DIRK EIDEMÜLLER

NUCLEAR POWER EXPLAINED

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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