or nuclear power plants, rules of conduct when handling radioactive substances and, if necessary, countermeasures such as iodine tablets or drugs that help to prevent **radionuclides** from being absorbed in the body in the first place or to excrete them more quickly.

Radioactive radiation **Ionizing radiation** emitted by radioactive substances (**radionuclides**). The most important subtypes of radioactive radiation are **alpha**, **beta** and **gamma radiation**.

Radioactive waste All types of **radionuclides** that accumulate as residues in scientific laboratories, hospitals, industry and nuclear power plants. Hazardous high-level radioactive waste includes above all the **fission products** and **transuranium elements** produced during **nuclear fission**.

Radioactivity Generic term for all types of **radioactive radiation**.

Radiology Branch of medicine that deals with the effects and applications of **ionizing radiation**, both in diagnostic and therapeutic terms.

Radionuclide Unstable atomic nucleus. Radionuclides decay sooner or later, on a time scale defined by their **half-life**, either into a stable **nuclide** or another radionuclide. (**decay series**)

Reactor pressure vessel Solid, cylindrical steel vessel that encloses the reactor core with the **fuel assemblies** in a **nuclear power plant**.

Reinforced concrete shell Outer protective shell of a **nuclear power plant**.

Reprocessing Serves to separate the resulting materials contained in used **fuel rods** into useful components (unused nuclear fuel and various **radionuclides** for technical or medical purposes) on the one hand and high-, medium- and low-level **radioactive waste** on the other. **Hot cells** are used to protect against the strong radiation. The most important process in reprocessing facilities is the **PUREX process**.

Sievert Unit of the measured radiation **equivalent dose**.

Tailings Residues from uranium mining and fuel rod production containing toxic heavy metals and radioactive decay products of the uranium-radium **decay series**.

Transmutation Conversion of **nuclides** into other nuclides, mainly by neutron bombardment and the processes of **activation** and/or **nuclear fission** and often also subsequent decay. With the help of large-scale transmutation, long-lived **fission products** and **transuranium elements** in **radioactive waste** could be converted into short-lived **radionuclides**, which would significantly alleviate the final storage problem.

Transuranium elements Superheavy atomic nuclei beyond uranium. All transuranic elements are radioactive heavy metals, mostly alpha emitters, some of which have very long **half-lives** of many thousands of years or even considerably longer. Besides plutonium and the **fission products**, they pose major problems for any treatment of **radioactive waste**. (**actinides**, **reprocessing**, **transmutation**)

X-rays Like **gamma radiation**, X-rays are part of electromagnetic radiation, which is why they are also very penetrating. They have less energy and are therefore less dangerous and penetrating than gamma radiation, but also belong to the category of **ionizing radiation** and can cause **radiation damage** in higher doses.

Literature

The titles in this list are recommendations for further study. The list contains mainly books, but also a few important scientific papers. It does not represent a complete bibliography of this book, as this would include too many specialized papers and reports. While inevitably being selective and subjective, this list aims at providing material that gives insight into very different aspects of and perspectives on nuclear energy and its related fields.

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