Chapter 8

Creators and Creations in Nuclear Science and Engineering

Ins Ewige wiederholen...
  Keiner gönnt das Reich
Dem andern; dem gönnt's keiner,
  der's mit Kraft erwarb
Und kräftig herrscht.
  Denn jeder, der sein innres Selbst
Nicht zu regieren weiß,
  regierte gar zu gern
Des Nachbars Willen,
  eignem stolzem Sinn gemäß...
Hier aber ward ein großes Beispiel
  durchgekämpft:
Wie sich Gewalt
  Gewaltigerem entgegenstellt, [...]
Das wird sich messen.
  Weiß die Welt doch, wem's gelang.
Wachfeuer glühen,
  rote Flammen spendende,
Der Boden haucht
  vergoßnen Blutes Widerschein, [...]
Der Zelten Trug verschwindet,
  Feuer brennen blau.
Doch über mir!
  welch unerwartet Meteor?
Es leuchtet und beleuchtet
  körperlichen Ball.

It repeats eternally...
  No one freely gives the realm
To another;
  to the one whose power won it
And whose strength rules.
  For everyone, who does not even know
How to govern his own inner self,
  would all too gladly rule over
His neighbour's will,
  prompted by his own proud mind...
But here a great example was
  fought to the end,
How force battles
  against a greater force, [...]
This is tested.
  The world knows who won.
Bonfires glow,
  sending out red flames:
The ground is soaked
  with images of spilled blood, [...]
The illusion of dwellings vanishes;
  the fires burn blue.
But overhead,
  what sudden meteor is this?
It shines and illuminates
  the whole world.

Johann von Goethe. 1832. *Faust Part Two.*
Act II. Klassische Walpurgisnacht. Erichtho.

A huge number of innovators and innovations in the field of nuclear science and engineering came from the predominantly German-speaking central European research world.[1] German-speaking contributions to early nuclear science are well documented and widely accepted, and include:

8.1. Nuclear diagnostics and therapeutics

8.2. Radiation detectors

8.3. Particle accelerators

8.4. Models of the atomic nucleus

8.5. Nuclear fission reactions

8.6. Nuclear fusion reactions

German-speaking contributions to specific engineering applications of that science are a much more complex topic, and are far less well known by the general public in the modern world. In fact, German-speaking scientists played decisive roles not just in the world's first nuclear engineering program, but in all three of the world's first nuclear engineering programs:

8.7. The World War II and postwar U.S./U.K. nuclear program

8.8. The wartime German nuclear program (For the full presentation and analysis of evidence that the wartime German nuclear program was much larger and more advanced than has been generally recognized, see Appendix D.)

8.9. The postwar Soviet nuclear program

[1] In addition to specific references that are cited in different areas throughout this chapter, this chapter makes use of general biographical and project information from: ACLS 2000; Albrecht et al. 1992; Ash and Söllner 1996; Bar-Zohar 1967; Bower 1987; Bunch and Hellemans 2004; Challoner 2009; Cornwell 2003; Crim 2018; EB 1911, 2010; Gillispie 1970–1990; Gimbel 1990a; Glatt 1994; Hall 2019a; István Hargittai 2006, 2011; Linda Hunt 1991; Impey et al. 2008; Jacobsen 2014; Koertge 2007; Kurowski 1982; Lasby 1971; Lusar 1956, 1971; Medawar and Pyke 2000; Mick 2000; Murray 2003; Nachmansohn 1979; NDB 1953–2020; Neufeld 2012; Nouzille and Huwart 1999; O'Reagan 2014, 2019; Porter 1994; Charles Walker 1946; Peter Watson 2010; Weitensfelder 2009.

I have deliberately left a blank space where images of some creators or creations should go. Those are people or projects that I felt were important enough that they should definitely be shown in this book, yet I have not yet been able to locate a suitable image that I have permission to use, despite my searches in Europe and in the United States. If readers have any relevant images and could send them to me, I would be very grateful and will include them in future editions of this book. Even where a suitable photo cannot be located, I believe that leaving a blank space pays tribute both to the scientific importance of that creator or creation and to how that historical fact has been very nearly forgotten.

There is significant evidence that German-speaking scientists and their technologies played critical roles in additional nuclear programs as well (in France, Israel, etc.), but for reasons of length this book will only focus on those earliest three programs. (Moreover, despite the loss of enormous numbers of nuclear scientists and resources to the United States, Soviet Union, United Kingdom, France, and other countries after the war, West Germany *still* had enough nuclear scientists and industry left to propose its own serious nuclear weapons program until that was terminated for political reasons [Kollert 2000].)

Some well-known aspects of nuclear science were discovered outside the German-speaking world.[2] Marie and Pierre Curie, as well as their daughter and son-in-law Irène and Frédéric Joliot-Curie, characterized several radioactive elements at their Paris laboratory. Ernest Rutherford pioneered the methods of experimental nuclear physics as he moved his lab from McGill University in Montreal to the University of Manchester to the University of Cambridge. Enrico Fermi conducted early nuclear physics experiments at his lab in Rome, before moving to the United States, where he played a key role in the Manhattan Project.

On the other hand, an enormous number of major early nuclear discoveries came from the German-speaking world, as illustrated by the examples in this chapter.[3]

8.1 Nuclear Diagnostics and Therapeutics

Creators from the German-speaking world developed the major methods of nuclear diagnostics and therapeutics that are still used today, including:

8.1.1. X-rays

8.1.2. Radioisotopes and isotope labeling

8.1.3. Nuclear magnetic resonance, or magnetic resonance imaging

8.1.1 X-Rays

In 1895, Wilhelm Röntgen (German, 1845–1923) discovered X-rays, which have often been called Röntgen rays ever since. Ludwig Zehnder (Swiss, 1854–1949, also known for the Mach-Zehnder interferometer—p. 1038) was making detailed whole-body X-ray photographs of humans by 1896; see Fig. 8.1. Of course, X-rays are still widely used for everything from medical exams and dental checkups to airport baggage screening and mechanical parts inspections.

Wilhelm Röntgen won the first Nobel Prize in Physics in 1901. At that first Nobel Prize ceremony, C. T. Odhner, President of the Royal Swedish Academy of Sciences, explained why the importance of Röntgen's work was already evident to the world just six years after his discovery [https://www.nobelprize.org/prizes/physics/1901/ceremony-speech/]:

[2]See for example: Beyer 1949; Cronin 2004; Curie 1938; Fermi 1950; Fermi 1987; L'Annunziata 2016; Reeves 2008; Segrè 1970; Weart 1979.

[3]See for example: Bethe 1991, 1997; Blatt and Weisskopf 1952; Brown and Lee 2006; Otto Hahn 1968; Irving 1967; L'Annunziata 2016; Nachmansohn 1979; Rife 1999; Schweber 2012; Sime 1996; Szanton 1992; Wigner 1967.

> The Academy awarded the Nobel Prize in Physics to Wilhelm Conrad Röntgen, Professor in the University of Munich, for the discovery with which his name is linked for all time: the discovery of the so-called Röntgen rays or, as he himself called them, X-rays. These are, as we know, a new form of energy and have received the name "rays" on account of their property of propagating themselves in straight lines as light does. The actual constitution of this radiation of energy is still unknown. Several of its characteristic properties have, however, been discovered first by Röntgen himself and then by other physicists who have directed their researches into this field. And there is no doubt that much success will be gained in physical science when this strange energy form is sufficiently investigated and its wide field thoroughly explored. Let us remind ourselves of but one of the properties which have been found in Röntgen rays; that which is the basis of the extensive use of X-rays in medical practice. Many bodies, just as they allow light to pass through them in varying degrees, behave likewise with X-rays, but with the difference that some which are totally impenetrable to light can easily be penetrated by X-rays, while other bodies stop them completely. Thus, for example, metals are impenetrable to them; wood, leather, cardboard and other materials are penetrable and this is also the case with the muscular tissues of animal organisms. Now, when a foreign body impenetrable to X-rays, e.g. a bullet or a needle, has entered these tissues its location can be determined by illuminating the appropriate part of the body with X-rays and taking a shadowgraph of it on a photographic plate, whereupon the impenetrable body is immediately detected. The importance of this for practical surgery, and how many operations have been made possible and facilitated by it is well known to all. If we add that in many cases severe skin diseases, e.g. lupus, have been successfully treated with Röntgen rays, we can say at once that Röntgen's discovery has already brought so much benefit to mankind that to reward it with the Nobel Prize fulfils the intention of the testator to a very high degree.

Leopold Freund (Austrian, 1868–1943) and Eduard Schiff (Austrian, 1849–1913) developed and employed radiation therapy from 1896 onward (Fig. 8.2). As shown in Fig. 8.3, Freund wrote the first medical textbook on radiation therapy in 1902 and published it in 1903 [Leopold Freund 1903]. Translations of the book in English and other languages were published in 1904, so Freund truly founded and shaped the field of radiation therapy worldwide. Freund also invented and successfully demonstrated the first chemical sunscreen, Antilux, in 1922 (p. 127).

Radiologist H. Dieter Kogelnik wrote about the historical and scientific importance of Leopold Freund in that field [Kogelnik 1997]:

> There is an increasing acceptance and knowledge of the fact that the inauguration of radiotherapy as a new scientific speciality was performed by Leopold Freund 100 years ago. With a clear and logical rationale, Freund provided the first scientific proof of the biological effectiveness of X-rays on a 5-year-old patient and performed the world's first successful treatment with X-rays. Before Freund's historical experimental treatments, which started in Vienna on November 24th, 1896, there were several suggestions and attempts at the therapeutic use of X-rays, however none of these mostly one-of-a-kind attempts was successful, and there was no scientific proof of a therapeutic effectiveness of X-rays in these previous experiments.

Carl H. F. Müller (German, 1845–1912) began producing vacuum tubes in 1880 and X-ray tubes in 1896. His company and its researchers remained at the forefront of producing instruments for nuclear science until 1945. Advanced German X-ray tubes—and information on how to make them—were publicly heralded as important prizes that the United States obtained from Germany after World War II (pp. 429, 3992–4004).

Hermanus Haga (Dutch, 1852–1936) and Dirk Coster (Dutch, 1889–1950) developed various applications of X-rays (p. 1521). During the period 1922–1924, Coster demonstrated X-ray spectroscopy, or methods to separate different wavelengths of X-rays and use them to make new discoveries. Using X-ray spectroscopy, Coster and George de Hevesy (Hungarian, 1885–1966) discovered hafnium in 1923 (p. 445).

Two other especially noteworthy scientists who worked on the medical implications and applications of radiation were Nikolai Timoféeff-Ressovsky (Russian but worked in Germany 1925–1945, lived 1900–1981) and Karl Günter Zimmer (German, 1911–1988). Along with Max Delbrück, in 1935 they published a groundbreaking paper on the effects of radiation on genetic mutations and structure (p. 104). They also studied applications of radiation in neuroscience and other areas of biology. In 1945, Timoféeff-Ressovsky, Zimmer, and some of their colleagues moved to Russia and continued to study the biological effects of radiation as part of the German-speaking scientific community there.

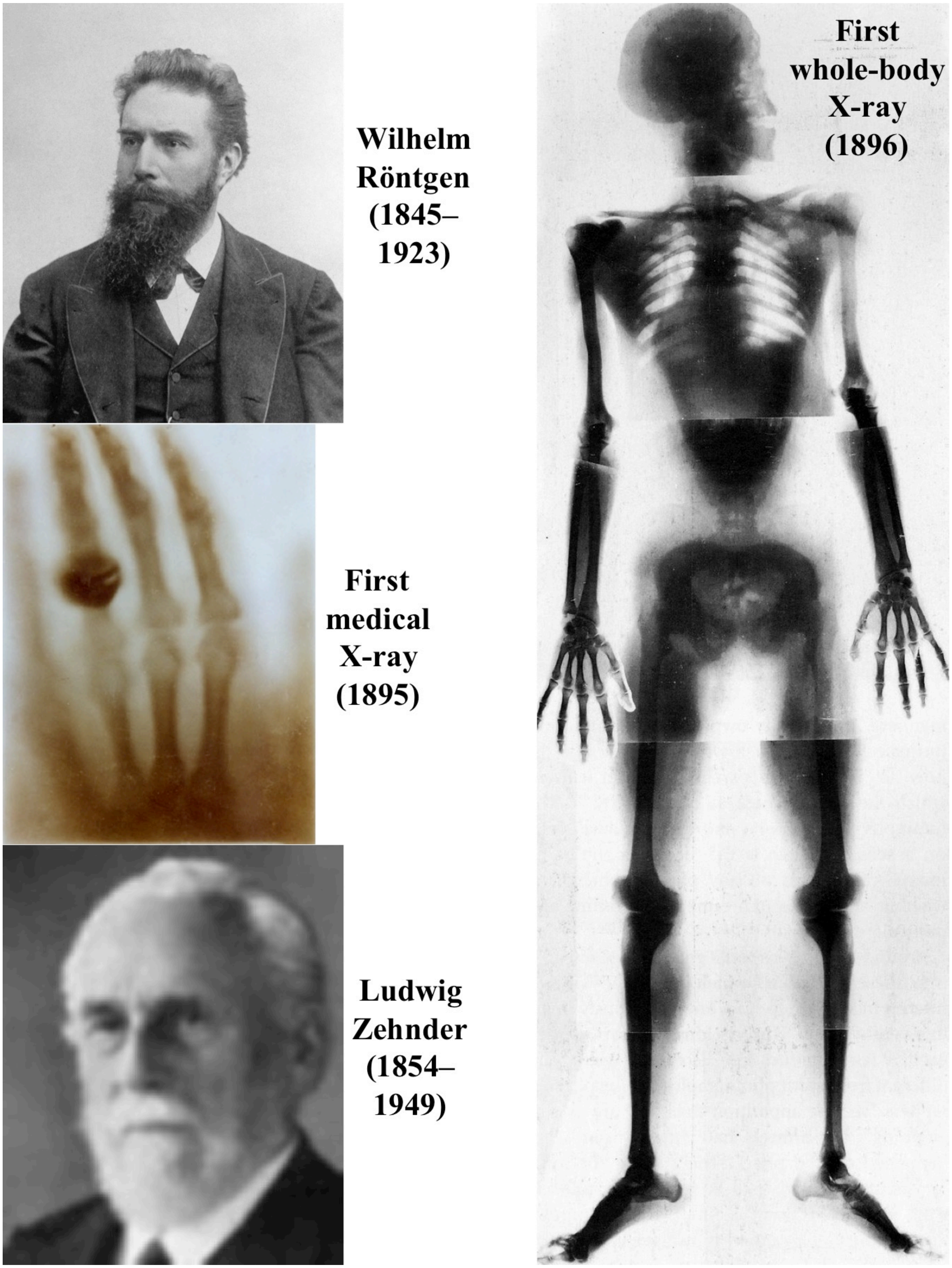


Figure 8.1: Wilhelm Röntgen discovered X-rays (often called Röntgen rays) and made the first human X-ray in 1895. Ludwig Zehnder made the first whole-body X-ray (a composite of nine X-ray films) in 1896.

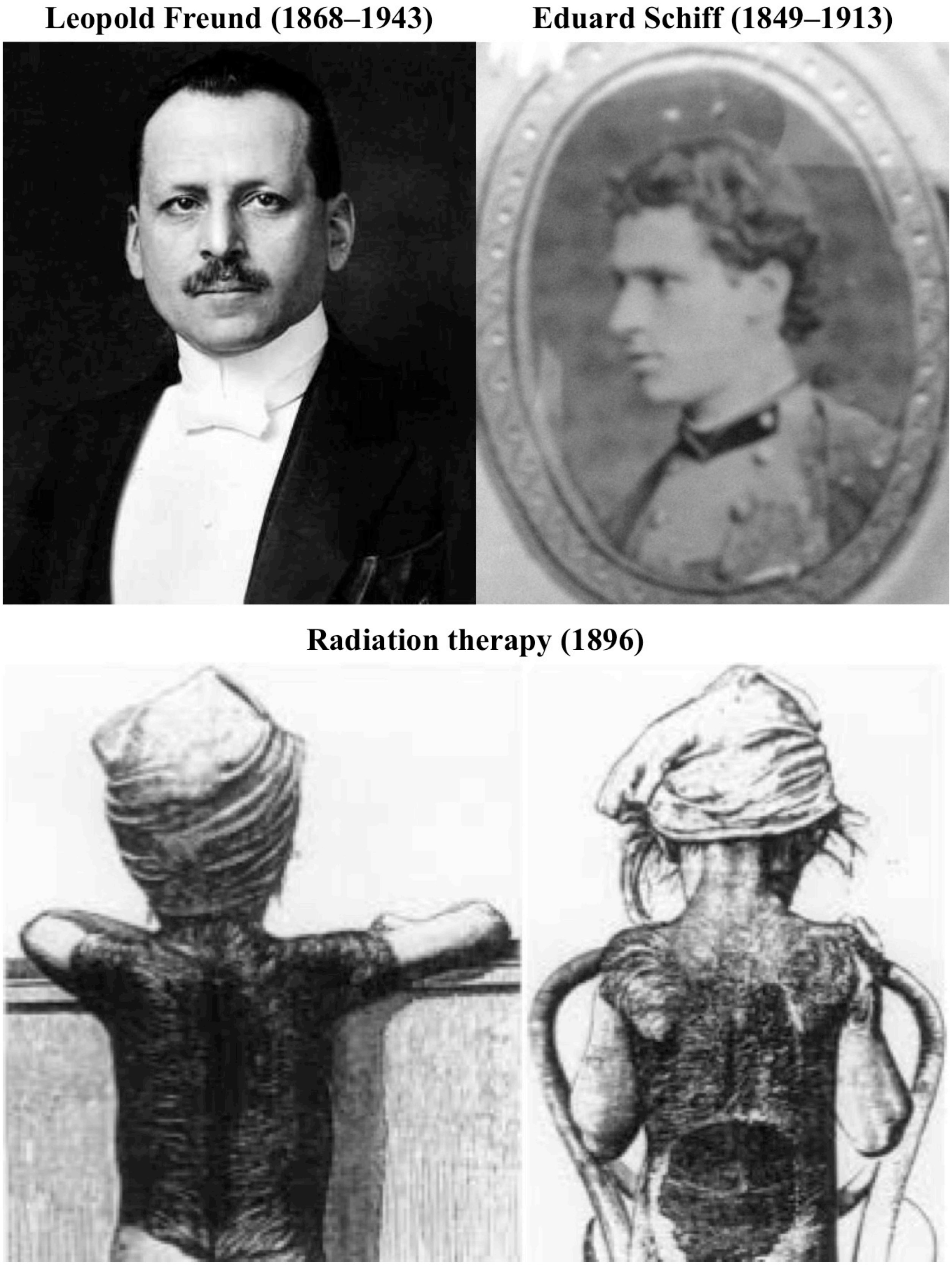
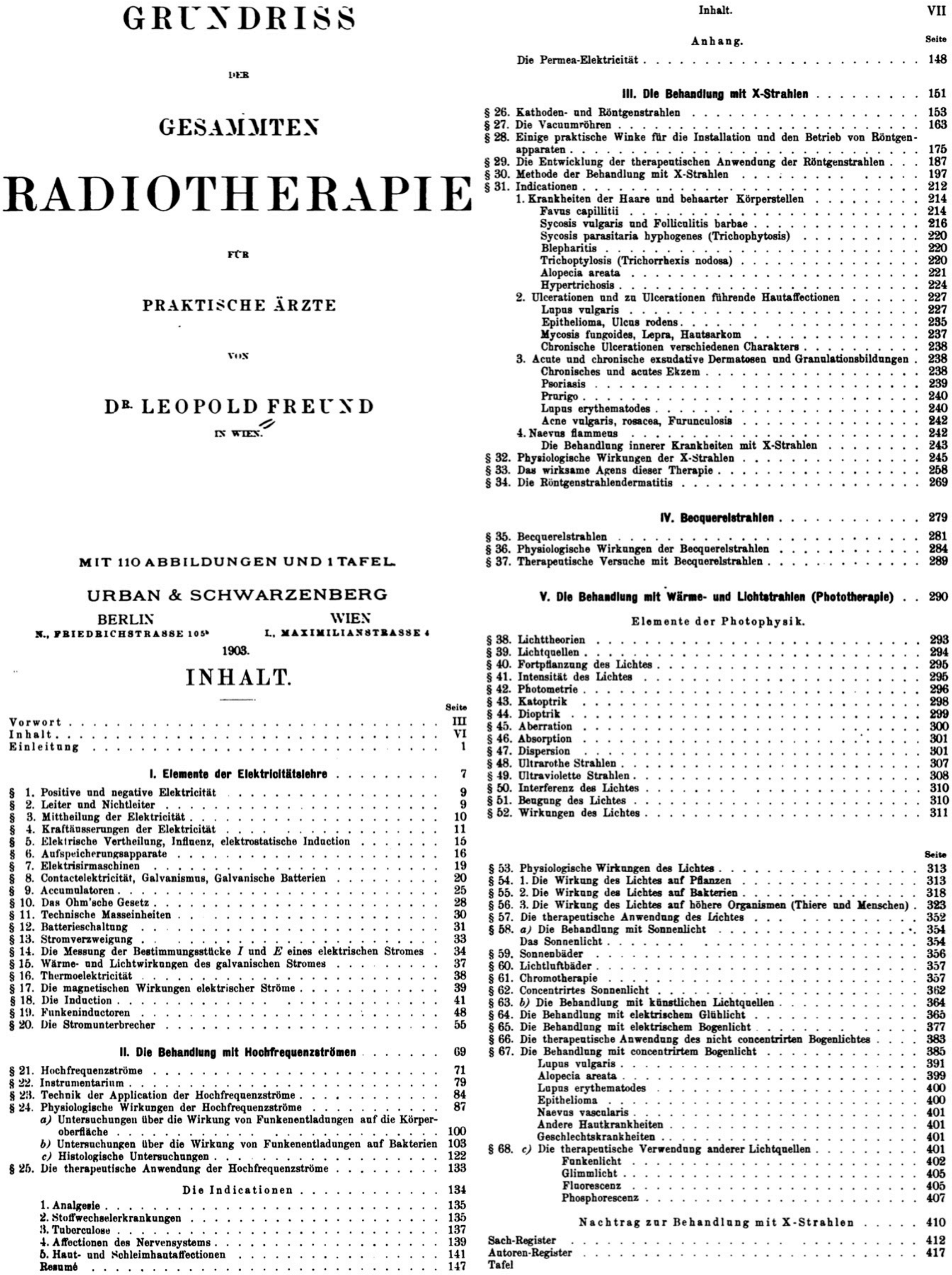


Figure 8.2: Leopold Freund and Eduard Schiff invented radiation therapy. In 1896, they used X-rays to successfully treat a young girl with hairy growths on her entire back. They continued to develop and employ radiation therapy in the following years.



GRUNDRISS

DER

GESAMMTEN

RADIOTHERAPIE

FÜR

PRAKTISCHE ÄRZTE

VON

DR. LEOPOLD FREUND

IN WIEN.

MIT 110 ABBILDUNGEN UND 1 TAFEL.

URBAN & SCHWARZENBERG

BERLIN N., FRIEDRICHSTRASSE 105ᵇ — WIEN I., MAXIMILIANSTRASSE 4

1903.

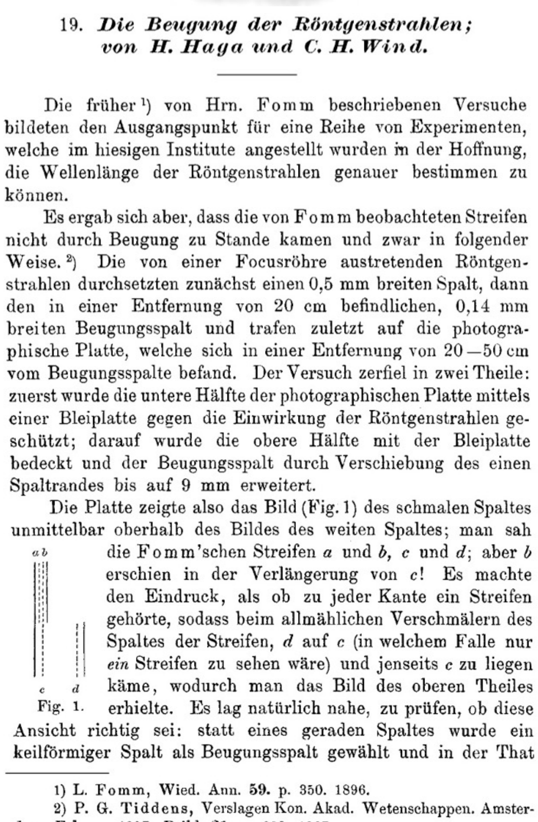
INHALT.

Inhalt. VII

Figure 8.3: Leopold Freund wrote the first medical textbook on radiation therapy in 1902 and published it in 1903 [Leopold Freund 1903].

X-ray applications

Hermanus Haga (1852–1936) **Dirk Coster (1889–1950)**



19. ***Die Beugung der Röntgenstrahlen; von H. Haga und C. H. Wind.***

Die früher [1]) von Hrn. Fomm beschriebenen Versuche bildeten den Ausgangspunkt für eine Reihe von Experimenten, welche im hiesigen Institute angestellt wurden in der Hoffnung, die Wellenlänge der Röntgenstrahlen genauer bestimmen zu können.

Es ergab sich aber, dass die von Fomm beobachteten Streifen nicht durch Beugung zu Stande kamen und zwar in folgender Weise. [2]) Die von einer Focusröhre austretenden Röntgenstrahlen durchsetzten zunächst einen 0,5 mm breiten Spalt, dann den in einer Entfernung von 20 cm befindlichen, 0,14 mm breiten Beugungsspalt und trafen zuletzt auf die photographische Platte, welche sich in einer Entfernung von 20—50 cm vom Beugungsspalte befand. Der Versuch zerfiel in zwei Theile: zuerst wurde die untere Hälfte der photographischen Platte mittels einer Bleiplatte gegen die Einwirkung der Röntgenstrahlen geschützt; darauf wurde die obere Hälfte mit der Bleiplatte bedeckt und der Beugungsspalt durch Verschiebung des einen Spaltrandes bis auf 9 mm erweitert.

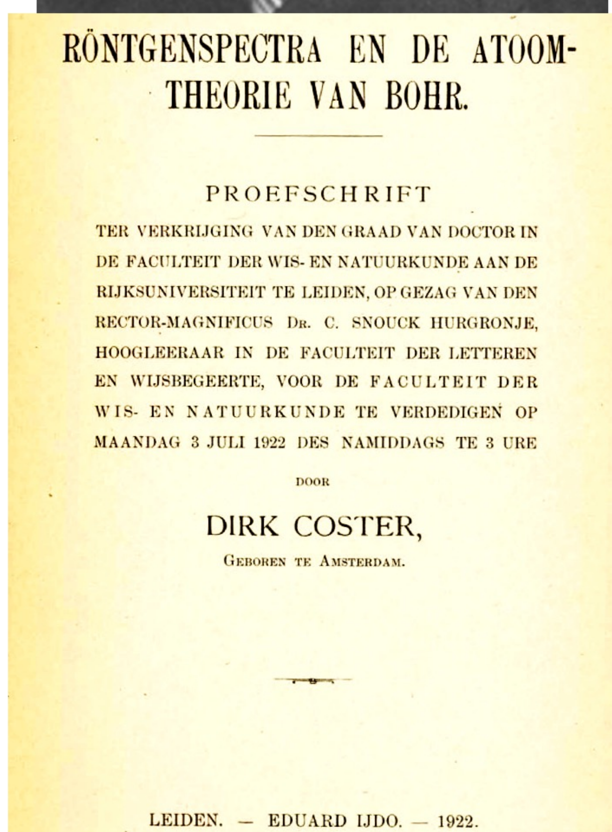
Die Platte zeigte also das Bild (Fig. 1) des schmalen Spaltes unmittelbar oberhalb des Bildes des weiten Spaltes; man sah die Fomm'schen Streifen *a* und *b*, *c* und *d*; aber *b* erschien in der Verlängerung von *c*! Es machte den Eindruck, als ob zu jeder Kante ein Streifen gehörte, sodass beim allmählichen Verschmälern des Spaltes der Streifen, *d* auf *c* (in welchem Falle nur *ein* Streifen zu sehen wäre) und jenseits *c* zu liegen käme, wodurch man das Bild des oberen Theiles erhielte. Es lag natürlich nahe, zu prüfen, ob diese Ansicht richtig sei: statt eines geraden Spaltes wurde ein keilförmiger Spalt als Beugungsspalt gewählt und in der That

a b / *c d*

Fig. 1.

1) L. Fomm, Wied. Ann. **59.** p. 350. 1896.

2) P. G. Tiddens, Verslagen Kon. Akad. Wetenschappen. Amsterdam. Februar 1897; Beibl. **21.** p. 603. 1897.



RÖNTGENSPECTRA EN DE ATOOMTHEORIE VAN BOHR.

PROEFSCHRIFT

TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE FACULTEIT DER WIS- EN NATUURKUNDE AAN DE RIJKSUNIVERSITEIT TE LEIDEN, OP GEZAG VAN DEN RECTOR-MAGNIFICUS DR. C. SNOUCK HURGRONJE, HOOGLEERAAR IN DE FACULTEIT DER LETTEREN EN WIJSBEGEERTE, VOOR DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP MAANDAG 3 JULI 1922 DES NAMIDDAGS TE 3 URE

DOOR

DIRK COSTER,

GEBOREN TE AMSTERDAM.

LEIDEN. — EDUARD IJDO. — 1922.

Figure 8.4: Hermanus Haga (Dutch, 1852–1936) and Dirk Coster (Dutch, 1889–1950) developed various applications of X-rays.

8.1.2 Radioisotopes and Isotope Labeling

Different isotopes of the same chemical element have the same number of protons and same number of electrons (and hence the same chemical properties), but different numbers of neutrons; that difference in neutron number creates a measurable mass difference, and also makes some isotopes radioactive. Isotopes that are radioactive can be extremely useful either for diagnostics or for radiation therapy. Even isotopes that are not radioactive can be detected by their mass differences and thus can be useful in chemistry and biology experiments.

Isotope labeling of chemical molecules was developed by George de Hevesy (Hungarian, 1885–1966), Hilde Levi (German, 1909–2003), Friedrich Paneth (Austrian, 1887–1958), and Rudolf Schoenheimer (German, 1898–1941); see Fig. 8.5. The ability to follow labeled molecules as they pass through chemical reactions, biological systems, and the environment revolutionized our understanding of chemistry, biology, and earth science. Radioisotope labeled molecules continue to be widely used for medical diagnostics and cancer therapeutics. De Hevesy won a Nobel Prize in Chemistry in 1943. Professor A. Westgren, member of the Nobel Committee for Chemistry, explained how extensive de Hevesy's research was [https://www.nobelprize.org/prizes/chemistry/1943/ceremony-speech/]:

> This discovery was made some ten years ago and the study of chemical processes by means of radioactive markers has since then been carried to such a point that it is now widely used in laboratories throughout the world. De Hevesy has remained the prime mover in this new field of activity and much first-class and important research has been carried out by him and his co-workers.
>
> Exceptionally valuable results have thus been obtained in biology. An isotope of radioactive phosphorus, which can be obtained by exposing sulphur to neutron radiation or ordinary phosphorus to radiation from nuclei of heavy hydrogen, has mostly been used. This radioactive phosphorus is sufficiently long-lasting for tests of this nature. It has a half-life of approximately 14.8 days. De Hevesy produced physiological solutions of sodium phosphate containing this marker and injected them into animals and humans. The distribution of the phosphorus was determined at certain intervals. A study of blood samples showed that the phosphorus thus introduced quickly left the blood. In human blood the radio-phosphorus content had fallen after only 2 hours to a mere 2% of its initial value. It diffuses into the extra-cellular body fluid and gradually changes places with the phosphorus atoms of the tissues, organs and skeleton. After some time it can even be found, though in very small quantities, in the enamel of the teeth. Exchanges small and slow as they may be, therefore occur between the outer hard parts of the teeth and the inner tissues of the bones and the lymph. Most of the phosphorus introduced, finds its way into the skeleton, muscles, liver and gastro-intestinal organs. Elimination of phosphorus from living organisms has also been studied by this method.
>
> Phosphorus is an extremely important element in biological processes. The knowledge of its functions in living organisms which has been acquired thanks to the use of radioactive markers is therefore of the very greatest interest. De Hevesy succeeded in detecting where and at what speed the various organic compounds of phosphorus are able to form and the paths which they take in the animal organism. In order to form from a phosphate which has been injected into the blood they must first penetrate into the cells. Acid-soluble compounds of phosphorus form rapidly, whereas phosphatides closely related to

> fatty substances are slower-forming. These latter form mainly in the liver, whence they are carried by the blood plasma to the places where they will be consumed. De Hevesy showed that the phosphatides of the chicken embryo are produced in the embryo itself and that they cannot be extracted from the egg yolk.
>
> De Hevesy also carried out several investigations with radioactive sodium and potassium. He studied how physiological saline containing radioactive sodium which was injected into a human subject first spread into the blood and then slowly penetrated into the cells; he also studied the manner in which it is excreted. After 24 hours the blood corpuscles had lost approximately half their sodium content.
>
> In addition to the above-mentioned markers, several other active isotopes, such as magnesium, sulphur, calcium, chlorine, manganese, iron, copper and zinc, have been used for this type of research. In the case of the lighter elements it has also been possible to use inactive isotopes such as heavy hydrogen, with an atomic weight of 2, nitrogen, with an atomic weight of 15, and oxygen, with an atomic weight of 18. It is of course less easy to determine the content of an inactive than of an active marker, but this can be done by determinations of density or mass-spectrographically. To determine the concentration of deuterium, or heavy hydrogen, which is twice as heavy as ordinary hydrogen, is a relatively easy matter. De Hevesy used deuterium as marker in many tests. He then noticed that a person who has drunk water containing heavy hydrogen excretes deuterium in the urine after only 26 minutes. Frogs and fishes swimming in water containing deuterium absorb it and, after about 4 hours, are in equilibrium with the medium as far as the deuterium is concerned. Heavy nitrogen and heavy oxygen have also been used in many investigations.

Technetium, which is especially useful for radioisotope labeling due to its short half-life and readily detectable gamma rays, was discovered in 1925 by Otto Berg (German, 1873–1939), Walter Noddack (German, 1893–1960), and Ida Tacke Noddack (German, 1896–1978); see p. 442.

Similarly, Berta Karlik (Austrian, 1904–1990), shown in Fig. 8.6, worked out the radioactive decay process that produces astatine, a previously undiscovered element (number 85) and ultimately an important radioactive treatment for cancer.[4]

Ulrich Henschke (German, 1914–1980) invented and commercialized a variety of brachytherapy methods for treating cancer with very localized radioactive sources or tightly targeted radiation beams. Henschke also made important contributions in several other unrelated fields. See p. 2526 for more information.

German-speaking scientists also led the rest of the world in research on all other aspects of cancer causes, prevention, and treatment (p. 114).

[4]As an aside, for this period in history, women appear to have been remarkably numerous and successful in the greater German-speaking nuclear physics community. Hilde Levi, Ida Tacke Noddack, and Berta Karlik have already been mentioned, and Marietta Blau, Erika Cremer, Klara Döpel, Maria Goeppert Mayer, and Lise Meitner are discussed in later sections. While these were some of the most prominent women in the nuclear physics community, there were a number of others as well. Unfortunately, even these most prominent women have been largely forgotten by history, except for Meitner, who has been the subject of two major biographies in recent decades [Rife 1999; Sime 1996]. It would be interesting to study whether other scientific fields had similarly large populations of female scientists who have been neglected by historians, or if there were certain factors that allowed women to go further in nuclear physics than in many other fields of science and engineering at that time. (Of course, Marie Curie and her daughter Irène Joliot-Curie are well-known examples of women who were successful in nuclear physics outside the

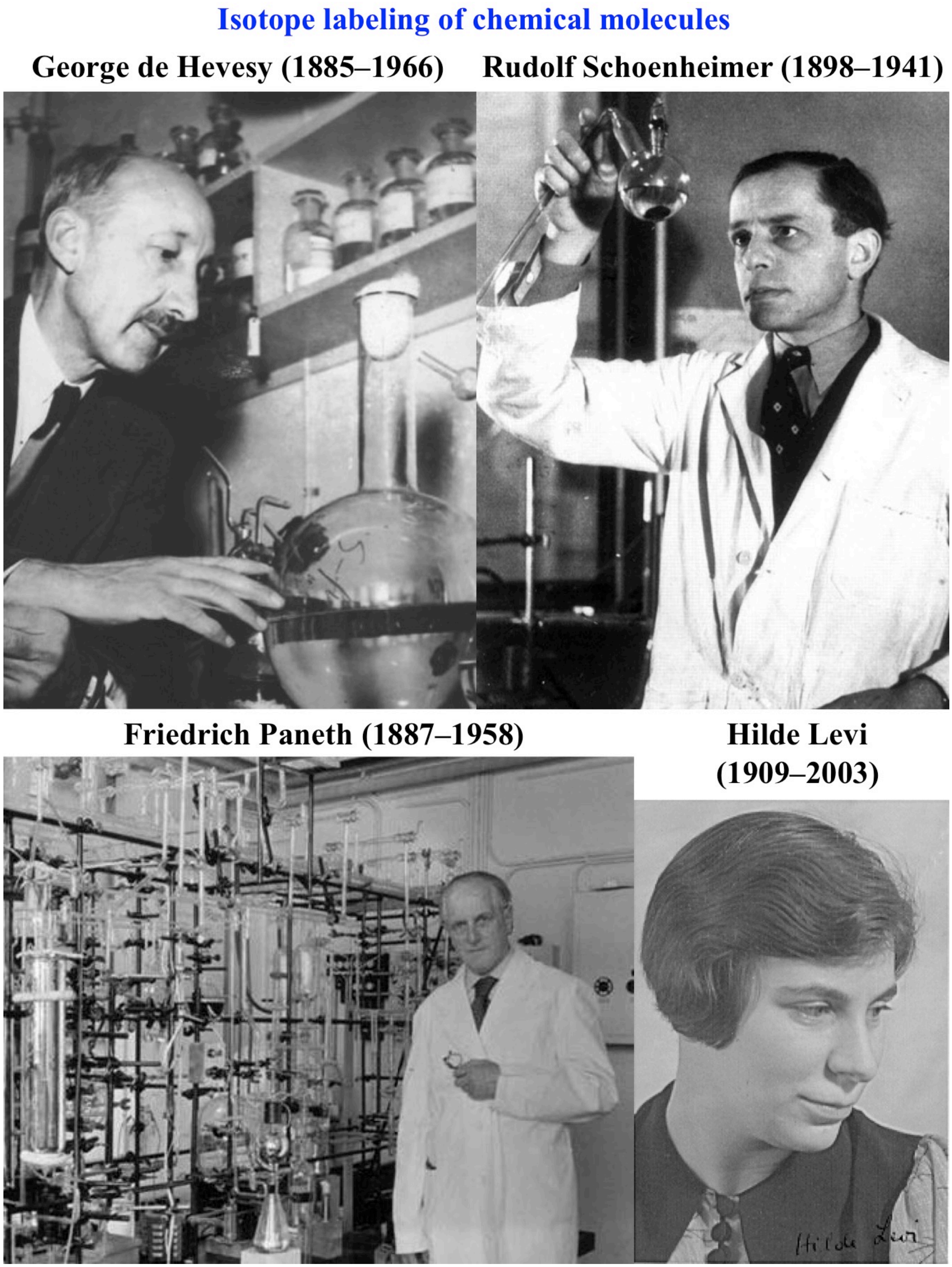


Figure 8.5: George de Hevesy, Hilde Levi, Friedrich Paneth, and Rudolf Schoenheimer developed isotope labeling of chemical molecules.

Berta Karlik (1904–1990)
Astatine

Figure 8.6: Berta Karlik worked out the radioactive decay process that produces astatine, a previously undiscovered element (number 85) and ultimately an important radioactive treatment for cancer.

8.1.3 Nuclear Magnetic Resonance (NMR)/Magnetic Resonance Imaging (MRI)

Nuclear magnetic resonance (NMR), also called magnetic resonance imaging (MRI), does not involve radiation or radioactivity, but rather uses intense magnetic fields to identify different types of atomic nuclei. Thus it can be used to identify various types of atoms and their relative locations within a chemical molecule, or to track the locations of oxygen or other atoms being used within the human body.

Pieter Zeeman (Dutch, 1865–1943) and Hendrik Antoon Lorentz (Dutch, 1853–1928) discovered that applied magnetic fields shift the energy levels of electrons orbiting in atoms, and therefore the frequencies of electromagnetic waves that they absorb and emit. For demonstrating and explaining what is now known as the Zeeman effect, both Zeeman and Lorentz won the Nobel Prize in Physics in 1902 (p. 899).

Beginning in the 1930s, I. I. Rabi (Austro-Hungarian by birth and educated in the German-speaking scientific community, 1898–1988) and Felix Bloch (Swiss, 1905–1983) demonstrated that sufficiently strong magnetic fields could create a Zeeman-type effect not just of the electrons orbiting in an atom, but of the nucleus at the center of an atom (Fig. 8.7). Under such conditions, the atomic nuclei of different chemical elements, or different isotopes of the same element, have slightly different magnetic signatures that can be detected using the fields.

For laying the foundations for NMR/MRI, Rabi won the Nobel Prize in Physics in 1944. At the award ceremony, Professor E. Hulthén of the Nobel Committee for Physics praised the cleverness and utility of Rabi's accomplishments [https://www.nobelprize.org/prizes/physics/1944/ceremony-speech/]:

> Let us now for a moment touch upon Rabi's achievements in this field. Returning to the essential point of the problem, let us put the question: How does the atom react to the magnetic field? According to a theorem stated by the English mathematician Larmor, this influence may be ascribed to a relatively slow precession movement on the part of the electron and the atomic nucleus around the field direction—a gyromagnetic effect most closely recalling the gyroscopic movement performed by a top when it spins around the vertical line. If the strength of the magnetic field is known, the magnetic factor of the electron and of the atomic nucleus can also be estimated by this means, provided that we can observe and measure these precessional frequencies. Rabi solved the problem in a manner as simple as it was brilliant. Within the magnetic field was inserted a loop of wire, attached to an oscillating circuit the frequency of which could be varied in the same manner as we tune in our radio receiving set to a given wavelength. Now, when the atomic beam passes through the magnetic field, the atoms are only influenced on condition that they precess in time with the electric current in the oscillating circuit. This influence might perhaps be described graphically: the nucleus performs a vault (salto)—the technical term for which is a "quantum jump"—thereby landing in another positional direction to the field. But this means that the atom has lost all chance of reaching the detector and of being registered by it. The effect of these quantum jumps is observable by the fact that the detector registers a marked resonance minimum, the frequency position of the registration being determined with the extraordinary precision achievable with the radio frequency gauge. By this method Rabi has literally established

German-speaking world.)

> radio relations with the most subtile particles of matter, with the world of the electron and of the atomic nucleus.

Felix Bloch won the Nobel Prize in Physics in 1952 for his own role in the development of NMR/MRI and related techniques. Professor E. Hulthén addressed him at the award ceremony [https://www.nobelprize.org/prizes/physics/1952/ceremony-speech/]:

> Professor Bloch. It would be difficult in the few minutes at my disposal to try to give the main features of the nuclear induction method for which you have been awarded your Nobel Prize. It would be still more difficult for me to give an exhaustive account of the ways that led you to this invention.
>
> You began your career as a theoretical physicist, well-known for your fundamental contributions to the theory of metals.
>
> When, quite unexpectedly, you went over to experimental research, this must have been, I feel, with deliberation and assurance. For you had in your kitbag a tool of extraordinary value, the method for the magnetic polarization of a beam of neutrons. The inestimable value of possessing a good idea, of indefatigably testing and perfecting it, is best illustrated by your precision-measurements of the magnetic moment of the neutron, one of the most difficult and at the same time most important tasks in nuclear physics.
>
> But ideas give birth to new ideas, and it was, as I understand, in this way that you hit upon the excellent notion of eliminating the difficult absolute determination of the magnetic field by a direct measurement of the neutron moment in units of the proton cycle (the nuclear magneton). According to your own account it was this solution which finally led you to the nuclear induction method.

Nicolaas Bloembergen (Dutch, 1920–2017, Fig. 6.64) was one of the major developers of early laboratory systems for NMR analysis. He won the Nobel Prize in Physics in 1981 for some of his other research on lasers. See p. 1042 for more information.

NMR/MRI was further developed by a number of scientists from the 1950s to the 1970s (including the American chemist Paul Lauterbur and the British physicist Peter Mansfield) and is now widely used for medical diagnostics and chemical analysis.

Richard Ernst (Swiss, 1933–, p. 613) developed NMR spectroscopy methods that are useful for studying chemical molecules and biological systems. For that work, he won the Nobel Prize in Chemistry in 1991. See p. 602 for more information.

Kurt Wüthrich (Swiss, 1938–, p. 620) developed methods to use NMR to study large molecules. For that innovation, he won the Nobel Prize in Chemistry in 2002 (p. 610).

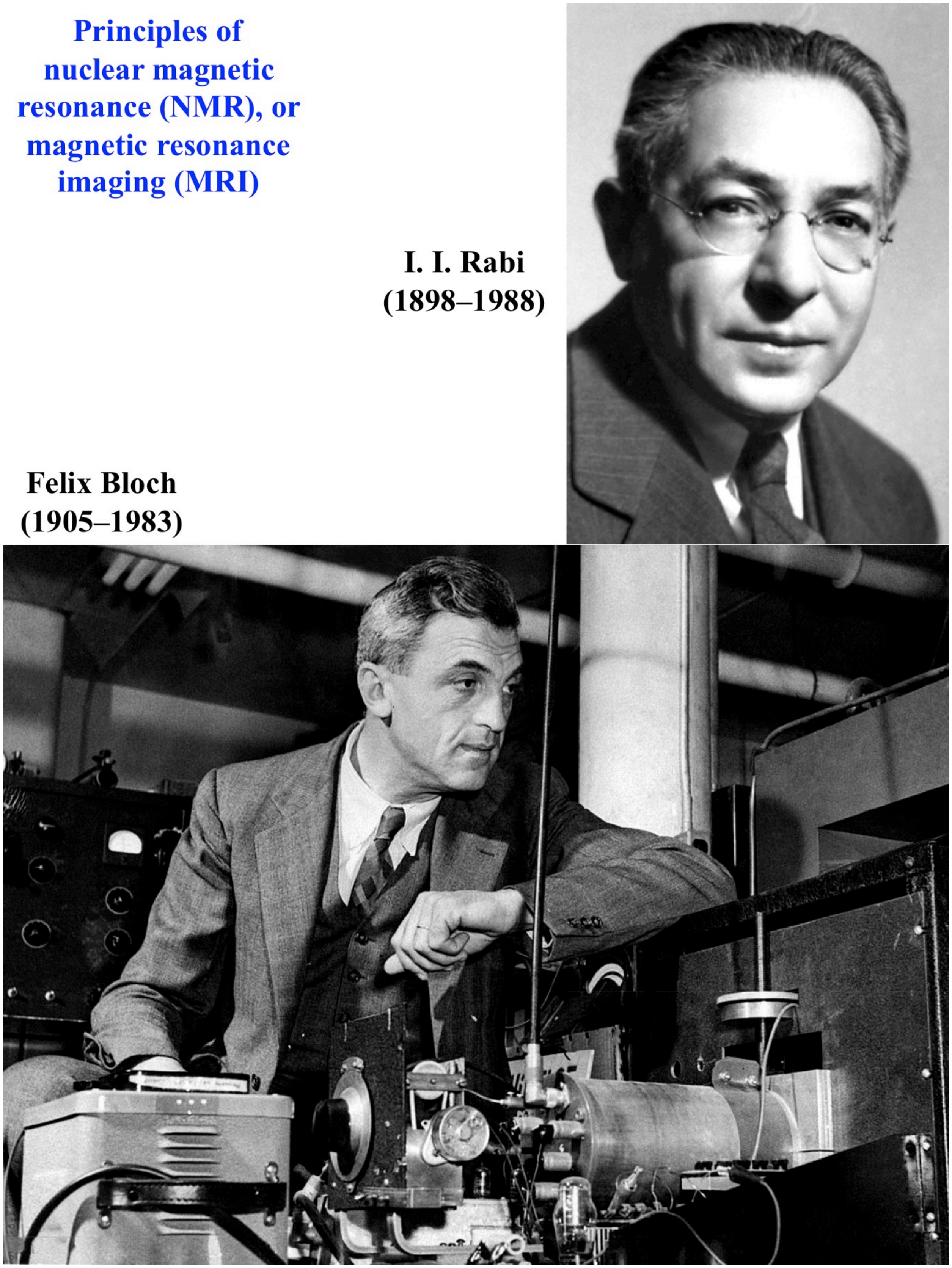


Figure 8.7: I. I. Rabi and Felix Bloch developed the principles of nuclear magnetic resonance (NMR), or magnetic resonance imaging (MRI).

8.2 Radiation Detectors

German-speaking scientists developed the major types of radiation detectors that are still widely used today, including electrical methods of detection (Section 8.2.1), optical methods of detection (Section 8.2.2), and more advanced methods such as Mössbauer spectroscopy (Section 8.2.3).

8.2.1 Electrical Detection of Radiation

German-speaking creators invented electrical methods of detecting radiation. Hans Geiger (German, 1882–1945) and Walther Müller (German, 1905–1979) developed Geiger counters or Geiger-Müller tubes between 1908 and 1928, while Heinrich Greinacher (Swiss, 1880–1974) developed similar proportional or spark counters in 1920. See Fig. 8.8.

Marc Shampo and his scientific colleagues gave an overview of Geiger's contributions [Shampo et al. 2011]:

> The German physicist Hans Wilhelm Geiger is best known as the inventor of the Geiger counter to measure radiation. In 1908, Geiger introduced the first successful detector of individual alpha particles. Later versions of this counter were able to count beta particles and other ionizing radiation. The introduction in July 1928 of the Geiger-Müller counter marked the introduction of modern electrical devices into radiation research. [...]
>
> In 1925, Geiger accepted his first teaching position, which was at the University of Kiel, Germany. Here, he and Walther Müller improved the sensitivity, performance, and durability of the counter, and it became known as the "Geiger-Müller counter." It could detect not only alpha particles but also beta particles (electrons) and ionizing photons. The counter was essentially in the same form as the modern counter.
>
> In 1929, Geiger moved to the University of Tübingen (Germany), where he was named professor of physics and director of research at the Institute of Physics. In 1929, while at the Institute, Geiger made his first observations of a cosmic-ray shower. Geiger continued to investigate cosmic rays, artificial radioactivity, and nuclear fission after accepting a position in 1936 at the Technische Hochschule in Berlin, a position he held until his death. In 1937, with Otto Zeiller, Geiger used the counter to measure a cosmic-ray shower.

Walther Bothe (German, 1891–1957, photo on p. 1623) developed methods of detecting a variety of different types of radiation, including alpha particles in 1927, cosmic rays in 1929, and neutrons in 1930. For this work, he won the Nobel Prize in Physics in 1954. Professor I. Waller, a member of the Nobel Committee for Physics, described Bothe's accomplishments [https://www.nobelprize.org/prizes/physics/1954/ceremony-speech/]:

> Professor Walther Bothe, who shares this year's Nobel Prize with Professor Born, began his scientific activity as a theoretical physicist.
>
> The work for which he has now been rewarded with the Nobel Prize was carried out by him in Berlin actually as an experimental physicist. These labours were based on a new use of counter tubes. A counter tube has the property of transmitting an electric current when a charged particle, e.g. an electron, passes through it; and also, with special contrivances, when a light particle collides with it. Bothe's idea was to use two counter tubes in such a manner that the two tubes would only register simultaneous

> collisions. Such coincidences can only come from two particles emitted in the same elemental process, or from a particle which has travelled through both tubes at high velocity so that the time it takes for the particle's passing from one tube to the other can be neglected.
>
> Bothe used this coincidence method in 1925 and also with improved apparatus about ten years later in order to decide whether the energy rule as well as its complement, the so-called impulse rule, is valid for every collision between a light particle and an electron—as Einstein and Compton assumed—or whether those rules are valid only on average for a large number of collisions—as Bohr and his collaborators had inferred. By investigating light particles and electrons by the coincidence method, Bothe and his co-workers were able to show convincingly that the rules mentioned are valid for every individual collision. This result was of great significance in principle. The coincidence method has been widely used in the study of cosmic radiation and is one of the most important experimental aids in the investigation of cosmic radiation. This method was first used in this way by Bothe when he was working with Kolhörster who had already given important contributions in the field of cosmic radiation. Bothe and Kolhörster used the coincidence method to pick out those particles in the cosmic radiation which had travelled through two counter tubes. The absorption of cosmic radiation into various materials was determined by placing layers of these substances between the tubes and studying the corresponding reduction in the number of coincidences. It was found that these particles are absorbed at about the same extent as the total cosmic radiation. From the experiments the particularly important result was obtained, that at sea level, cosmic radiation consists in the main of particles of very high penetration.
>
> Bothe and other researchers later improved the coincidence method and extended its field of application. This method has now become one of the most important aids in the study of both nuclear reactions and cosmic radiation.
>
> By many other discoveries and penetrating investigations also, Bothe has enriched our knowledge in these fields in very great measure and has provided an important stimulus to other researchers.

For more information on the contributions of the German-speaking world to the detection and analysis of cosmic rays, see p. 811.

8.2.2 Optical Detection of Radiation

German-speaking scientists also created the major optical methods of detecting radiation (Fig. 8.9).

As already described, Wilhelm Röntgen and Ludwig Zehnder developed X-ray photography in 1895 and 1896 (p. 1518).

Marietta Blau (Austrian, 1894–1970) demonstrated that photographic film could also be used to make practical particle detectors during the period 1927–1937.

Hartmut Kallmann (German, 1896–1978) created organic scintillator particle detectors that emitted light when radiation passed through them.

Karl Przibram (Austrian, 1878–1973) developed inorganic scintillator detectors with that same property.

Figure 8.8: Geiger-Müller radiation detectors were developed by Hans Geiger and Walther Müller. Similar proportional and spark counter radiation detectors were developed by Heinrich Greinacher.

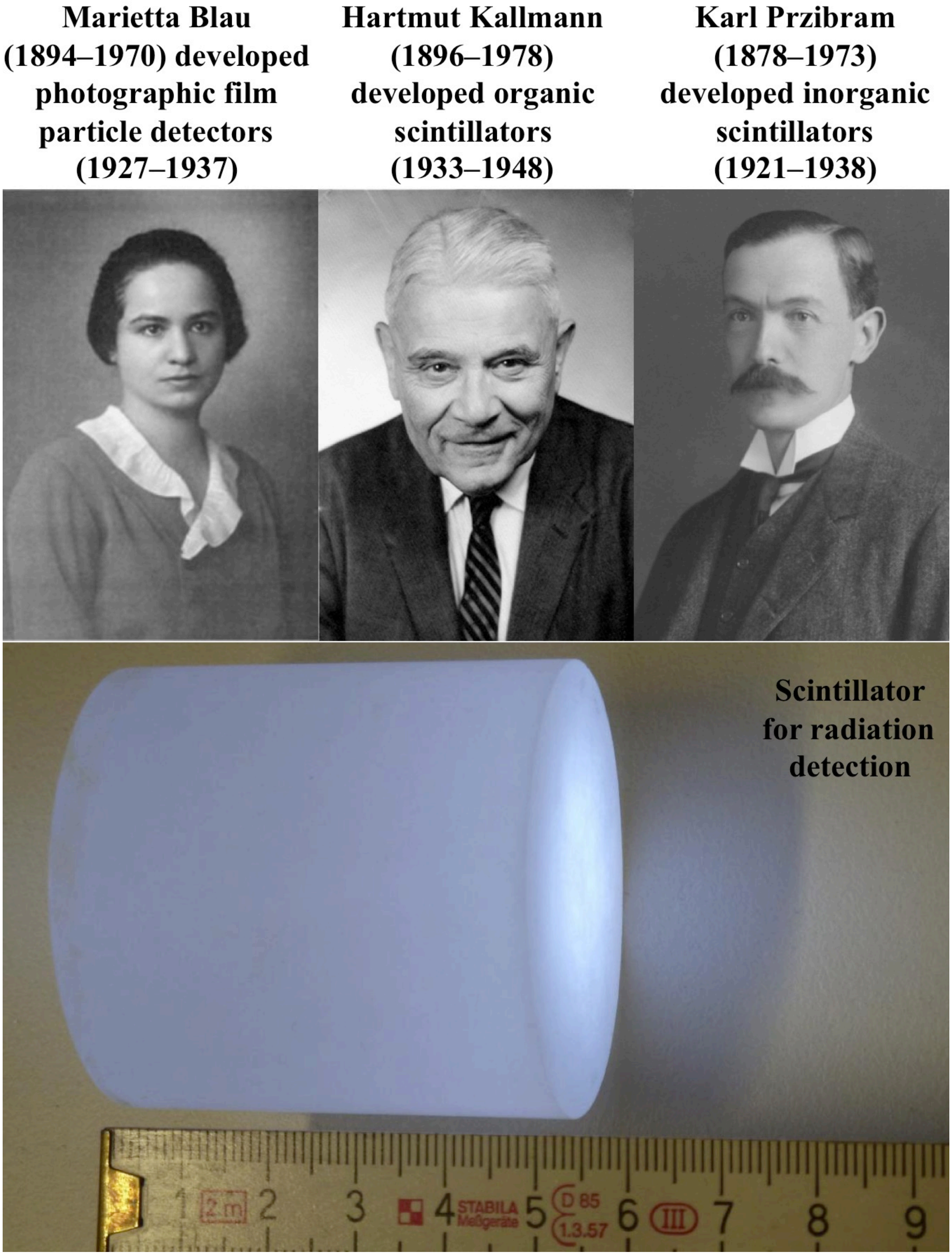


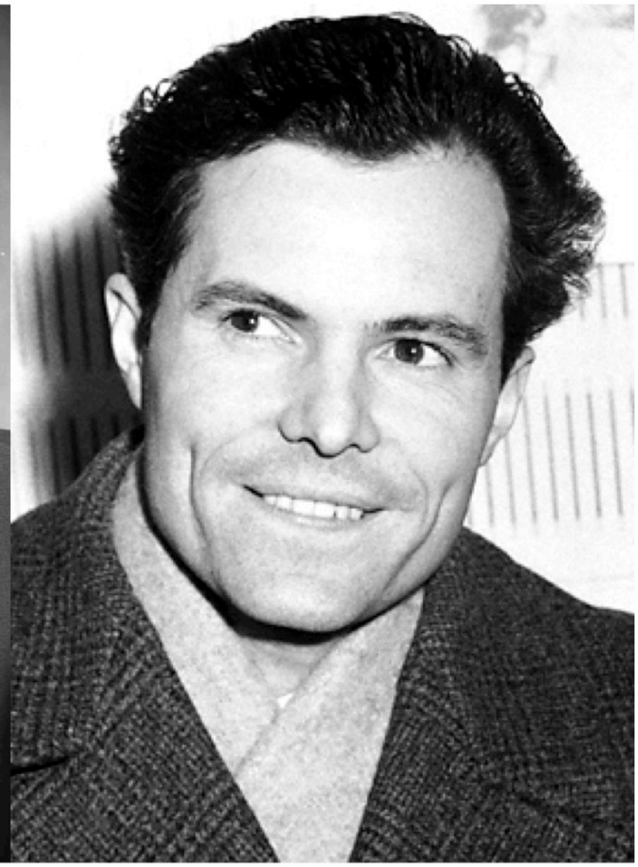
Figure 8.9: Marietta Blau developed photographic film particle detectors, Hartmut Kallmann created organic scintillator particle detectors, and Karl Przibram developed inorganic scintillator detectors.

8.2.3 Mössbauer Spectroscopy

Following the suggestions of his doctoral thesis advisor Heinz Maier-Leibnitz (German, 1911–2000), during the period 1953–1958 Rudolf Mössbauer (German, 1929–2011) developed recoilless nuclear resonance absorption, which became known as the Mössbauer effect or Mössbauer spectroscopy (Fig. 8.10). Mössbauer won the Nobel Prize in Physics in 1961. Professor I. Waller of the Nobel Committee for Physics described the significance of this work [https://www.nobelprize.org/prizes/physics/1961/ceremony-speech/]:

> Professor Rudolf Mössbauer's investigations concern the emission and absorption of gamma radiation by the atomic nuclei. This radiation is of the same kind as the light and the radio waves. It is well known that incoming radio waves can be received only if the receiver is tuned to the same frequency as the sender. Resonance is then taking place. It has since long been tried to observe the corresponding phenomenon for nuclei, where it is called "resonance absorption". The method was to let gamma radiation from some kind of nuclei act upon other nuclei of exactly the same kind. There is however a certain difficulty connected with this experiment. The gamma radiation can be considered as made up of particles. When emitting a gamma particle the atom receives a recoil whereby the energy and therefore also the frequency of the gamma radiation is decreased. The same phenomenon occurs when the gamma particle is absorbed in the receiving nucleus. The resonance will be completely destroyed if the frequency change is not compensated for, as had been done already before Mössbauer's work. Mössbauer discovered experimentally and showed also theoretically that for atoms bound in a solid, an appreciable part of the radiation can be emitted without frequency change whereby the resonance absorption can be studied directly. This discovery was published by Mössbauer in 1958. Because of the very small width of the gamma lines the resonance is very sharp and can, as Mössbauer found, be influenced and finally inhibited by the Doppler effect if the source or the absorber for the gamma radiation is moved. The velocities required depend upon the sharpness of the gamma line and can be as small as some millimeters per hour.
>
> Mössbauer's discovery has been received with considerable interest. Research on the Mössbauer effect has been started at a great number of places. It has thereby been possible to verify in the laboratory, fundamental consequences of Einstein's theory of relativity. Other important applications depend on the separation and displacement of nuclear energy levels which occur in solids because of the influence of the surroundings. Many phenomena of this kind can in spite of their smallness be studied by the Mössbauer effect. It has been possible in this way to get most important information on the properties of solids.
>
> Mössbauer made his discovery when he investigated the resonance absorption on the suggestion of Professor Maier-Leibnitz in München. He found then some unexpected results which he investigated systematically and was thereby led to his discovery. [...]
>
> Professor Mössbauer. While doing research for your doctor's thesis you have discovered an unexpected effect which now bears your name. You have explained this effect experimentally and theoretically, and thereby created a device which is of fundamental importance in numerous realms of physics, and which is nowadays being investigated and put to use in a large number of physical laboratories. By your discovery it has become possible to examine precisely, numerous important phenomena formerly beyond or at the limit of attainable accuracy of measurement.

Heinz Maier-Leibnitz (1911–2000) **Rudolf Mössbauer (1929–2011)**



Zeitschrift für Physik, Bd. 151, S. 124—143 (1958)

Aus dem Institut für Physik im Max-Planck-Institut für medizinische Forschung, Heidelberg

Kernresonanzfluoreszenz von Gammastrahlung in Ir^{191}

Von

RUDOLF L. MÖSSBAUER *

Die Kernresonanzabsorption der dem Zerfall von Os^{191} folgenden 129 keV-Gammastrahlung in Ir^{191} wird untersucht. Der Wirkungsquerschnitt für die Resonanzabsorption wird als Funktion der Temperaturen von Quelle und Absorber im Temperaturbereich $90° \text{ K} < T < 370° \text{ K}$ gemessen. Die Lebenszeit τ_γ des 129 keV-Niveaus in Ir^{191} ergibt sich zu $(3{,}6^{+1{,}3}_{-0{,}8})\, 10^{-10}$ sec. Der Absorptionsquerschnitt zeigt bei tiefen Temperaturen einen starken Anstieg als Folge der Kristallbindung der Absorber- und Präparatsubstanzen. Die Theorie von LAMB über die Resonanzabsorption langsamer Neutronen in Kristallen wird auf die Kernresonanzabsorption von Gammastrahlung übertragen. Bei tiefen Temperaturen ergibt sich eine starke Abhängigkeit des Wirkungsquerschnittes für die Kernabsorption von der Frequenzverteilung im Schwingungsspektrum des Festkörpers.

Figure 8.10: Following the suggestions of Heinz Maier-Leibnitz, Rudolf Mössbauer developed recoilless nuclear resonance absorption, or Mössbauer spectroscopy.

8.3 Particle Accelerators and Ion Traps

Both particle accelerators and ion traps are important scientific tools for studying the fundamental physical properties of ions and other particles under different conditions:

> Particle accelerators (Section 8.3.1) are designed to increase the kinetic energy of particles as much as possible.
>
> Ion traps (Section 8.3.2) are intended to reduce the energy of particles as much as possible, in order to hold them relatively still for measurements.

8.3.1 Particle Accelerators

Although it is not widely known, German-speaking scientists invented particle accelerators in the 1920s and did an enormous amount of work before, during, and after World War II to develop them for various applications [Dippel 1992; Pancheri 2022; Sørheim 2020; Waloschek 2004, 2007, 2012; Burghard Weiss 1996].

Rolf Wideröe (Norwegian but studied and worked in Germany, 1902–1996) designed the first particle accelerators in 1923 and spent decades developing and building particle accelerators. See Fig. 8.11.

Max Steenbeck (German, 1904–1981, Fig. 8.12) began developing particle accelerators in 1927 and invented the first practical betatron (circular particle accelerator for electrons) in 1935.

Many other German-speaking scientists also developed and tested particle accelerators, including:

Manfred von Ardenne (German, 1907–1997)	H. Lange (German?, 19??–19??)
Otto Baier (German?, 19??–19??)	H. Salow (German?, 19??–19??)
Walther Bothe (German, 1891–1957)	Ernst Schiebold (German, 1894–1963)
Walter Dällenbach (Swiss, 1892–1990)	Heinz Schmellenmeier (German, 1909–1994)
K. Fink (German?, 19??–19??)	W. Schmitz (German?, 19??–19??)
Siegfried Flügge (German, 1912–1997)	Gerhard Schumann (German, 1911–19??)
Richard Gans (German, 1880–1954)	Bruno Touschek (Austrian, 1921–1978)
Rudolf Kollath (German, 1900–1978)	A. Weckesser (German?, 19??–19??)
Helmuth Kulenkampff (German, 1895–1971)	W. Wiebe (German?, 19??–19??)

In the German-speaking world, work on particle accelerators focused on at least four different but overlapping areas:

- Developing particle accelerator technology itself, including reaching higher and higher energies and numbers of particles in the beam.

- Using particle accelerators to answer fundamental questions in nuclear physics and other aspects of physics.

- Electronuclear breeding of weapons-grade fission fuel, and other applications relevant to developing nuclear weapons and nuclear reactors (see pp. 3988–4056, 4549–4555, and 5179–5180).

- Directed energy weapons (Section C.1). Many different versions of such weapons were under development during the war; they would have fired a beam of high-energy electrons and/or ions, or in some cases they would have harnessed the energy from those charged particles to produce an intense beam of X-rays, a burst of high-energy neutrons, or other forms of radiation. If some of the reports available in archives are correct, at least some of these weapons apparently reached the stage of successful tests against laboratory animals or solid targets.

In the 1930s, the U.S. physicists Ernest Lawrence and Donald Kerst discovered the early accelerator designs and writings of Rolf Wideröe and Max Steenbeck, copied them, and attained far greater fame than Wideröe and Steenbeck as the "inventors" of particle accelerators.

By the end of World War II, a number of advanced particle accelerators of various types had been built in the German-speaking world. The accelerators were seized and closely studied by different Allied countries after the war.

For more information on particle accelerators, see Section C.1 and pp. 3988–4056, 4549–4555, and 5179–5180. Much more archival research should be conducted to unearth new information on the development of particle accelerators in the German-speaking world, in order to determine exactly how far it progressed and how much it influenced programs in other countries.

Rolf Wideröe (1902–1996)
Particle accelerators (1923–)

Über ein neues Prinzip zur Herstellung hoher Spannungen[1].

Von

Rolf Wideröe, Berlin.

I. Einleitung.
II. Die Bewegungsgleichungen des Elektrons.
III. Kinetische Spannungstransformation mit Potentialfeldern.
 1. Das Prinzip.
 2. Theorie der resultierenden Spannungen.
 3. Die experimentelle Untersuchung.
 4. Einzelheiten der Versuchsanordnung.
 5. Aussichten des Verfahrens.
IV. Der Strahlentransformator.
 1. Das Prinzip.
 2. Die Grundgleichungen.
 3. Experimentelle Untersuchungen.
V. Zusammenfassung.

I. Einleitung.

Schwierigkeiten in der Beherrschung hoher Spannungen.

Bekanntlich liegen alle Schwierigkeiten bei der Herstellung hoher Spannungen in der Beherrschung der elektrostatischen Felder. Alle technischen Isoliermaterialien haben eine begrenzte Isolierfähigkeit, bei einer gewissen Feldstärke schlagen sie durch und werden leitend. Die Höhe der erzeugten Spannung wird deswegen hauptsächlich durch die stark zunehmenden Dimensionen der Isolierung begrenzt.

Es besteht nun aber die Möglichkeit, diese Grenze der erzeugten Spannungen wesentlich zu erhöhen, indem man elektrostatische Felder weitgehend vermeidet und die Hochtransformierung mit Hilfe schnellbewegten Elektronen und Ionen vornimmt.

Potentielle und kinetische Spannungen.

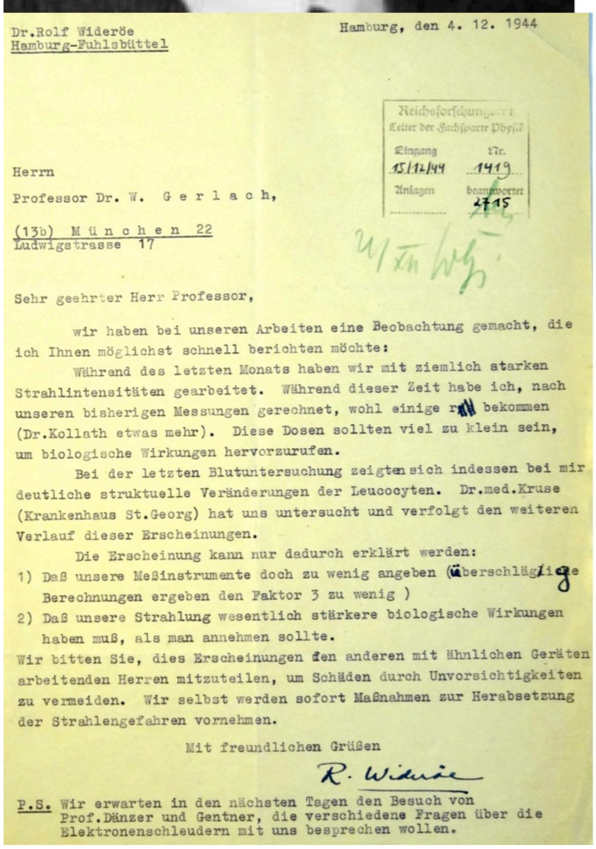
Wenn sich elektrische Ladungen durch ein elektrisches Feld bewegen, speichern sie einen Teil der Feldenergie als kinetische Energie auf. Für die kinetische Energie gilt das allgemeine Gesetz, daß sie immer mit der potentiellen Energie verknüpft ist, im Entstehen und im Verschwinden.

Entsprechend dieser Tatsache erscheint es deswegen auch zweckmäßig, von der Spannung einer bewegten Ladung zu reden. Die Ladung erhält dann (in Analogie zu den Energiebegriffen) diese kinetische Spannung, wenn sie durch eine entsprechende potentielle Spannung gefallen ist.

Zwei Wege der Spannungserzeugung.

Bei der Herstellung hoher potentieller Spannungen ist man hauptsächlich zwei Wege gegangen.

[1] Dissertation eingereicht am 29. 10. 1927 bei der Technischen Hochschule Aachen.



Dr.Rolf Wideröe
Hamburg-Fuhlsbüttel

Hamburg, den 4. 12. 1944

Reichsforschungsrat
Leiter der Fachsparte Physik
Eingang 15/12/44 Nr. 1419
Anlagen beantwortet 27/15

Herrn
Professor Dr. W. G e r l a c h,
(13b) M ü n c h e n 22
Ludwigstrasse 17

Sehr geehrter Herr Professor,

wir haben bei unseren Arbeiten eine Beobachtung gemacht, die ich Ihnen möglichst schnell berichten möchte:

Während des letzten Monats haben wir mit ziemlich starken Strahlintensitäten gearbeitet. Während dieser Zeit habe ich, nach unseren bisherigen Messungen gerechnet, wohl einige r bekommen (Dr.Kollath etwas mehr). Diese Dosen sollten viel zu klein sein, um biologische Wirkungen hervorzurufen.

Bei der letzten Blutuntersuchung zeigten sich indessen bei mir deutliche struktuelle Veränderungen der Leucocyten. Dr.med.Kruse (Krankenhaus St.Georg) hat uns untersucht und verfolgt den weiteren Verlauf dieser Erscheinungen.

Die Erscheinung kann nur dadurch erklärt werden:
1) Daß unsere Meßinstrumente doch zu wenig angeben (überschlägige Berechnungen ergeben den Faktor 3 zu wenig)
2) Daß unsere Strahlung wesentlich stärkere biologische Wirkungen haben muß, als man annehmen sollte.

Wir bitten Sie, dies Erscheinungen den anderen mit ähnlichen Geräten arbeitenden Herren mitzuteilen, um Schäden durch Unvorsichtigkeiten zu vermeiden. Wir selbst werden sofort Maßnahmen zur Herabsetzung der Strahlengefahren vornehmen.

Mit freundlichen Grüßen

R. Wideröe

P.S. Wir erwarten in den nächsten Tagen den Besuch von Prof.Dänzer und Gentner, die verschiedene Fragen über die Elektronenschleudern mit uns besprechen wollen.

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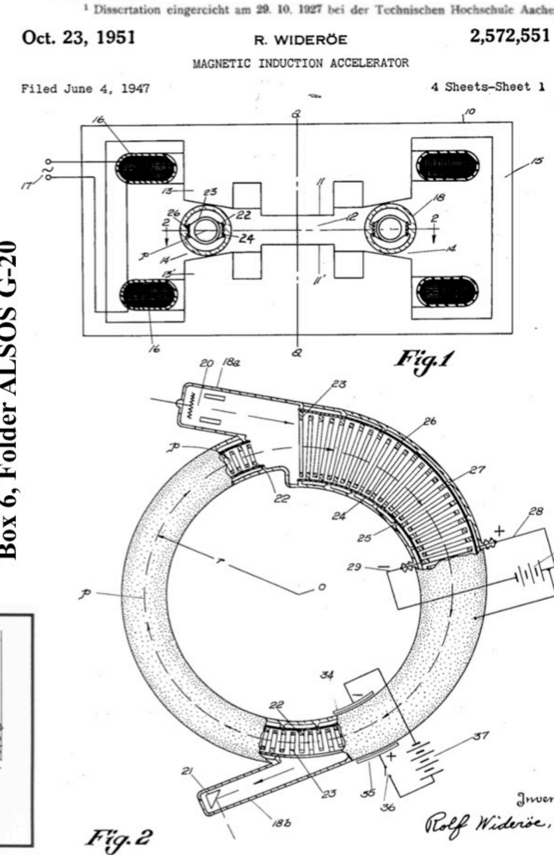


Figure 8.11: Rolf Wideröe designed the first particle accelerators in 1923 and spent decades developing and building particle accelerators.

Max Steenbeck (1904–1981) **Particle accelerators (1927 onward)**

DEUTSCHES REICH

AUSGEGEBEN AM
6. DEZEMBER 1940

REICHSPATENTAMT

PATENTSCHRIFT

№ 698867

KLASSE 21g GRUPPE 36

S 117417 VIII c/21 g

Siemens-Schuckertwerke Akt.-Ges. in Berlin-Siemensstadt*)

Vorrichtung zur Erzeugung von Elektronen hoher Energie durch das elektrische Wirbelfeld eines sich zeitlich ändernden magnetischen Hauptfeldes

Patentiert im Deutschen Reiche vom 7. März 1935 ab

Patenterteilung bekanntgemacht am 17. Oktober 1940

Der Erfindung liegt die Aufgabe zugrunde, mit möglichst einfachen technischen Mitteln, vor allen Dingen ohne Anwendung hoher Spannungen, Elektronenstrahlen hoher Energie, beispielsweise Strahlen mit einer Geschwindigkeit von mehreren Millionen Volt zu erzeugen.

Es ist vorgeschlagen worden, zu diesem Zweck ein magnetisches Wechselfeld zu verwenden, durch das ein elektrisches Wirbelfeld erzeugt wird, welches dem Elektron die notwendige Geschwindigkeit erteilt. Die Anordnung ist dabei so getroffen, daß die Elektronenbahn das magnetische Feld umschließt wie die Windungen der Sekundärwicklung eines Transformators den Transformatorkern und damit den diesen Kern durchsetzenden Fluß.

Bei einer bekannten Anordnung dieser Art umschließt ein ringförmiges hochevakuiertes Entladungsgefäß den Kern eines dreischenkligen Transformators, dessen mittlerer Kern eine an technische Wechselspannung üblicher Spannung und Frequenz angeschlossene Erregerwicklung trägt. In dem Entladungsgefäß ist eine Glühkathode angeordnet, welche die für die Strahlung notwendigen Elektronen aussendet. Außer dem Wechselfeld wirkt auf die Elektronen noch ein zusätzliches, von Dauermagneten erzeugtes Magnetfeld, welches dazu dienen soll, die um den Transformatorkern kreisenden Elektronen in einer bestimmten, durch das Entladungsgefäß gegebenen Ebene zu halten, d. h. zu verhindern, daß die Elektronen an irgendeiner Stelle auf die Gefäßwandung auftreffen.

Es ist auch schon vorgeschlagen worden, zur Beschleunigung und Führung der Elektronen bei einer Anordnung zur Herstellung von Röntgenstrahlen ein Magnetfeld zu verwenden, welches von der Mitte nach dem Rande hin abfällt. Dabei ist der Körper, der durch das Auftreffen schnell fliegender Elektronen zum Aussenden von Röntgenstrahlen angeregt werden soll, in der Mitte des Magnetfeldes angeordnet.

Diese bekannten bzw. vorgeschlagenen Anordnungen sind zwar im Prinzip brauchbar, doch geben sie entweder eine verhältnismäßig geringe Ausbeute an schnellen Elektronen, oder sie sind für den vorliegenden Zweck der Erzeugung sehr rascher Elektronen nicht besonders geeignet. Um praktisch wirklich brauchbare Ergebnisse zu erzielen, muß man

*) *Von dem Patentsucher ist als der Erfinder angegeben worden:*
Dr. phil. Max Steenbeck in Berlin-Siemensstadt.

Zu der Patentschrift 698 867
Kl. 21g Gr. 36

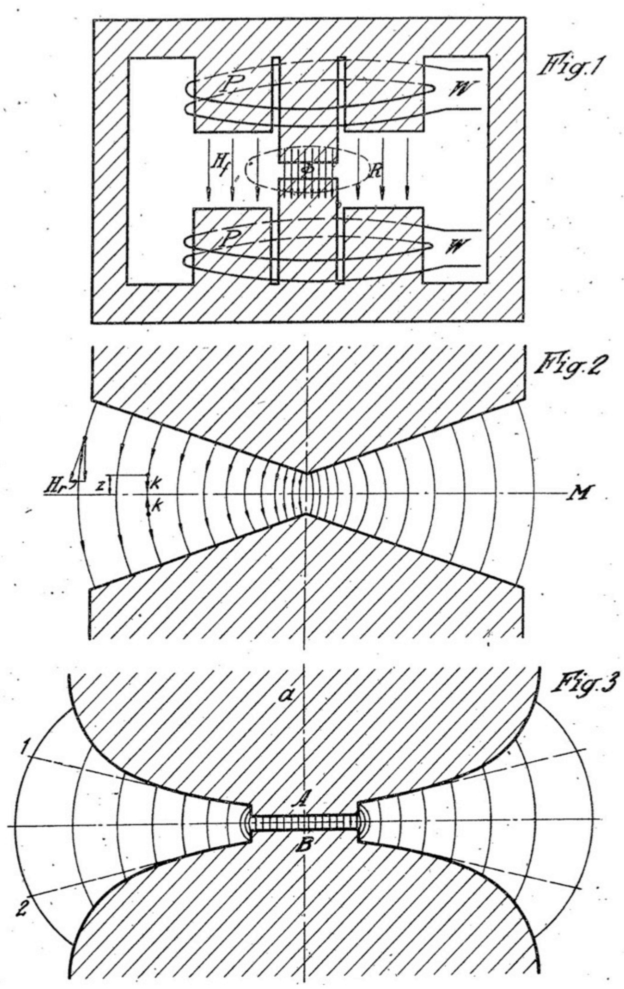
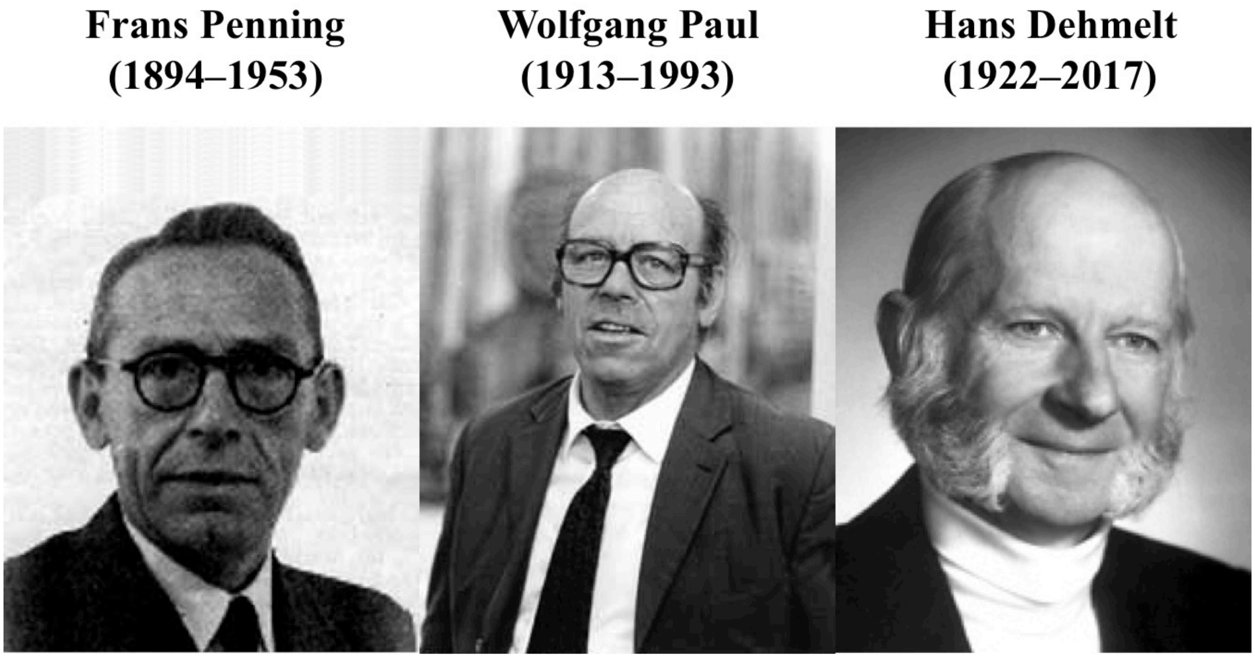


Figure 8.12: Max Steenbeck began developing particle accelerators in 1927 and invented the betatron for accelerating electrons.

8.3.2 Ion Traps

As shown in Fig. 8.13, Frans Penning (Dutch, 1894–1953), Wolfgang Paul (German, 1913–1993, not to be confused with the theoretical physicist Wolfgang Pauli), and Hans Dehmelt (German, 1922–2017) developed electromagnetic mass spectrometers and electromagnetic ion traps (Penning traps) to confine small numbers of ions of different elements for direct measurements. For that work, Paul and Dehmelt won the Nobel Prize in Physics in 1989. Professor Ingvar Lindgren of the Royal Swedish Academy of Sciences explained the importance of their innovations [https://www.nobelprize.org/prizes/physics/1989/ceremony-speech/]:

> An atom has certain fixed energy levels, and transition between these levels can take place by means of emission or absorption of electromagnetic radiation, such as light. Transition between closely spaced levels can be induced by means of radio-frequency radiation, and this forms the basis for so-called resonance methods. The first method of this kind was introduced by Professor I. Rabi in 1937, and the same basic idea underlies the resonance methods developed later, such as nuclear magnetic resonance (NMR), electron-spin resonance (ESR) and optical pumping. [...]
>
> The dream of the spectroscopist is to be able to study a single atom or ion under constant conditions for a long period of time. In recent years, this dream has to a large extent been realized. The basic tool is here the ion trap, which was introduced in the 1950s by another of this year's laureates, Wolfgang Paul in Bonn. His technique was further refined by the third laureate, Hans Dehmelt, and his co-workers in Seattle into what is now known as ion-trap spectroscopy.
>
> Dehmelt and his associates used this spectroscopy primarily for studying electrons, and in 1973 they succeeded for the first time in observing a single electron in an ion trap, and in confining it there for weeks and months. One property of the electron, its magnetic moment, was measured to 12 digits, 11 of which have later been verified theoretically. This represents a most stringent test of the atomic theory known as quantum electrodynamics (QED).
>
> In a similar way, Dehmelt and others were later able to trap and study a single ion, which represents a true landmark in the history of spectroscopy. The technique is now being used in development of improved atomic clocks, in particular at the National Institute for Standards and Technology (formerly the National Bureau of Standards) in Boulder, Colorado.



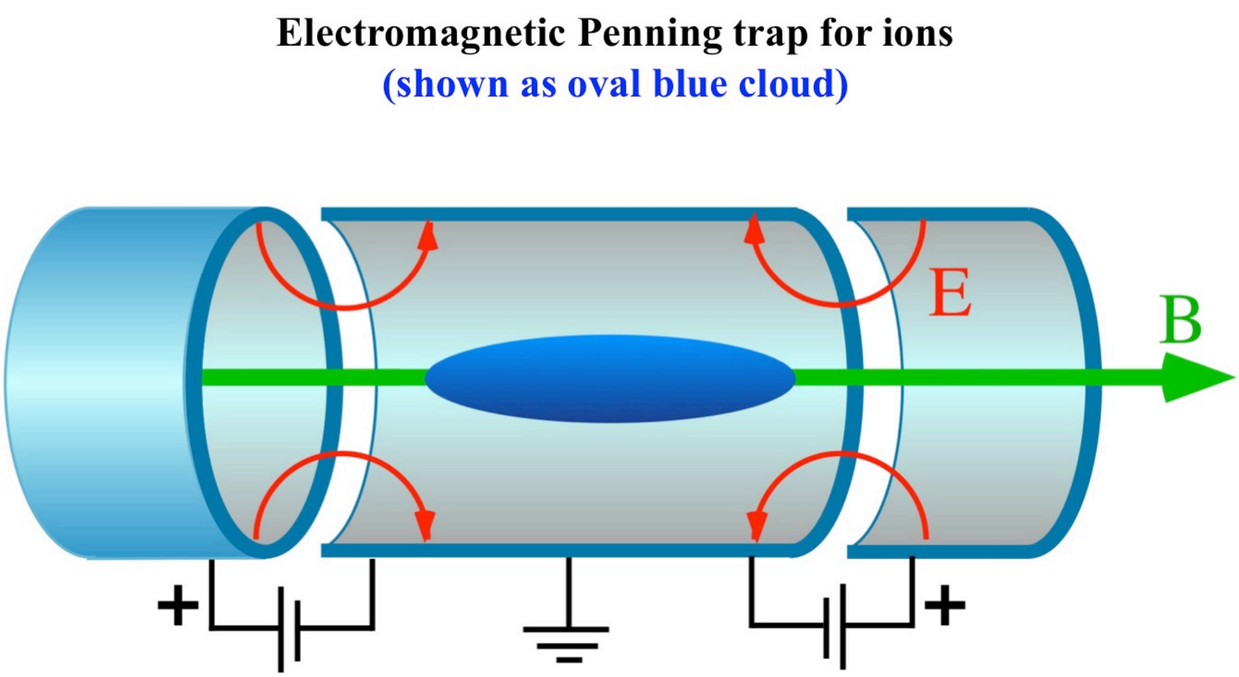


Figure 8.13: Frans Penning, Wolfgang Paul, and Hans Dehmelt developed electromagnetic mass spectrometers and electromagnetic ion traps.

8.4 Models of the Atomic Nucleus

Scientists from the German-speaking world discovered all three of the building blocks of atoms: electrons, protons, and neutrons (Section 5.2.3).

German-speaking scientists were also directly responsible for developing detailed mathematical models of the behavior of the protons and neutrons in the atomic nucleus. These models are necessary for predicting various types of radioactive decays and nuclear reactions [Karen Johnson 2004; Shaviv 2012]. See Figs. 8.14–8.17.

For simplicity, these nuclear models may be divided into two broad categories:

> The liquid drop model (Section 8.4.1) essentially treats the nucleus like a continuous drop of liquid rather than a collection of individual particles, although it does incorporate quantum corrections for interactions between the individual particles.
>
> The shell model (Section 8.4.2) refines the liquid drop model by also considering the different energy levels or shells that particles within the nucleus can occupy, and the maximum allowable numbers of particles per shell.

8.4.1 Liquid Drop Model

Serious study of the internal structure of the nucleus arguably began in 1913, when Kasimir Fajans (Polish, 1887–1975) first worked out the radioactive displacement law of how alpha and beta radioactive decay transform one element into another.

In 1935, Carl Friedrich von Weizsäcker (German, 1912–2007) published a remarkably comprehensive and detailed mathematical model of the structure and energy levels of the nucleus (Figs. 8.16–8.17). It is still widely used today to accurately predict nuclear decays and reactions, and is known as the von Weizsäcker semi-empirical mass formula. Hans Bethe (German, 1906–2005) modified and utilized von Weizsäcker's formula in his own research. George Stetter (Austrian, 1895–1988) also conducted very early and very meticulous comparisons of theoretical and experimental results of nuclear energy levels and masses (Fig. 8.16).

George Gamow (Russian but educated and worked in Germany, lived 1904–1968) applied quantum physics to nuclear models in order to explain the rates of alpha decay [Gamow 1932].

Victor Weisskopf (Austrian, 1908–2002) and John (Johann) M. Blatt (Austrian, 1921–1990) produced what was at the time (and arguably remains, apart from coverage of the shell model) the most comprehensive theoretical compilation of information on nuclear structure [Blatt and Weisskopf 1952].

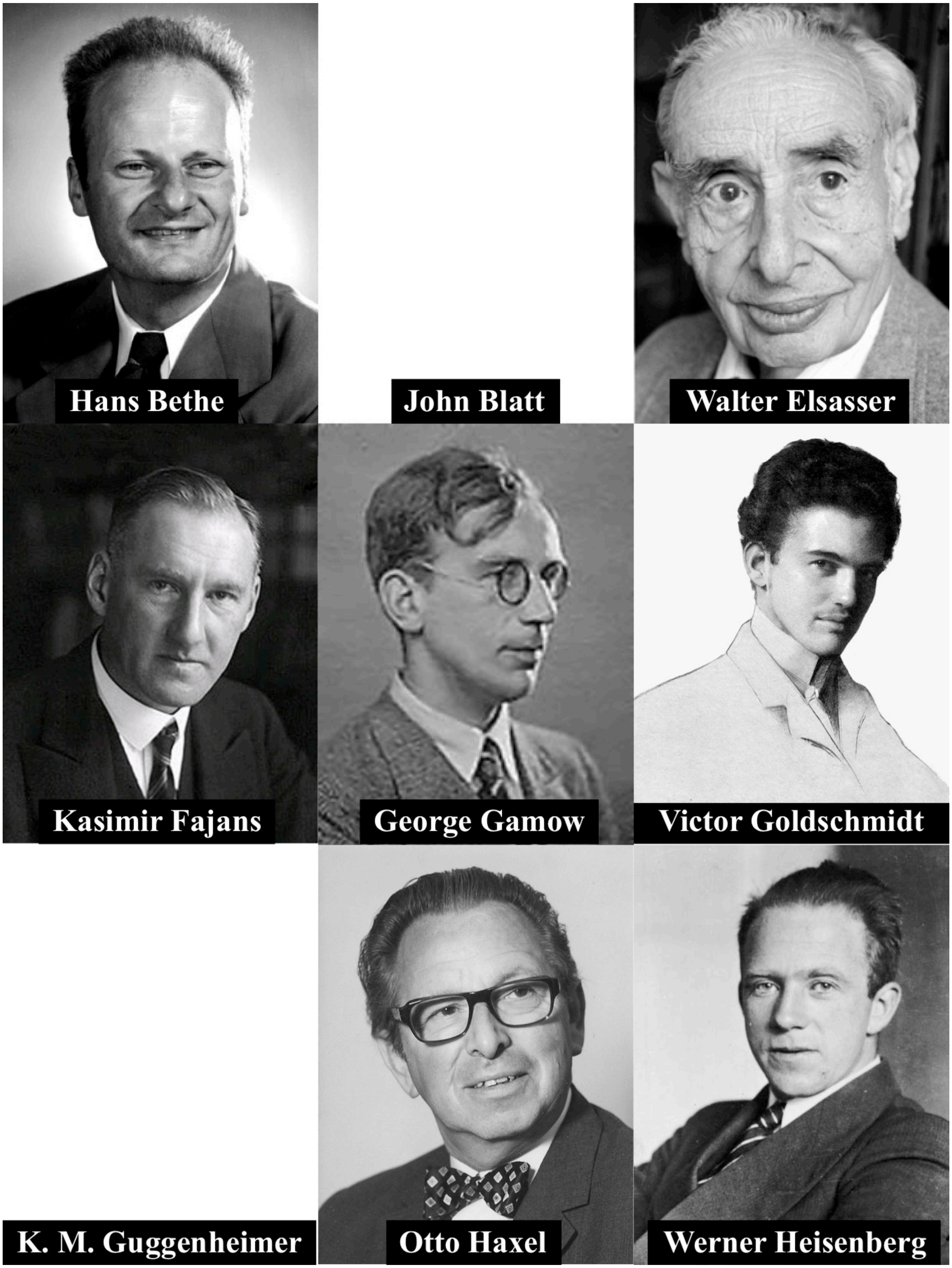


Figure 8.14: Mathematical models of nuclear structure and decays were developed or improved by Hans Bethe, John (Johann) Blatt, Walter Elsasser, Kasimir Fajans, George Gamow, Victor Goldschmidt, K. M. Guggenheimer, Otto Haxel, and Werner Heisenberg.

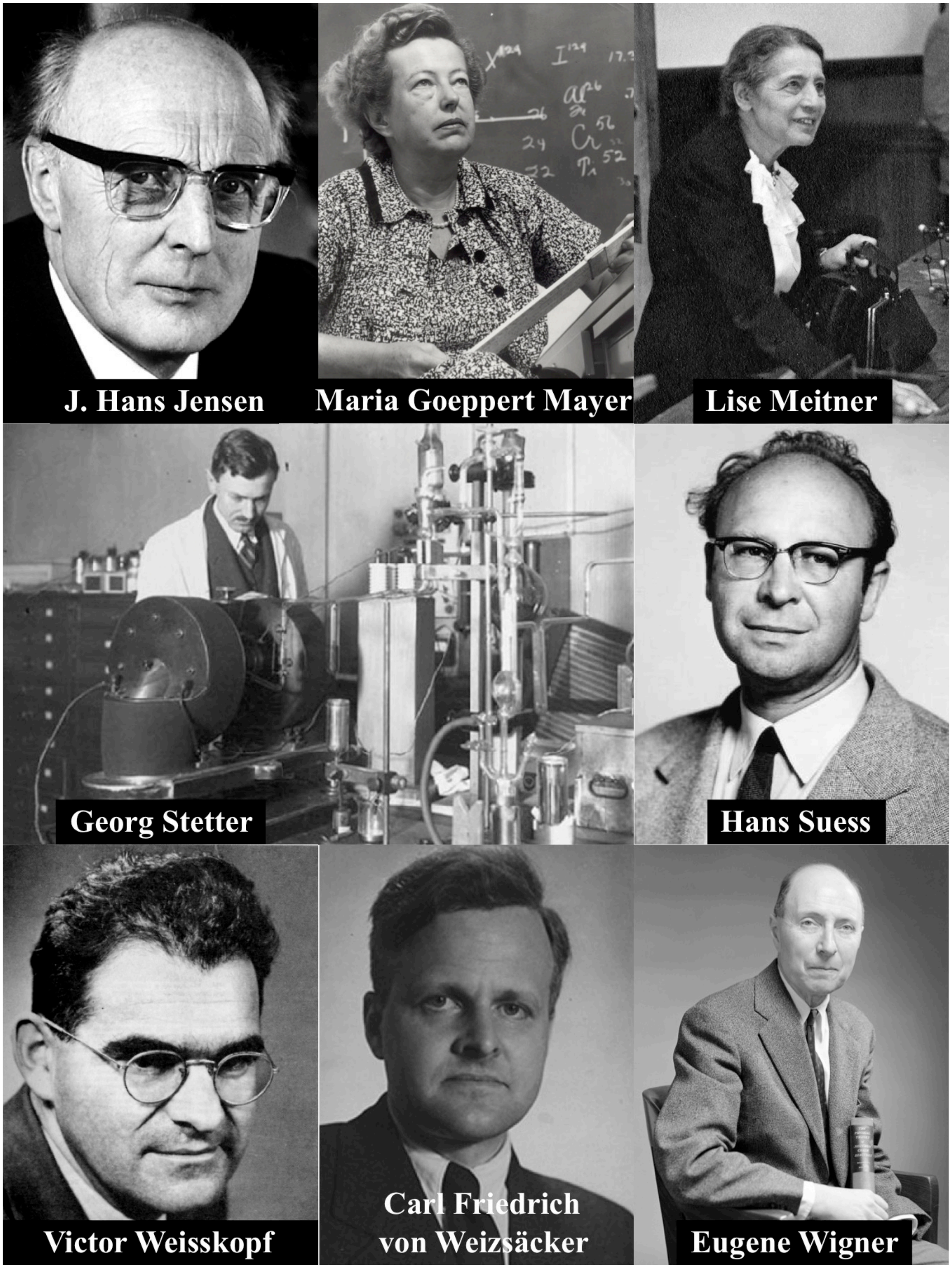


Figure 8.15: Mathematical models of nuclear structure and decays were also developed or improved by Johannes Hans Jensen, Maria Goeppert Mayer, Lise Meitner, Georg Stetter, Hans Suess, Victor Weisskopf, Carl Friedrich von Weizsäcker, and Eugene Wigner.

Die Massenbestimmung von Atomtrümmern aus Aluminium, Kohlenstoff, Bor und Eisen.

Von **Georg Stetter** in Wien.

Mit 6 Abbildungen. (Eingegangen am 22. März 1927.)

Mit dem früher beschriebenen Massenspektroskop für schnelle und seltene Korpuskularstrahlen werden nach entsprechender Weiterbildung der Methodik Spektralkurven der Sekundärteilchen aus den Elementen Al, C, B und Fe aufgenommen und außer α^{++}- und α^{+}-Teilchen in allen vier Fällen H-Teilchen (Fehlergrenze 5%) einwandfrei festgestellt; somit auch die Zertrümmerbarkeit dieser vier Atomkerne endgültig bewiesen. Die über Zahl und Reichweite der Atomtrümmer sich ergebenden Daten stimmen mit früher in Wien gefundenen Resultaten im großen und ganzen überein.

Einleitung. Vor etwa $1^1/_2$ Jahren habe ich in dieser Zeitschrift[1]) einen Apparat zur Massenbestimmung schneller und seltener Korpuskularstrahlen beschrieben, wobei hauptsächlich an die e/m-Bestimmung der bei der Atomzertrümmerung beobachteten „H^a-Partikeln gedacht war. In derselben Arbeit konnte ich noch über erfolgreiche Messungen an α-Strahlen aus Polonium sowie an natürlichen H-Strahlen (aus Paraffin) berichten, später auch an α-Strahlen anderer Herkunft[2]). Anfang 1926 gelangen die ersten einwandfreien Versuche an Atomtrümmern aus Aluminium, die zusammen mit einer Diskussion der zahlenmäßigen Beziehungen im Massenspektroskop an anderer Stelle veröffentlicht sind[3]). Gelegentlich von noch nicht abgeschlossenen Untersuchungen an Actinium, die gemeinsam mit Frl. E. Rona unternommen wurden, trat infolge Platzens einer sehr dünnwandigen Kapillare eine starke radioaktive Verseuchung des Apparates auf, die trotz gründlichster Reinigung nicht völlig beseitigt werden konnte und diesen auf längere Zeit unbrauchbar machte. Er mußte fast zur Gänze neu gebaut werden, um die Versuche mit Atomtrümmern, bei denen wegen der minimalen Ausbeute auch eine schwache Verseuchung einen Erfolg unmöglich macht, fortsetzen zu können.

Für die weitere Arbeit war zunächst beabsichtigt, womöglich andere Nachweismethoden zu verwenden, von denen die von G. Ortner und dem

[1]) ZS. f. Phys. **34**, 158, 1925.
[2]) Phys. ZS. **27**, 735, 1926 (Vortrag, geh. a. d. Düsseldorfer Naturf.-Vers.); Verh. d. D. Phys. Ges. **7**, 34, 1926.
[3]) Mitt. a. d. Inst. f. Radiumforschung Nr. 181. Wien. Ber. **135** [2a], 1926; Ark. f. Mat., Astr. och Fys. **19** B, Nr. 10, 1926.

Zur Theorie der Kernmassen.

Von **C. F. v. Weizsäcker** in Leipzig.

Mit 5 Abbildungen. (Eingegangen am 6. Juli 1935.)

§ 1. Problemstellung. § 2. Erweiterung der Thomas-Fermi-Methode. § 3. Numerische Auswertung (gemeinsam mit F. S. Wang). § 4. Die Auszeichnung gerader Teilchenzahlen. § 5. Halbempirische Darstellung der Massendefekte. § 6. Zusammenfassung.

§ 1. Problemstellung.

Es ist heute sehr wahrscheinlich geworden, daß Protonen und Neutronen die einzigen elementaren Bausteine der Kerne sind. Da die Ruhenergien dieser Teilchen groß sind gegen die Bindungsenergien der Kerne, sollte man ihre Bewegung im Kern in erster Näherung nach der unrelativistischen Quantenmechanik beschreiben können[1]). Wenn die Kräfte zwischen den Elementarteilchen bekannt wären, müßte es also im Prinzip möglich sein, die Bindungsenergien, d. h. die Massendefekte aller Atomkerne zu berechnen. Da die Versuche, diese Kräfte direkt theoretisch zu bestimmen[2]), noch nicht zu eindeutigen Ergebnissen geführt haben, sind wir vorläufig auf den umgekehrten Weg angewiesen: auf die Ableitung der Kernkräfte aus den empirisch bekannten Massendefekten.

Die Massendefekte der leichtesten Kerne sind heute aus den Energiebilanzen von Zertrümmerungsprozessen sehr genau bekannt[3]). Mit etwas geringerer Genauigkeit umfassen die massenspektroskopischen Messungen von Aston und Bainbridge[4]) Elemente aus dem ganzen periodischen System. Ergänzt werden diese Angaben durch die oberen Schranken für die Bindungsenergien[5]), die sich aus dem Zerfall oder der Nichtexistenz gewisser Kerne gewinnen lassen: z. B. muß das radioaktive Isotop N_7^{13} jedenfalls eine geringere Bindungsenergie haben als C_6^{13}, da es spontan in diesen Kern zerfällt. Das Erfahrungsmaterial zeigt im wesentlichen die folgenden Gesetzmäßigkeiten:

[1]) W. Heisenberg, ZS. f. Phys. **77**, 1, 1932 (I); **78**, 156, 1932 (II); **80**, 587, 1933 (III); Rapport du VII[me] Congrès Solvay, Paris 1934, S. 289 (Solvay-Bericht); Zeeman-Festschrift, Haag 1935, S. 108. — [2]) I. Tamm, D. Ivanenko, Nature **133**, 981, 1934; W. Heisenberg, Zeeman-Festschrift. — [3]) M. L. E. Oliphant, A. R. Kempton u. Lord Rutherford, Proc. Roy. Soc. London (A) **149**, 406, 1935; H. Bethe, Phys. Rev. **47**, 640, 1935. — [4]) Quantitative Daten bei F. W. Aston, Mass Spectra and Isotopes. London 1933; vgl. auch Nature **135**, 541, 1935. — [5]) Unter Bindungsenergie ist im folgenden stets eine positive Größe verstanden. Größerer Bindungsenergie entspricht also geringerer Energieinhalt, tiefere Lage des Grundterms.

Zeitschrift für Physik. Bd. 96. 90

ELEMENTARY THEORY OF NUCLEAR SHELL STRUCTURE

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New York · JOHN WILEY & SONS, Inc.
London · CHAPMAN & HALL, Ltd.
1955

THEORETICAL NUCLEAR PHYSICS

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Figure 8.16: Just a few examples of seminal works on nuclear models by German-speaking scientists.

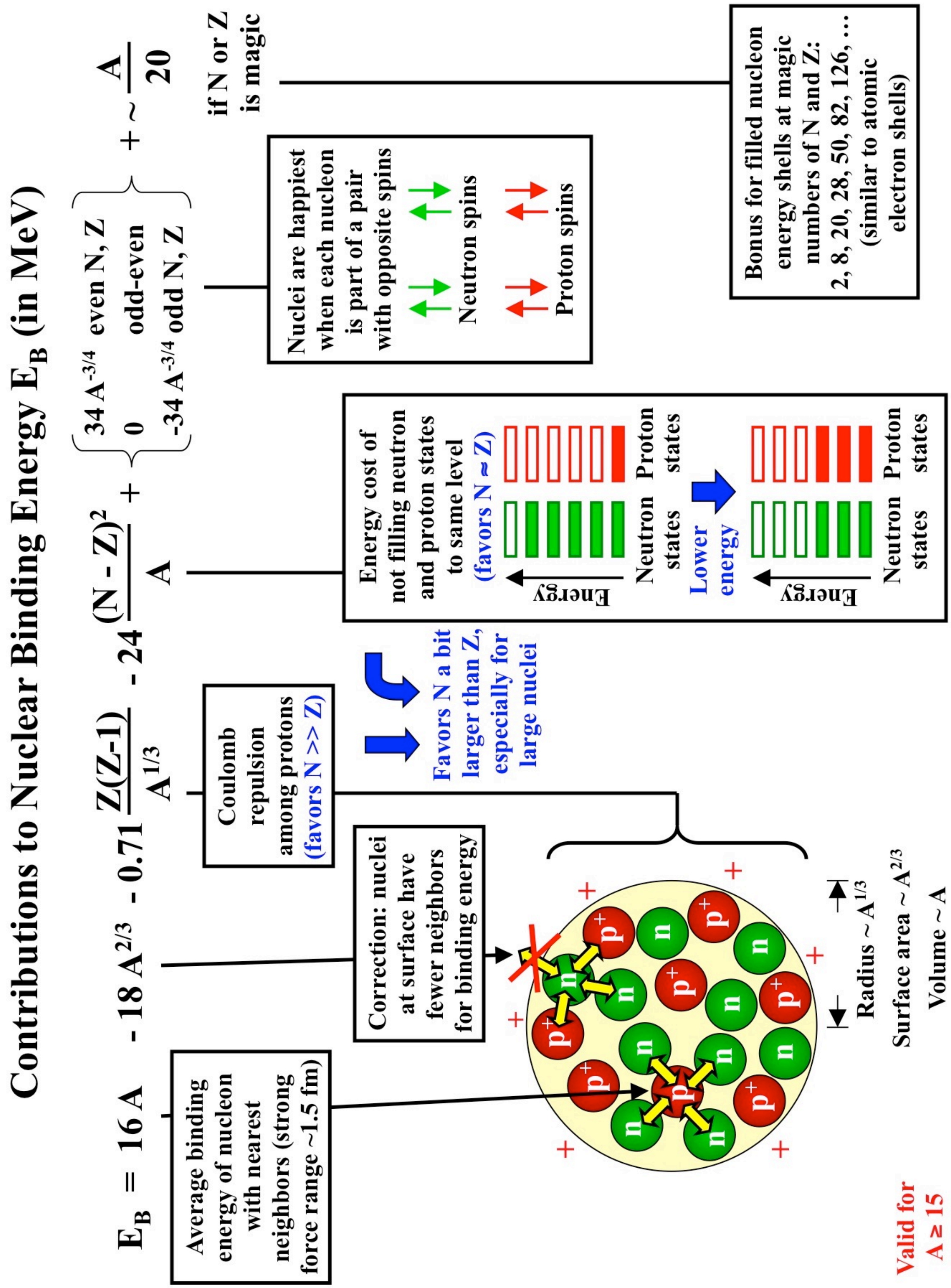


Figure 8.17: Nuclear binding energies in millions of electron-volts (MeV) as given by the von Weizsäcker semi-empirical mass formula with shell model corrections, for nuclei with Z protons, N neutrons, and $A = Z + N$ nucleons.

8.4.2 Shell Model

The most puzzling detail of nuclear models was working out the shell model of the "magic numbers" of protons and neutrons that are required to fill different energy levels or shells within the nucleus. Victor Goldschmidt (Swiss, 1888–1947), Walter Elsasser (German, 1904–1991), and Kurt M. Guggenheimer (German, 19??–19??) made very insightful proposals in the 1930s that partially explained the shell model's magic numbers. (Elsasser was a brilliant polymath who, among other insights, also developed the dynamo model that explains how the Earth's magnetic field is generated by the Earth's core—see p. 746 [Rubin 1995].) The final details of the shell model were worked out in the 1940s by Otto Haxel (German, 1909–1998), Johannes Hans Jensen (German, 1907–1973), Maria Goeppert Mayer (German, 1906–1972), Hans Suess (Austrian, 1909–1993), and Eugene Wigner (Hungarian, 1902–1995).

Johannes Hans Jensen, Maria Goeppert Mayer, and Eugene Wigner won the 1963 Nobel Prize in Physics for their contributions to nuclear models. Professor I. Waller of the Nobel Committee for Physics gave an overview of their contributions, as well as those of Walter Elsasser, Otto Haxel, and Hans Suess [https://www.nobelprize.org/prizes/physics/1963/ceremony-speech/]:

> In order to be able to calculate the motion of the nucleons it was, however, necessary to know also the forces which act between them. A very important step in the investigation of these forces was taken by Wigner in 1933 when he found, deducing from some experiments, that the force between two nucleons is very weak except when their distance apart is very small but that the force is then a million times stronger than the electric forces between the electrons in the outer part of the atoms. Wigner discovered later other important properties of the nuclear forces.
>
> Notwithstanding the efforts of many physicists our knowledge of the nuclear forces is yet rather incomplete. It was therefore fundamentally important that Wigner could show that most essential properties of the nuclei follow from generally valid symmetries of the laws of motion. Earlier Wigner had performed pioneering work by studying such symmetries in the laws of motion for the electrons and had made important discoveries by investigating e.g. those symmetries which express the fact that the laws mentioned make no difference between left and right and that backward in time according to them is equivalent to forward in time. These investigations were extended by Wigner to the atomic nuclei at the end of the 1930's and he explored then also the newly discovered symmetry property of the force between two nucleons to be the same whether either of the nucleons is a proton or a neutron. This work by Wigner and his other investigations of the symmetry principles in physics are important far beyond nuclear physics proper. His methods and results have become an indispensable guide for the interpretation of the rich and complicated picture which has emerged from recent years' experimental research on elementary particles. [...]
>
> Wigner has made many other important contributions to nuclear physics. He has given a general theory of nuclear reactions and has made decisive contributions to the practical use of nuclear energy. He has, often in collaboration with younger scientists, broken new paths in many other domains of physics.

It was found during the 1920's and in particular during the 1930's that the protons and the neutrons each form particularly stable systems in an atomic nucleus when the numbers of either kind of nucleons is one of the so-called magic numbers 2, 8, 20, 28, 50, 82 and 126. Several physicists, in particular Elsasser, tried to interpret the magic numbers in analogy to Niels Bohr's successful explanation of the periodic system of the elements. It was then assumed that the nucleons move in orbits in a common field of force and that these orbits are arranged in so-called shells which are energetically well separated. The magic numbers should correspond to complete shells. This interpretation was successful for light nuclei. It was, however, not possible to explain more than the three first magic numbers and for many years another model dominated.

A paper published by Goeppert Mayer in 1948 marked the beginning of a new era in the appreciation of the shell model. For the first time convincing evidence was there given for the existence of the higher magic numbers and it was stressed that the experiments support the existence of closed shells very strongly.

Somewhat later Goeppert Mayer and independently Haxel, Jensen and Suess published the new idea, which was needed for the explanation of the higher magic numbers. The idea was that a nucleon should have different energies when it "spins" in the same or opposite sense as it revolves around the nucleus.

Goeppert Mayer and Jensen collaborated later on the development of the shell model. They published together a book, where they applied the model to the extensive experimental material on atomic nuclei. They gave convincing evidence for the great importance of the shell model in systematizing this material and predicting new phenomena concerning the ground state and the low excited states of the nuclei. The general methods introduced by Wigner have been most important for the applications of the shell model. It has also been possible to give a deeper justification of the shell model. Its fundamental importance has thereby been further confirmed.

8.5 Nuclear Fission Reactions

Fission is the separation of a large (parent) nucleus into two smaller nuclei, and it can be either spontaneous (essentially a form of radioactive decay) or induced by neutron absorption. In addition to the two smaller nuclei, fission also generally produces a few loose neutrons and a large amount of energy. If the loose neutrons from one fission reaction are absorbed by other nuclei and cause them to fission as well, leading to the release of still more fission-inducing neutrons, a chain reaction can occur. Because a chain reaction can cause many nuclei to undergo fission and release their energy within a short period of time, it can be used to create everything from controlled fission power reactors to uncontrolled fission explosives.

In 1934, fission reactions were first theoretically predicted by Ida Tacke Noddack (German, 1896–1978), who together with her husband Walter Noddack (German, 1893–1960) had previously discovered the elements rhenium and technetium (p. 442). See Figs. 8.18–8.19. In the following quote from her often-overlooked but astonishing paper, Ida Noddack correctly predicted both neutron-induced fission of uranium and neutron capture/beta decay in uranium to produce element 93 (later named neptunium), which would beta decay to element 94 (later named plutonium) that could be easily chemically separated from the remaining parent uranium [Noddack 1934]:

> Man kann ebensogut annehmen, daß bei dieser neuartigen Kernzertrümmerung durch Neutronen erheblich andere “Kernreaktionen” stattfinden, als man sie bisher bei der Einwirkung von Protonen- und α-Strahlen auf Atomkerne beobachtet hat. Bei den letztgenannten Bestrahlungen findet man nur Kernumwandlungen unter Abgabe von Elektronen, Protonen und Heliumkernen, wodurch sich bei schweren Elementen die Masse der bestrahlten Atomkerne nur wenig ändert, da nahe benachbarte Elemente entstehen. Es wäre denkbar, daß bei der Beschießung schwerer Kerne mit Neutronen diese Kerne in mehrere größere Bruchstücke zerfallen, die zwar Isotope bekannter Elemente, aber nicht Nachbarn der bestrahlten Elemente sind.
>
> [...] aus dem β-strahlenden Element 93 das Element 94 entstehen müßte. Dieses Element sollte man verhältnismäßig leicht chemisch von 93 trennen können.

> One could assume equally well that when neutrons are used to produce nuclear disintegrations, some distinctly new nuclear reactions take place which have not been observed previously with proton or alpha-particle bombardment of atomic nuclei. In the past one has found that transmutations of nuclei only take place with the emission of electrons, protons, or helium nuclei, so that the heavy elements change their mass only a small amount to produce near neighboring elements. When heavy nuclei are bombarded by neutrons, it is conceivable that the nucleus breaks up into several large fragments, which would of course be isotopes of known elements but would not be neighbors of the irradiated element.
>
> [...] Beta decay of element 93 must produce element 94. It should be relatively easy to separate this element chemically from element 93.

At the Kaiser Wilhelm Institute for Chemistry in Berlin-Dahlem, Otto Hahn (German, 1879–1968) and Fritz Strassmann (German, 1902–1980) experimentally demonstrated neutron-induced fission of uranium into lighter elements in 1938 (Fig. 8.19), and published their results in January 1939 [Hahn and Strassmann 1939]:

> [...] Bei der energetisch nicht leicht zu verstehenden Bildung von Radiumisotopen aus Uran beim Beschießen mit langsamen Neutronen war eine besonders gründliche Bestimmung des chemischen Charakters der neu entstehenden künstlichen Radioelemente unerläßlich. Durch die Abtrennung einzelner analytischer Gruppen von Elementen aus der Lösung des bestrahlten Urans wurde außer der großen Gruppe der Transurane eine Aktivität stets bei den Erdalkalien (Trägersubstanz Ba), den seltenen Erden (Trägersubstanz La) und bei Elementen der vierten Gruppe des Periodischen Systems (Trägersubstanz Zr) gefunden. Eingehender untersucht wurden zunächst die Bariumfällungen, die offensichtlich die Anfangsglieder der beobachteten isomeren Reihen enthielten. Es soll gezeigt werden, daß Transurane, Uran, Protactinium, Thorium und Actinium sich stets leicht und vollständig von der mit Barium ausfallenden Aktivität trennen lassen. [...]

> [...] Since it is not easy to understand from energy considerations how radium isotopes can be produced when uranium is bombarded with slow neutrons, a very careful determination of the chemical properties of the new artificially made radioelements was necessary. Various analytic groups of elements were separated from a solution containing the irradiated uranium. Besides the large group of transuranic elements, some radioactivity was always found in the alkaline-earth group (barium carrier), the rare-earth group (lanthanum carrier), and also with elements in group IV of the periodic table (zirconium carrier). The barium precipitate was the first to be investigated more thoroughly, since it apparently contains the parent isotopes of the observed isomeric series. The goal was to show that the transuranic elements, and also uranium, protactinium, thorium, and actinium could always be separated easily and completely from the activity which precipitates with barium. [...]

The fission reaction results of Hahn and Strassmann were further analyzed in 1939 by Lise Meitner (Austrian, 1878–1968, Fig. 8.19) and her nephew Otto Frisch (Austrian, 1904–1979, photo on p. 1565). The news of fission reactions provoked strong scientific and political responses around the world, immediately launched major nuclear programs in Germany, the United States, and the United Kingdom, aroused interest that eventually gave rise to serious nuclear programs in many other countries, and of course made possible everything from fission reactors to fission bombs.

For his research on fission, Otto Hahn won the 1944 Nobel Prize in Chemistry, which was delayed by the war as well as his postwar internment at Farm Hall in the United Kingdom (p. 3354). In awarding the Prize, Professor A. Westgren of the Nobel Committee in Chemistry noted [https://www.nobelprize.org/prizes/chemistry/1944/ceremony-speech/]:

> In collaboration with Lise Meitner, with whom he has worked for nearly thirty years, Hahn studied from 1936 to 1938 the products obtained by projecting neutrons on to the heaviest elements, thorium and uranium. [...] But towards the end of 1938, Hahn, in an investigation carried out with one of his young colleagues, F. Strassmann, found that one of the products formed through the reaction of uranium with neutrons and which had been assumed to be a kind of radium, behaved chemically in fact like barium. In

> January 1939 Hahn announced this discovery and expressed in very discreet terms the daring opinion that on being allied with neutrons, the atoms of the heaviest elements could split in half as it were and produce elements belonging to the middle of the Periodic Table of the elements. [...]
>
> Hahn's discovery caused great surprise and evoked lively interest among the world's scientists. It was immediately made the object of important theoretical investigations by Lise Meitner and Frisch, who based their study on the theory of the structure of atomic nuclei developed by Bohr. [...]
>
> Without equal in the art of the chemical identification of radioactive elements in minute quantities, Hahn, together with his colleagues, paved the way for the chemical research which had to be carried out on the numerous products of the splitting of heavy atomic nuclei. [...]
>
> The discovery of nuclear fission is very momentous and indeed dangerous, but even more, it is full of promise. [...]
>
> Hahn's work has been inspired throughout by an invincible desire to solve the problems which he has encountered.

For much more information on the history of nuclear fission research in the German-speaking world, see Appendix D.

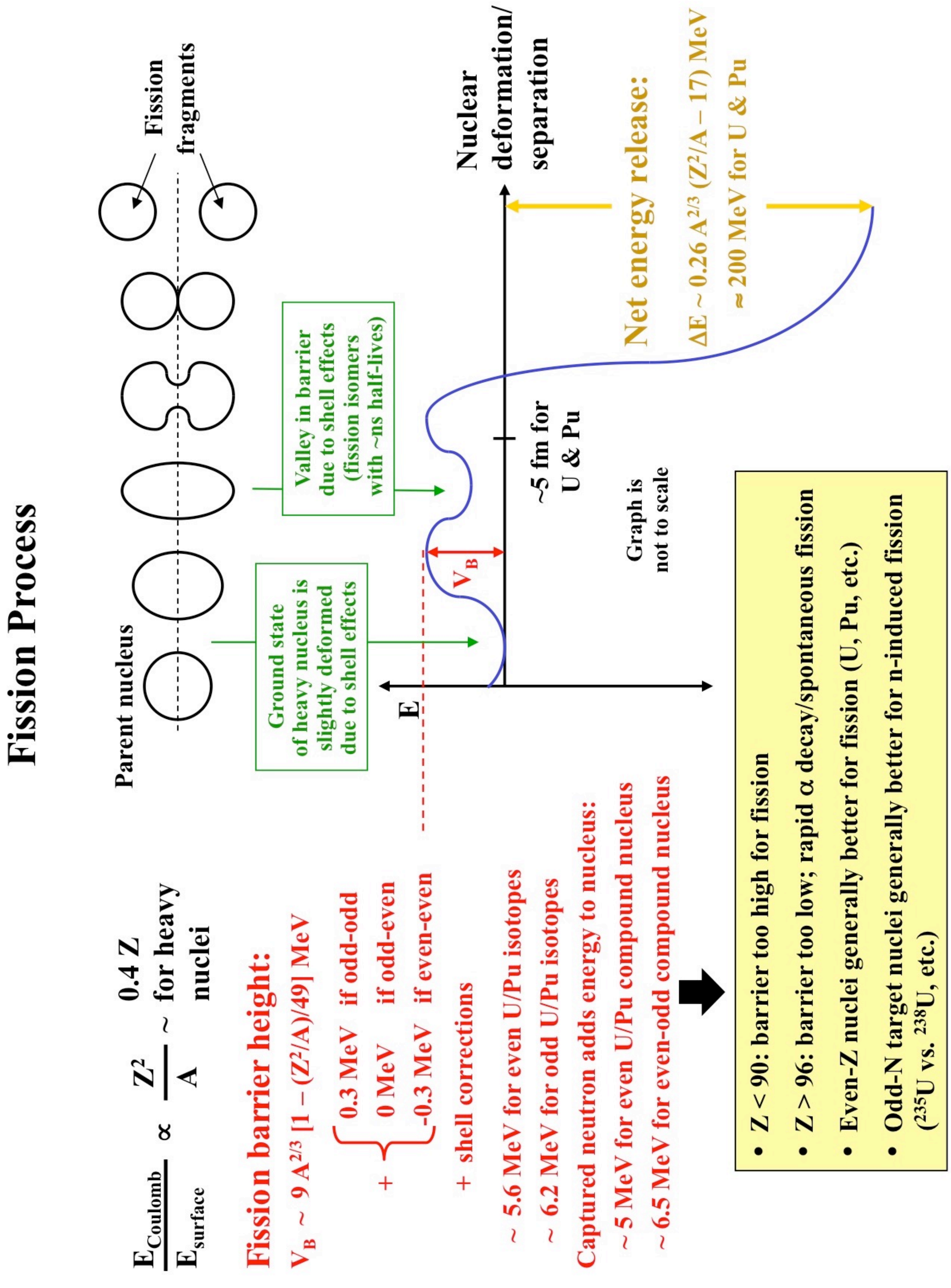


Figure 8.18: The fission reaction rate depends on the potential energy peak or fission barrier that one nucleus must pass through in order to become two separate nuclei. The parent nucleus undergoing fission has Z protons, N neutrons, and $A = Z + N$ nucleons.

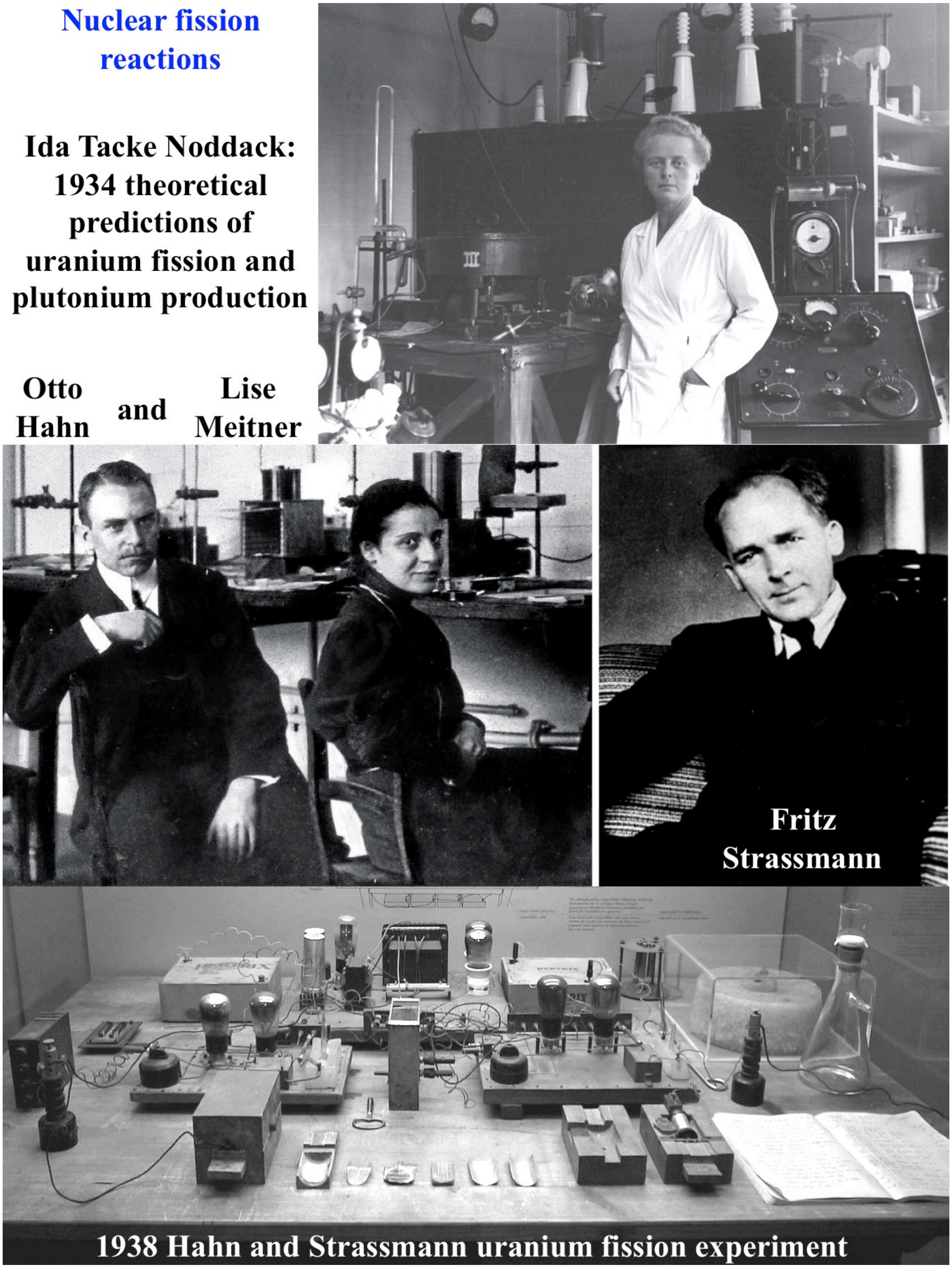


Figure 8.19: In 1934, Ida Tacke Noddack accurately predicted both the neutron-induced fission of uranium and the production of a new fissile element 94 (later named plutonium) via neutron capture in uranium. Otto Hahn and Fritz Strassmann demonstrated uranium fission reactions in their 1938 experiment, and then Lise Meitner and her nephew Otto Frisch provided further theoretical analysis.

8.6 Nuclear Fusion Reactions

In fusion, two small nuclei join together to form a larger nucleus, generally releasing a large amount of energy in the process. Forcing small nuclei together even though they are positively charged and repel each other typically requires enormous thermal energies (temperatures) and pressures. If fusion fuel is so dense and so well confined that the energy released by one fusion reaction is trapped within the fuel and triggers additional fusion reactions, a chain reaction of fusion reactions can occur (analogous to the chain reaction of fission reactions). Stars and hydrogen bombs are both sufficiently large and dense to trap the fusion energy and sustain a fusion chain reaction. To date it has not been possible to create a practical fusion reactor, though, since too much of the fusion energy escapes from any system that is smaller (and less destructive) than a hydrogen bomb.

Fusion reactions such as those that power the sun and other stars were proposed and theoretically analyzed by Fritz Houtermans (German, 1903–1966) and his student Robert Atkinson (British but studied in Germany, 1898–1982) in 1928, and published in 1929 (Figs. 8.20–8.21). The abstract from that paper demonstrates the remarkable and very early insight that Houtermans and Atkinson had [Atkinson and Houtermans 1929a]:

> Die quantenmechanische Wahrscheinlichkeit dafür, daß ein Proton in einen Atomkern eindringt, wird nach der Methode von Gamow berechnet. Dabei zeigt sich, daß unter den Temperatur- und Dichteverhältnissen im Innern der Sterne die Eindringung von Protonen, nicht aber von α-Teilchen, in leichtere Elemente genügend häufig vorkommt, um dort einen Aufbau dieser Elemente wahrscheinlich erscheinen zu lassen. Daraus ergibt sieh die Möglichkeit, die Energieentwicklung der Sterne auss den Massendefekten der Elemente zu erklären, wobei die Annahme von Sechserstößen für den He-Aufbau vermieden wird. Hieran schließen sich einige weitere hypothetische Betrachtungen über den Aufbau der schwereren Elemente.

> The quantum-mechanical probability of a proton penetrating into an atomic nucleus is calculated by Gamow's method. It is found that for the temperature and density values in the interior of the stars, the penetration of protons, but not of alpha particles, into lighter elements is sufficiently frequent to make a fusion of these elements probable. This gives us the possibility of explaining the energy production of the stars by the mass defects of the elements, avoiding the assumption of six steps for the production of helium. This is followed by a few other hypothetical considerations on the structure of the heavier elements.

The detailed theory of fusion reactions was refined during the period 1937–1939 by Carl Friedrich von Weizsäcker and Hans Bethe (German, 1906–2005). For that work, Bethe won a Nobel Prize in Physics in 1967. In the award ceremony speech for Bethe, Professor O. Klein of the Swedish Academy of Sciences explained [https://www.nobelprize.org/prizes/physics/1967/ceremony-speech/]:

> [...] At that time it was already apparent that Bethe belonged to the small group of young theoretical physicists who through skill and knowledge were particularly qualified for tackling the many theoretical problems turning up in close connection with the rapidly appearing experimental discoveries. The centre of these problems was to find the properties of the force that keeps the protons and neutrons together in the nucleus, the counterpart of the electric force which binds the atomic electrons to the nucleus.

> Bethe's contributions to the solution of these problems have been numerous and are still continuing. They put him clearly in the first row among the workers in this field – as in several other fields. Moreover, about the middle of the thirties he wrote, partly alone, partly together with some colleagues, what nuclear physicists at the time used to call the Bethe bible, a penetrating review of about all that was known of atomic nuclei, experimental as well as theoretical.
>
> This extensive and profound knowledge of his regarding atomic nuclei together with a rare gift of rapidly grasping the essence of a physical problem and finding ways of solving it explains that Bethe could so swiftly do the work awarded by the Nobel Prize. He started his work after a conference taking place in Washington in March 1938 and the paper containing a thorough description of it was delivered for print at the beginning of September the same year. During that conference and afterwards he seems also to have acquired the necessary astrophysical knowledge. [...]
>
> [...] If it were not for the quantum-mechanical tunnel effect studied very closely in this connection by Gamow – who must be considered the main forerunner of Bethe with respect to the application of nuclear physics to astronomy – even the velocities of the protons at the high temperature of the sun would not be able to produce any such processes. But through this effect the required slow reactions do occur. [...]
>
> A very important part of his work resulted in eliminating a great number of thinkable nuclear processes under the conditions at the centre of the sun, after which only two possible processes remained. The simplest of them begins with two protons colliding and forming a nucleus of heavy hydrogen, the surplus of electric charge vanishing in the form of a positive electron. After capturing a few more protons the result of the process is the formation of a helium nucleus from four protons. Thereby the energy release from a given weight of hydrogen is nearly 20 million times greater than that produced by burning the same weight of carbon into carbon dioxide. The second process is more complicated. It requires the presence of carbon which, however, will practically not be consumed but acts as a catalyst, the result being the same as in the former process. It should be mentioned that the first process had been proposed a few years earlier by Atkinson and later discussed by von Weizsacker, who also considered the second process independently of and at about the same time as Bethe. [...]

For much more information on the history of nuclear fusion research in the German-speaking world, see Section D.9.

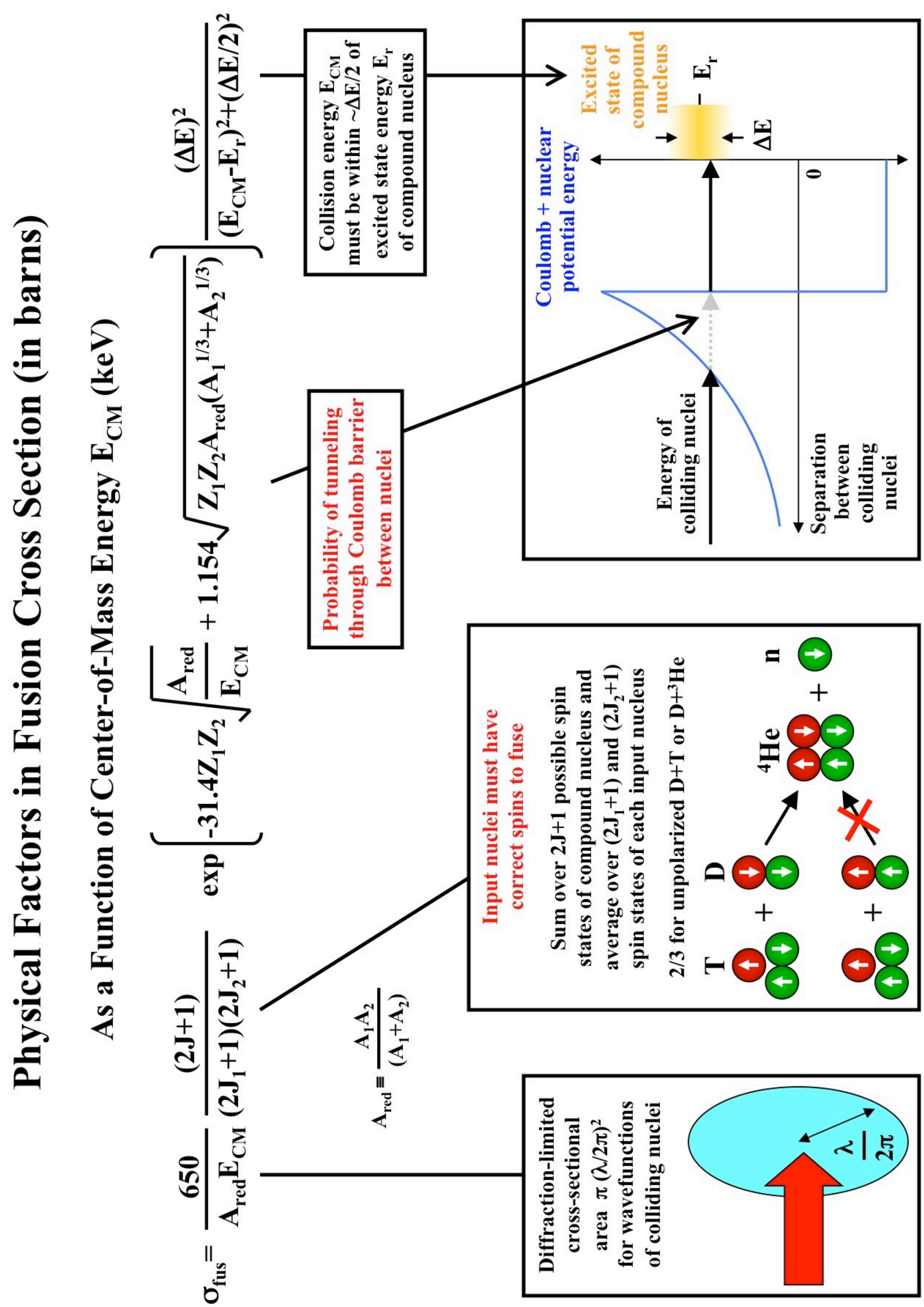


Figure 8.20: The fusion reaction rate is expressed in terms of the reaction cross section formula, which contains four different factors that describe different physical effects.

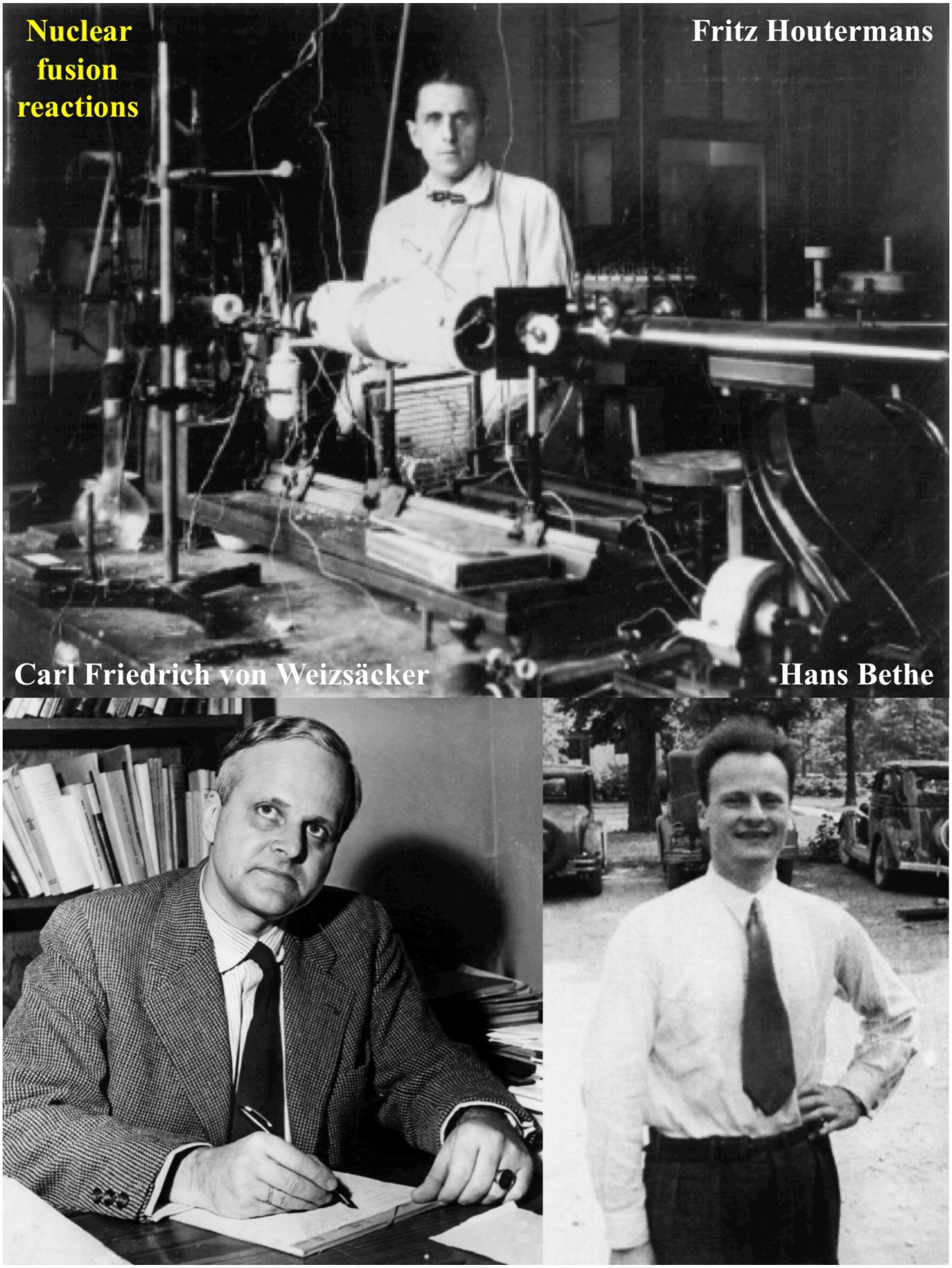


Figure 8.21: Friedrich "Fritz" Houtermans and his student Robert Atkinson described and calculated nuclear fusion reactions in stars in 1928–1929. Carl Friedrich von Weizsäcker and Hans Bethe refined those calculations 1937–1939.

8.7 Nuclear Engineering in the United States and United Kingdom

A large number of scientists who were trained in the German-speaking research world moved temporarily or permanently to the United States and/or United Kingdom and made vital contributions to those countries' nuclear programs both during and after World War II.[5] Some examples of German-speaking and German-educated scientists who played critical roles in the U.S./U.K. nuclear programs are listed in Table 8.1 and shown in Figs. 8.22–8.28. The table and figures also list a few other scientists who were very closely coupled into the German research system during their careers, such as Niels Bohr, a Dane, and Enrico Fermi, an Italian. Note that even the American-born J. Robert Oppenheimer, who was the scientific director of the wartime nuclear program, the Manhattan Project, had a German father and second-generation German-American mother, was raised speaking German, repeatedly visited family in Germany during his childhood, and received his Ph.D. in Germany under Max Born at Göttingen University.

The U.S. nuclear program was initiated by a 2 August 1939 letter to Franklin Roosevelt from two refugees from the German-speaking scientific world, Albert Einstein (who signed the letter) and Leo Szilard (who helped write the letter) [Fig. 8.22 and https://www.atomicarchive.com/resources/documents/beginnings/einstein.html]:

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable—through the work of Joliot in France as well as Fermi and Szilard in America—that it may become possible

[5] Bethe 1991, 1997; Bird and Sherwin 2005; Blatt and Weisskopf 1952; Brown and Lee 2006; Coster-Mullen 2012; Ford 2015; Groves 1962; Chuck Hansen 1988, 2007; István Hargittai 2006, 2010; Hawkins et al. 1983; Hoddeson et al. 1993; Jungk 1958; Kelly 2007; Lanouette and Silard 1992; Medawar and Pyke 2000; Nachmansohn 1979; Bruce Cameron Reed 2015a, 2019; Rhodes 1986, 1995; Schweber 2012; Serber 1992; Smyth 1945; Sublette 2019; Szanton 1992; Teller 1979; Teller and Shoolery 2001; Teller et al. 1968; Ulam 1991; Weart and Szilard 1978; Weinberg and Wigner 1958; Weisskopf 1972, 1989; Wigner 1967.

to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable—though much less certain—that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove too heavy for transportation by air.

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an unofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,

Albert Einstein

Einstein's letter prompted Franklin Roosevelt to authorize the initiation of what would become the Manhattan Project, and of course Einstein's famous equation $E = mc^2$ was the foundation for how a tiny fraction of the mass of fission fuel could be converted into an enormous (and potentially enormously destructive) amount of energy. In March 1940, Einstein and Szilard wrote a second letter to Roosevelt that successfully persuaded him to accelerate the nuclear program. Later, Einstein carried out calculations to help the United States use gaseous diffusion to enrich uranium (concentrate the fissionable U-235 isotope of uranium). Separately, he worked with the U.S. Navy on various military projects. Nonetheless, U.S. government officials such as J. Edgar Hoover distrusted Einstein's longtime inclination toward pacifism and excluded him from the official Manhattan Project [Isaacson 2007, pp. 469–486].

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

-2-

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,
A. Einstein
(Albert Einstein)

Figure 8.22: The U.S. nuclear program was initiated by a 2 August 1939 letter to Franklin Roosevelt from two refugees from the German-speaking scientific world, Albert Einstein (who signed the letter) and Leo Szilard (who helped write the letter).

Name	Born	Lived	German world	Scientific contributions
Hans Bethe	German	1906–2005	Education, work	Fission-/H-bomb theory
Felix Bloch	Swiss	1905–1983	Education, work	Fission reactions
Niels Bohr	Danish	1885–1962	Work	Neutron initiator
Karl-Friedrich Bonhoeffer	German	1899–1957	Education, work	Fission reactors
Gregory Breit	Russian	1899–1981	Work	Bomb design
Egon Bretscher	Swiss	1901–1973	Education, work	Plutonium, H bomb
Rudolf Brill	German	1899–1989	Education, work	Nuclear chemistry
Englebert Broda	Austrian	1910–1983	Education, work	Fission reactions
Adolf Busemann	German	1901–1986	Education, work	Shock waves
Frederic de Hoffmann	German	1924–1989	Education	H bomb, reactors
Martin Deutsch	Austrian	1917–2002	Family, education	Fission measurements
Rudolf Edse	German	1913–1998	Education, work	Nuclear chemistry
Albert Einstein	German	1879–1955	Education, work	Letters to FDR, gaseous diffusion
Wilhelm Eitel	German	1891–1979	Education, work	Materials science
Gerhard Falck (?)	German	19??–19??	Education, work	Uranium?
Enrico Fermi	Italian	1901–1954	Work	Reactors, H bomb
Wolfgang Finkelnburg	German	1905–1967	Education, work	Fission reactors
Rudolf Fleischmann	German	1903–2002	Education, work	Isotope separation
Siegfried Flügge	German	1912–1997	Education, work	Many aspects of fission and H-bombs
James Franck	German	1882–1964	Education, work	Plutonium
Herbert Freundlich	German	1880–1941	Education, work	MAUD Committee
Otto Frisch	Austrian	1904–1979	Education, work	Critical mass
Klaus Fuchs	German	1911–1988	Education	Implosion, H bomb
George Gamow	Russian	1904–1968	Education, work	H bomb
Gertrude Goldhaber	German	1911–1998	Education	Spontaneous fission
Maurice Goldhaber	Austrian	1911–2011	Education	Neutron moderation/reactions
Samuel Goudsmit	Dutch	1902–1978	Education, work	Investigation of German program
Wilhelm Groth	German	1904–1977	Education, work	Centrifuges, H-bomb
Dieter Gruen	German	1922–	Family, education	U enrichment, fission reactors
Gottfried Guderley	German	1910–1997	Education, work	Shock waves
Eugene Guth	Hungarian	1905–1990	Education, work	Nuclear physics, Oak Ridge, polymers
Hans von Halban	German	1908–1964	Education, work	Reactors
Paul Harteck	Austrian	1902–1985	Education, work	Many aspects of fission and H-bombs
Richard Herzog	Austrian	1911–1999	Education, work	Isotope separation
Lilli (Schwenk) Hornig	Czech	1921–2017	Family, education	Plutonium, explosive lenses
Johannes Hans Jensen	German	1907–1973	Education, work	Nuclear theory, isotope separation
Willibald Jentschke	Austrian	1911–2002	Education, work	Many aspects of fission and H-bombs
Ulrich Jetter	German	1914–??	Education, work	H-bombs
Georg Joos	German	1894–1959	Education, work	Fission applications
Hartmut Kallmann	German	1896–1978	Education, work	Fission, fusion, radiation detectors

Table 8.1: Examples of German-speaking creators (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs, their nationality by birth, the years they lived, their background in the German-speaking world, and their major contributions to the U.S./U.K. programs.

Name	Born	Lived	German world	Scientific contributions
Hans Kammler	German	1901–??	Education, work	Bomb designs/components
Nicholas Kemmer	Russian	1911–1998	Education, work	Plutonium
George Kistiakowsky	Russian	1900–1982	Education	Implosion
Gerald Klein	German	19??–19??	Education, work	Nuclear devices
Stanley Kronenberg	Polish	1927–2000	Education	Nuclear bomb tests
Heinrich Gerhard Kuhn	German	1904–1994	Education, work	Gaseous diffusion
Nicholas Kurti	Hungarian	1908–1998	Education, work	Gaseous diffusion
Heinz London	German	1907–1970	Education, work	MAUD Committee
Heinz Maier-Leibnitz	German	1911–2000	Education, work	Fission reactors
Werner Maurer	German	19??–19??	Education, work	Fission reactors
Maria Goeppert Mayer	German	1906–1972	Education	U enrichment, H bomb
Kurt Mendelssohn	German	1906–1980	Education, work	MAUD Committee
Hans Mohaupt	Swiss	1915–2001	Education, work	Shaped charges
Stanisław Mrozowski	Polish	1902–1999	Education, work	U enrichment
John von Neumann	Hungarian	1903–1957	Education, work	Implosion, H bomb
Klara Dan von Neumann	Hungarian	1911–1963	Education, work	Computation
Lothar Nordheim	German	1899–1985	Education, work	Reactors, plutonium
J. Robert Oppenheimer	American	1904–1967	Family, education	Director
Friedrich Paneth	Austrian	1887–1958	Education, work	Nuclear chemistry
Wolfgang Panofsky	German	1919–2007	Family, education	Shockwaves
Rudolf Peierls	German	1907–1995	Education	Bomb design
George Placzek	Czech	1905–1955	Education, work	Reactors, bomb theory
I. I. Rabi	Austrian	1898–1988	Work	Bomb theory
Eugene Rabinowitch	Russian	1901–1973	Education, work	Reactors
Joseph Rotblat	Polish	1908–2005	Education	Radiation
Heinz Schlicke (?)	German	1912–2006	Education, work	Detonators?
Otto Schwede	German	1912–2005	Education, work	U enrichment
Emilio Segrè	Italian	1905–1989	Education	Fission measurements
Franz Simon	German	1893–1956	Education, work	U enrichment
Kurt Starke	German	1911–2000	Education, work	Enrichment, breeding, extraction
Ernst Stuhlinger	German	1913–2008	Education, work	Reactors, particle accelerators
Hans Suess	Austrian	1909–1993	Education, work	Nuclear theory, D_2O, enrichment
Leo Szilard	Hungarian	1898–1964	Education, work	Reactors
Edward Teller	Hungarian	1908–2003	Education, work	H bomb
Stanislaw Ulam	Polish	1909–1984	Education	Implosion, H bomb
Victor Weisskopf	Austrian	1908–2002	Education, work	Fission bomb theory
Wilhelm Westphal	German	1882–1978	Education, work	Fission applications
Eugene Wigner	Hungarian	1902–1995	Education, work	Reactors, plutonium
Friedwardt Winterberg	German	1929–	Education, work	Many aspects of fission/H-bombs
Karl Wirtz	German	1910–1994	Education, work	Heavy water, enrichment, reactors
Gernot Zippe	Austrian	1917–2008	Education, work	Uranium centrifuges

Table 8.1 (continued).

Likewise, the U.K. nuclear program was also initiated by two refugees from the German-speaking world, Otto Frisch and Rudolf Peierls. In a March 1940 memorandum to the U.K. government, they wrote [https://www.atomicarchive.com/resources/documents/beginnings/frisch-peierls.html]:

> The attached detailed report concerns the possibility of constructing a "super-bomb" which utilises the energy stored in atomic nuclei as a source of energy. The energy liberated in the explosion of such a super-bomb is about the same as that produced by the explosion of 1,000 tons of dynamite. This energy is liberated in a small volume, in which it will, for an instant, produce a temperature comparable to that in the interior of the sun. The blast from such an explosion would destroy life in a wide area. The size of this area is difficult to estimate, but it will probably cover the center of a big city.
>
> In addition, some part of the energy set free by the bomb goes to produce radioactive substances, and these will emit very powerful and dangerous radiations. The effects of these radiations is greatest immediately after the explosion, but it decays only gradually and even for days after the explosion any person entering the affected area will be killed.
>
> Some of this radioactivity will be carried along with the wind and will spread the contamination; several miles downwind this may kill people.
>
> In order to produce such a bomb it is necessary to treat a substantial amount of uranium by a process which will separate from the uranium its light isotope (U235) of which it contains about 0.7 percent. Methods for the separation of such isotopes have recently been developed. They are slow and they have not until now been applied to uranium, whose chemical properties give rise to technical difficulties. But these difficulties are by no means insuperable. We have not sufficient experience with large-scale chemical plant to give a reliable estimate of the cost, but it is certainly not prohibitive.
>
> It is a property of these super-bombs that there exists a "critical size" of about one pound. A quantity of the separated uranium isotope that exceeds the critical amount is explosive; yet a quantity less than the critical amount is absolutely safe. The bomb would therefore be manufactured in two (or more) parts, each being less than the critical size, and in transport all danger of a premature explosion would be avoided if these parts were kept at a distance of a few inches from each other. The bomb would be provided with a mechanism that brings the two parts together when the bomb is intended to go off. [...]

The U.S. and U.K. nuclear programs eventually joined together for the duration of the war under the umbrella of the Manhattan Project. As listed in Table 8.1 and shown in Figs. 8.29–8.31, German-speaking and German-trained scientists played critical roles in all areas of the Manhattan Project, including enriching uranium, developing fission reactors, producing plutonium, and creating fission bombs. The fission reactor technologies that they developed were ultimately used to power everything from nuclear submarines to commercial electric generation plants.

There is also evidence that some scientists who had spent the war in Germany may have materially contributed to the U.S. nuclear program in the crucial final months of the war (see p. 4738 for more details). For example, when the German submarine U-234 surrendered to the United States in May 1945, it was found to contain 560 kg of uranium oxide (possibly enriched), infrared fuses that may have been suitable for implosion bombs, at least two experts on those materials (Gerhard Falck for the uranium and Heinz Schlicke for the infrared fuses), and potentially other nuclear-related materials and information. As another important example, Hans Kammler, who was in charge of virtually all advanced German weapons programs (including the nuclear program) by the end of the war, was secretly captured and kept indefinitely by the United States for extended interrogations (see pp. 4977–5005). In view of the fact that the United States never turned him over to the Nuremberg war crimes trials or even informed those trials that Kammler was alive and in U.S. custody, it seems likely that Kammler provided the United States with valuable information and/or materials. It is possible that assistance from these and other German sources may have appreciably accelerated the delivery schedule for the first U.S. fission bombs and also helped the postwar U.S. nuclear program. Much more archival research is needed to address this question.

After the war, many of these German-speaking and German-educated scientists (most notably Edward Teller and Stanislaw Ulam) went on to create the first U.S. fusion bombs (hydrogen or H-bombs) in 1952 and 1954. Postwar U.S./U.K. nuclear programs were also aided directly or indirectly by an influx of many additional German and Austrian scientists who were from or at least had knowledge of the German nuclear program, such as Karl-Friedrich Bonhoeffer, Wernher von Braun, Rudolf Brill, Adolf Busemann, Walter Dornberger, Rudolf Edse, Krafft Ehricke, Wilhelm Eitel, Gerhard Falck, Karl Fiebinger, Wolfgang Finkelnburg, Rudolf Fleischmann, Siegfried Flügge, Walter Glaser, Wilhelm Groth, Gottfried Guderley, Paul Harteck, Otto Haxel, Richard Herzog, Johannes Hans Jensen, Willibald Jentschke, Ulrich Jetter, Georg Joos, Hartmut Kallmann, Hans Kammler, Gerald Klein, Stanley Kronenberg, Heinz Maier-Leibnitz, Werner Maurer, Hugo Neuert, Walter Nielsch (?), Edgar Petersen, Heinz Schlicke, Otto Schwede, Erich Schumann, Edmund Sorg, Kurt Starke, Wolfgang Steurer, Ernst Stuhlinger, Hans Suess, Herbert Wagner, Wilhelm Westphal, Friedwardt Winterberg, Karl Wirtz, Gernot Zippe, etc. (p. 5038).

For more information on the influence of the wartime German nuclear program on the wartime and postwar U.S./U.K. nuclear programs, see Sections 8.8.14 and D.14.

Klaus Fuchs, who had spent many years working on the U.S./U.K. fission and fusion bomb programs, was discovered in 1950 to have been forwarding details of those programs to the Soviet Union throughout that time; he was imprisoned in the United Kingdom before being handed over to East Germany in 1959. Some scientists such as Rudolf Fleischmann, Siegfried Flügge, and Johannes Hans Jensen returned to Europe sooner or later. However, most of the German-trained scientists continued their careers in nuclear and defense fields in the United States, in some cases exerting their influence for many decades (Edward Teller died in 2003 and Hans Bethe died in 2005).

Of course, the massive U.S. nuclear weapons program was built up by U.S. industries, and employed many notable U.S.-born scientists, such as Ernest Lawrence, Glenn Seaborg, and John Wheeler and his freshly graduated student Richard Feynman. Nonetheless, for a program that involved over 100,000 people and was critical to the U.S. war effort, it is remarkable how many of the key innovations were made by scientists who came from the German-speaking world. One must wonder how rapidly the U.S. nuclear program would have advanced if it had not had the benefit of any personnel or information from the greater German-speaking scientific world.

Even the Atomic Heritage Foundation, based in Washington D.C. and founded to celebrate the history and success of the United States nuclear program, has publicly recognized the role that scientists from the greater German-speaking world played in that program [www.atomicheritage.org/article/scientist-refugees-and-manhattan-project]:

> One of the ironies of Hitler's desire for racial purity was that it drove out of continental Europe or into the camps many individuals who would have been extremely useful to the Axis war effort. Nowhere was this more evident than in the effort to produce an atomic bomb. A startling proportion of the most famous names on the project belonged to scientists who came to England or America to flee from the Axis. The large number of refugees and immigrants working on the Manhattan Project gave the American nuclear program an international character unusual in such a top-secret program—and unique amongst the nuclear programs that followed in other countries—and helped give life in Los Alamos, NM during the war its unique character.

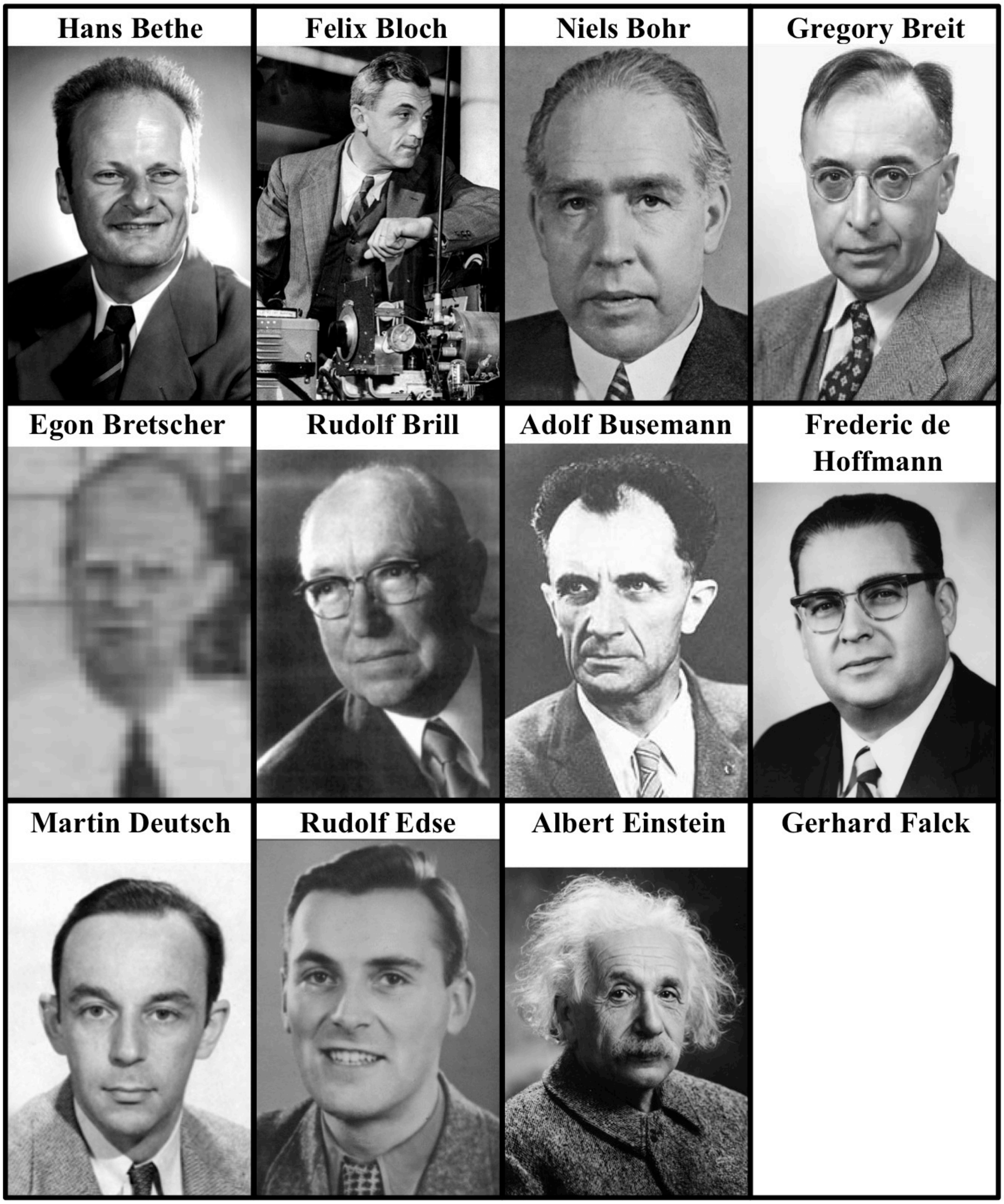


Figure 8.23: Examples of German-speaking scientists (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs.

Figure 8.24: More examples of German-speaking scientists (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs.

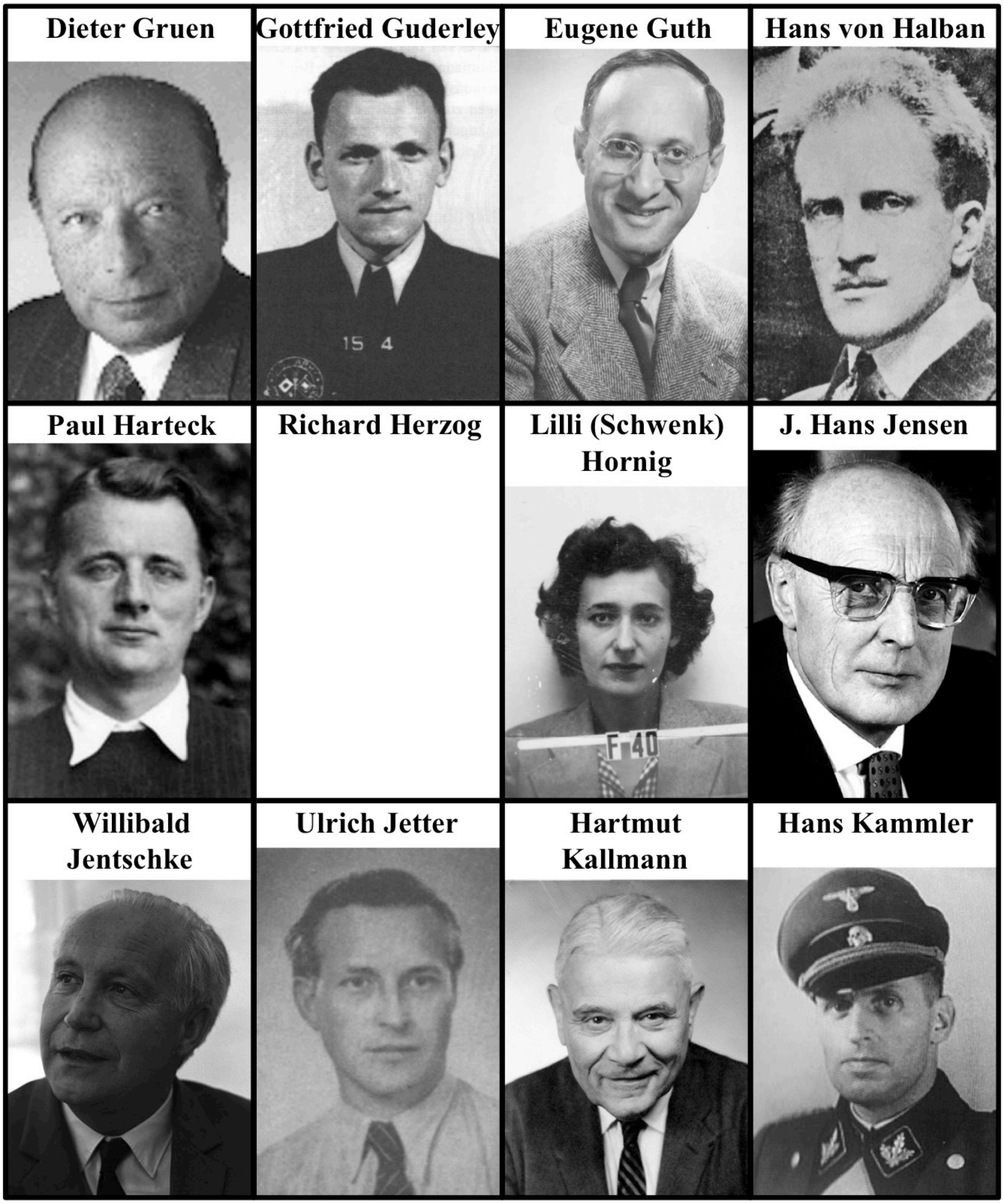


Figure 8.25: More examples of German-speaking scientists (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs.

Figure 8.26: More examples of German-speaking scientists (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs.

Figure 8.27: More examples of German-speaking scientists (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs.

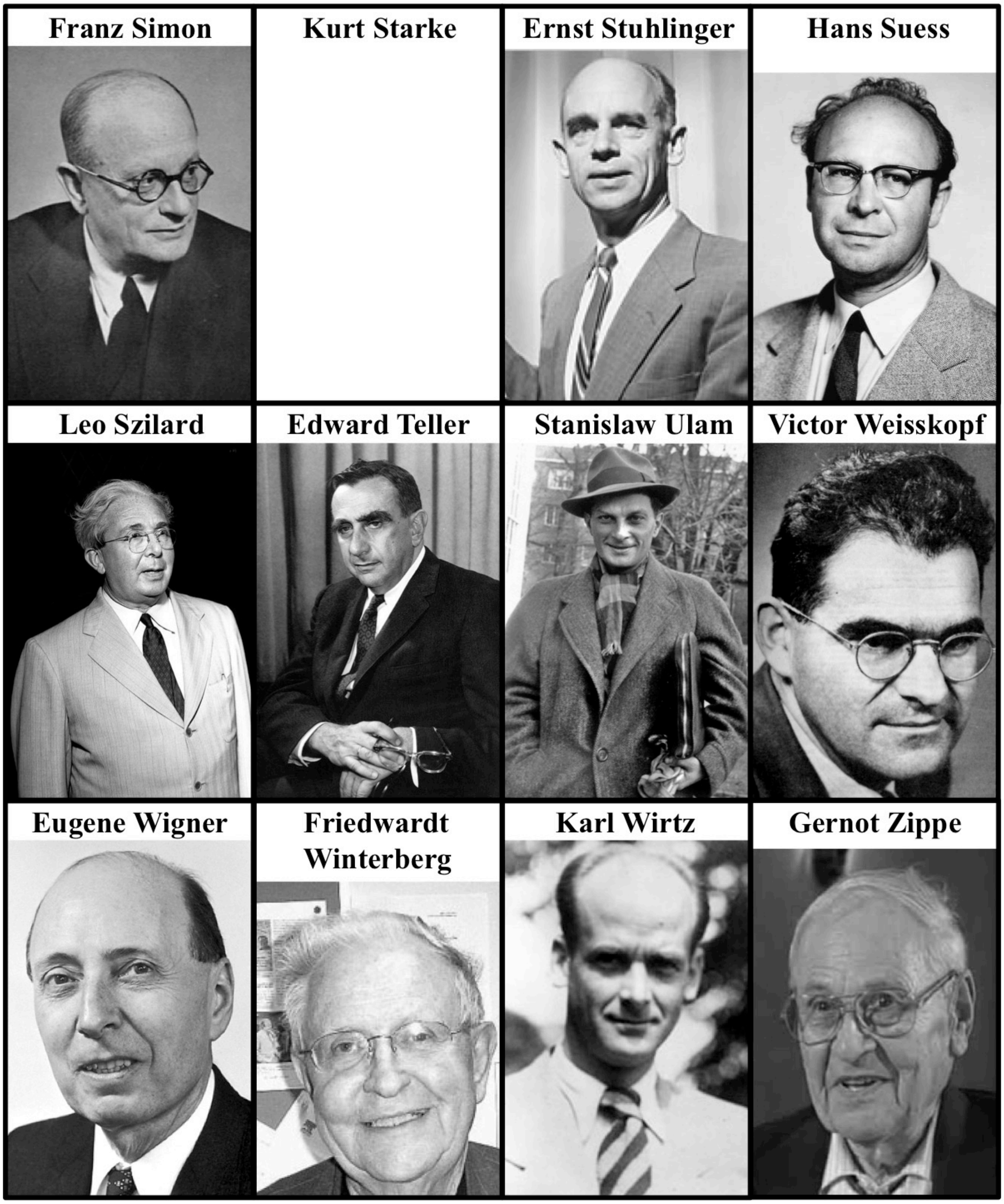


Figure 8.28: More examples of German-speaking scientists (and some scientists who were very strongly coupled to the German-speaking world) who contributed to the wartime and postwar U.S./U.K. nuclear programs.

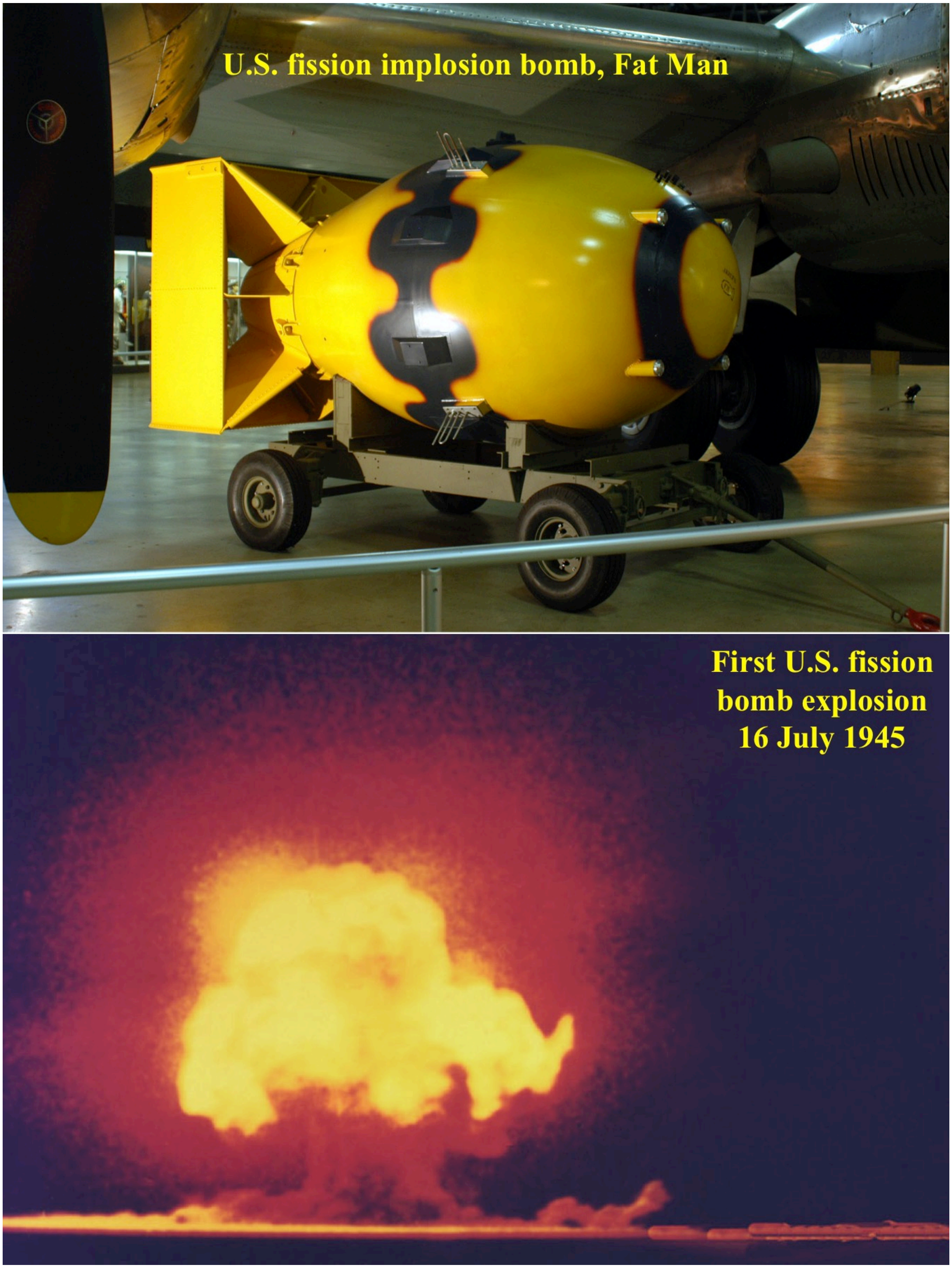


Figure 8.29: Examples of early U.S. nuclear weapons: a replica of the Fat Man design (called the Gadget without the external aerodynamic casing—see p. 5201), the first U.S. fission implosion bomb, and the explosion of the first U.S. fission implosion bomb on 16 July 1945.

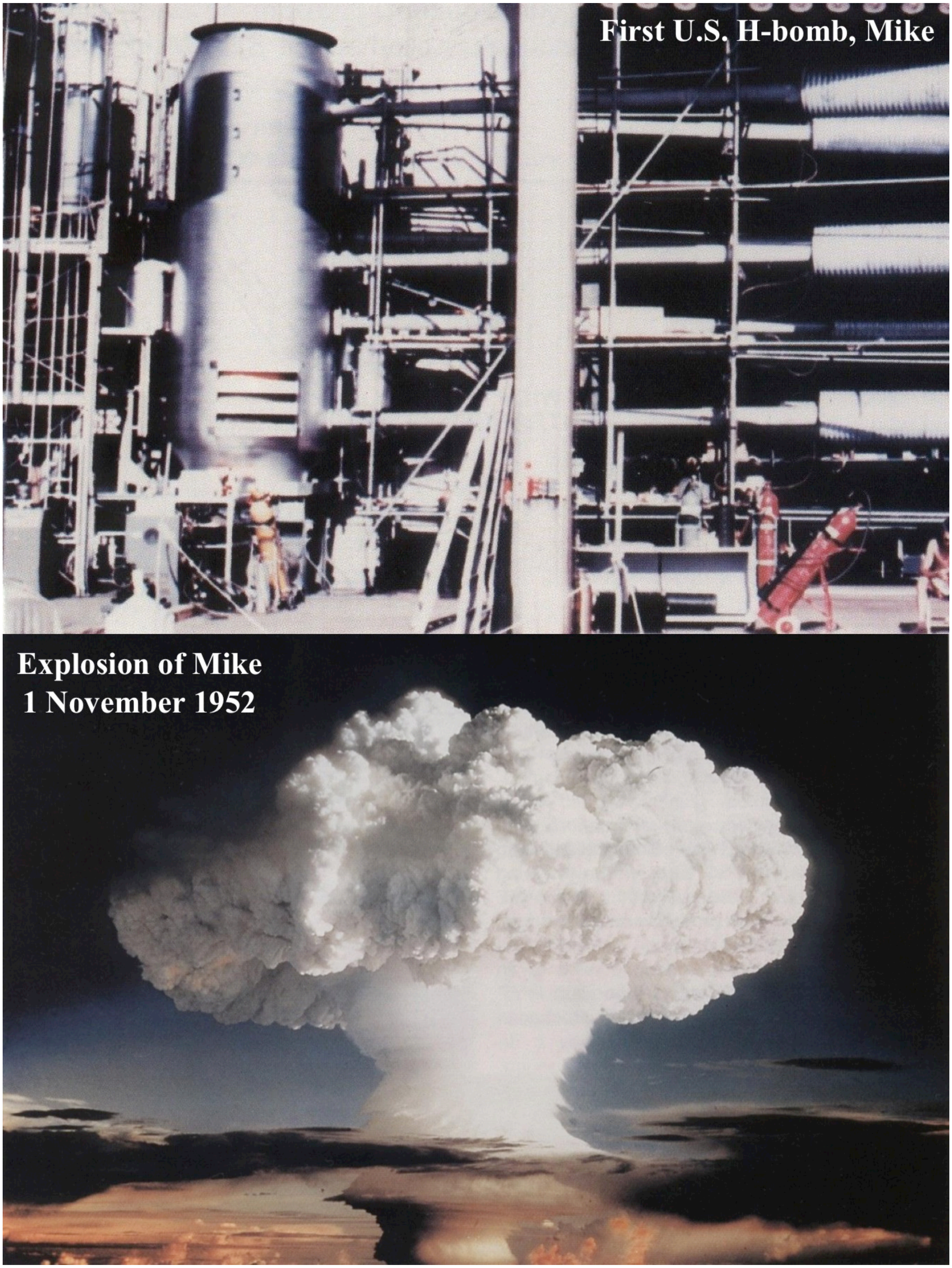


Figure 8.30: Examples of early U.S. nuclear weapons: Mike, the first U.S. hydrogen bomb, and the explosion of Mike on 1 November 1952.

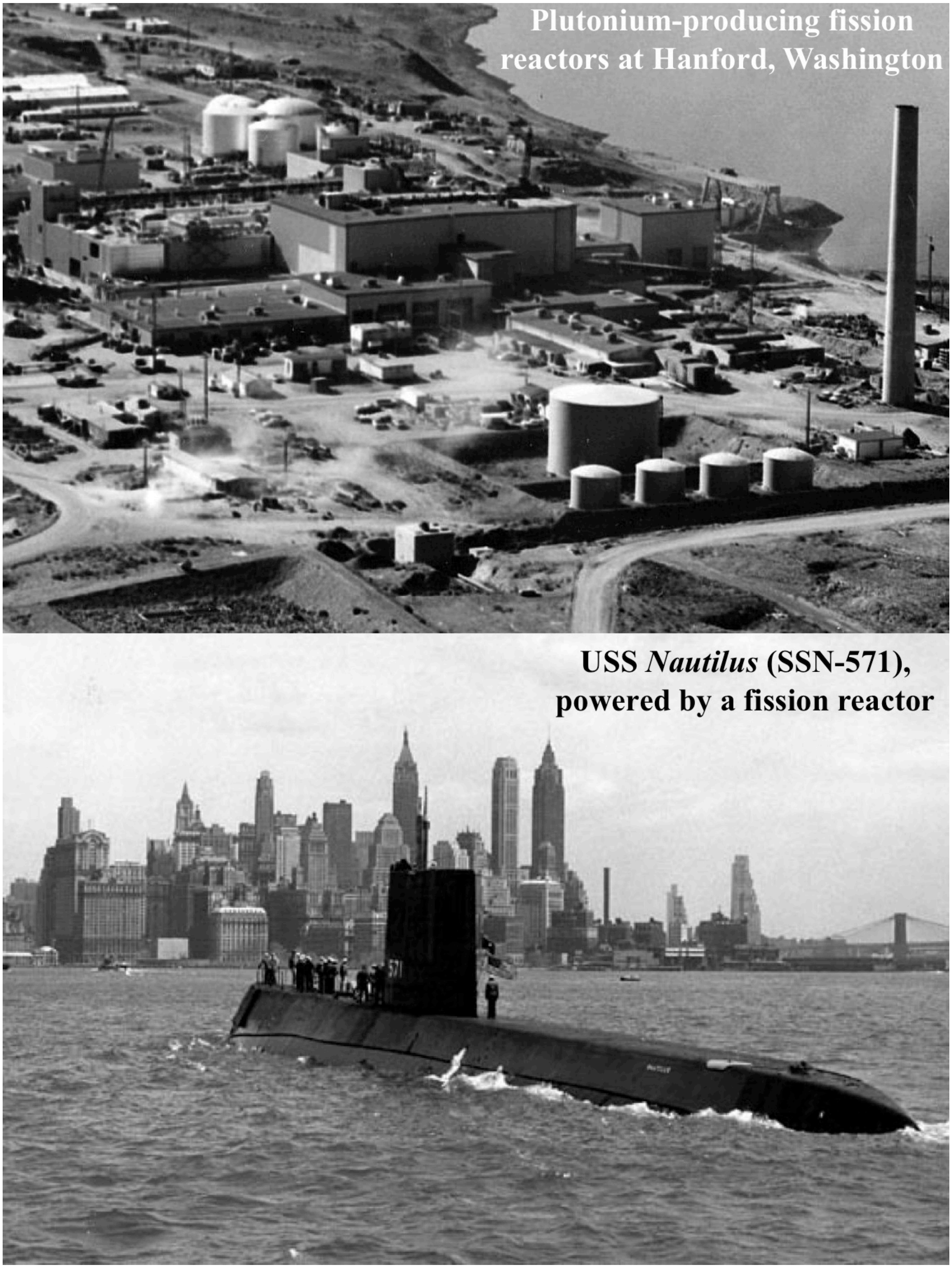


Figure 8.31: Examples of early U.S. fission reactors: plutonium-producing reactors were constructed at Hanford, Washington during the period 1943–1963; the USS *Nautilus* (SSN-571), the first submarine powered by a fission reactor, was launched in 1954.

8.8 Nuclear Engineering in the Third Reich

This section presents evidence which suggests that the World War II German nuclear program was much larger and much more advanced than has previously been generally understood. While this claim may seem controversial, much of the relevant archival evidence has only been declassified and rediscovered in recent years, and was not publicly available when earlier historical assessments were made. The evidence presented here covers:

8.8.1. Flaws in the conventional historical view of the German program.

8.8.2. The fundamental scientific knowledge and planning of the program.

8.8.3. Sources of uranium and thorium.

8.8.4. Enrichment of uranium-235.

8.8.5. Fission reactors for breeding plutonium-239 and/or uranium-233.

8.8.6. Electronuclear systems for breeding plutonium-239 and/or uranium-233.

8.8.7. The production of other potentially nuclear-related materials.

8.8.8. Fission bomb designs.

8.8.9. Hydrogen bomb designs.

8.8.10. An October 1944 test explosion on the Baltic coast.

8.8.11. A circa November 1944 test explosion in Poland.

8.8.12. March 1945 test explosions in Thuringia.

8.8.13. Axis belief in the reality of German nuclear weapons.

8.8.14. Allied belief in the reality of German nuclear weapons.

8.8.15. Further research that is needed.

For a far more detailed presentation of the currently available evidence, see Appendix D. As explained in Section 8.8.15, much more work is needed to uncover and evaluate evidence regarding the true history and extent of the wartime nuclear program.

8.8.1 Flaws in the Conventional Historical View of the German Program

The conventional historical view that has been held from 1945 to the present is that the World War II German nuclear program was very small and poorly funded, that Germany was still trying to complete its first prototype fission reactor when the war ended, and that Germany never even made a serious attempt to develop nuclear weapons.[6] This view is based on three categories of evidence, although each category has its own limitations as summarized below and in Section D.1:

[6]E.g., Goudsmit 1945, Goudsmit 1947; Groves 1962; Hentschel and Hentschel 1996; Hoffmann 2023; Irving 1967; Pash 1969; Popp 2016, 2021; Powers 1993; Rhodes 1986; Rose 1998; Walker 1989, 1995, 2020, 2024a, 2024b.

1. The U.S.-led Alsos Mission searching for evidence of nuclear-related work at the end of the war found the incomplete fission reactor at Haigerloch, some papers on basic nuclear physics, and apparently not much else, according to the public accounts. Unfortunately, the Alsos Mission failed to properly investigate numerous specific organizations, scientists, and locations that could have revealed a more advanced nuclear program. If any more advanced nuclear work had in fact been discovered, that information would have been automatically classified at the time, and could remain classified or buried in archives and unreleased to this day.[7]

2. Ten German nuclear scientists (Erich Bagge, Kurt Diebner, Walther Gerlach, Otto Hahn, Paul Harteck, Werner Heisenberg, Horst Korsching, Max von Laue, Carl Friedrich von Weizsäcker, and Karl Wirtz) rounded up by the Alsos Mission were kept under house arrest from July 1945 until January 1946 at Farm Hall in the United Kingdom, where their private conversations were recorded without their knowledge. The transcripts, which were not released to the public until 1992, record the scientists' surprise at news of the 6 August 1945 Hiroshima bombing and do not reveal significant apparent knowledge of nuclear weapons design and development. However, a huge number of relevant nuclear scientists were not at Farm Hall. There is evidence that those who were there suspected surveillance and conducted their conversations accordingly. The preserved transcripts document only a small fraction of the discussions that would have occurred among ten people and their British attendants during those six months. Moreover, the transcripts are English translations, which may not accurately reflect the original German conversations. Both the original recordings and the original German transcripts are said to have been permanently lost, a shocking lapse for such an important operation.[8]

3. In their public interviews and writings in the years after the war, German nuclear scientists professed a lack of desire, plans, materials and/or political support to produce nuclear weapons for the Third Reich. On the other hand, only a small number of nuclear scientists went on the public record. It is not clear how much of what they said was factual history versus personal spin meant to avoid postwar criticism; the answer may vary for different scientists in question. Certainly it would have been in their best personal interests to downplay their support for weapons-related work as much as possible.[9]

With access to some of the previously unavailable former Soviet and East German archives and witness testimony, as well as newly discovered and released U.S. and British documents, beginning in the 1990s several authors argued (with varying degrees of success and accuracy) that wartime German work on nuclear weapons was actually much more extensive, involved many more scientists, and progressed much further than had been accepted by the conventional historical narrative.[10]

[7] See Section D.1; Goudsmit 1945, 1947; Groves 1962; Pash 1969.

[8] See p. 3354; Bernstein 2001; Frank 1993; Hoffmann 2023.

[9] Cassidy 1992, 2009; Heisenberg 1953, 1971; Irving 1967; Powers 1993; NYT 1948-12-28 p. 10.

[10] E.g., Frank Döbert in *Walpersberg Geschichts- und Forschungsjournal* 2015, 2016; Eilers 2007, 2015; Fengler 2014; Fengler and Sachse 2012; *Geheimnis Jonastal* 2002–2024; Georg 2009; Henshall 1998, 2000, 2002; Hirschfeld and Brooks 1996; Hydrick 1998, 2016; Karlsch 2005, 2006, 2011; Karlsch and Laufer 2002; Karlsch and Petermann 2007; Karlsch and Zeman 2016; Mayer and Mehner 2001, 2002, 2004a, 2004b, 2009, 2010; Mehner 2004; Nagel 2003, 2011, 2012a, 2016; Oleynikov 2000; Petermann 2000; Schmitzberger 2004; Stevens 2007; Sulzer and Brauburger 2015; Matthias Uhl quoted in Schauka 2015; Wilcox 2019; Zeman and Karlsch 2008.

8.8.2 Fundamental Knowledge and Planning

There is ample documentation that the German nuclear program began very early and with great determination (Section D.2).[11]

In 1934, Ida Tacke Noddack accurately predicted both the neutron-induced fission of uranium and the production of a new fissile element 94 (later named plutonium-239, ^{239}Pu) via neutron capture in uranium (p. 1548).

Also in 1934, the experimental nuclear physicist Kurt Diebner (German, 1905–1964) began working closely with the implosion expert Erich Schumann (German, 1898–1985) at the Heereswaffenamt (Army Ordnance Office), which seems to indicate just how early the military applications and necessary methods of nuclear technologies were envisioned (p. 3394). Both Diebner and Schumann appear to have played hugely important roles in the development of nuclear weapons through the end of the war.

Germany seized control of the St. Joachimsthal (or Jáchymov) uranium mine in Czech territory in 1938 and made the mining and shipment of uranium from there to sites in Germany and Austria a high priority throughout the entire war [Hayes 2004, pp. 132–133, 235, 243]. See also p. 4032.

German organizations began operating and receiving shipments from a uranium mine at Buchovo (or Buhovo), a suburb of Sofia, Bulgaria, in 1938 [Hayes 2004, p. 235; https://ejatlas.org/conflict/life-after-the-uranium-mines-in-buhovo-bulgaria]. See also p. 4634.

Germany also acquired control of a number of other sources of uranium and thorium (Section 8.8.3).

At the Kaiser Wilhelm Institute (KWI) for Chemistry, Otto Hahn and Fritz Strassmann experimentally confirmed Noddack's prediction of the neutron-induced fission of uranium into lighter elements in 1938. They published their results in January 1939 (p. 1549).

In April 1939, Paul Harteck (Austrian, 1902–1985) and Wilhelm Groth (German, 1904–1977) at the University of Hamburg informed the German War Office that nuclear fission could be harnessed to create a strategically decisive bomb many orders of magnitude more powerful than conventional explosives (p. 3382). Harteck and Groth worked on many different important aspects of the German nuclear program throughout the war.

No later than April 1939, the German government was conducting very secret, high-level meetings of nuclear scientists and government officials concerning a program for the strategic military applications of nuclear physics (p. 3394).

[11] For comparison with the German timeline, it is instructive to consider the wartime U.S. nuclear program. Despite Albert Einstein's letter to Franklin Roosevelt in August 1939 (p. 1559), the U.S. program languished in committee meetings until it was jolted into action in the aftermath of Pearl Harbor. Leslie Groves was not appointed to head the newly dubbed Manhattan Project until September 1942, and construction of the buildings for the Los Alamos, Oak Ridge, and Hanford facilities did not even begin until early 1943. Serious design work on the Gadget/Fat Man implosion bomb did not begin until August 1944 [Groves 1962; Bruce Cameron Reed 2019; Rhodes 1986].

In June 1939, Siegfried Flügge (German, 1912–1997), a nuclear physicist at the KWI for Chemistry, published calculations showing the feasibility of using pure uranium-235 fuel and fast neutrons to create an explosive chain reaction, estimating both the time scale and energy release for the explosion. He stated: "The energy release happens in such a short time that we are dealing with an extraordinarily violent explosion." In the same article, he explicitly proposed water-moderated fission power reactors using thermal neutrons, derived and used the neutron diffusion and kinetics equations that are still taught in modern nuclear engineering textbooks, and correctly stated that cadmium could be used as a neutron absorber to maintain control of the neutron-induced fission reactions (p. 3384). Due to this and his other papers, Flügge apparently became the chief theorist of the German nuclear weapons program. He ended up working simultaneously for many different organizations that were all involved in the nuclear program—including the KWI, Reichspost (Postal Service), Heereswaffenamt, Reichsforschungsrat (Reich Research Council), SS, and universities—apparently serving to coordinate the scientific details of all of their activities (p. 5044).

Georg Stetter (Austrian, 1895–1988) led a large and advanced nuclear physics group at the University of Vienna. In June 1939, he filed a patent application that included a remarkably detailed description of a fission reactor (p. 3390). Stetter and all of his fellow Austrians seem to have played large roles in the German nuclear weapons program throughout the war.

Around 1939, the experimental physicist and inventor Manfred von Ardenne (German, 1907–1997) joined up with Wilhelm Ohnesorge, the very science-minded and deep-pocketed head of the Reichspost (government postal service, but like an even more advanced version of the U.S. Bell Laboratories), to conduct nuclear-weapons-related work (p. 3394). Due to Ohnesorge's strong support, the Reichspost was one of the most important organizations in the nuclear weapons program throughout the war.

Germany began ordering heavy water from Vemork, Norway in December 1939 (p. 4065). Heavy water would make an excellent moderator to facilitate the operation of a uranium reactor to produce power and/or plutonium.

No later than 1940, Carl Friedrich von Weizsäcker (German, 1912–2007) understood that ^{239}Pu could be used to create a bomb. No later than 1941, von Weizsäcker, Fritz Houtermans (German, 1903–1966), Josef Schintlmeister (Austrian, 1908–1971), and Friedrich Hernegger provided many more details about the properties, production, and military applications of plutonium. See pp. 3828–3860.

During the war, Houtermans and other scientists in the German program also understood how uranium-233 (^{233}U) could be bred from natural thorium-232 (^{232}Th) and used to create a bomb (pp. 3866–3870).

As shown in Fig. 8.32, the wartime nuclear program was spread among the Heereswaffenamt, Kriegsmarine (Navy), Luftwaffe (Air Force), Reichspost, SS, several Kaiser Wilhelm Institutes (KWI), Physikalische-Techische Reichsanstalt (Physical-Technical Reich Institute), several universities, a number of companies, and groups in Czechoslovakia, Poland, Denmark, Norway, and elsewhere.[12] In the early years of the war, the work of these many groups was coordinated by the Heereswaffenamt. From 1942 until the end of the war, the coordination was managed by the SS.

[12] See pp. 3394–3421; Irving 1967; Karlsch 2005, Karlsch and Petermann 2007; Nagel 2003, 2011, 2012a, 2016.

For an incomplete list of some of the more important scientists and engineers in the program, see pp. 1579, 1623–1641.[13] Many of those German-speaking nuclear experts subsequently worked in the postwar Soviet nuclear weapons program (Figs. 8.53–8.56), whereas others visited or moved to the United States or United Kingdom and apparently aided their programs (Figs. 8.23–8.28). Still others went to France or other countries after the war.

Note that for the last 75+ years, conventional histories of the German nuclear program have generally only covered a very small and relatively minor part of what was actually a far larger program.

Because the German nuclear program was so widely dispersed, it was much more resistant to Allied bombing and Allied intelligence; unfortunately that has also made it far more difficult for modern historians to reconstruct the details of the wartime nuclear program and its scientific accomplishments. Adding to the complications for both wartime intelligence and modern historians, the German nuclear program was highly compartmentalized, with individual people and groups only knowing as much as they needed to do their parts, just as the German chemical weapons program and the other most secretive programs were.

[13] This list has been compiled from sources throughout the Bibliography and Appendix D, but most of the names can be found in: Hentschel and Hentschel 1996; Hoffmann 2023; Irving 1967; Karlsch 2005, Karlsch and Petermann 2007; Nagel 2003, 2011, 2012a, 2016 Powers 1993 Rose 1998; Walker 1989, 1995, 2020, 2024a, 2024b.

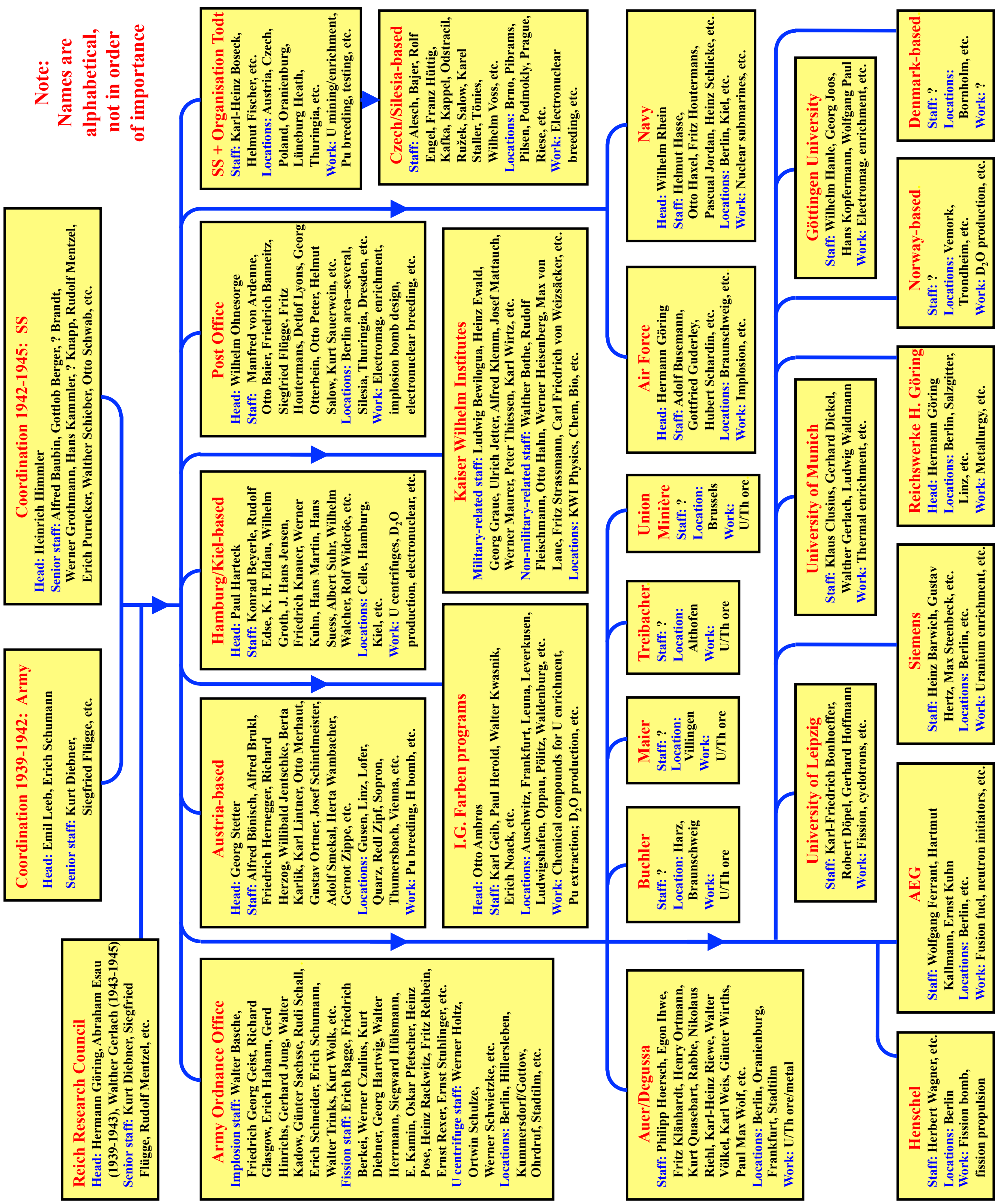


Figure 8.32: Very tentative organizational chart of the German nuclear program.

8.8.3 Sources of Uranium and Thorium

Scientists such as Nikolaus Riehl (German, 1901–1990), Günter Wirths (German, 1911–2005), Egon Ihwe (German, 18??–19??), and many others played vital roles in the processing of uranium and thorium for the German nuclear weapons program (Section D.3). Many of those scientists went on the play equally important roles in the postwar Soviet nuclear weapons program (Section 8.9).

During the war, Germany had access to large amounts of natural uranium and thorium ore by (see map on p. 3423):

- Acquiring at least 1200 tons, and according to some well-informed sources 3500 tons, of uranium compounds (originally mined in the Belgian Congo) from Union Minière in Brussels [e.g., pp. 3353, 3426–3432].
- Expanding uranium mining at St. Joachimsthal (Jachymov), Bohemia [e.g., pp. 3436–3447, 3463, 3487–3488, 5024–5030; Hayes 2004, pp. 132–133, 235, 243].
- Mining uranium at Příbram/Przibram/Pibrans, Bohemia [e.g, pp. 3442, 3488, 3785–3788].
- Mining uranium at Schmiedeberg, Silesia [e.g., pp. 3346, 3442, 3447, 3463, 3489].
- Possibly using any of several uranium deposits in Thuringia [e.g., pp. 3486–3487; Zeman and Karlsch 2008].
- Mining uranium at Schneeberg, Saxony [e.g., pp. 3434, 3442, 3444–3446, 3451–3455, 3463, 3474, 3486–3487, 3742, 4968; Zeman and Karlsch 2008].
- Mining uranium at Johanngeorgenstadt, Saxony [e.g., pp. 3434, 3442, 3444–3446, 3451–3455, 3474, 3486–3487, 3742, 4968; Zeman and Karlsch 2008].
- Mining uranium at Freiberg, Saxony [e.g., pp. 3442, 3444–3447, 3463, 3486–3487].
- Mining uranium at Durrnaul near Marienbad [e.g., p. 3442].
- Mining or planning to mine uranium at Mladkov/Wichstadt, Bohemia [e.g., p. 3443].
- Operating and receiving shipments from Bulgarian uranium mines such as a mine at Buchovo (or Buhovo, a suburb of Sofia), since 1938 [e.g., Hayes 2004, p. 235; https://ejatlas.org/conflict/life-after-the-uranium-mines-in-buhovo-bulgaria]. See also pp. 3464, 3488, 4634.
- Mining uranium at Băiţa-Plai and other sites in Romania [e.g., pp. 3467–3473, 3489].
- Acquiring uranium from mines at Viseu and Guarda, Portugal [e.g., p. 3463; Hayes 2004, p. 235].
- Procuring all available monazite thorium ore in occupied Europe [e.g., Irving 1967].
- Exploiting other possible sources—Spain, Scandinavia, etc.?

One 1946 U.S. intelligence report on Czech uranium mines noted, “The Germans put mining on a high priority and only mining was done throughout the 6 years occupation. The ore was delivered by special planes to Germany and Austria” (p. 4032). Another 1946 U.S. intelligence report added: “The Germans continued operations in this mine to the very last moment” (p. 5027).

Thus Germany began actively mining uranium in 1938 and continued until the end of the war. During that time, Germany had access to (1) the same quality and a comparable quantity of Congolese uranium that served the Manhattan Project well, (2) Central/Eastern European uranium mines that later served the Soviet nuclear program well, and (3) additional uranium mines too.

Germany processed uranium and thorium ore to uranium oxide and thorium oxide, and thence to uranium or thorium metal or to a variety of useful chemical compounds—uranium hexafluoride, uranium tetrachloride, uranium nitrate, etc.—at numerous locations including (see map on p. 3425):

- Union Minière in Brussels [e.g., pp. 3353, 3426–3432; Irving 1967, p. 65].
- Auer in Oranienburg, Katowice/Kattowitz, and other locations [e.g., pp. 3464, 3476, 3479–3481, 3483, 5026; Nagel 2016].
- Buchler in Braunschweig [e.g., pp. 3438, 3448–3449, 3476, 3478–3481, 3483, 5026].
- Treibacher Chemische Werke in Althofen, Austria [e.g., pp. 3438, 3450–3455, 3476, 3478, 5026; Gollmann 1994].
- Degussa in Frankfurt, Berlin, Stadtilm, and possibly other locations [e.g., pp. 3476, 3479–3483; Hayes 2004; Nagel 2016].
- Chemische Fabrik Grünau in Berlin [e.g., pp. 3456–3457, 3479–3481].
- I.G. Farben in Leverkusen and other locations [e.g., pp. 3506–3507, 3510–3511, 3712–3714, 3782–3784, 4484–4521; Mader 1965, pp. 193–202, 229-233].
- Krupp in Essen [e.g., pp. 3476, 3479–3481, 3483–3485].
- W. de Boer in Hamburg and Wittingen [e.g., pp. 3476, 3479–3481, 3483].
- Radium-Chemie AG in Frankfurt [e.g., pp. 3458–3459, 3476, 3483].
- W. Maier KG Radiumchemische Industrie und Laboratorium in Villingen-Schwenningen am Neckar and other locations [e.g., Oleynikov 2000].
- Příbram/Przibram/Pibrans, Bohemia [e.g., pp. 3441, 3785–3788].
- Facilities in Dresden [e.g., pp. 3441, 3444].
- Reichswerke Hermann Göring in Linz and other locations [e.g., pp. 3911–3914].
- Possibly other facilities.

At the end of the war, Allied countries removed over 2800 tons of uranium and thorium compounds from former German-controlled territory (p. 3474). In addition, in 1974, Alwin Urff, deputy technical plant manager of the Asse nuclear disposal site in Germany, stated: “When we began storage in 1967, our company first sank radioactive waste from the last war, that uranium waste which arose in the preparation of the German atomic bomb” (p. 3490).

8.8.4 Enrichment of ^{235}U

Only 0.72% of natural uranium is ^{235}U, the fissile isotope. In order to achieve high concentrations of ^{235}U for a fission bomb, it is necessary to enrich or separate ^{235}U from the other uranium isotopes (Section D.4).

Uranium is converted into the gaseous compound uranium hexafluoride (UF_6) for most enrichment processes (except uranium tetrachloride for electromagnetic separation). UF_6 is highly corrosive to most materials except nickel. German reports captured by the Alsos Mission demonstrate that at least as early as 1940, the German program was fully aware of this information and capable of producing UF_6, and that much of that production capability was at I.G. Farben. Some especially noteworthy researchers in the development and handling of UF_6 were Erich Noack (German, 19??–19??) and Walter Kwasnik (German, 19??–19??) at I.G. Farben Leverkusen, and Paul Harteck and Wilhelm Groth in Hamburg (Section D.4.1).

Georg Bredig (German, 1868–1944) demonstrated the first gas centrifuges in 1895, and the technology was further developed by Fritz Haber (German, 1868–1934) and other researchers. By the time of the Third Reich, gas centrifuges for uranium isotope enrichment were built, tested, and even mass-produced by engineers all over the greater German-speaking world (Section D.4.2). Some of the key personnel included Konrad Beyerle (German, 1900–1979), Klaus Clusius (German, 1903–1963), K. H. Eldau (German, 19??–19??), Wilhelm Groth, Paul Harteck, Helmuth Hausen (German, 1895–1987), Werner Holtz (German, 19??–19??), Johannes Hans Jensen (German, 1907–1973, later won a Nobel Prize for the nuclear shell model), Werner Kuhn (Swiss, 1899–1963), Detlof Lyons (German, 19??–19??, also worked for the Reichspost), Hans Martin (German, 19??–19??), R. Schlatterer (German?, 18??–19??), Ortwin Schulze (German, 19??–19??), Werner Schwietzke (German, 1910–1987), Hans Suess (Austrian, 1909–1993), and Albert Suhr (German, 1920–1996).

Currently available documents indicate that gas centrifuges were produced by:

- Anschütz in Kiel (pp. 3512–3533).
- PHYWE (Physicalische Werkstatte) in Göttingen (pp. 3560–3562), which also made extremely advanced liquid centrifuges for biochemical research (pp. 2409–2411).
- Linde Eismaschinen in Munich (pp. 3516–3525), which had decades of experience with gas handling and rotating compressor machinery.
- Hellige in Freiburg (pp. 3530–3558).
- Hellige in Breslau/Wrocław (p. 4567).
- One or more factories in Switzerland for export to Germany (pp. 3563–3566).
- Quite possibly other locations as well.

How many uranium gas centrifuges were produced by or for Germany during the war? At what sites were they installed and operated? How much enriched uranium did they produce in total, and how highly enriched was it? Can files that would answer these questions be located in various national archives and declassified?

Centrifugation proved so superior to the U.S. Manhattan Project's enrichment methods that the German gas centrifuge designs are now the worldwide standard for uranium enrichment (pp. 3567–3587). The evidence clearly shows that the technology was developed and demonstrated over the course of half a century (1895–1945) by German scientists and engineers, and spread by German scientists and engineers (as well as the prototypes and documentation they had produced) to other countries after the war. The Soviet Union was one of those countries to which the technology spread (via scientists such as Max Steenbeck and Gernot Zippe), but not the origin of the technology [Benedict et al. 1981; Glaser 2008; Helmbold 2016; Kemp 2009, 2012, 2017; NYT 2004-03-23].

Manfred von Ardenne (German, 1907–1997), Heinz Ewald (German, 1914–1992), Wolfgang Paul (German, 1913–1993), Wilhelm Walcher (German, 1910–2005), and many others worked in teams to develop electromagnetic separators (called calutrons in the United States) to enrich uranium (Section D.4.3). By 1941, von Ardenne and his collaborators had built and successfully demonstrated a prototype electromagnetic separator, and were trying to persuade German industry to mass-produce such separators. In March 1942 Ewald delivered a final report on calculations for the optimal performance of electromagnetic separators. According to a June 1944 OSS report, von Ardenne, Siegfried Flügge, and the Reichspost (which was working closely with the SS) had supervised the construction of three secretive high-voltage facilities at undisclosed locations. Were those three electromagnetic enrichment facilities? Von Ardenne became a central figure in the Soviet nuclear weapons program after the war.

Gustav Hertz (German, 1887–1975) patented gaseous diffusion separation in 1923 and a gaseous diffusion cascade system in 1925. Hertz, Erika Cremer (German, 1900–1996), Hubert Krüger (German, 18??–19??), Rudolf Fleischmann (German, 1903–2002), Erich Bagge (German, 1912–1996), and others built and demonstrated prototype gaseous diffusion enrichment systems before and during the war (Section D.4.4). Hertz's secret wartime work was deemed so important by the German government that he was allowed to live and work in relative comfort throughout the war despite his Jewish ancestry. After the war, he played a vital role in the Soviet nuclear program.

After the war, leftover wartime factories in Neustadt an der Orla, East Germany, were already perfectly set up to make high-quality nickel membrane filters for gaseous diffusion enrichment plants (pp. 3667–3672, 5098, 5101–5103). Manufacturing the filters was so difficult that even years after the war, Soviet plants could not make comparable items. What exactly did these German factories do during the war?

Stanisław Mrozowski (Polish, 1902–1999), K. Zuber (Swiss, 19??–19??), Werner Kuhn, Hans Martin, K. H. Eldau, Paul Harteck, and others developed photochemical methods of isotope separation, demonstrated them with elements such as mercury, and worked to apply them to uranium (Section D.4.5). Although it is currently unclear how far that work progressed during the war, it became the basis of laser isotope separation after the war. (For early work toward lasers in the German-speaking world, see Section C.3).

As a basis for comparison, one can consider the U.S. uranium enrichment facility at Oak Ridge, Tennessee. For the 12 months ending 1 September 1945, the total electrical consumption for Oak Ridge (Y-12 calutrons + K-25 gaseous diffusion + all other nuclear facilities + the town itself) was 1659 GW hr for the year, or 0.189 GW time-averaged (pp. 5168–5169).

At the end of 1944 the Greater German Reich (Grossdeutsches Reich) had a total known electrical production capacity of at least 22–23 GW, despite territorial losses, extensive bombing, and ongoing repairs (pp. 2114–2118). Including secretive or specialized power plants for classified or dedicated projects within the Greater German Reich that were not known to the Allied investigators plus the electrical production capacities of other countries that were occupied by Germany, allied with Germany, or nominally neutral but exporting aid to Germany, a reasonable estimate of the total electrical production capacity supporting the German war effort is roughly double the 22–23 GW figure, or ∼44–46 GW.

Using the average total electrical consumption of Oak Ridge during the final year of the war, Germany could have powered a fully equal facility by using less than 1% of the known wartime electrical capacity in the Greater German Reich, or less than 0.5% of the estimated total electrical production capacity that was available to aid Germany during the war. German centrifuges would have been more energy-efficient than U.S. enrichment methods, and the German implosion design would have needed much less ^{235}U than the U.S. Little Boy, so German uranium enrichment plants may have required far less total electrical power than Oak Ridge.

If Germany scaled up any of its proven uranium enrichment methods during the war, rather than building one giant Oak-Ridge-like plant that could be highly vulnerable to Allied bombing, it would have distributed its enrichment capability among a number of (especially underground) locations. Indeed, that is exactly what was done, according to a declassified October 1944 OSS report based on information from Adolf Schneider, a senior manager of the Deutsche Waffen und Munitions-Fabrik (pp. 4440–4443).

Archival documents, most of which are found in the declassified files of the OSS and the Manhattan Project's Foreign Intelligence Unit, mention dozens of highly suspicious sites that might have been used for that purpose and that have never been properly investigated, at least not publicly (Section D.4.6). Just a few illustrative examples are given below.

An October 1943 OSS intelligence report from Frederick Loofbourow described what sound like underground uranium enrichment facilities staffed by hundreds of workers near Lüneburger Heide. There were also other reports of nuclear-related work at Lüneburger Heide (pp. 4214–4220, 4446).

A May 1944 OSS intelligence report described what sound like two massive uranium enrichment facilities, each with 30,000 workers, run by I.G. Farben in Opava and Ostrava in eastern Czech territory (p. 3782).

Julius Schaub, Hitler's chief adjutant, stated there was another 30,000-worker uranium enrichment facility at an underground site in Thuringia (4681–4685).

Several sources mentioned Reichspost enrichment facilities on the outskirts of Berlin (pp. 3642–3651, 3742–3743, 4681–4685).

Throughout the war, large amounts of electricity were consumed by high-security weapons work that produced no obvious products (Sections D.4.6 and 8.8.11).

In September 1946, General Leslie Groves (the head of the U.S. nuclear weapons program) sent Percival C. Keith (the construction chief of the Oak Ridge enrichment plant) on a two-week Top Secret mission to Czechoslovakia (pp. 3804–3805). What target would involve Groves, require the specific expertise of Keith, and justify the great risk if Keith were captured by Czech or Soviet forces? Was Keith's mission to help inspect, remove, or destroy key components of a wartime enrichment facility?

As a quantitative example of what might have been required of a German enrichment facility, one can consider the case of electromagnetic separation, using the U.S. calutrons at the Oak Ridge Y-12 plant for reference. In early 1945, Y-12 was producing approximately 0.2 kg ^{235}U per day, or approximately 73 kg/year. The U.S. electromagnetic separation plant was designed to produce so much ^{235}U because the United States planned to use that uranium in Little Boy, a gun-type fission bomb that needed over 60 kg of fuel since it did not compress the fuel and had a very low efficiency. The U.S. plant provided enough uranium for approximately one bomb of that design per year.

The sources that describe the German fission bomb design all indicate that it was an implosion bomb (Section 8.8.8), which compresses the fuel, is much more efficient than a gun-type bomb, and therefore requires roughly 1/10 as much fuel as a gun-type bomb. If a German enrichment facility were designed to produce enough ^{235}U for one full-sized bomb per year (or several test bombs with smaller amounts of fuel and smaller explosive yields, as described by the sources), a German electromagnetic enrichment plant could have been roughly 1/10 the size of the U.S. Y-12 plant, as extrapolated in Table 8.2. Likewise, Table 8.3 shows the extrapolated characteristics of a hypothetical German centrifuge separation plant. If that same production capacity were distributed among several production plants to minimize the risk of Allied bombing (p. 4440), each plant would have been even smaller.

Characteristic	**U.S. Y-12 Plant**	**Hypothetical German Plant**
^{235}U production rate	73 kg/year	~ 7 kg/year
Number of ion beams	3120	~ 310
Number of workers	22,482	~ 2,200
Facility floor space	~ 400,000 m^2	~ 40,000 m^2
Electric power consumption	200 MW	~ 20 MW
Cost (1940s U.S. dollars)	$477,631,000	~ $48,000,000

Table 8.2: Known characteristics of the U.S. electromagnetic separation plant and extrapolated characteristics of a hypothetical German electromagnetic separation plant. (See Section D.15.2.A for details.)

Characteristic	**Hypothetical German Plant**
^{235}U production rate	~ 7 kg/year
Number of centrifuges	~ 467
Number of workers	< 1,400
Facility floor space	< 4,200 m^2
Electric power consumption	< 1 MW
Cost (1940s U.S. dollars)	< $48,000,000

Table 8.3: Extrapolated characteristics of a hypothetical German centrifuge separation plant. (See Section D.15.2.C for details.)

8.8.5 Fission Reactors for Breeding ^{239}Pu and/or ^{233}U

The available documentation shows that German scientists were aware that either ^{239}Pu or ^{233}U would make good fuel for fission bombs (Section D.5) and could be produced in a fission reactor by the following respective processes:

$$^{238}_{92}\mathrm{U} + \mathrm{n} \xrightarrow{(\mathrm{n},\gamma)} {}^{239}_{92}\mathrm{U} \xrightarrow{\beta\ 23.5\ \mathrm{min}} {}^{239}_{93}\mathrm{Np} \xrightarrow{\beta\ 2.36\ \mathrm{days}} {}^{239}_{94}\mathrm{Pu} \tag{8.1}$$

$$^{232}_{90}\mathrm{Th} + \mathrm{n} \xrightarrow{(\mathrm{n},\gamma)} {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta\ 21.8\ \mathrm{min}} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta\ 27.0\ \mathrm{days}} {}^{233}_{92}\mathrm{U} \tag{8.2}$$

^{237}Np fission fuel [Sanchez et al. 2008] could also have been bred in fission reactors (e.g., by knocking a neutron out of ^{238}U), although it probably would have been more difficult to produce in quantity than ^{239}Pu or ^{233}U [Benedict et al. 1981].

Ludwig Bewilogua (German, 1906–1983), Kurt Diebner, Paul Harteck, Otto Haxel (German, 1909–1998), and many others worked in teams trying to develop suitable fission reactors.

By far the best known German reactor was the one built by Werner Heisenberg's group, first located at the KWI for Physics in Berlin-Dahlem, and later moved to Haigerloch (pp. 3877–3887). It never achieved criticality (a self-sustaining neutron chain reaction) during the war. There were also smaller subcritical fission experiments, such as those built by Robert Döpel's team in Leipzig and Paul Harteck's team in Hamburg.[14]

Throughout the war, Kurt Diebner's Heereswaffenamt group built a series of reactor experiments of increasing size and complexity at Gottow (Kummersdorf) through 1944, and at Stadtilm in 1945 (pp. 3888–3902). According to official histories, Diebner's reactor experiments never achieved criticality during the war. In fact, there is some evidence that they may have achieved criticality in late 1944 and/or early 1945 [Karlsch 2005; Nagel 2016]. However, even if Diebner's reactor did go critical, it was a small experimental system, not a large production reactor for breeding useful quantities of ^{239}Pu or ^{233}U.

There is some evidence that a number of other, larger fission reactors were under construction during the war, and that some of them may have even been operational. Just a few examples are cited here; for more information, see pp. 3874–3987.

There may have been fission reactors and a fuel reprocessing facility near Königsberg (now Kaliningrad) in East Prussia (pp. 3962–3967). Heinrich Himmler's close diplomatic contact, Muhammad Amin Al-Husayni, the Grand Mufti of Jerusalem, reported those reactors after the war (pp. 4624–4625): "After 1945 the Grand Mufti said that the enemy espionage by 'Jewish, English and American intelligence services' caused 'the greatest damage.' They were able to discover the locations of 'atomic reactors' in East Prussia."

As already noted, Siegfried Flügge, who was probably the top nuclear physicist in the German nuclear weapons program, worked for many different organizations that were involved in the program, apparently serving to coordinate the scientific details of all of their activities. Among his many other urgent and nuclear-focused duties, he was appointed to a professorship at the Uni-

[14] Goudsmit 1947; Groves 1962; Irving 1967; Pash 1969; Powers 1993; Walker 1989.

versity of Königsberg in 1944, late in the war as Russian forces were advancing (p. 5044). That appointment only makes sense if there was a nuclear facility there that was deemed critical to the war, such as fission reactors breeding plutonium for nuclear weapons.

During the war, Königsberg had a large staff of inorganic chemists with world-class expertise in methods that would have been useful for reprocessing irradiated fuel from fission reactors. After the war, many of those chemists were interrogated by at least two teams from the U.S. Alsos Mission, which suggests that U.S. officials suspected the Königsberg chemists had been involved in nuclear work (pp. 3964–3967).

There were tens of thousands of forced laborers working in and near Königsberg during the war. They are known to have worked with toxic chemicals such as ship paints and suffered the consequences [Jasiński 1994]. This labor pool might also have been used for hazardous nuclear work.

During the period 26–30 August 1944, U.K. Royal Air Force bombers, operating at the very limits of their range, devastated targets in and near Königsberg (p. 3962). That only makes sense if there were targets of great military value and urgency, such as a nuclear facility on the verge of producing enough fuel for nuclear weapons. It also explains the Grand Mufti's comment.

Despite the Allied bombings and fierce offensives by Soviet forces, German troops successfully defended East Prussia until April 1945, rather than retreating to more central areas of Germany and using their strength to defend those. Once again, that only makes sense if there were something in East Prussia that Germany considered to be of great strategic significance until the very end of the war.

After the war, East Prussia was claimed as Soviet territory, even though it was geographically disconnected from any other Soviet territory, rather than allotting it to the surrounding countries, Poland or Lithuania. Again, that suggests something rather unusual was found there. (Of course, it did also provide a desirable seaport for the Soviet Union.)

There are a number of archival documents, witness statements, aerial photographs, and other evidence strongly suggesting that part of the Bergkristall tunnel complex at St. Georgen an der Gusen (near Linz, Austria) was conducting nuclear-weapons-related work during the war (pp. 3908–3954). From some of the evidence, it sounds as if the complex may have included a fission reactor and fuel reprocessing facility. German forces sealed the entrances and air shafts to that part of the tunnel complex shortly before the end of the war, and they have remained sealed for 75+ years. U.S. officials inspected this site and interrogated witnesses after the war (pp. 5008–5016). Their reports on what they found and learned there have never been publicly released. Air and water samples taken from the site in recent years have remarkably high levels of radioactivity, which may or may not be due to purely natural causes. Until all of the documentary evidence is available, and/or until the site can be properly excavated and analyzed, the true nature of this facility cannot be settled.

According to U.S. intelligence reports, there was a highly secret, heavy concrete installation at the I.G. Farben Leverkusen plant that may have been a fission reactor (pp. 3968–3969). It is known that I.G. Farben Leverkusen was doing extensive work involving uranium hexafluoride throughout the war (Section 8.8.4), and that other I.G. Farben facilities were producing many other potentially nuclear-related materials (Section 8.8.7).

According to some sources, a fission reactor was built and operated by the SS, likely in an underground facility in Thuringia, and was reported to have been operational in March 1945 (pp. 3899–3902).

A possible fission reactor at Unterraderach near Friedrichshafen (on the coast of the Obersee Bodensee) was reported to have been operational in 1944 (pp. 3955–3959).

A fission reactor at an underground facility in Berlin-Lichterfelde was reported to have been operational in 1944 (pp. 3960–3962).

According to other sources, there may have been a fission reactor at Bodenbach/Krizik-Werke/Weser-Werke/Podmokly (pp. 3970–3971, 4021–4032).

There is evidence that there may have been additional fission reactors at other locations (pp. 3972–3987).

Heavy water (D_2O) is an excellent moderator for fission reactors. Germany appears to have been producing heavy water in at least 25 plants all over Europe (including several run by I.G. Farben, Section 8.8.7), despite the difficulties of Allied bombing and the urgent wartime needs to produce other materials and products. This additional evidence strongly suggests that Germany possessed operational fission reactors, or at least was trying to get reactors operational as soon as possible.

The Soviet Union demonstrated its first fission reactor (F-1) on 25 December 1946, only about 12 months after its captured German nuclear scientists were able to begin setting up the captured German nuclear materials (including at least 300 tons of German-produced uranium oxide, which fueled both F-1 and the larger second Soviet reactor for breeding Pu-239); see Section 8.9. If German scientists and German materials accomplished that feat so quickly after starting over in the Soviet Union after the war, they certainly could have done it in German territory during the war.

If uranium or thorium is left in a fission reactor too long, much of the ^{239}Pu and/or ^{233}U that had initially been created by neutron bombardment will be fissioned and destroyed by later neutrons. Moreover, prolonged neutron exposure can also breed undesirable isotopes—especially ^{240}Pu from natural uranium or ^{232}U from natural thorium—that are highly radioactive and therefore greatly complicate the handling of that fuel in reprocessing and in bombs. For both of those reasons, large amounts of uranium or thorium fuel are generally moved in and out of breeder reactors over fairly short periods of time.

In the wartime U.S. nuclear program, the main reactors breeding plutonium were three reactors in Hanford, Washington, dubbed reactors B, D, and F. When fully operational, each of those reactors produced approximately 250 MW of thermal power from approximately 250 tons of natural uranium, or about 1 MW/ton. At that power, each reactor bred approximately 0.19 kg of ^{239}Pu per day, or approximately 69 kg per year. To limit the production of ^{240}Pu, the 250 tons of reactor fuel was removed after approximately 100 days, and then the reactor was restarted with fresh natural uranium fuel [Bruce Cameron Reed 2015a, 2019]. Comparing the ^{239}Pu production rate of 0.19 kg/day to the rate of using natural uranium, 250 tons/100 days = 2.5 tons/day, the amount of ^{239}Pu bred per ton of natural uranium was

$$\frac{\text{Bred Pu-239}}{\text{Natural uranium}} \approx \frac{0.19 \text{ kg/day}}{2.5 \text{ tons/day}} \approx 0.076 \ \frac{\text{kg}}{\text{ton}} \tag{8.3}$$

Note that the amount of fissionable ^{239}Pu produced from a ton of natural uranium is roughly 100 times smaller than the maximum amount of fissionable ^{235}U (7.2 kg) that could be extracted from that same ton of natural uranium via the enrichment methods of the previous section. Again, this low level of production is due to the need to avoid creating much ^{240}Pu in the fuel. As a result, a fission fuel breeding program would use $\sim$100 times more uranium than a fission fuel enrichment program (unless the irradiated uranium were reused in the breeder reactor after the plutonium had been removed, which may or may not have been practical under the urgent pressures of the war).

Counterbalancing that disadvantage is the advantage that a breeder reactor and the accompanying chemical purification processes handle fission fuel in a very dense solid or liquid state, whereas enrichment methods handle fission fuel in a far less dense gaseous or plasma state. Therefore the equipment for breeding would be much more compact, and could potentially be built and operated by fewer people, than the equipment for enrichment.

As long as the reactor is large enough to have a self-sustaining fission chain reaction, these characteristics can be scaled up or down in a linear fashion, using the approximate numbers in Table 8.4 as a basis for reference [Kemp 2005]. For example, if each Hanford reactor held 250 tons of natural uranium and produced approximately 69 kg of ^{239}Pu per year, a hypothetical German reactor holding approximately 22 tons of natural uranium could produce approximately 6 kg of ^{239}Pu per year, enough for one full-sized $\sim$20 kiloton implosion bomb (like the U.S. Gadget and Fat Man bombs) per year. From Eq. 8.3, producing 6 kg of plutonium would require processing approximately 79 tons of uranium.

Characteristic	**Approximate value (scales linearly)**
Thermal power	25 MW
Reactor core volume	100 m^3
Moderator	150 tons of graphite, or 80 tons of heavy water, or some of both
Natural uranium in reactor	25 tons
Replace uranium every	100 days
Uranium consumption rate	91 tons/year
Plutonium production rate	6.9 kg/year
Cost (1940s U.S. dollars)	$6,000,000

Table 8.4: Approximate characteristics of a breeder reactor for producing ^{239}Pu.

^{232}Th is useful for breeding ^{233}U but cannot sustain a fission chain reaction on its own. The reactor would need to contain natural uranium or uranium enriched in ^{235}U. On the order of $\sim$90% of the neutrons from the uranium would be needed to sustain the chain reaction, so only $\sim$10% of the neutrons could be spared to breed ^{233}U from ^{232}Th, and hence only $\sim$10% of the total fuel in the reactor could be thorium. Thus a fission reactor for breeding ^{233}U might be $\sim$10 times larger in volume or mass than a reactor for breeding ^{239}Pu. (Of course, plutonium would also be bred within the $\sim$90% of the reactor fuel that was uranium, and that plutonium could be extracted as well.) For this reason, it seems likely that the German nuclear program would have generally preferred producing ^{239}Pu instead of ^{233}U, although scientists may have certainly tried ^{233}U (especially because of the large amount of thorium that was available to the German nuclear program).

Many highly radioactive isotopes with short half-lives are created when fuel is bombarded with neutrons in a fission reactor, so it is customary to let the fuel "cool off" for a month or so after being removed from the breeder reactor before it is processed by people. Since the German nuclear program would have had a great sense of urgency and likely did not value the lives of its low-level workers, it might have processed irradiated fuel with a much shorter cooling off period.

There is some evidence that Germany developed chemical reprocessing methods to extract and purify the bred ^{239}Pu or ^{233}U (p. 3860). Although it is currently unknown just how far that work progressed during the war, or in what geographic locations, the scientific details of reprocessing constrain where and how it could have been done, and may guide historians in locating relevant documents and geographic sites:

- Due to the relatively sophisticated chemistry involved in reprocessing (p. 5181) and the fact that it would be tied to secret weapons development, it seems probable that any such reprocessing would have been run by I.G. Farben, or at the very least would have intimately involved I.G. Farben.

- Because of the large amount of irradiated uranium or thorium fuel that would need to be processed for a much smaller amount of ^{239}Pu or ^{233}U, and because of the great personal danger involved in exposure to the associated high levels of radiation and toxic chemicals, it also seems likely that any such work in wartime Germany would have involved slave labor and high fatalities (at least if it advanced beyond small-scale proof-of-concept laboratory experiments).

- Because of the large amount of material to be processed and the extreme danger in handling it, chemical reprocessing would probably have been conducted at or near the fission reactor(s) or electronuclear breeding site(s) where the ^{239}Pu or ^{233}U was bred.

- For cooling of the fission reactor and for both cooling and chemical steps during reprocessing, a breeding/reprocessing facility would likely be located very close to an abundant source of fresh water.

Tritium could also be bred from lithium and/or heavy water by neutron bombardment in a fission reactor. Tritium would be very useful for fusion boosting of fission bombs and/or for hydrogen bombs (Section 8.8.9).

8.8.6 Electronuclear Breeding of ^{239}Pu and/or ^{233}U

Even without a fission reactor, it is possible to produce significant amounts of ^{239}Pu or ^{233}U via electronuclear breeding (Section D.6). In this process, a particle accelerator fires a beam of high-energy charged particles (typically protons, deuterons, or electrons with a kinetic energy of many millions of electron-volts or MeV) at a target containing ^{238}U or ^{232}Th. When those energetic charged particles strike the nuclei of the target material, they knock some neutrons free; those neutrons are absorbed by the ^{238}U to become ^{239}Pu, or by ^{232}Th to become ^{233}U, as shown in Eqs. (8.1)–(8.2). In more sophisticated and efficient systems, the target may also contain an initial layer of lithium or beryllium atoms, which are especially good at releasing neutrons when struck by high-energy charged particles. If furthermore the target is immersed in a neutron moderator (such as heavy water or pure graphite) and surrounded by a neutron reflector (such as beryllium), each neutron that is originally generated can lead to a cascade of several more neutrons by subcritical fission reactions, yielding several atoms of bred fuel per charged particle in the beam. If the target is lithium without uranium or thorium, electronuclear breeding can be used to produce tritium.

Electronuclear breeding was seriously pursued by the United States and other countries after World War II, and even now is of concern as a proliferation risk for how new countries could produce nuclear weapons.[15]

Archival documents show that in German-controlled areas from the Netherlands to Czech territory, a considerable number of high-energy particle accelerators were produced and used as high priorities during the war. Rolf Wideröe (Norwegian but studied and worked in Germany, 1902–1996), Max Steenbeck (German, 1904–1981), Walter Dällenbach (Swiss, 1892–1990), Walther Bothe (German, 1891–1957), and many others worked to design, build, and test the accelerators (pp. 3032–3103, 3988–4056, 4549–4555).

Purely scientific research would not have been sufficient justification for all of the funding, labor, and materials that went into these accelerators when war needs and shortages were so dire. While accelerators would certainly be useful for measuring fundamental nuclear properties that are relevant to designing nuclear reactors and bombs, one or two modest accelerators would have been sufficient for that purpose. Indeed, Germany already had access to the Joliot-Curie cyclotron in Paris for such measurements.

Most of the accelerators appear to have been closely linked with the German nuclear weapons program and treated as a high priority for that program until the very end of the war. Electronuclear breeding seems to be the best explanation.

In August 1945, after some nuclear-related censorship of the U.S. press had been lifted, newspapers belatedly reported that sabotage and U.S. bombing had delayed German nuclear weapons work in Czech territory, probably a reference to cyclotrons that were produced there: "A shattering American air raid, Czech sabotage and an accident frustrated German experiments in Czechoslovakia seeking to develop an atomic bomb, newspaper accounts said here today" (p. 4013).

[15] Barashenkov et al. 1987; Barber and George 1959; Chichester 2009; Kemp 2005; Livdahl 1981; Magill and Peerani 1999; Riendeau et al. 1999; Van Atta 1977.

In November 1945, *Time* magazine reported evidence of secret wartime German work to mass-produce cyclotrons in Czech territory for a nuclear weapons program (p. 4021).

In May 1945, the Soviet physicist Georgy Flerov was sent by Joseph Stalin and Igor Kurchatov to investigate the German nuclear program. In 1983, Flerov described his interrogation of a German cyclotron expert who had been captured by Soviet forces at the end of the war. The German physicist told of at least one highly secret underground SS/Reichspost installation in the Riese complex in Silesia that was using multiple cyclotrons for urgent war-related work—most likely electronuclear breeding (p. 4549).

Werner Grothmann, Heinrich Himmler's chief adjutant, independently confirmed that there was a high-priority, highly secret, joint SS/Reichspost program to breed plutonium without a reactor—electronuclear breeding—in underground installations using particle accelerators that had been manufactured in Czech territory and in Austria (p. 4058).

Simple physics calculations (pp. 5179–5180) demonstrate that electronuclear breeding of kilograms of ^{239}Pu or ^{233}U for a fission bomb, or tens of grams of tritium for fusion boosting a bomb, would potentially have been quite feasible (though technically challenging) for the wartime German program.[16] Of course, any ^{239}Pu or ^{233}U created via electronuclear breeding would still have needed to be chemically extracted from the target material, just as with breeding in a fission reactor (p. 5181).

It is important for historians to search for more evidence of a wartime electronuclear breeding program (both in archival documents and at physical sites that may have been involved in this work), and to ascertain just how far any such electronuclear program actually progressed during the war.

[16] ^{237}Np fission fuel [Sanchez et al. 2008] could also have been bred using accelerators (e.g., by knocking a neutron out of ^{238}U), although it probably would have been more difficult to produce in quantity than ^{239}Pu or ^{233}U [Benedict et al. 1981].

8.8.7 Production of Other Potentially Nuclear-Related Materials

During the war, Germany produced large quantities of materials that had non-nuclear applications, yet would also have been extremely useful for a nuclear weapons program (Section D.7). From archival documents that are currently available, it is not possible to determine whether or how much of each material was used for nuclear applications, but clearly the materials were readily available if some quantity of them had been requisitioned by a high-priority nuclear program.

Any nuclear-related production programs in wartime Germany would have had access to a larger labor pool than comparable programs in the United States. The population of the greater German-speaking world was equal to or somewhat greater than that of the United States at the time (Section 10.1.1). Including the populations of countries that were allied with or occupied by Germany, the total population of German-controlled territory was far larger than that of the United States.

Likewise, the gross domestic product (GDP, a measure of economic and industrial resources) of German-controlled territory was roughly comparable to or by some measures even greater than that of the United States (pp. 2112–2113).

Just as importantly, the electrical power production of German-controlled Europe was fairly comparable to or even greater than that of the United States (pp. 2112–2116). Germany had access to power plants and fuel sources throughout most of Europe, and also built more during the war (e.g., pp. 3789–3793), so energy would not have been a limiting factor for nuclear-related production.

Deuterium can serve as a great fusion fuel and source for producing neutrons and tritium, and an excellent neutron moderator for fission reactors when in the form of deuterated (heavy) water. According to official histories, heavy water was only produced in significant quantities at the Norsk Hydro hydrogen factory in Vemork, Norway, which was famously attacked by Allied forces and the Norwegian Resistance and forced to shut down. In fact, documents indicate that heavy water production facilities for the German nuclear program were known or reported to be located at sites all over German-occupied Europe (see map on p. 4064):

1. Vemork, Norway (pp. 4065–4073).
2. Såheim, Norway (p. 4074).
3. Notodden, Norway (p. 4075).
4. I.G. Farben Leuna Werke, low-pressure production plant (pp. 4076–4086).
5. I.G. Farben Leuna Werke, high-pressure production plant (pp. 4076–4086).
6. I.G. Farben Bitterfeld (pp. 4086–4087) [Karlsch 2005, p. 110; Sadovsky 2011b].
7. I.G. Farben Halle (pp. 4088–4091).
8. Kiel, probably adjacent to the Deutsche Werke Kiel (pp. 4092–4097).
9. Dräger Werke, Lübeck (pp. 4098–4099).

10. Müggenberg (pp. 4100–4101).

11. Chemische Fabrik Griesheim-Elektron, Frankfurt am Main (pp. 3712–3714, 4102–4103).

12. Berlin plant (p. 4104).

13. Linde plant, Munich (p. 4104).

14. Montecatini plant, Sinigo-Merano, Italy (p. 4105).

15. Montecatini plant, Cotrone/Crotone, Italy (p. 4105).

16. I.G. Farben Auschwitz in Poland (pp. 4105, 4496).

17. Plant near the Schmiedeberg (now Kowary, Poland) uranium mine (p. 4105).

18. Plant near Breslau (now Wrocław, Poland; pp. 4106–4107).

19. Ljungaverk, Sweden (p. 4108).

20. Brixlegg, Tyrol, in the Austrian Alps (p. 4109).

21. Weer, near Wattens, Tyrol, in the Austrian Alps (pp. 4110–4115).

22. B9 Quarz underground complex near Roggendorf and Melk, Austria (p. 4116–4117).

23. Degussa plant at Rheinfelden, Austria (pp. 4118–4119).

24. Austrian Chemical Works plant at Weissenstein, Austria (pp. 4118–4119).

25. Siemens and Halske plant in Lehesten (pp. 3723, 3730, 4118).

26. Bayrische Stickstoffwerke in Piesteritz (pp. 4120, 4496–4497).

27. Pardubice/Wesser, Czechia (pp. 3464, 4120–4121).

28. Other possible locations (pp. 4122–4124).

Thus Germany was producing large quantities of heavy water in a very determined fashion at numerous plants all over Europe, despite the difficulties of Allied bombing and the urgent wartime needs to produce other materials and products. The existence of this massive, high priority, highly secretive heavy water production program strongly suggests that one or more fission reactors may have actually been operational during the war. At the very least, it seems to indicate that Germany was trying to get reactors operational as soon as possible. Germany may have also needed significant quantities of deuterium/heavy water for electronuclear breeding of fission fuel and/or for fusion fuel production.

Lithium was utilized for processing ceramics, glass, and metals, but it would also have been extremely useful for producing tritium, neutrons, and/or fusion reactions. Germany produced hundreds of tons of lithium and lithium compounds during the war (p. 4128). Alfred Klemm developed methods to separate the naturally occurring ^{6}Li and ^{7}Li isotopes, which would have been required only for nuclear applications (pp. 4382–4385). Klemm also knew of work on tritium being conducted by other scientists (p. 4384).

High-quality graphite was widely used for high-temperature exhaust steering rudders on the A-4 (V-2) and other rockets, and was utilized for making electrodes, filters, and other components too. However, graphite could also have been quite useful as a neutron moderator to slow down neutrons and promote chain reactions in a fission reactor. Germany produced many tens of thousands of tons of graphite during the war (p. 4148).

While some historians have claimed that the German nuclear program was unwise to choose heavy water instead of graphite as a reactor moderator, the actual historical and scientific record suggests otherwise.

First of all, it is far from certain that the German program did exclude graphite. For example, I.G. Farben's Bitterfeld facility was mass-producing both graphite (p. 4148) and heavy water (p. 4086) as well as other nuclear-related materials (pp. 4166, 4171, 4174). Similarly, Griesheim plants were producing both graphite (pp. 4152–4154) and heavy water (pp. 4102–4103), with other nuclear-related facilities such as Degussa in the same area [Hayes 2004; Nagel 2016]. Graphite was also mass-produced at the Siemens Plania Werke in Racibórz/Ratibor, Poland (pp. 4148–4152), near a reported heavy water plant at Auschwitz (pp. 4105, 4496) and reported uranium enrichment plants at Opava and Ostrava (p. 3783).

It may well be that the German program was aware that graphite could be used as a moderator but preferred heavy water for several reasons:

- The "moderating ratio," the ratio of how strongly a moderating material slows down neutrons vs. how strongly it absorbs neutrons, is $\sim$25–100 times larger for heavy water than for graphite (depending on the purity of the heavy water). Since heavy water is far more effective than graphite at slowing neutrons without absorbing them, much less moderator and/or natural uranium would be required for a reactor to achieve criticality, or the reactor could be more easily loaded with other neutron-absorbing materials such as lithium for tritium production. Because of these advantages, the United States built five heavy water reactors at the Savannah River Site in the 1950s and used them to breed over 36,000 kg of plutonium during the Cold War.[17]

- Using heavy water would avoid "Wigner's disease," in which irradiated graphite swells, stores/releases large amount of energy, and creates problems in a reactor, as caused major headaches in both the United States (diagnosed by Eugene Wigner) and the Soviet Union (e.g., the January 1949 Chelyabinsk Reactor A accident that shortened Igor Kurchatov's life) [Kojevnikov 2004, p. 151; Bruce Cameron Reed 2019, pp. 260–261; Rhodes 1995, p. 277].

[17]DOE 1996; Glasstone 1958, pp. 464–465; Glasstone and Sesonske 1981, pp. 470, 786;
https://ansn.iaea.org/Common/topics/OpenTopic.aspx?ID=19022
https://nucleus.iaea.org/sites/graphiteknowledgebase/wiki/Wiki%20Pages/Nuclear%20Properties.aspx

- Graphite is flammable and could cause or contribute to a catastrophic reactor accident, as in the 1957 Windscale reactor fire in the U.K. nuclear weapons program [Lorna Arnold 2007; Mahaffey 2014, p. 176].

- While being used as a moderator for fission reactions, heavy water will simultaneously breed tritium. Further tritium can be bred by inserting lithium into the heavy water reactor (which can spare more neutrons for that purpose than a graphite reactor could, since the moderating ratio of heavy water is much higher). For example, the five heavy water reactors at the U.S. Savannah River Site produced around 200 kg of tritium during the Cold War [Høibråten 2020]. There is evidence that the wartime German program wanted fusion fuels such as tritium for (a) neutron initiators in fission bombs, (b) fusion neutron boosting in fission bombs, and (c) fusion fuel for a megaton-level H-bomb (Section D.9).

- Using heavy water for reactors would leave all of Germany's graphite available for other urgent applications, such as electrodes, rocket exhaust steering rudders, and steel production.

Beryllium was used for producing certain metal alloys, but it also could have been quite useful as a neutron reflector and multiplier in a fission reactor, electronuclear breeding system, or fission bomb. Wartime production of beryllium was in the tons (p. 4134).

Boron was needed for producing certain types of glass, ceramics, and metals, but it also would have been very useful as a neutron absorber. Large quantities of boron were produced in wartime Germany (p. 4142).

Fluorine was used for various industrial chemical production processes, but it also would have been essential for producing uranium hexafluoride for the enrichment of ^{235}U. Wartime production of fluorine was in the thousands of tons (p. 4156).

Aluminum was employed for fabricating a wide variety of metal structures and packaging. On the other hand, aluminum could have been quite useful as cladding around fission fuel in a reactor, or as spherical pusher and casing shells in a fission bomb as described in Section 8.8.8. Thousands of tons of aluminum were produced in wartime Germany (p. 4164).

Calcium was used in making certain metal alloys, but it also would have been extremely useful in key steps of the purification of thorium, uranium, and/or plutonium. Germany produced thousands of tons of calcium during the war, and is even documented to have utilized calcium to purify thorium and uranium (p. 4170).

Nickel was needed for nickel-cadmium batteries and certain alloys. Yet because nickel is much more resistant than other metals to corrosion by uranium hexafluoride (used in uranium enrichment), it would have been invaluable in a nuclear program. Wartime production of nickel was many thousands of tons (p. 4176).

Zirconium was used for high-temperature metals and ceramics in non-nuclear applications, but its high temperature resistance and other properties also would have made it ideal as a fuel cladding material in fission reactors. Tons of zirconium were produced in wartime Germany. There was also an apparently related story about the SS *Flying Enterprise*, which sank on 10 January 1952 while carrying cargo from Hamburg to the United States. Its captain, Kurt Carlsen, later told interviewers such as Bjarne Bekker that the cargo included five tons of zirconium, left over from the wartime German nuclear program, which was salvaged from his sunken ship and used in the first U.S. nuclear submarine, USS *Nautilus* (p. 4180).

Cadmium was important for nickel-cadmium batteries and soldering, but it also could have been extremely useful as a neutron absorber. Germany produced thousands of tons of cadmium during the war (p. 4186). Germany also possessed methods for electroplating thin layers of materials such as cadmium onto aluminum. Such methods are potentially quite relevant for creating a neutron-absorbing cadmium layer on a spherical aluminum pusher as in the German fission implosion bomb described in March 1945 (Section 8.8.8).

Some sites were producing multiple nuclear-related materials at the same location. For example, I.G. Farben's Bitterfeld facility is documented to have been producing heavy water (p. 4086), graphite (p. 4148), aluminum (p. 4166), and calcium (pp. 4171, 4174); Bitterfeld may have produced other relevant materials as well.

Intriguingly, significant quantities of many of these nuclear-related materials were also shipped to Japan, Germany's wartime ally, along with at least 560 kg of (possibly enriched) uranium and other cutting-edge military technologies (pp. 4132, 4141, 4904–4938).

8.8.8 Fission Bomb Designs

A number of independent sources provided information about wartime German fission bomb designs (Section D.8).

No later than 1940, the mathematicians Walter Hantzsche (German, 19??–19??) and Hilmar Wendt (German, 1913–19??) derived pressure, density, and temperature solutions that are applicable to spherical and cylindrical implosion bomb configurations, and that are still used today (pp. 4204–4207).

No later than 1942, Gottfried Guderley (German, 1910–1997), a hydrodynamics expert working for the German military, performed very similar calculations for spherical and cylindrical implosions (pp. 4208–4209).

As already noted in Section 8.8.4, a 1943 U.S. intelligence report stated that "several factories and hundreds of workers" in underground facilities near Lüneburger Heide were producing a special new type of explosive that was so energetic that one kilogram of the new material would have a blast radius of several kilometers, and that would be placed into bombs of a highly unusual spherical design (p. 4214).

In November 1944, *Time* magazine published a news report that Germany was developing a fission bomb with a spherical implosion design. The implications of the article were so clear that Leslie Groves, the military leader of the Manhattan Project, had a strong reaction when he found out (p. 4223).

A 23 March 1945 letter from General Ivan Ilyichev, chief of intelligence for the Soviet army, to Joseph Stalin reported that the Germans had an atomic bomb and described it in considerable detail as a 2-ton, 1.3-meter-diameter spherical implosion device with multiple concentric layers and a ^{235}U core (Fig. 8.33, Table 8.5, and Section 8.8.12).

Erich Schumann (German, 1898–1985), the Heereswaffenamt's head physicist, was an expert on shaped-charge explosives and X-ray diagnostics for explosives, Wernher von Braun's Ph.D. thesis advisor for the development of rockets, and a key figure in Germany's biological warfare program and other advanced research programs. No later than 1940, he, Walter Trinks (German, 1910–1995), Rudi Schall (German, 1913–2002), and others began investigating the use of shaped-charge explosives (especially spherical, but also other geometries) and explosive lenses to generate implosive shock waves strong enough to initiate fission and fusion reactions and produce a large nuclear explosion, and Schumann continued to advance that work throughout the war. Schumann filed approximately 40 secret patents on this work during the war, which ultimately led to several unclassified postwar patents. Those published patents described designs extremely similar to the design that Ilyichev said was tested in March 1945: spherical implosion bombs with a total mass of approximately 2 tons, an outer layer of segmented explosive lenses, inner spherical layers of cadmium, uranium, and other materials, and fusion fuel in the center (pp. 4225–4293). (Since the United States possessed much of this evidence, one must wonder why Samuel Goudsmit knowingly gave false testimony to the U.S. Senate by claiming that Schumann was mainly just interested in "the physics of piano strings"—see pp. 3312–3315, 3319.)

In November 1945, the German economist Erwin Respondek wrote that Erich Schumann had been involved in the development of an atomic bomb that used uranium fuel and a neutron initiator (and apparently Schumann's expertise, conventional explosives for spherical implosion), and that the problem was "solved" in 1944 (p. 4232).

Adolf Busemann (German, 1901–1986), Rolf Engel (German, 1912–1993), Hubert Schardin (German, 1902–1965), and others also played major roles in the development of implosion bombs [Karlsch 2005; Krehl 2009].

A Top Secret U.S. cable from March 1946 stated that a "capable young engineer" in Poland knew that atomic bomb casings included a layer of cadmium, which was true for the implosion bomb designs described by both Ilyichev and Schumann (p. 4293).

1946 U.S. intelligence documents described how SS General Hans Kammler's deputy Erich Purucker and a car full of German atomic bomb plans were captured by Russian forces in May 1945 (p. 4960).

After the war, Kurt Diebner discussed spherical implosion bomb designs, specifically showing a hollow spherical pit of fission fuel with fusion fuel in the center, likely based on the wartime work in which he had participated (pp. 4298–4305).

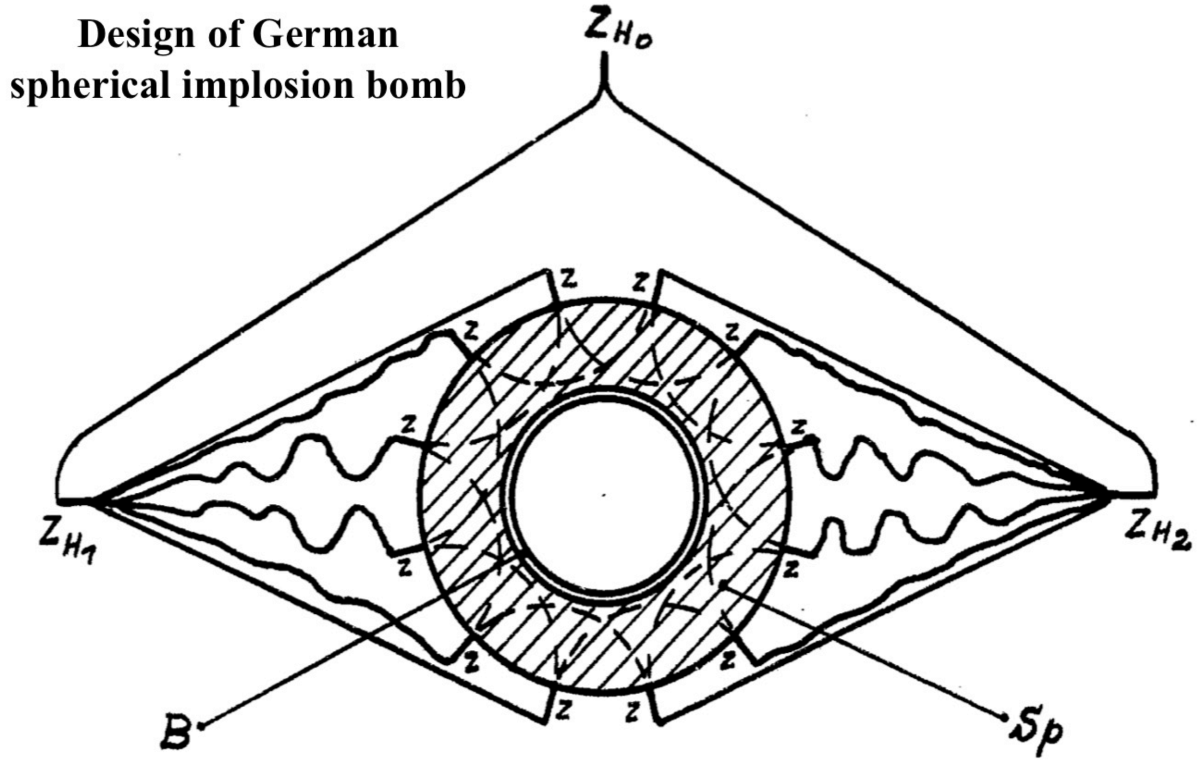
German witnesses described secretive and mysterious work that had been conducted during the war to produce and test nesting aluminum spheres that apparently matched the description of those in the implosion bomb designs (p. 4308).

Werner Grothmann recounted the development of an atomic bomb that "possessed a spherical shape with a diameter of over one meter. It was very heavy, even though the bomb body itself was supposed to be out of aluminum. It was said, if one reduces the weight, the yield is not as high" (pp. 4309–4311).

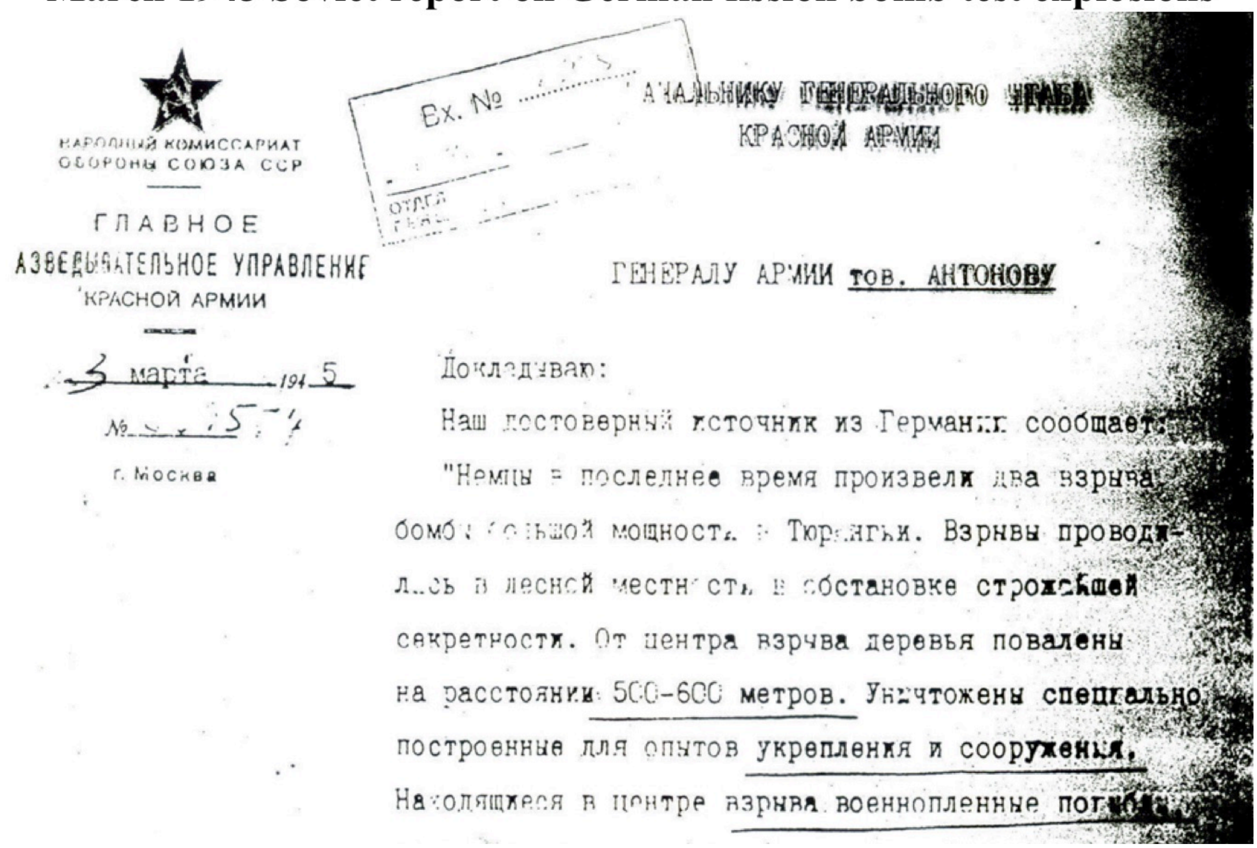
All of these independent sources appear to have been describing the same spherical implosion fission bomb design, or very closely related variations of the same basic design. Their details have been correlated and compared with fundamental physics and unclassified documents about the first U.S. implosion bombs (Gadget, tested in New Mexico on 16 July 1945, and its fully packaged version, Fat Man, dropped on Nagasaki on 9 August 1945) and other nuclear weapon designs.[18] Based on this information, approximate design parameters have been calculated for the German spherical implosion bomb, specifically the version that Ilyichev reported was tested in Thuringia in March 1945. The results are summarized in Table 8.5. For much more information, see Section D.15.5.

The implosion design described by Ilyichev and the other sources seems very detailed, physically feasible, and deeply grounded in experimental and engineering details. While similar to the U.S. Gadget/Fat Man, it does not appear to be a carbon copy of that design, suggesting that it was arrived at independently and not by any German espionage of the U.S. program. In fact, in some respects the German design was several years more advanced than U.S. designs. The German design seems to have been far more than an abstract concept that was never reduced to practice, or a hasty idea that was thrown together at the end of the war. It appears to have been the end product of a well-funded, long-running, highly scientifically skilled nuclear weapons development program.

[18] E.g., Coster-Mullen 2012; Goncharov 1996a, 1996b; Goncharov and Riabev 2001; Gsponer and Hurni 2009; Chuck Hansen 1988, 2007; Bruce Cameron Reed 2015a, 2019; Serber 1992; Sublette 2019; Wellerstein and Geist 2017; Winterberg 2010.



March 1945 Soviet report on German fission bomb test explosions



НАРОДНЫЙ КОМИССАРИАТ
ОБОРОНЫ СОЮЗА ССР

ГЛАВНОЕ
АЗВЕДЫВАТЕЛЬНОЕ УПРАВЛЕНИЕ
КРАСНОЙ АРМИИ

3 марта 1945

№ ...

г. Москва

Ex. № ...

НАЧАЛЬНИКУ ГЕНЕРАЛЬНОГО ШТАБА
КРАСНОЙ АРМИИ

ГЕНЕРАЛУ АРМИИ тов. АНТОНОВУ

Докладываю:

Наш достоверный источник из Германии сообщает:

"Немцы в последнее время произвели два взрыва бомб большой мощности в Тюрингии. Взрывы проводились в лесной местности в обстановке строжайшей секретности. От центра взрыва деревья повалены на расстоянии 500-600 метров. Уничтожены специально построенные для опытов укрепления и сооружения. Находящиеся в центре взрыва военнопленные погибли,

Figure 8.33: Examples of some of the evidence for the development of a fission implosion bomb in wartime Germany. Above: Erich Schumann's schematic design for a spherical implosion bomb (Section D.8). Below: the beginning of a March 1945 Soviet intelligence report giving Joseph Stalin details about successful German tests of a fission implosion bomb (Section D.12).

Component	Gadget/Fat Man	Thuringian Device
Neutron initiator	~ 7 g beryllium/polonium-210 "urchin" 1.25 cm radius	Deuterium + lithium with high voltage ~ 1.25 cm radius and/or external 6 MeV betatron
Pit	6.2 kg ^{239}Pu 4.6 cm radius	**For test:** ~1 kg inner layer of ^{235}U with ~ 5–10 kg natural or low-enriched U outer layer **For deployment:** ~ 5–10 kg ^{235}U ~ 5 cm radius
Tamper/ reflector	108 kg natural U 11.1 cm radius	~ 100 kg natural U ~ 11 cm radius
Neutron absorber	Boron-10 plastic 3.2 mm thick	~ 1.3 kg cadmium ~ 1 mm thick
Pusher	130 kg aluminum 23.5 cm radius	~ 130 kg aluminum ~ 23 cm radius
Explosive	Composition B and baratol 2500 kg, segmented ~ 70 cm radius	TNT, RDX, and liquid oxygen ~ 1400 kg, segmented ~ 63 cm radius
Explosive case	~ 180 kg aluminum 72.5 cm radius	~ 140 kg aluminum ~ 64 cm radius
Ballistic case	Steel 4.5 mm thick 75 cm radius	~ 190 kg steel ~ 4.5 mm thick 65 cm radius
Overall radius	75 cm	~ 65 cm
Total mass	3000 kg (bomb only) 4670 kg (with shell and fins)	~ 2000 kg
Delivery system	Boeing B-29 heavy bomber	A-4, A-9, or A-9/A-10 ballistic missile
Explosive yield	20 kilotons	**For test:** < 1 kiloton **For deployment:** ~ 5–100 kilotons

Table 8.5: Comparison of the U.S. Gadget/Fat Man implosion design (from unclassified sources) with extrapolated design parameters of the March 1945 Thuringian device (Section D.15.5). The explosive yield of the German design was highly dependent on how much fission and fusion fuel were used.

Neutron initiator. A neutron initiator provides neutrons to start a fission chain reaction at the optimal time during implosion. Gadget/Fat Man used a crude polonium-210/beryllium "urchin" initiator that produced $\sim 2 \times 10^8$ neutrons/sec when crushed at the center of the bomb [Reed 2019, p. 305]. Ilyichev and other sources reported that the neutron initiator at the center of the German bomb used fusion fuel (e.g., deuterium + lithium) stimulated by high voltage (similar to the high-voltage fusion neutron initiators used by modern nuclear weapons). During the final two years of the war, the C. H. F. Müller company in Hamburg produced and delivered at least five high-voltage fusion neutron generators that produced up to 2×10^{11} neutrons/sec, 1000 times higher than the U.S. urchin (pp. 3997, 4356). Hans Ritz, the managing director of C. H. F. Müller, told Allied investigators in May 1945 that his company's work was important for nuclear weapons (pp. 4356–4358). A Dutch physicist told postwar Allied investigators that "the S.S. placed high importance on obtaining neutron generators" from Müller and other suppliers for secret "new weapons" (p.

4352). After the war, Kurt Diebner patented a high-voltage fusion neutron initiator at the center of an implosion bomb (pp. 4298–4299).

In addition to serving as a neutron initiator, the fusion fuel at the center of the German bomb design could have caused significant fusion boosting of the explosive yield of the bomb. Fusion reactions produce copious neutrons, which would promote many fission reactions in the surrounding pit, greatly increasing the number of fission reactions and hence the yield before the bomb flew apart and the reactions stopped. Fusion boosting was not even tested by the United States until the Greenhouse Item test in 1951 [https://nuclearweaponarchive.org/Usa/Tests/Grnhouse.html]; it is now commonly used in nuclear weapons.

Ilyichev also referred to a second neutron initiator: an external compact betatron directing electrons with energies of at least 6 MeV toward the center. The $\geq$6 MeV electrons would produce $\leq$6 MeV gamma-ray photons in the uranium via bremsstrahlung and other absorptive processes, the photons would induce photofission reactions in the uranium, and neutrons would be released. This second neutron initiator would have further increased the number of initial neutrons and hence the yield. It also would have served as a backup initiator in case the fusion neutron initiator failed to fire at the right time. Several manufacturers produced betatrons during the war; in particular, Siemens-Reiniger in Erlangen built compact 6-MeV and 7-MeV betatrons. The United States did not use a betatron as a neutron initiator in a bomb until the George test of Operation Tumbler-Snapper in 1952 (pp. 3100–3101, 3991–4004, 5206).

Pit. Ilyichev described the pit of the Thuringian device as a hollow sphere of ^{235}U that was imploded to achieve criticality. Gadget/Fat Man used a hollow spherical pit with 6.2 kg ^{239}Pu. Since the Thuringian device appears to have been fairly comparable in overall size and design, it seems reasonable to assume that it could have accommodated a pit of up to 5–10 kg of ^{235}U. Much less ^{235}U may have been used in the test explosions, especially if the central fusion fuel provided a significant number of neutrons. Multiple independent sources appear to have mentioned the wartime German production of fission pits with masses between 1 and 8 kg (pp. 3368–3369, 3861–3864, 4214, 4221, 4245–4248, 4451, 4610, 4681–4685, 4949).

Tamper/reflector. Ilyichev listed a "delay mechanism" between the "sphere made of metal uranium 235" and the aluminum "protective casing." Gadget/Fat Man used a 108 kg natural uranium tamper between the pit and the aluminum pusher to "delay" the expansion of the fissioning center and to reflect escaping neutrons, thereby increasing the yield. The German tamper probably also used around 100 kg of natural uranium. Elsewhere in his report, Ilyichev appears to have simply lumped the uranium pit and uranium tamper together in describing the inner part of the bomb as being "filled with uranium." Uranium metal was available from suppliers such as Auergesellschaft, Degussa, Buchler, and Treibacher.

Pusher. Ilyichev stated: "The uranium sphere is encased in a protective aluminum casing." Gadget/Fat Man used a 130 kg aluminum "pusher" between the conventional explosive and the uranium reflector/tamper. Because the aluminum pusher's density was higher than that of the explosive but lower than that of the uranium, the pusher helped to efficiently transfer the implosive shock wave from the explosive to the uranium. The Thuringian device apparently used the same approach. The wartime German aluminum industry was enormous and highly capable, and witnesses described secretive work that had been conducted during the war to produce and test nesting aluminum spheres closely resembling the description of those in the implosion bomb designs (pp. 4164–4169, 4308).

Neutron absorber. Ilyichev, Schumann, and the "capable young engineer" in Poland mentioned a layer of neutron-absorbing cadmium to prevent stray neutrons from initiating fission reactions in the core at the wrong time. Gadget/Fat Man used a layer rich in boron-10 for that same purpose. Wartime German companies such as Kampschulte, Blasberg, and Wilhelm Meyer did electroplating of aluminum components, including electroplating with cadmium, and would have been capable of producing a cadmium-electroplated aluminum pusher (pp. 4186–4190).

Explosive. Ilyichev said the Thuringian device used specially shaped segments of TNT, although that might mean any of several TNT-related explosives that were widely produced by Germany during the war. Erich Schumann and Walter Trinks demonstrated a sophisticated knowledge of TNT, hexogen/RDX, other explosives, and explosive lenses using combinations of those materials. Schumann and his colleagues began working on explosive lenses no later than 1940, and by 1942–1943 they were testing large explosive lenses (pp. 4249–4257). Based on information from Ilyichev, Schumann, and Trinks, the explosive layer's mass appears to have been approximately 1400 kg.

TNT molecules ($C_7H_5N_3O_6$) contain relatively few oxygen atoms and normally release their explosive energy by decomposing into a number of smaller oxygen-deficient molecules. Without providing added oxygen, detonation releases 4.184 GJ of energy per ton of TNT. If enough liquid oxygen were provided, detonation could release up to 14.5 GJ per ton of TNT. Thus with liquid oxygen, the $\sim$1400 kg of explosives in the Thuringian device could easily have been quite comparable to or even significantly more powerful than the 2500 kg of explosives in the Gadget/Fat Man design.

Explosive case. According to Ilyichev: "TNT is covered by a protective layer made of a light aluminum alloy." If the aluminum explosive case had an outside radius of $R = 64$ cm (just smaller than Ilyichev's quoted radius for the outer steel case), a thickness of 1 cm, and a density of 2.70 g/cm^3, its mass would have been approximately 140 kg.

Ballistic case. Ilyichev stated: "An exterior casing of armored steel is installed above the blasting mechanism." Steel alloys have densities in the range of 7.75–8.05 g/cm^3, so one may use an average density of 7.9 g/cm^3. If the Thuringian device had a steel ballistic case with an outside radius of $R = 65$ cm and the same thickness as Fat Man's case (0.45 cm), the mass of the case would have been approximately 190 kg.

Total mass. The component masses for the Thuringian device in Table 8.5 add up to a total mass of approximately 2000 kg, just as Ilyichev and Schumann reported. Thus the German bomb had a total deployed mass less than half that of the first U.S. fission bombs (4670 kg for Fat Man), yet could have had a comparable or even greater yield.

Smaller version. In addition to the two-ton spherical fission implosion bomb described above, several sources discussed the wartime development of a smaller fission bomb. It was described as a tactical, nonspherical, two-point-ignition, fission implosion bomb that was externally similar to a standard German 250 kg bomb, had a full yield likely less than one kiloton, and was potentially ready for deployment (pp. 4284–4286, 4309–4315, 5076).

Delivery vehicles. It took the United States several years to reduce the size and mass of fission bombs from its initial Fat Man and Little Boy designs. According to dozens of independent sources (p. 5923), the German fission bombs were intended to be launched on a rocket; the United States was not prepared to do that until 1958 (after extensive help from hundreds of German-speaking scientists and engineers it had acquired). During the war, jet bombers and submarine-launched missiles were also under development as delivery vehicles for the fission bombs (p. 5922).

8.8.9 Hydrogen Bomb Designs

Wolfgang Ferrant (German?, ??–??), Ulrich Jetter (German, 1914–??), Alfred Klemm (German, 1913–2013), Karl Lintner (Austrian, 1917–2015), Josef Mattauch (Austrian, 1895–1976), Erich Schumann, Georg Stetter (Austrian, 1895–1988), Walter Trinks, and many others worked in teams that researched and produced significant amounts of fusion fuels and potential methods to use them (Section D.9).

German patents, articles, and other documents from 1933 through 1945 discussed how to produce fusion reactions in high-voltage tubes (pp. 3992–4004 and 4319–4365). That technology would have been very useful as a fusion neutron initiator in a fission bomb, as described by Kurt Diebner (p. 4299) and Ivan Ilyichev (p. 4529).

In postwar papers apparently based on wartime work, Erich Schumann and Walter Trinks (pp. 4225–4293) and Kurt Diebner (pp. 4298–4305) described spherical implosion bomb designs with a center of fusion fuel inside a spherical shell of fission fuel. That "fusion boosting" approach could have greatly increased the yield of a fission bomb by supplying far more neutrons to induce fission reactions.

A number of documents show that there was wartime work using lithium and deuterium together as fusion fuel (pp. 4343–4379). Because lithium deuteride is solid and not a gas or cryogenic liquid, it makes an ideal fuel for hydrogen bombs.

During the war, Alfred Klemm (under the direction of Josef Mattauch) perfected a method to separate the lithium-6 isotope from the predominant lithium-7 in natural lithium (pp. 4382–4385). That would only be useful for nuclear applications. Klemm also stated that there was wartime work to produce tritium, another very potent fusion fuel (p. 4384).

In 1950, Ulrich Jetter (German, 1914–??) published a detailed proposal that fusion bombs could use lithium-6 deuteride as readily storable solid fuel, rather than the much more troublesome cryogenic deuterium and tritium (p. 4386). Based on the other documents available, Jetter's description appears to be directly based on wartime German work. According to conventional histories, lithium-6 deuteride was first considered in the United States by Edward Teller in 1947 and in the Soviet Union by Vitaly Ginzberg in 1949, was first tested by the United States in 1954, and is commonly used in modern H bombs.[19]

In 1946, several scientists and engineers reported that during the war, Germany had been working on a 6-ton radioactive bomb, as well as methods to deliver it by rockets or aircraft (pp. 4376, 4388–4401, and 5411). Such a massive bomb would have been very challenging to deliver, and could presumably only have been justified if it were a hydrogen bomb. Conventional explosives, a "dirty bomb" of conventional explosives with radioactive material, chemical weapons, biological weapons, and even fission bombs could have been packaged into much smaller and much more easily deliverable sizes (and if necessary, several of them could have been delivered separately to the same target).

A 1946 U.S. intelligence document mentioned wartime German research on H-bomb development as well as nuclear-armed ballistic missiles (p. 4406).

In 1944–1945, several independent sources reported that Germany was developing a bomb with a six-mile blast radius, which is characteristic of the several-megaton energy of an H bomb, in stark

[19] Goncharov 1996a, 1996b; Chuck Hansen 1988, 2007; Rhodes 1995; Sublette 2019; Wellerstein and Geist 2017.

contrast to the much smaller several-kiloton energy of a plain fission bomb (pp. 4403–4405).

From the currently available sources, the detailed design of the German H-bomb is unclear. However, according to unclassified references, there are two major types of H-bomb designs.[20]

The simpler one to build is what the Soviets later called a "layer cake" (*sloika*), a spherical implosion bomb with layers of fusion fuel interspersed with layers of fission fuel. The fusion reactions contribute only a modest amount of energy, but a huge number of neutrons that enable the consumption of far more fission fuel than would otherwise be possible. The postwar Soviet nuclear program was heavily dependent upon German scientists, materials, and ideas, and the first Soviet H-bomb (Joe-4 or RDS-6, tested on 12 August 1953; see p. 1650) employed the layer cake design, with a weight of 4.5 tons, diameter of 1.5 meters, and explosive yield of 400 kilotons. Joe-4's yield could have been higher if its surrounding layer of conventional explosives had been better able to compress the layers of fission and fusion fuel [Wellerstein and Geist 2017]. If there was a wartime German design that was very similar but had 1.5 tons more of surrounding conventional explosives (total weight of 6 tons), its diameter would have been around 1.8 meters, and its explosive yield could easily have been in the 1.5-megaton range (corresponding to a six-mile blast radius).

The second major type of H-bomb is a "two-stage" design, in which the dense outer bomb casing surrounds both a fission implosion bomb (the first stage) and a neighboring mass of fusion fuel (the second stage). When the fission bomb detonates, its heat and pressure ignite fusion reactions in the adjacent fusion fuel. If the outer bomb casing is made of fission fuel (even natural uranium), high-energy neutrons from the fusion reactions can trigger extensive fission reactions in the outer bomb casing, making it effectively a third stage of the explosion. Friedwardt Winterberg, who worked very closely with Kurt Diebner after the war, published a highly distinctive ellipsoidal two-stage H-bomb design that looks rather different than standard U.S. H-bomb designs, but that is deeply steeped in earlier German hydrodynamics and physics research (p. 4411). A surviving 1944 sketch from Walther Gerlach shows an ellipsoid in conjunction with nuclear reactions involving deuterium, which seems to support the wartime origin of Winterberg's ellipsoidal H-bomb design (p. 4415).

Werner Grothmann stated that the German nuclear program was developing several different bomb types, including a hydrogen bomb. He said that the hydrogen bomb looked like a "swollen bomb" (ellipsoidal?), would have been a hundred times more powerful than a fission bomb (megatons vs. tens of kilotons), and was expected to be ready in 1946 (which suggests that it had already progressed far in its development by 1945); see pp. 3419 and 4310. Other sources expected the German hydrogen bomb to be ready even sooner, sometime in 1945, if the war had continued (pp. 4405, 4372, 4397).

In 1947, when Edward Teller was trying unsuccessfully to invent a workable design for the U.S. hydrogen bomb, he sent a highly unusual, specific, and urgent request for Siegfried Flügge to help him with a "physics... program... of interest and importance to the national security," stating that Flügge would "be of marked assistance in carrying out the aforementioned program" (p. 5042). Flügge was indeed brought to the United States, and it has never been publicly revealed what he worked on. In fact, late in the war and after the war, there was a large influx of scientists and engineers who came to the United States and/or United Kingdom and who were from or had knowledge of the German nuclear program (p. 1620). Many of those scientists appear to have been closely tied to the wartime German work on H-bombs, and may have especially aided the U.S. H-bomb development program between 1945 and 1954.

[20] Goncharov 1996a, 1996b; Chuck Hansen 1988, 2007; Rhodes 1995; Sublette 2019; Wellerstein and Geist 2017.

8.8.10 October 1944 Test Explosion on the Baltic Coast

A number of sources reported a test explosion on the Baltic coast in October 1944 (Section D.10).

A May 1944 U.S. Army Air Forces intelligence document listed numerous research and development sites in Germany. It correctly identified the rocket and jet propulsion work being conducted at Peenemünde and the experiments being conducted at many other highly classified locations, but noted that the "most secret research" was conducted on Rügen and Usedom islands—research even more secret than the rockets and jets (p. 4431).

In August 1944, a German prisoner of war reported that "experiments are conducted on an estate in Pomerania and it is alleged that this explosive is capable of destroying everything in a radius of several kilometers" (p. 4434).

On 20 October 1944, the U.S. physicist and intelligence analyst Philip Morrison mentioned "recent reports of Baltic explosions" that were being investigated by the Manhattan Project as possible tests of a German atomic bomb (p. 4437).

A 21 October 1944 OSS intelligence report described the October test: "The Germans have completed a weapon which is founded on the principle of the disintegration of matter (Atomzertruemmerung). Experiments have been performed which have proved conclusive[...] The radius of action is supposed to be about three kilometers" (pp. 4440–4443).

A 19 January 1945 U.S. military intelligence summary covering many areas of advanced German research included a subject heading for "ATOMIC BOMB," under which it mentioned "close surveillance of the area in which tests are alleged to have taken place" (p. 4444). The report focused largely on the most recent work being conducted on the Baltic coast, suggesting that the tests occurred in late 1944 on the Baltic coast.

In May 1945, German prisoner of war Friedrich Olmes said there had been "experiments with the atom-splitting bomb" and "practical experiments were conducted on the Baltic coast" (p. 4446).

A 19 August 1945 U.S. Army Air Forces intelligence report entitled "Investigations, Research, Developments, and Practical Use of the German Atomic Bomb" presented testimony by Rudolf Zinsser, a German pilot captured by U.S. forces, that in October 1944 he flew near the massive explosion of a new German bomb on or near the Baltic coast, describing in detail a very large mushroom cloud and severe electrical disturbances (p. 4448). After further investigation, rather than dismissing Zinsser's report, the United States decided to upgrade it from Secret to Top Secret in October 1945 (p. 4462).

In consistent public testimony from 1945 until his death in 2007, Italian military correspondent Luigi Romersa stated that by a special arrangement between Benito Mussolini and Adolf Hitler, on 12 October 1944 he witnessed the massive explosion of a new German bomb on the Baltic coast (apparently Rügen island), had to wait in a bunker for many hours afterward for the site to become less dangerous (short radioactive half-lives?), and then had to wear a special protective suit when inspecting the leveled test site afterward (pp. 4468–4478).

Werner Grothmann stated in 2000–2002 interviews that there was a successful atomic bomb test in October 1944 (p. 4480).

In a 13 March 2005 television interview, Elisabeth Mestlin stated that she observed a massive explosion on Rügen from a neighboring island on 12 October 1944 (p. 4479).

8.8.11 Circa November 1944 Test Explosion in Poland

Multiple sources reported a test explosion in Poland in approximately November 1944 (Section D.11).

A Top Secret U.S. cable from Warsaw in March 1946 stated: "Information has been given this Embassy by a capable young engineer working in the zinc industry, that one of the best if not the only material for atomic bomb containers is cadmium" (p. 4293). This "capable young engineer" in Poland knew that atomic bomb casings included a layer of cadmium, which was true for the implosion bomb designs described by both Ilyichev and Schumann (Section 8.8.8). The Polish engineer's knowledge suggests that German-run industry in wartime Poland was involved in developing and/or testing an atomic bomb.

Robert Jackson, chief U.S. prosecutor at the Nuremberg trials, stated on 21 June 1946 that he had received evidence that a new bomb design producing very intense heat had killed 20,000 Jewish prisoners in a specially constructed test village in Poland (p. 4502).

In August 1946, a FIAT intelligence document mentioned that there had been a number of unconfirmed reports that "about Christmas 1944, successful experiments were conducted in Pomerania with V-1 and atomic warheads, radio directed. The ensuing crater was 2 km in diameter" (p. 4504). There was also an August 1944 report of nuclear weapons development work in Pomerania (p. 4434).

In December 1946, Otto Hahn said that there had been rumors that "atom bomb tests had been carried out in Poland during the last year of the war which were supposed to have had an effect similar to the first atom bomb dropped on Hiroshima though on a considerably smaller scale" (p. 4504).

Gezo Mansfeldt, a survivor of Auschwitz, reported in December 1946 that he was frequently interrogated by Soviet officials about high-security wartime production work at Auschwitz and that he "learned of the atomic bomb tests" that were apparently related to that work (p. 4507).

A 1947 U.S. intelligence report stated that the Germans built a heavy water production plant near Auschwitz and that it was removed by the Soviets (p. 4507). Heavy water would only be useful for nuclear work, and the production of heavy water near Auschwitz suggests the presence of other nuclear work in Poland.

Another 1947 intelligence report discussed wartime nuclear weapons work at Tucheler Heide in Poland, including the production of ^{235}U and ^{239}Pu and apparently even 1–5 kg fission pits for atomic bombs (p. 4948).

In 1947, Heinrich Himmler's physical therapist, Felix Kersten, stated that Franz Göring, a senior SS security official, had told him late in the war that a new bomb design producing several thousand degrees of heat had killed 20,000 Jewish prisoners at a test site in Poland (p. 4514).

Heinrich Himmler's personal astrologer, Wilhelm Wulff, confirmed that Franz Göring had told him the same story about an atomic bomb test in Poland (p. 4515).

Werner Grothmann stated that there was a successful atomic bomb test in or around November 1944 (p. 4480).

8.8.12 March 1945 Test Explosions in Thuringia

A number of sources reported test explosions in Thuringia in March 1945 (Section D.12).

A 15 November 1944 letter from General Ivan Ilyichev to Joseph Stalin reported that the Germans in Thuringia were preparing under hurried but very high security conditions to test a new spherical "bomb of unusual construction" with a "large destructive power" that might be an atomic bomb (p. 4525).

A 23 March 1945 letter from General Ilyichev to Joseph Stalin reported that the Germans in Thuringia had recently conducted two very high-security test explosions of a new bomb design, described in considerable detail as a 2-ton, 1.3-meter-diameter spherical implosion device with multiple concentric layers and a ^{235}U core that created a "massive radioactive effect," incinerated or burned nearby prisoners of war, and destroyed buildings and trees within a radius of 500–600 meters (Fig. 8.33 bottom and p. 4529).

In a 30 March 1945 letter from Igor Kurchatov to Joseph Stalin, Kurchatov repeated and analyzed the details reported in the 23 March 1945 letter, said it gave a "very believable description of the construction of the bomb," and requested further information (p. 4540).

21 and 29 May 1945 letters from Georgy Flerov to Igor Kurchatov reported that Flerov was currently in Dresden and en route to study the alleged German atomic test site using Geiger counters. Flerov also requested that former prisoners of war returning from Germany to the Soviet Union should be interviewed to learn if any of them knew anything about the test (p. 4548).

After all of those Soviet investigations, an October 1945 report from Marshal Georgy Zhukov to Stalin stated: "Based on the collected materials, it can be concluded that the German scientists in the field of theoretical and practical research and application of atomic energy have achieved good results up to the creation of the atomic bomb" (p. 4568).

A 1946 Russian interrogation summary reported that Robert Döpel stated that there was an atomic bomb test on a German military base before the end of the war (p. 4576).

It seems there is or at least was considerably more information about the apparent German nuclear tests in Russian government archives, including even a captured German film entitled "Film of the Launch of a V-2 and the Explosion of an Atomic Bomb" (p. 4579). At a bare minimum, there are probably documents identifying the Soviet spy who provided the information given in Ilyichev's two reports, documents reporting the suspected test site location to Flerov (which he seemed to know, but which was not in Ilyichev's two reports), documents reporting what (if anything) Flerov ultimately found, and documents describing the "collected materials" to which Zhukov referred.

21 March 1945 and 9 June 1945 U.S. aerial reconnaissance photos of the Ohrdruf Truppenübungsplatz military base appeared to show a large circular area of possible blast damage, as well as surrounding buildings and vegetation that may have been affected by blast and/or radioactive fallout, whereas a 12 August 1944 aerial reconnaissance photo did not show those features (pp. 4587–4591). There are also other potential craters of interest in the immediate vicinity.

In what appears to be a transcript of her testimony before an East German government inquiry on 16 May 1962, Cläre Werner, a wartime lookout at the Veste Wachsenburg castle near the Ohrdruf military base, reported witnessing a large nearby test explosion on 4 March and another one on 12 March 1945, as well as being informed of the historic nature of the explosions by visiting military and SS officials. She reported that she and some other local residents suffered from symptoms that sound like radiation sickness. Although there are unresolved questions about the nature and the chain of custody of the 1962 transcript, Cläre Werner confirmed the key points of her testimony in several interviews conducted between 1998 and 2003 (p. 4597).

In a transcript of his apparent testimony before the same East German government inquiry on 16 May 1962, Heinz Wachsmut reported being conscripted into a unique work assignment for the afternoon and evening of 5 March 1945 in Thuringia. He reported encountering large numbers of living, dying, and dead people suffering from what sounds like radiation sickness and burns in the aftermath of what the SS told him was a history-making test explosion. Under the close supervision of the SS, he was instructed to wear protective gear, and he burned approximately 450 bodies on woodpiles and saw a total of approximately 700 bodies being burned. (It is not clear if all of those were victims of the test explosion, or if some were victims of the daily harsh treatment of prisoners.) Afterward his protective gear and clothing were burned, he was instructed to wash himself thoroughly, and he was unable to eat for days afterward possibly due to radiation sickness. While there are again unresolved questions about the 1962 transcript, the family of Heinz Wachsmut confirmed that he had described the same events and details to them (p. 4603).

In transcripts of his testimony before East German government inquiries in 1966, Erich Rundnagel, a plumber who had worked for Kurt Diebner's nuclear research group in Thuringia during the war, reported that the scientists had told him they had two eight-kilogram atomic bombs (most likely fission pits for atomic bombs) in their safe (p. 4610).

Colonel Oscar Koch, one of George Patton's top intelligence officers, stated that a German prisoner of war described the massive explosion of a new bomb type in Thuringia in March 1945 (p. 4612).

Werner Grothmann stated in 2000–2002 interviews that there was an atomic bomb test in Thuringia on 4 March 1945 (p. 4480).

The explosive yield of the Thuringian device would have strongly depended on how much fission and fusion fuel were used. If the Thuringian device had been furnished with a ∼5–10 kg pit of weapons-grade fission fuel comparable to that in Gadget/Fat Man, it seems likely that it would have had a comparable yield in the ∼20-kiloton range. If significant fusion neutron boosting occurred from the fusion fuel at the center, the device could have fissioned far more of its fission fuel and hence achieved far larger yields—potentially up to ∼100 kilotons for a ∼10 kg pit with ∼50% efficiency. In fact, a number of independent contemporary sources gave the expected blast radius of the deployed device as 2–4 km (likely depending upon the amount of fuel used), corresponding to explosive yields in the range of 13–100 kilotons (p. 5216).

Ilyichev reported the blast radius of the tests was 500–600 meters. That would correspond to a yield equivalent to roughly 200–350 tons of TNT (p. 5187). To conserve weapons-grade fuel, minimize the mess made in central Germany, and avoid Allied detection, scientists would have been strongly motivated to keep the test explosion as small as possible by using just enough fuel to briefly achieve criticality during peak compression.

People at the test site would have been exposed to the prompt radiation (gamma, neutrons, and beta) released during the explosion. For a fission explosion of 200–350 tons, the lethality [10 Grays (Gy)] radius for this prompt radiation is ~500 meters, very comparable to the blast radius [Glasstone and Dolan 1977, p. 333].

The test would also produce radioactive fallout, which would emit 80% of its total radiation within the first 24 hours and the remaining 20% more gradually over the following days, months, and years [Glasstone and Dolan 1977, pp. 390–397]. The area over which the fallout was distributed would depend on local winds and topography. Using a plausible area of ~100 km^2 and the estimated yield of 200–350 tons, the radioactive exposure from the fallout averaged over the whole area would be ~0.15–0.26 Gy/hr at 1 hour, or ~1.1–2.0 Gy for the first 24 hours (p. 5192). Noticeable symptoms of radiation sickness would begin at a cumulative exposure of ~1 Gy, very serious illness at ~2 Gy, and fairly consistent lethality (within hours or days after exposure) at ~10 Gy [Glasstone and Dolan 1977, pp. 575–587]. Ilyichev reported that most of the civilian population in the surrounding area had been evacuated; even those who were not may not have had enough outdoor exposure to develop symptoms. Any German teams surveying the after-effects of the explosion in nearby areas with Geiger counters would certainly have noticed the radioactive fallout.

Data from U.S. nuclear tests suggests that the fallout dosage immediately around a test site is ~10–100 times higher than that in the much larger surrounding area that receives significant fallout, with a geometric mean value of ~30 times higher (depending on local winds and geography) [Glasstone and Dolan 1977, pp. 419–439]. Using that mean value to multiply the area-averaged dose, ballpark values for the radiation dose right at the Thuringian test site would be ~4.5–7.9 Gy/hr at 1 hour, or ~34–59 Gy for the first 24 hours, lethal doses that may help to account for the lack of later witnesses.

Thus the explosion's prompt radiation at the test site, the radioactive fallout at the test site within the first 24 hours, and the radioactive fallout in nearby towns within 24 hours would easily fit Ilyichev's description that a "massive radioactive effect was observed."

After 75+ years, the radioactivity of the fallout would have dropped to $\sim 2\times10^{-9}$ of its radioactivity 1 hour after the explosion [Glasstone and Dolan 1977, p. 393], or 2.6–4.6×10^{-6} Gy/yr averaged over the area and 7–14×10^{-5} Gy/year at the test site. The residual radioactivity at the test site would be at least ~10–30 times smaller than the natural background radiation (1–2×10^{-3} Gy/yr) and hence extremely difficult to detect. In fact, after 75+ years of water, wind, and human activity, the fallout could easily have become scattered over a significantly larger area than the initial area assumed here, and/or become buried to varying depths in the ground, making it even harder to detect than has been calculated here.

Therefore modern measurements of residual radioactivity cannot prove or disprove whether the March 1945 Thuringian nuclear tests (or other possible wartime German nuclear tests) occurred.

Other scientific methods (especially using mass spectrometry, particle-induced X-ray emission, neutron activation analysis, or other highly sensitive methods; looking for ^{238}U from the tamper; and comparing data at and away from the test sites to eliminate background signals), may or may not be able to detect signs of the tests.

8.8.13 Wartime/Postwar Axis Belief in the Reality of German Nuclear Weapons

Among Axis officials in positions of knowledge, there was a widespread belief in the reality of German nuclear weapons, both during and after the war (Section D.13).

One of Heinrich Himmler's closest diplomatic contacts, Grand Mufti Amin al-Husaini of Jerusalem, said Himmler had informed him in July 1943 that Germany was developing an atomic bomb (p. 4624).

Himmler's political rival, Albert Speer, confirmed that Himmler was keenly interested in developing an atomic bomb during the war (p. 4639).

Hans Ulrich Rudel, the most decorated German pilot of the war, reported that in March 1944 Hitler told him that (1) atomic bombs were at a highly advanced stage of development and (2) the bombs were intended to be delivered via V-type rockets (p. 4637).

On 5 August 1944, Hitler informed the Romanian Prime Minister Ion Antonescu that Germany had developed and would use a V-series weapon with "such a tremendous effect that all human life would be destroyed within a radius of three to four kilometers from the impact point" (p. 4640).

On 16 December 1944, Benito Mussolini stated that "thousands of German scientists are working day and night" to develop new weapons that would change the war, apparently in reference to information he received via Luigi Romersa (p. 4649).

In 16 November 1944 and 9 February 1945 letters from FBI Director J. Edgar Hoover to Franklin Roosevelt's top advisor Harry Hopkins, Hoover reported that intercepted messages from Germany to German spies in the U.S. asked the spies about "the probable reaction of the people of the United States if Germany used the explosive power obtained through the splitting of the uranium atom," high-priority targets in the United States that Germany could bomb, and methods that U.S. laboratories used to avoid criticality accidents with large quantities of enriched uranium, suggesting that Germany possessed large quantities of enriched uranium (pp. 4650–4671).

Widespread German reports from late 1944 through 1945 claimed that Germany was on the verge of deploying atomic bombs and missiles for them (p. 4673).

On 14 February 1945, Hitler told one of his doctors: "In no time at all, I'm going to start using my Victory weapon and then the war will come to a glorious end. Some time ago we solved the problem of nuclear fission, and we have developed it so far that we can exploit the energy for armaments purposes. They won't know what hit them! It's the weapon of the future. With it Germany's future is assured" (p. 4680).

Heinrich Himmler's physical therapist, Felix Kersten, and his personal astrologer, Wilhelm Wulff, independently wrote that in early March 1945, Himmler was very optimistic about the imminent success of an atomic bomb (pp. 4514, 4515).

Henry Picker, a close confidant of Hitler, wrote that before the war ended, prototype fission bombs were completed and ready, and facilities for mass-producing the bombs had been built (pp. 4681–

4685).

In 2000–2002 interviews, Werner Grothmann described how an extensive program run by Heinrich Himmler developed, tested, and debated the deployment of atomic bombs (p. 4714).

In a 1 April 1945 telegram to Allied leaders, Allen Dulles reported that Luftwaffe General Albert Kesselring mentioned deliberations among Hitler's top staff about whether to use a final secret weapon, referred to as the "desperation weapon," that would cause a "terrible blood bath" (p. 4716).

In a September 1945 interrogation, the father of an SS officer told Americans about deliberations among Hitler's top staff over an atomic bomb in April 1945 (p. 4716).

In Otto Hahn's autobiography, he wrote that he had heard from reliable sources that there were at least three completed atomic bombs at the end of the war (p. 4220). Lending additional credibility to Hahn's story, the bombs were said to be at Lüneburger Heide, which wartime Allied intelligence reports had identified as the site of what sounded like large underground uranium enrichment facilities producing fuel for spherical implosion bombs (Section 8.8.4). There were also other reports of nuclear-related work at Lüneburger Heide (pp. 4214–4219, 4446).

Former SS officer Erwin Bartmann reported very similar information from his insider knowledge of conversations among Hitler, Göring, and others—there were specific mentions of "three special bombs" and even up to nine completed bombs by the end of the war (p. 4713).

Shortly after the war, German rocket engineers Wernher von Braun and Walter Dornberger, as well as American officials who examined the German rocket program, reported that Germany planned to use its rockets to carry a "much more powerful explosive," presumably atomic bombs (p. 4727).

In the end, Germany never used nuclear weapons in combat. Franklin Roosevelt and Winston Churchill had made it clear that if Germany used anything other than conventional weapons in the war, the Allies would respond by killing millions of German civilians with crude but effective WWI-style chemical weapons (mustard agent and phosgene) or other means (pp. 2644–2663). German leaders appear to have concluded that they did not have a sufficient number of nuclear weapons and/or sufficiently reliable delivery vehicles to overcome that threat and alter the ultimate outcome of the war. Individual German political or military leaders may have also feared even greater postwar prosecutions if they used nuclear weapons, or considered it more personally beneficial to try to trade German nuclear and other technologies to the Allies than to employ them against the Allies.

8.8.14 Wartime/Postwar Allied Belief in the Reality of German Nuclear Weapons

Both during and after the war, highly placed Allied officials expressed belief in the reality of advanced German nuclear weapons programs. In fact, it appears that after the war, the four major Allied countries found and benefited from materials and expertise from the German nuclear weapons program (Section D.14). All of the relevant wartime and postwar reports with the detailed evidence remain classified or missing entirely from archives. Nonetheless, enough sources are available to prove that those reports did indeed exist, and presumably still do exist. This section gives numerous examples, although it is by no means exhaustive. See Appendix D for much more information.

In two December 1943 cables to Washington, the U.S. Military Attaché in Istanbul warned that "an engineer of the Todt organization revealed in Sofia that the Germans now possess a new type of incendiary far surpassing anything yet used in warfare. The engineer intimated that London would suffer a fate worse than that of Berlin or Hamburg in the near future." The reports added: "The Germans have a weapon in preparation which is more devastating than anything we have ever seen" (p. 4634). Germany had been mining uranium in Sofia since 1938 (Section 8.8.3).

In July 1944, Manhattan Project physicists Philip Morrison and Karl Cohen analyzed available intelligence on the German nuclear program and concluded (p. 4785):

> Recent evidence essentially confirms our earlier general statements on enemy bomb production. The reports now at hand lead us to conclude:
>
> 1. A German "Y" [enrichment] project has been underway since early 1943.
>
> 2. A D_2O pile is in operation, but we do not believe that this is on production level.
>
> 3. It is implied that a separation method is operating at a production level, for it is surely improbable that the enemy will organize a utilization group without something to use.
>
> We include a time schedule, and a technical discuss of the probable means employed.
>
> Enemy production of devices can be as high as:
>
> 1. 1 device every 3 months—on the assumption that 30 kg of material are required per device.
>
> 2. 1 device every month—on the assumption that 10 kg of material are required per device.
>
> In either case the first completed device could be in enemy hands now.

The *Daily Telegraph and Morning Post* reported that in August 1944, the British government had intelligence that Germany was preparing "an atomic bomb" with "an explosive radius of more than two miles," or three kilometers (p. 5057). As noted in Section 8.8.5, the Royal Air Force went to extreme lengths to bomb what appears to have been a German fission reactor and fuel reprocessing complex near Königsberg during the period 26–30 August 1944 (p. 3962).

In September 1944, the *Los Angeles Times* reported that invading U.S. troops in France had found evidence that Germany was preparing a rocket-launched bomb “with an explosive radius of three kilometers” (p. 5058).

Margaret Suckley, Franklin Roosevelt’s secretary, wrote in her diary on 9 December 1944 that Roosevelt had received reliable reports that the Germans had successfully developed a bomb capable of killing everything within a mile and that the German program was “way ahead” of similar U.S. research (p. 4748).

A tantalizing December 1944 summary report from the Manhattan Project’s Foreign Intelligence Unit concluded (p. 4748):

> 1. Intelligence indicates that the enemy is working in the project field. It is likely that he has undertaken one or several of the various processes for the production of bombs on a small scale and to have organized an installation equivalent to our project on final utilization. (TAB A).
>
> 2. The various methods for the production of U-233, U-235 and Pu-239 have been considered in the light of scientific development, basic materials, and industrial effort required. (TAB B). The liquid thermal diffusion process for production of U-235 on a moderate scale and the pile process using heavy water for the production of Pu-239 on a small scale appear to be the most likely possibilities; the production of U-233 on a useful scale appears to be unlikely. Activities inferred from the intelligence and other reports indicate that these processes could have come into operation during 1943. (TAB C).
>
> 3. On the basis of the above analysis it is possible for the enemy to have at least one device in his hands now, but it is improbable for him to have more than three.
>
> [Handwritten in lower right corner:] Cross referenced in Enemy Prod.[uction] of Devices—G[roves?]

Unfortunately, instead of TAB A, the collected intelligence evidence for the German nuclear weapons program, the NARA file only includes a note stating: “In the review of this file this item was removed because access to it is restricted” (p. 4753).

In March 1945, Gerard Kuiper, a highly knowledgeable investigator in the Alsos Mission, wrote a letter that contradicted what the heads of Alsos were claiming at that time (p. 4812): “One is again surprised to see quotations from U.S. senators who think that the war will be over ‘within a few days’. It would be wiser to worry about the chance we still have of losing it if certain high explosives are developed in time. This possibility may, incidentally, be one reason why the Germans are not giving in.”

Rather than heading toward the logical objective of Berlin to topple the German government and beat Soviet forces to the prize, U.S. troops under Generals Patton, Bradley, and Eisenhower rushed straight toward Thuringia. Justifications for this strategy have ranged from preventing Hitler from fleeing south to liberating concentration camps. However, at the very least it seems like an intriguing coincidence that Patton, Bradley, Eisenhower, and other top Allied officials were personally inspecting the Ohrdruf Truppenübungsplatz military base all together on 12 April 1945

(U.S. forces captured the base on 4 April), only a month after the possible nuclear weapons tests at that site (Section 8.8.12) [Karlsch 2005, p. 218]. Other than photos of the generals and some of the concentration camp victims, none of what must have been numerous detailed written reports about what technologies or documents the U.S. forces found at that and nearby facilities have ever been declassified and released to the public.

A 31 May 1945 cable from Eisenhower to Washington, D.C. reported: "A laboratory containing equipment and documents related to experimental work on atomic bombs and AA rockets was located near Lofer, E 7399 by Third US Army" (p. 5020). Eisenhower later told *The New York Times* how seriously he regarded the German nuclear program: "My main concern was that the Germans did not get the atomic bomb to use on us" (pp. 5079–5080).

In fact, at the end of the war, Allied investigators personally inspected many sites that conducted work related to the German nuclear weapons program, including sites in Germany (Lüneburger Heide, Hillersleben, I.G. Farben installations, numerous locations in Thuringia, etc.), Austria (St. Georgen an der Gusen, Ebensee, Redl-Zipf, Lofer, etc.), Czech territory (Pilsen, Podmokly, St. Joachimsthal/Jáchymov, etc.), and elsewhere (pp. 3704–3711, 5008–5031). Detailed reports on what they discovered and learned about the German nuclear program have never been publicly released.

In May 1945, the German submarine U-234 surrendered to the United States. It contained 560 kg of uranium oxide (possibly enriched), bomb detonators, other materials, plans, and technical experts that would have shed light on the German nuclear program. Other submarines carried additional relevant materials, documents, and personnel (Section D.14.5). Where are the many tons of documents, prototypes, and other cargo from the U-234 and the other submarines, as well as all of the reports on the German nuclear and other technology programs that the United States compiled in the process of investigating the submarines' cargoes and interrogating their passengers?

By the end of the war, SS General (and Dr. Ing.) Hans Kammler controlled and knew the details of virtually all German secret weapons research and development programs, including the nuclear weapons program. According to official histories, Kammler died in early May 1945. However, multiple documents in U.S. government archives prove that he surrendered to U.S. forces in May 1945 and was alive and being interrogated by the United States for many months (and perhaps even many years) after the war (pp. 4960–5007). The U.S. government must possess lengthy transcripts or even audio/video recordings of Kammler's interrogations. It would also possess any documents and materials that Kammler had with him when he was captured, or that he was able to direct the Americans to afterward. Kammler's interrogations and documents would almost certainly have provided the United States with considerable detail about the German nuclear program and other very advanced developments. (Albert Speer's capture and interrogation resulted in many shelves full of documents.) How can all of that Kammler material be located and declassified from U.S. government archives?

When nuclear-related censorship was relaxed somewhat after the U.S. atomic bombings of Japan in August 1945, Allied officials made a stunning admission to *Newsweek* (p. 5068): "Since the surrender of the Nazi armies, Allied officers have revealed that Germany would have been able to strike with atomic bombs by January 1945, if the invasion had not come six months before. The highest Allied officials knew that such explosives could have won the war for the Axis."

In a 25 August 1945 press release, the U.S. Office of War Information stated that "Germany's inner war secrets" included "experiments with the atomic bomb," that "Germans made significant progress in the development of an atomic bomb," and that not all "of the secrets. . . may be disclosed at this time" (p. 5069).

A 31 August 1945 U.S. report mentioned "Gerald Klein (Dr.), Dipl.-Eng., Manager of LGW. . . Worked at Peenemünde and later became group director of atomic devices in RLM. At present being used by the British. Evacuated by 'T' Force" (p. 5056). Klein was listed as the manager of "LGW," which was the Luftgerätewerk Hakenfelde A.G., part of the huge Siemens electrical company. If wartime Germany never had atomic devices or even serious plans to make them, as maintained by official histories, why did the RLM or Reichsluftfahrtministerium (Ministry of Aviation) have an entire group dedicated to atomic devices, of which Dr. Klein was the director? Where are the U.K. and U.S. reports on Klein, the organizations named, and the nuclear work?

A remarkable 14 September 1945 OSS cable hinted at far more detailed knowledge about the German nuclear weapons program than has ever been publicly released (p. 5091):

> Our work on this subject is to correlate and cooperate with specially appointed general who has charge of the whole AZUSA [German nuclear] situation and has overall responsibility. [...]
>
> On present sub feature of AZUSA about assisting locating German scientists, special general asked to have the information sent only to Calvert, London Embassy, or to Washington. [...]
>
> This now done and all AZUSA information obtained by OSS in ETO and applicable in ETO situations now to be coordinated only between you or Wisner Sibert and Calvert and advising OSS Washington of resulting decisions or information. This insures desired maximum security with fewest number persons involved. Copies of any reports to be sent OSS Washington without delay and showing action taken.
>
> This subject so tight at this time we are playing very close with special general.

Does this OSS cable show that the U.S. started to really appreciate the full extent of the wartime German nuclear program by September 1945, and took steps to limit that knowledge to the "fewest number persons"? Is that why Zinsser's report of a German atomic bomb test was upgraded from Secret to Top Secret in early October 1945 (Section 8.8.10)? Who was the "special general" mentioned in this cable—Leslie Groves or someone else?

The joint chairs of CIOS, U.S. General Thomas Jeffries Betts, Deputy G-2 of SHAEF, and U.K. Ministry of Supply chief advisor and F.R.S. Professor Reginald Patrick Linstead, wrote a 15 September 1945 final report based on specific discoveries by their CIOS investigators (p. 5076):

> Certain items have been omitted because of security considerations. . . Of particular significance were the statements, made by German experts in the rocket and controlled missile field, that much of the priority accorded their work by the German High Command was in anticipation of the use of atomic explosives. These authorities stated that KWI had repeatedly assured Hitler that an atomic explosive would be available for use within a comparatively short time. During the last months of work by the Peenemünde staff, V-weapons were designed with much smaller war-heads. Quite possibly this trend was in anticipation of the successful development of a German atomic explosive.

Thus the CIOS chairs directly contradicted the public statements of the Alsos Mission and confirmed that there was indeed a German program to develop an atomic bomb, and that it was far more than a paper design program—its hardware had passed through sufficient development, production, and testing by the end of the war that it was ready or nearly ready to be used in combat.

In September and October 1945, General George C. Marshall made several noteworthy public statements: (1) "German technological advances such as in the development of atomic explosives made it imperative that we attack before these terrible weapons could be turned against us." (2) "At the close of the German war in Europe they [U.S. factories] were just on the outer fringes of the range of fire from an enemy in Europe. Goering stated after his capture that it was a certainty the eastern American cities would have been under rocket bombardment had Germany remained undefeated for two more years. The first attacks would have started much sooner." (3) "It is not hard to predict that supersonic atomic rockets will have a profound influence on any war that ever again has to be fought" (p. 5077).

T. M. Odarenko, a longtime physicist from Bell Telephone, was one of the senior scientists involved in transferring advanced electronics and other technologies from Germany and Austria to the United States after the war. He wrote of encountering a large group of refugee nuclear scientists in Austria (pp. 4834–4831):

> Among these evacuees there is a very large group of capable scientists who worked in the field of nuclear physics and chemistry and who have been carrying this work with such facilities as they have been able to assemble. There are two (or possibly more) institutes which were directly involved before the end of the war in a secret German project called "Uranmotor" whose purpose was to split uran[ium] atoms in order to obtain a powerful source of intra-atomic energy. It is apparent that the end result of this work is a method of obtaining an explosive release of atomic energy, or atomic bomb.
>
> ——
>
> Contrary to the statements, attributed by the U.S. newspapers to the various U.S. atomic experts, that it "would take the Germans some 100 years to solve the problem of atomic disintegration on an explosive basis" (for the manufacture of bombs), the opinion of the members of the Institute themselves was that, given a supply of radium and uranium, and permitting their return to Vienna, where certain of their materials and equipments are stored, they would be able to "complete their work" in some 3 to 6 months. Some small scale experiments were claimed to be performed successfully by the Institute before the end of the war in Europe.
>
> That these claims of the Institute are not to be disregarded too readily would follow from the fact that Prof. Smyth spent considerable time with the Institute, revisited them several times, and thought it necessary to insist on the most stringent type of control over the scientific activities of the group, as well as on close individual observations. Perhaps equally significant are the indications of the substantial interest of the Russians in several members of the Institute.

"Prof. Smyth" was Charles P. Smyth, a Princeton chemistry professor and member of the Alsos Mission, who reported to Leslie Groves. Odarenko's reports on the nuclear scientists were also forwarded to Groves.[21] As a result of the reports of Odarenko and Smyth, the Austrian nuclear scientists were closely monitored and controlled for years by U.S. intelligence and military agencies. For example, the leader of the Austrian group, Georg Stetter, was kept under virtual house arrest by U.S. agents in Austria from 1945 until the 1950s, nearly destroying his career (pp. 4844–4846).

A large number of Alsos-related documents from Samuel Goudsmit's files remain classified (pp. 4818–4825). Likewise, some very important German-related files from the Manhattan Project's Foreign Intelligence Unit and the OSS remain classified and unavailable (pp. 4858–4873) [NARA RG 77, Entry UD-22A; NARA RG 226]. Even Lt. Col. George R. Eckman's "Final Report on the ALSOS Mission," written in December 1945, seems to be missing from modern archives (p. 3351). There may be countless other relevant files whose absence is not even noted in the archives.

There is evidence that Dutch intelligence provided important information about the German nuclear weapons program to the United States during and after the war (pp. 4878–4899). Samuel Goudsmit's entire folder of Dutch intelligence on the German nuclear program remains classified and unavailable.

Likewise, there is evidence that French intelligence gave important information about the German nuclear weapons program to the United States (pp. 4900–4901).

Werner Grothmann stated that the fission fuel and components of at least one German atomic bomb were found and removed from Germany by U.S. forces in 1945 (pp. 5086–5089). An archived card catalog of U.S. intelligence reports on Germany shows that there were postwar reports containing detailed information on the German atomic bomb, including a 2 January 1946 document labelled "Blueprints of Atomic Bomb," a 28 March 1946 report on "Atom Bomb Research in Germany & Influence on Developments in Soviet Russia," a 4 June 1947 report entitled "Atomic Bomb," a 25 July 1947 report on "Atomic Bomb Detonating Plans," and others. The reports themselves are still classified and unavailable to the public (pp. 5120–5121).

In private, General Leslie Groves wrote a February 1946 secret memorandum revealing (p. 4852):

> Government measures to encourage the long term exploitation of German scientists by the United States are desirable, particularly with reference to nuclear physicists and chemists who might be of some service to scientists in this country in the field of atomic energy. . . I suggest, therefore, a fifth category, defined as, those German scientists of outstanding ability in the field of nuclear physics and chemistry who, by their past reputation and present knowledge, would be of more value to the national interest of this country if they could be employed here rather than in any other country. . . However, it is extremely important that these persons be prevented from giving their services to a potential enemy of the United States.

In public, though, Groves knowingly and repeatedly made false claims that Germany's nuclear scientists had been few in number and hopelessly backward [Groves 1962].

At the "Ashcan" interrogation center after the war, Hermann Goering told his Allied interrogators that "Germany was within 90 days of producing its first atom bomb when the war ended" (p. 4940).

[21]NARA RG 77, Entry UD-22A, Box 174, Folder 10.10 Austria: Personnel. Shuler to Leslie R. Groves, 26 November 1945, Subject: Problem of Displaced Scientists in American Zone of Austria.

In similar postwar interrogations, Wilhelm Voss, the former director of the Skoda works, told Allied interrogators about the organization and results of the German nuclear weapons program (p. 4960).

A U.S. Department of Commerce press release praised wartime German scientific accomplishments that were more advanced than those of the United States and that were being transferred to the United States to improve its programs: "Spectacular accomplishments in uranium, nitrogen, oxygen recovery, plastics, nuclear physics and many other fields, have been uncovered in the investigation of the chemicals field alone" (p. 5112).

In July 1946, the U.S. *Army Air Forces Review* published an article stating, "it is still a matter of scientific conjecture just how many weeks—or days—it might have taken Germany to be ready with her atomic devices for the V-2s" (p. 5084).

In 1946, U.S. Army Air Forces Colonel George Woods wrote of "Germany's Plans for the 'A-9' with Atomic Bomb": "it is well known that the Germans originally had hoped to have their atomic bomb developments completed by the end of 1944." See p. 5119.

Top Secret 1946 cables from the U.S. Joint Chiefs of Staff to General Joseph T. McNarney (the military governor of the U.S.-occupied zone of Germany and also the commander in chief of the U.S. Forces of Occupation in Europe) ordered him (pp. 5111–5112):

> Except for most cogent reasons you will not permit representatives of nations other than British Commonwealth (excluding Eire) to have access in any U.S. zone of occupation under your jurisdiction to technical information on the following subjects or to related intelligence targets:
>
> ——
>
> Applied and theoretical nuclear physics, including design and operation of devices for producing highly energetic particles, and isotope separation.

These Top Secret Orders from the highest level were written over a year after the end of the war in Europe, after the U.S. had had time to investigate wartime German programs in detail, and they specifically noted advanced nuclear-weapons-related work.

In a 17 August 1946 interrogation, Edmund Sorg described a piloted version of the V-1 cruise missile armed with an atomic bomb (p. 4942).

In discussing German rockets as weapons in an August 1947 interview, General William L. Richardson said "there is evidence to believe that the Germans intended to utilize an atomic warhead which would have made this weapon extremely deadly" (pp. 5081–5082). General Richardson would have been a highly knowledgeable and very sober source for this information. What "evidence" did he have?

In a 19 August 1947 intelligence report that is still heavily censored, Edmund Tilley discussed wartime nuclear weapons work at Tucheler Heide in Poland, including the production of ^{235}U and ^{239}Pu and apparently even 1–5 kg fission pits for atomic bombs. According to Tilley, one of the German scientists most directly responsible for that work, "Dr. Niels" (Walter Nielsch?), had already been taken to the United States for interrogation and/or work (p. 4948).

Many German and Austrian scientists who appear to have been involved in the nuclear program visited or worked in the United States and/or United Kingdom after the war. They may have provided information about wartime German work and aided the U.S./U.K. nuclear programs. Even basic files for some scientists are still not available to the public. For example, virtually the entire "Foreign Scientist Case File" (Paperclip file) of nuclear physicist Otto Haxel has been redacted in response to recent Freedom of Information Act Requests, and Wernher von Braun's Paperclip file is missing entirely. The late-wartime and postwar influx of scientists and engineers who were from or at least had knowledge of the German nuclear program included (pp. 4977–5005, 4904, 5038):

Karl-Friedrich Bonhoeffer	Gottfried Guderley	"Dr. Niels" (Walter Nielsch?)
Wernher von Braun	Paul Harteck	Edgar Petersen
Rudolf Brill	Otto Haxel	Heinz Schlicke
Adolf Busemann	Richard Herzog	Erich Schumann
Walter Dornberger	Johannes Hans Jensen	Otto Schwede
Rudolf Edse	Willibald Jentschke	Edmund Sorg
Krafft Ehricke	Ulrich Jetter	Kurt Starke
Wilhelm Eitel	Georg Joos	Wolfgang Steurer
Gerhard Falck	Hartmut Kallmann	Ernst Stuhlinger
Karl Fiebinger	Hans Kammler	Hans Suess
Wolfgang Finkelnburg	Gerald Klein	Herbert Wagner
Rudolf Fleischmann	Stanley Kronenberg	Wilhelm Westphal
Siegfried Flügge	Heinz Maier-Leibnitz	Friedwardt Winterberg
Walter Glaser	Werner Maurer	Karl Wirtz
Wilhelm Groth	Hugo Neuert	Gernot Zippe

This list is far from exhaustive. Furthermore, a large number of additional scientists were interrogated in Europe. The complete interrogation reports and all other files on all of these scientists and engineers should be sought and released. (Kronenberg and Winterberg came later but were educated by scientists from the wartime nuclear program and appear to have learned some of their secrets.)

From examples such as those given throughout this section and Appendix D, it is clear that there is an enormous amount of information about the wartime German nuclear weapons program that remains classified and/or hidden by various governments. Why is that the case, if the German program was as small and as primitive as government officials and historians have maintained for 75+ years? What is the true history of the German program? What is the true history of Allied knowledge about the German program, both during and after the war? Where is all of the relevant archival and physical evidence stored now?

8.8.15 Further Research That Is Needed

The very incomplete information that is currently available about the wartime German nuclear weapons program, as summarized above and in more detail in Appendix D, appears to best match the pattern of a large and advanced program, not the small and primitive program that has generally been depicted for the last 75+ years (Section D.15). Some readers may object to this claim, but historians should actively search for additional information that could help to confirm or refute this picture:

- Any relevant records in U.S., U.K., French, Russian, or other national archives should be located, declassified, and released to the public. Even from the currently available evidence, it is abundantly clear than highly relevant documents (wartime intelligence on German nuclear tests and progress; postwar interrogations of Hans Kammler, German and Austrian nuclear scientists, and other key players; reports on postwar investigations of nuclear-related sites and submarines; etc.) remain classified and unavailable to the public. The war ended 75+ years ago, and government censorship of all those historical documents must finally end.

- Any relevant information in personal collections (war diaries, preserved documents, photographs, etc.) should be located, authenticated, and analyzed with the other available data.

- Thorough scientific analyses of suspected test sites should be conducted (especially using mass spectrometry, particle-induced X-ray emission, neutron activation analysis, or other highly sensitive methods; looking for ^{238}U from the tamper; and comparing data at and away from the test sites to eliminate background signals), although after 75+ years of radioactive decay and weathering, even the most diligent testing might be inconclusive.

- Extensive and meticulous industrial archaeological digs should be conducted at sites suspected to have been involved in developing or storing nuclear materials or nuclear weapons. Even if much of the material at those sites had been removed by German or Allied forces, any remaining evidence could provide conclusive proof about the nature and extent of the wartime nuclear program.

Until those searches have been thoroughly conducted, historians and scientists should cease making authoritative-sounding declarations that the nuclear program was small and unsuccessful, since there is already a great deal of evidence to the contrary.

If the German nuclear weapons program was indeed successful, one can understand why the major countries involved would have wanted to conceal that fact at the end of World War II and the beginning of the Cold War. Individual Germans with knowledge of the program would not want to appear guilty of additional acts for which they might be punished after the war. Key German players may have been rewarded for offering the fruits of the nuclear program to Allied nations and remaining silent. For purposes of internal morale and external public image, Allied countries would prefer to claim that such technological accomplishments were really their own, and in any case would be highly motivated to try to protect any new weapons technologies from rival Allied nations in the incipient Cold War.

Likewise, if the German nuclear weapons program was successful, one can also understand why the major countries involved might desire to preserve that secret even 75+ years later. The German and

Austrian governments might not want yet another Third Reich offense from their past for which they would need to apologize. Former Allied countries might not want to admit that their wartime and postwar technological prowess was not as great as they had boasted for so many decades, or that that of their vanquished enemy was greater than they had claimed for so long. In any event, routine security classification rules would prevent the release of archival documents with useful details about nuclear weapons designs and production methods, no matter what their age, history, and country of origin might have been (even though far more dangerous, detailed, and up-to-date information is now readily available to everyone on the internet).

Yet if the German nuclear weapons program truly was more successful than the governments have previously admitted, on the whole it would seem far more beneficial for all countries to finally acknowledge that fact than to continue to deny it:

1. As with "truth and reconciliation commissions" in other countries, Germany and Austria could finally acknowledge and address the full extent of the Third Reich's actions, their current citizens (who were too young to have been involved in any of those events) could have a detailed understanding of those actions and history, and these countries could move forward with that chapter fully closed, rather than still having to hide or fear further revelations in the indefinite future.

2. Carefully inspecting and cleaning up any sites involved in producing or storing nuclear materials would prevent contamination of local drinking water, farms, and homes with radioactive isotopes, heavy metals, solvents, or other toxic chemicals.

3. Elucidating all the concentration camp prisoners who died in the preparation, production, and testing of nuclear weapons would finally bring justice to what may be many thousands of currently forgotten victims of the war.

4. The media-consuming public in former Allied countries seems fascinated with and proud of their countries' roles in World War II, so they should be extremely interested in new details about that war, and should in fact find it exciting to learn that their victory was even more hard-won and more consequential than previously known (somewhat similar to how sports fans are more excited by especially close or high-stakes wins).

5. Everyone would gain a much better understanding of the strategic decisions made by all countries during and after the war, making more sense of events and actions that have previously not been as well explained in the history books.

6. All nations would benefit tremendously by learning exactly how revolutionary technologies have been created in the past, so that they could better create and enjoy the benefits of new revolutionary technologies in the future.

For much more information on the German nuclear weapons program, see Appendix D.

For information on wartime German programs to develop intercontinental jets, rockets, and other delivery vehicles for nuclear weapons, see Appendix E.

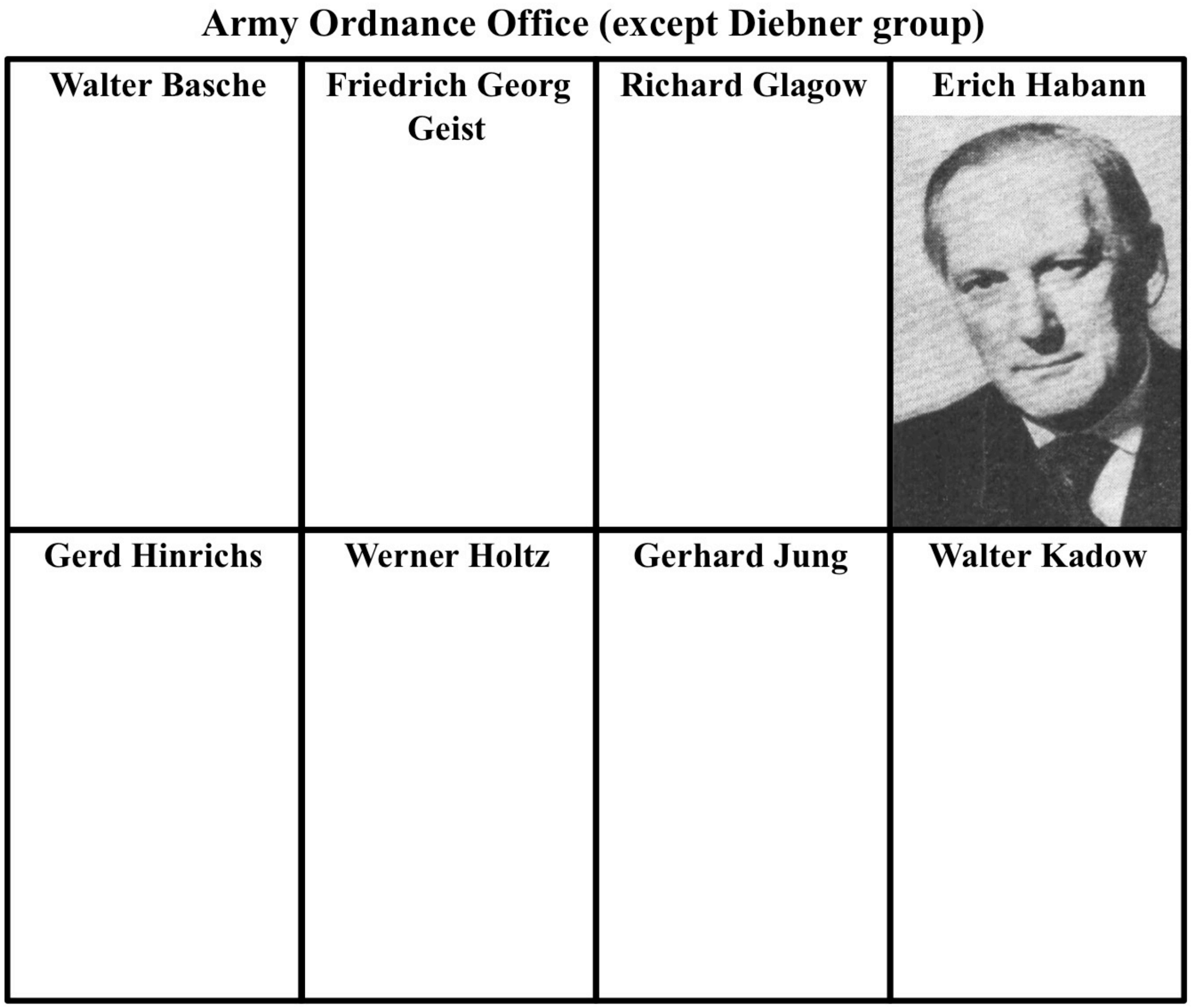


Figure 8.34: Examples of scientists and engineers at the Army Ordnance Office (Heereswaffenamt) who played critical roles in the development of nuclear technologies in wartime Germany.

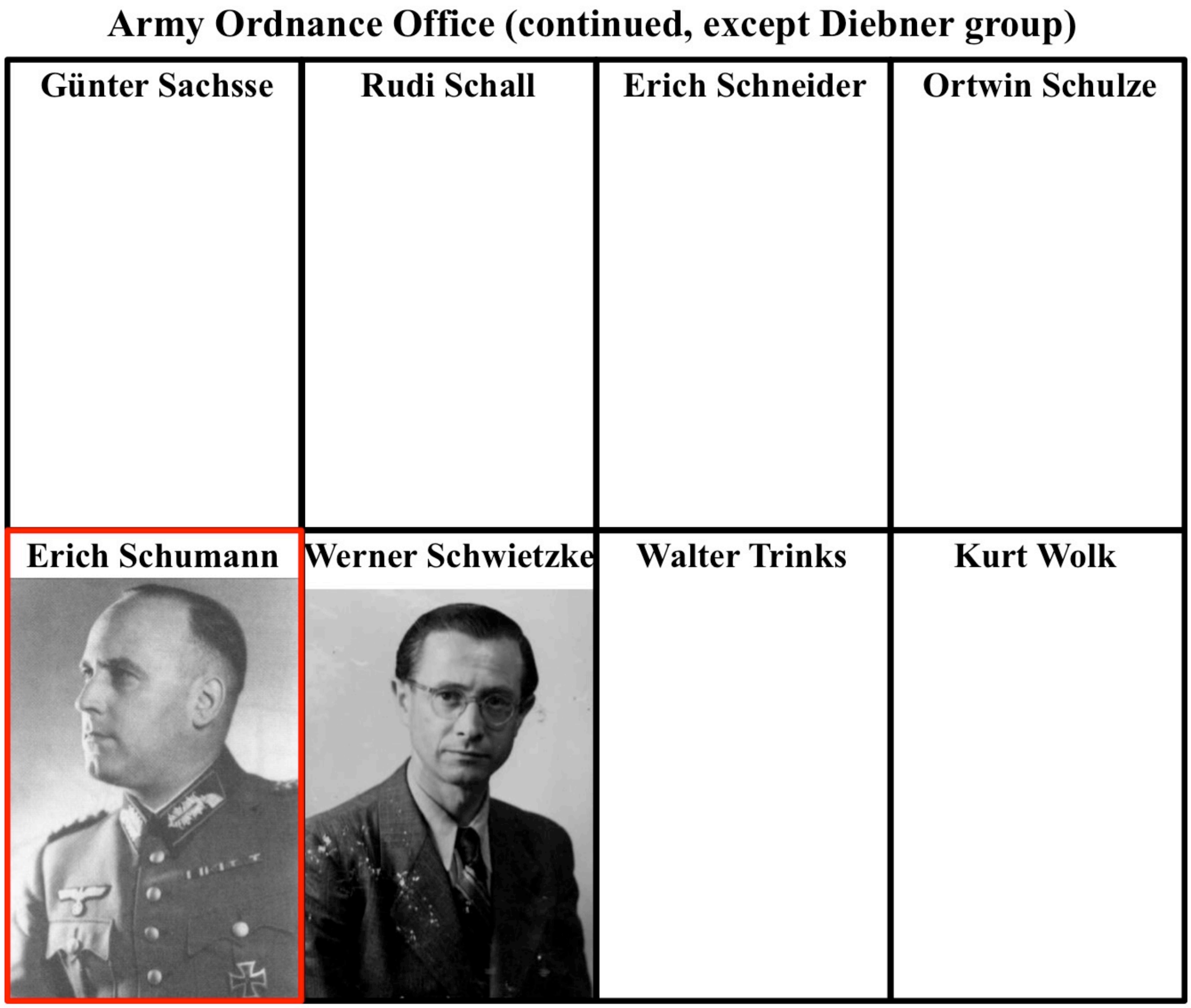


Figure 8.35: More examples of scientists and engineers at the Army Ordnance Office (Heereswaffenamt) who played critical roles in the development of nuclear technologies in wartime Germany. Erich Schumann was the head scientist.

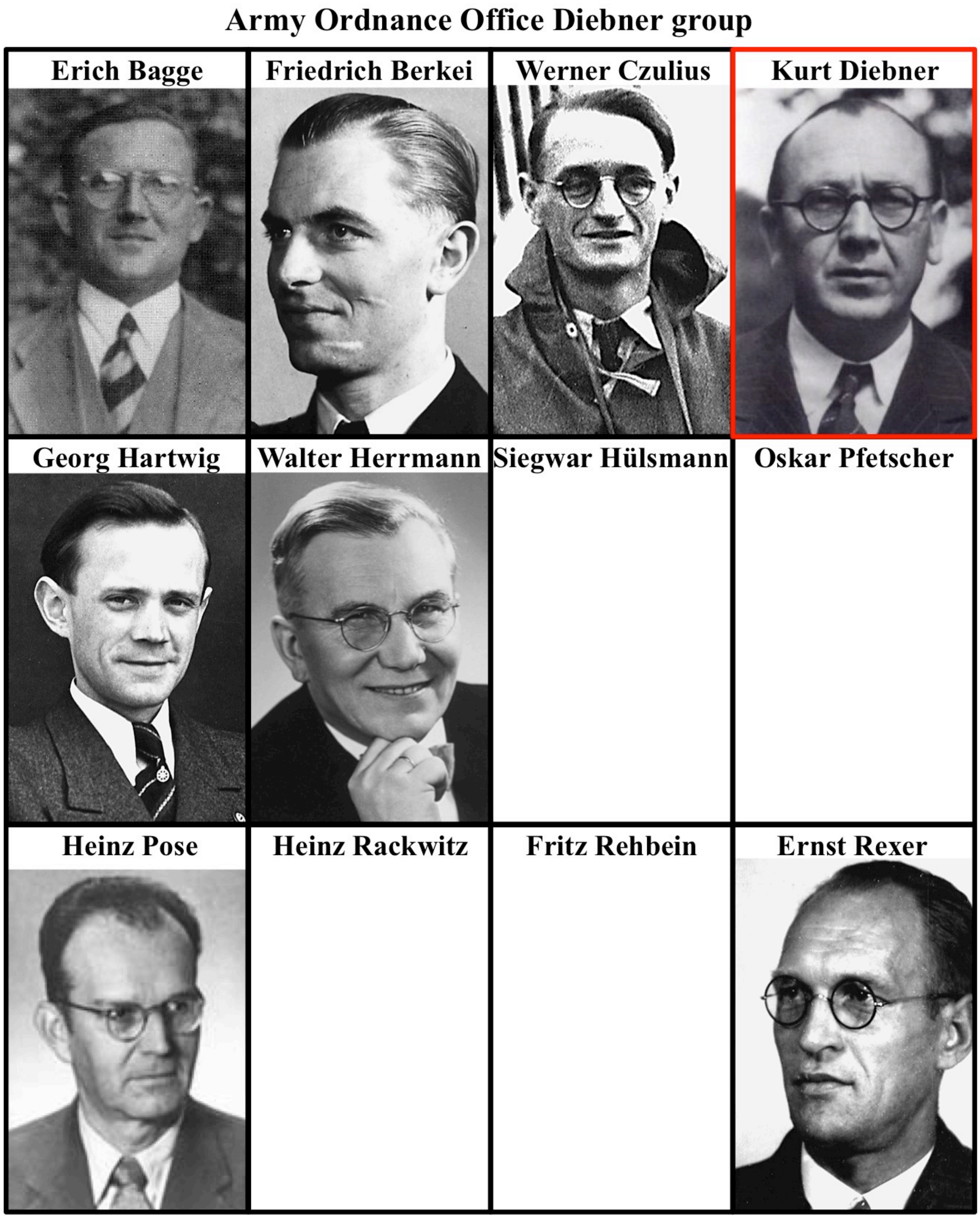


Figure 8.36: Examples of scientists and engineers in Kurt Diebner's group at the Army Ordnance Office (Heereswaffenamt) who played critical roles in the development of nuclear technologies in wartime Germany.

Figure 8.37: Examples of scientists and engineers at Navy (Kriegsmarine, under chief scientist Helmut Hasse) and Air Force (Luftwaffe) laboratories who played critical roles in the development of nuclear technologies in wartime Germany.

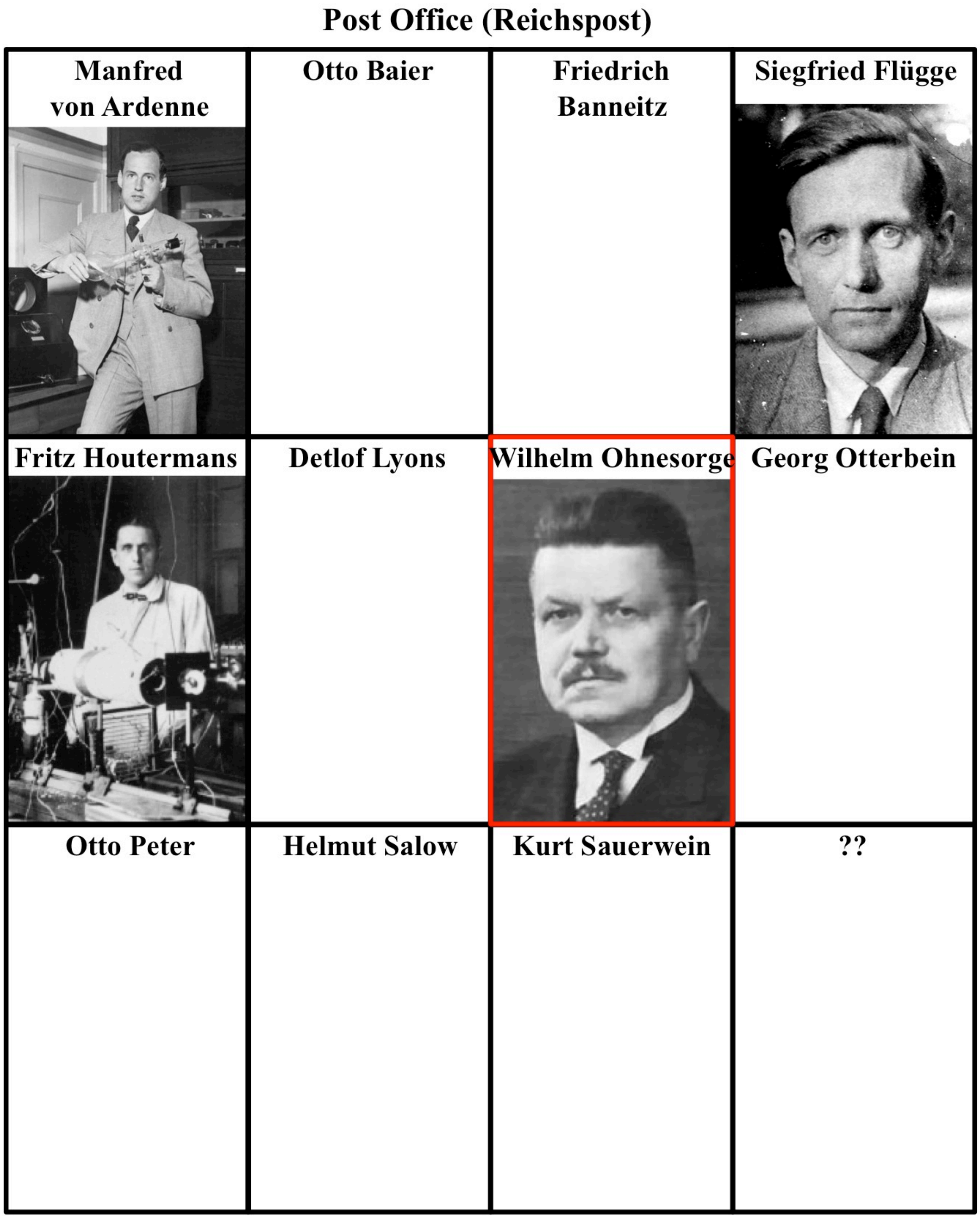


Figure 8.38: Examples of scientists and engineers at Post Office (Reichspost, led by Wilhelm Ohnesorge) laboratories who played critical roles in the development of nuclear technologies in wartime Germany.

Figure 8.39: Examples of scientists and engineers in the SS (ultimately led by Hans Kammler) who played critical roles in the development of nuclear technologies in wartime Germany.

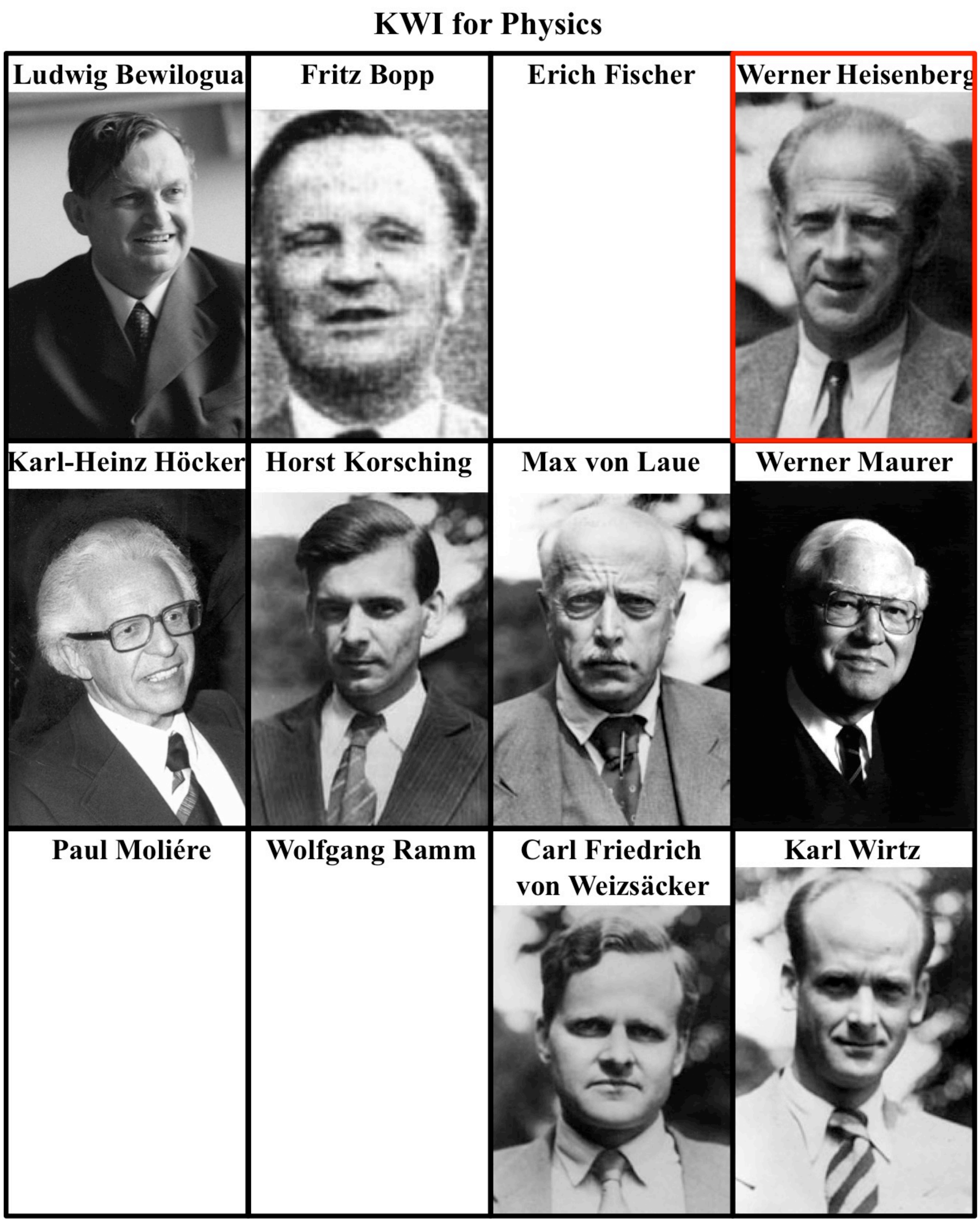


Figure 8.40: Examples of scientists and engineers at the Kaiser Wilhelm Institute (KWI) for Physics who played critical roles in the development of nuclear technologies in wartime Germany. Werner Heisenberg was the head scientist.

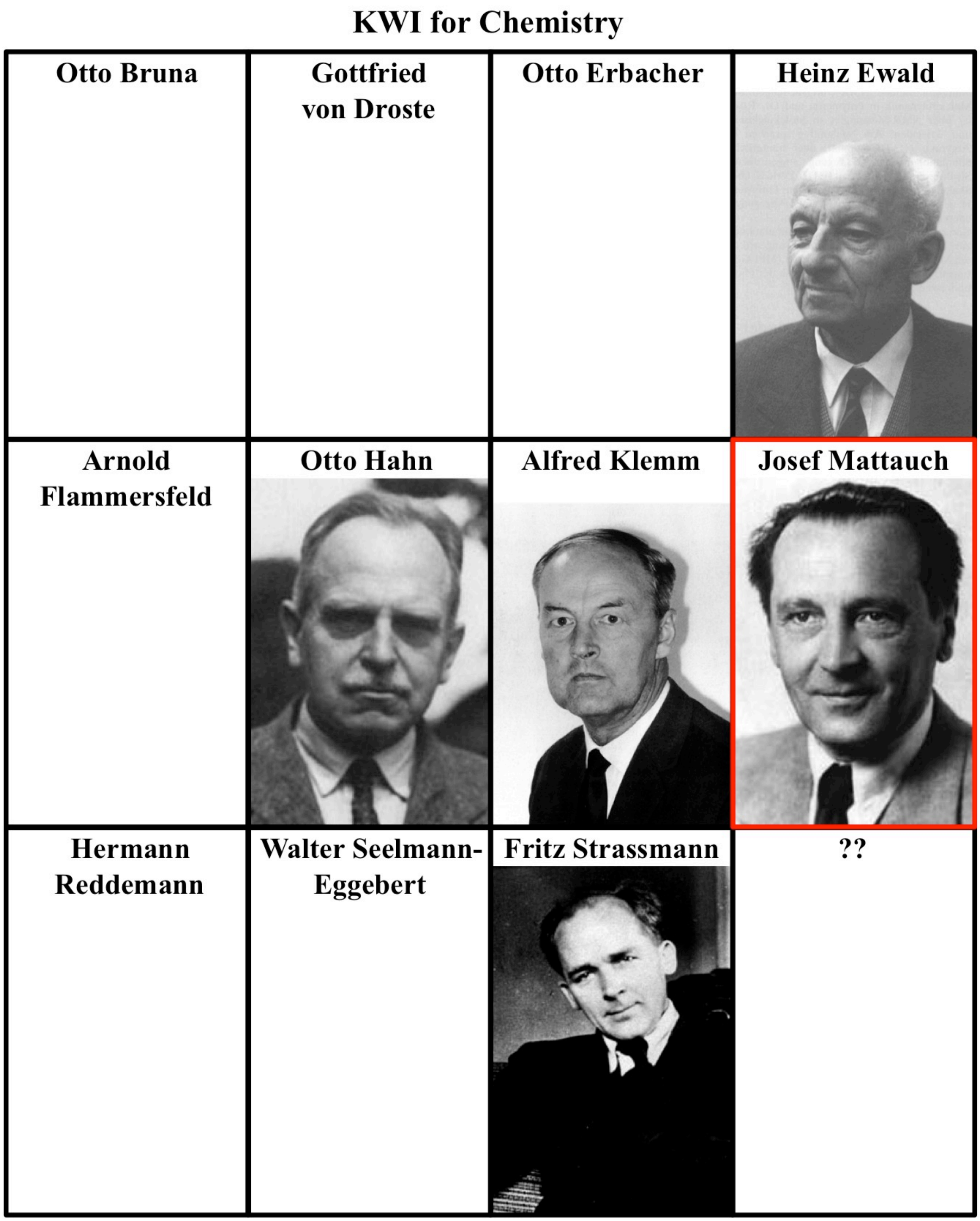


Figure 8.41: Examples of scientists and engineers at the Kaiser Wilhelm Institute (KWI) for Chemistry who played critical roles in the development of nuclear technologies in wartime Germany. Josef Mattauch was the head scientist.

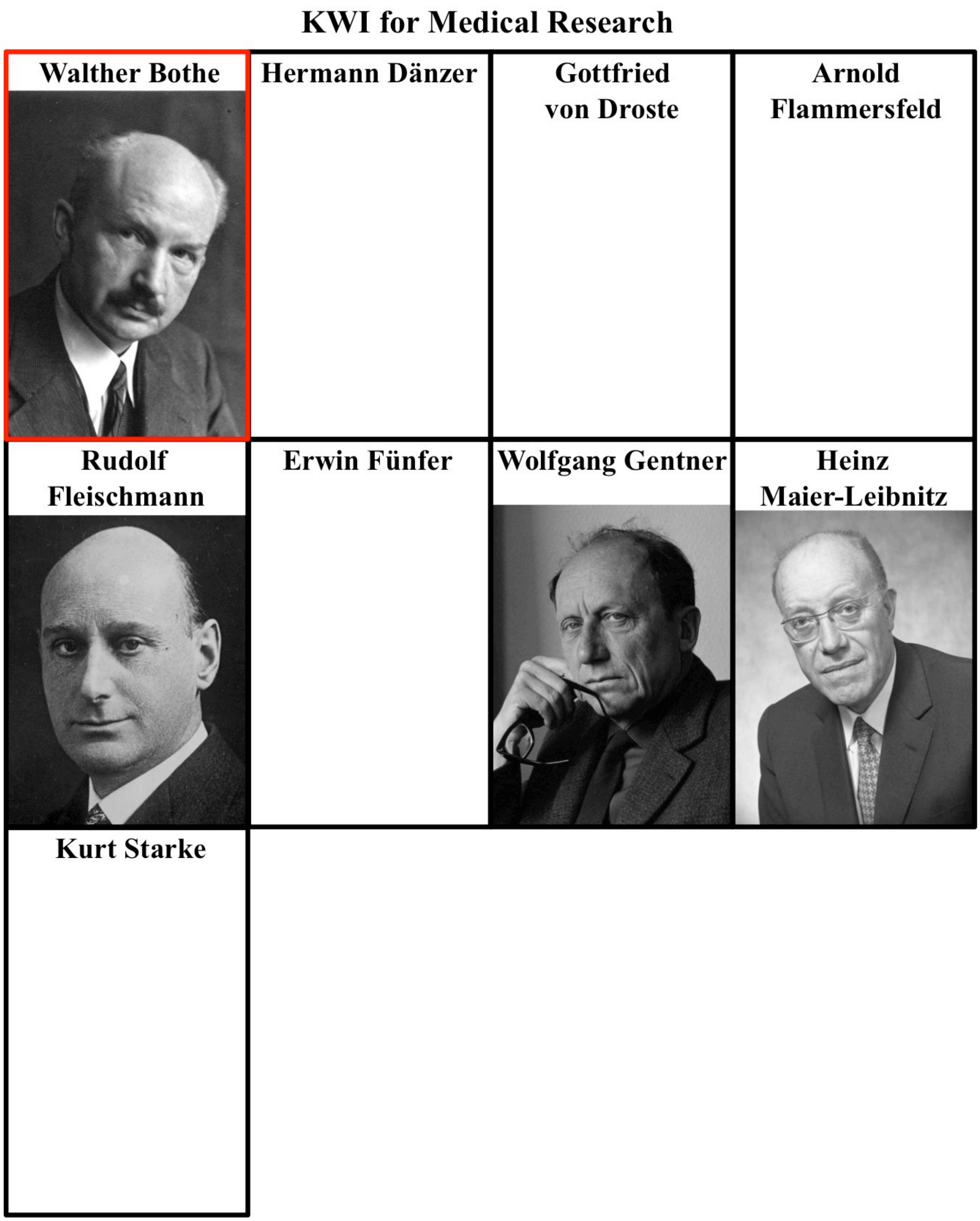
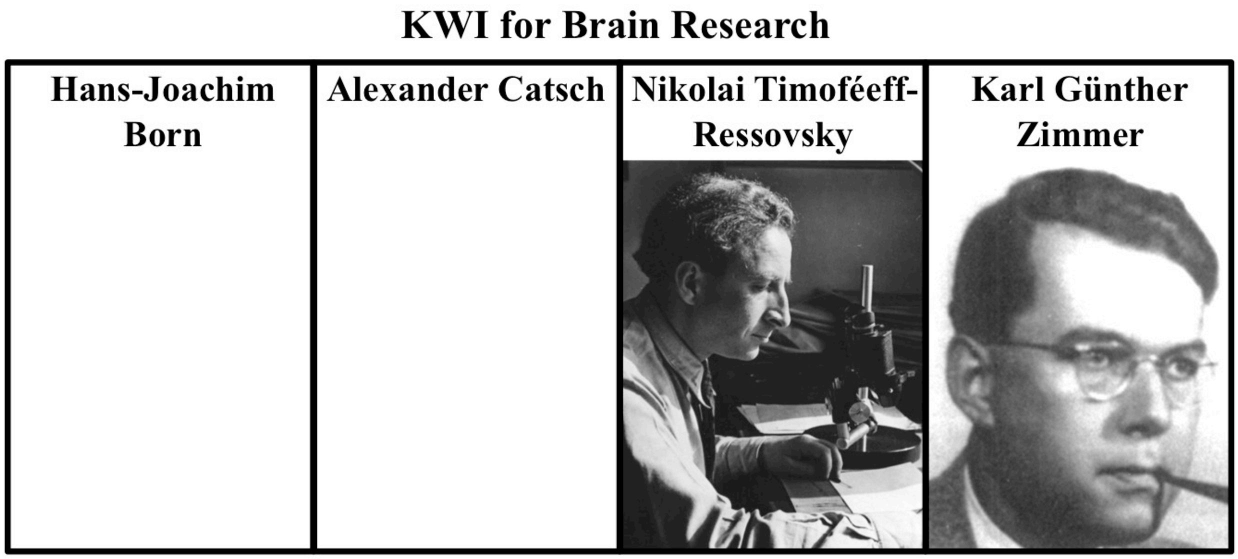


Figure 8.42: Examples of scientists and engineers at the Kaiser Wilhelm Institute (KWI) for Medical Research who played critical roles in the development of nuclear technologies in wartime Germany. Walther Bothe was the head scientist.



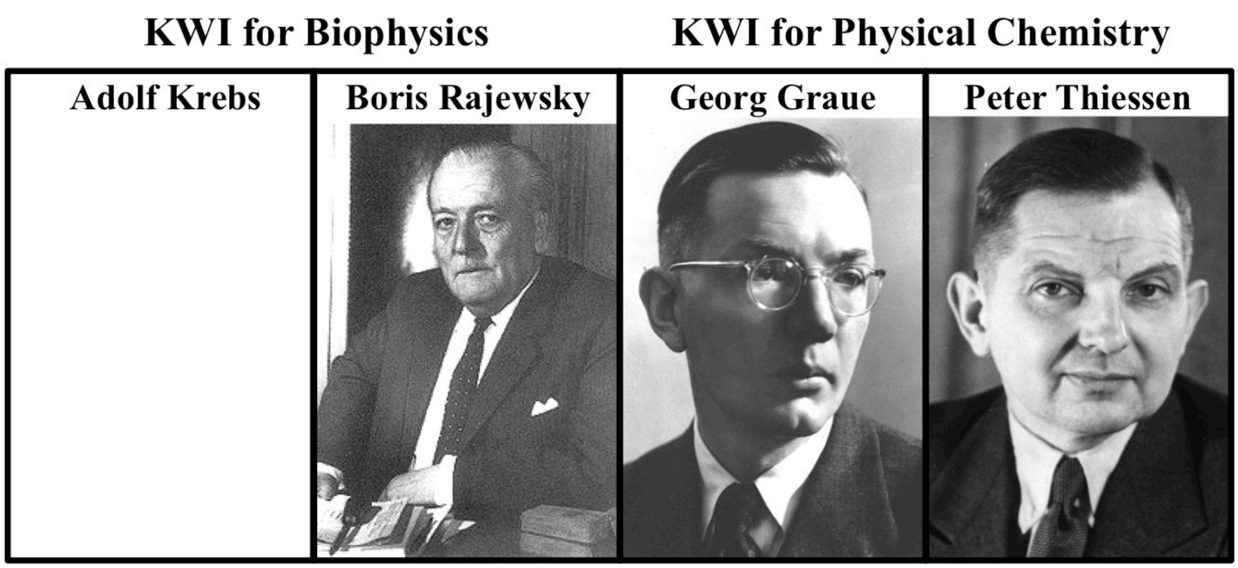


Figure 8.43: Examples of scientists and engineers at the Kaiser Wilhelm Institutes (KWI) for Brain Research, Biophysics, and Physical Chemistry who played critical roles in the development of nuclear technologies in wartime Germany.

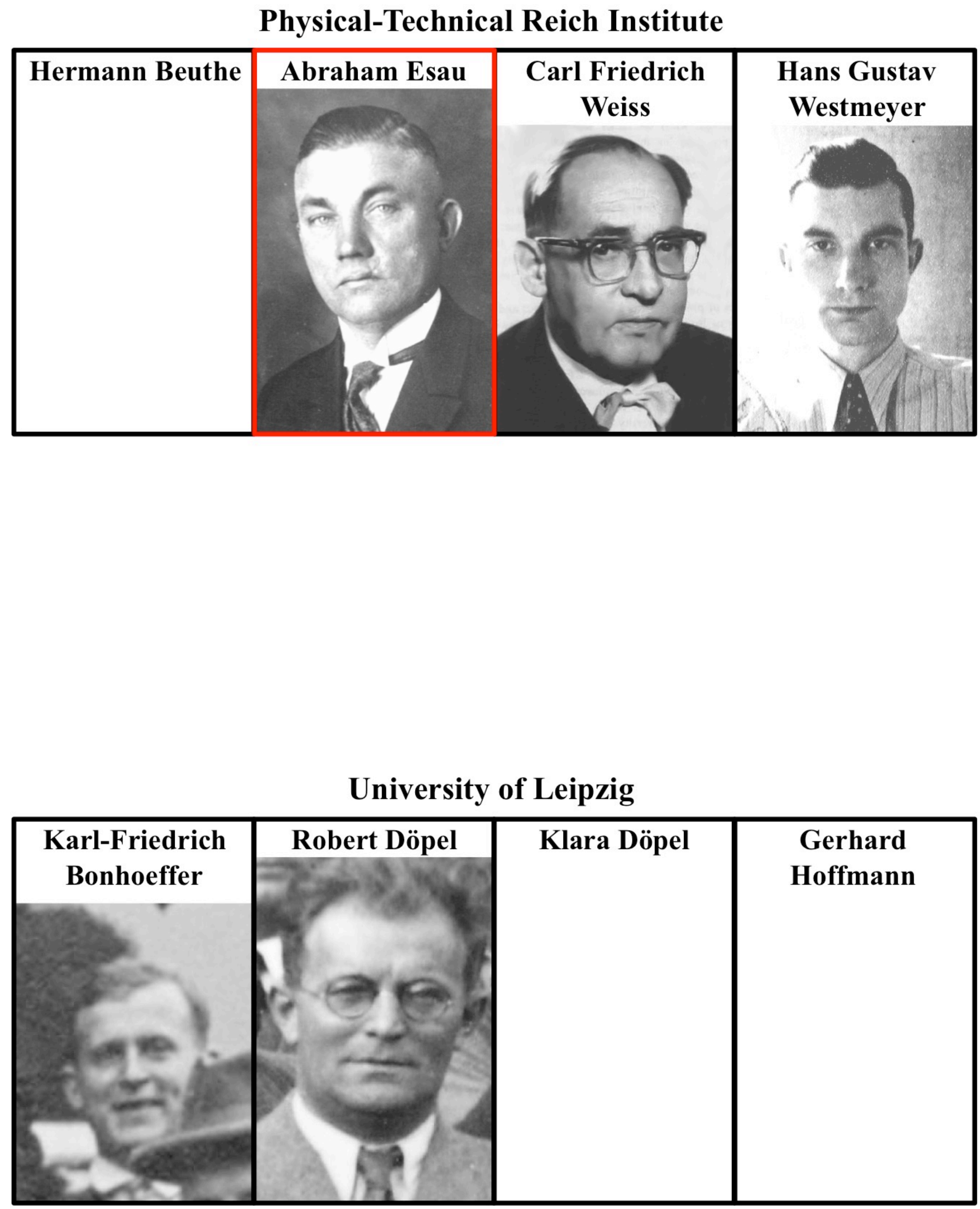


Figure 8.44: Examples of scientists and engineers at the Physical-Technical Reich Institute (Physikalische-Techische Reichsanstalt, PTR) and the University of Leipzig who played critical roles in the development of nuclear technologies in wartime Germany. Abraham Esau was the head scientist of the PTR, and was in charge of large parts of the German nuclear program early in the war.

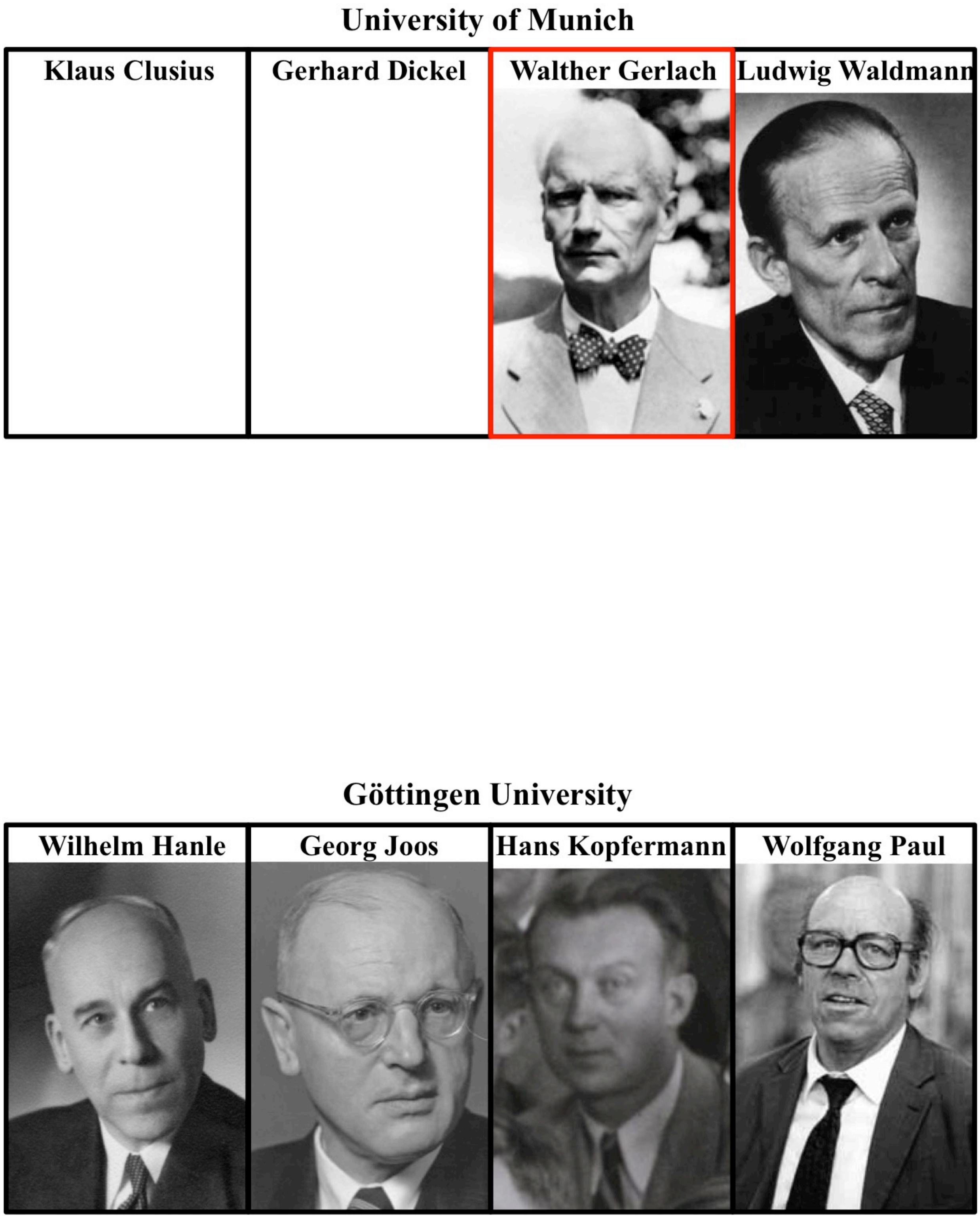


Figure 8.45: Examples of scientists and engineers at the University of Munich and Göttingen University who played critical roles in the development of nuclear technologies in wartime Germany. Walther Gerlach was in charge of large parts of the German nuclear program later in the war.

Figure 8.46: Examples of scientists and engineers at the University of Hamburg and elsewhere in the Hamburg/Kiel area who played critical roles in the development of nuclear technologies in wartime Germany. Paul Harteck was the head scientist.

Figure 8.47: Examples of scientists and engineers at the University of Vienna who played critical roles in the development of nuclear technologies in wartime Germany. Georg Stetter was the head scientist.

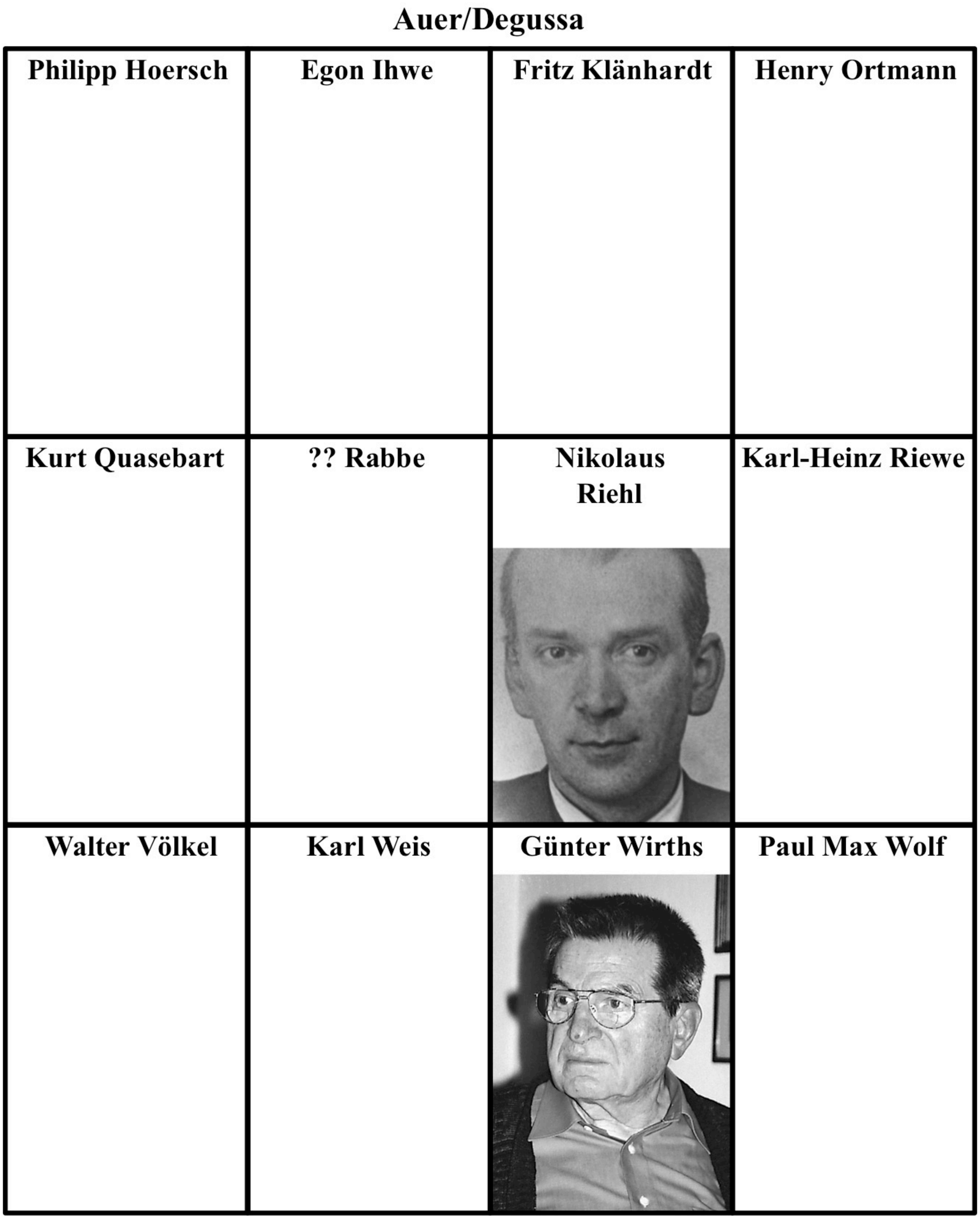


Figure 8.48: Examples of scientists and engineers at Auergesellschaft/Degussa company laboratories who played critical roles in the development of nuclear technologies in wartime Germany.

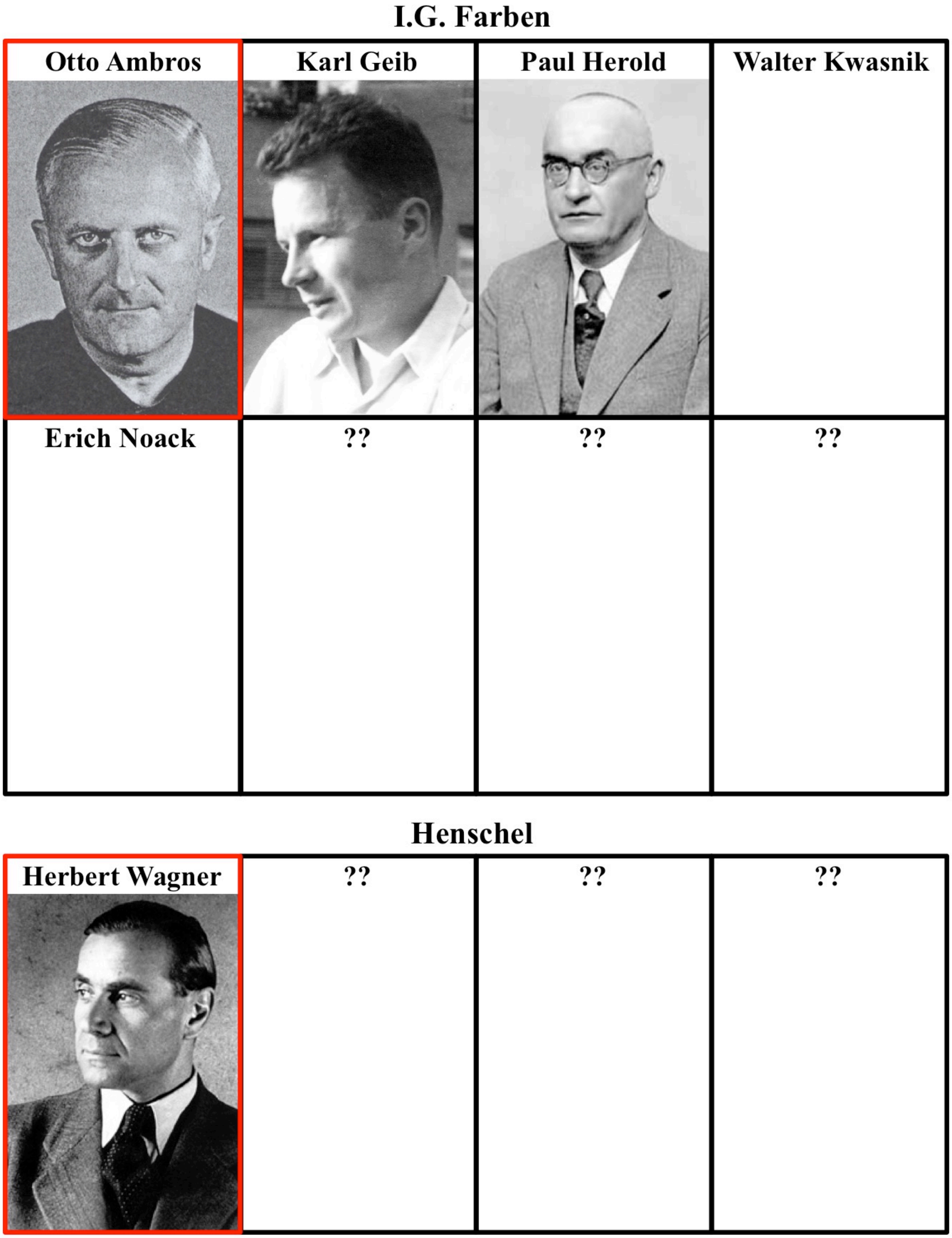


Figure 8.49: Examples of scientists and engineers at I.G. Farben and Henschel company laboratories who played critical roles in the development of nuclear technologies in wartime Germany. Otto Ambros was the head scientist at I.G. Farben, and Herbert Wagner was the lead scientist at Henschel.

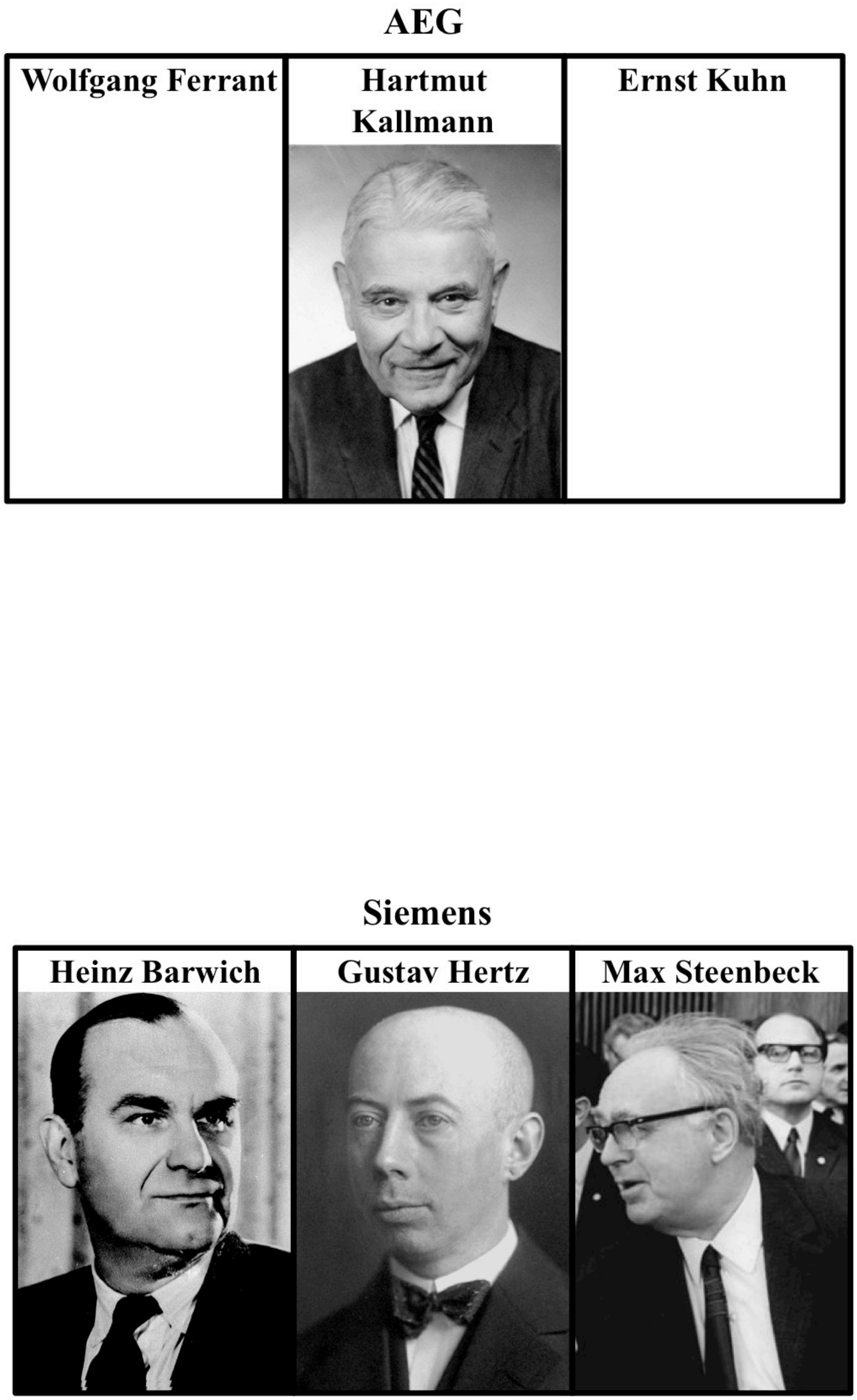


Figure 8.50: Examples of scientists and engineers at AEG and Siemens company laboratories who played critical roles in the development of nuclear technologies in wartime Germany.

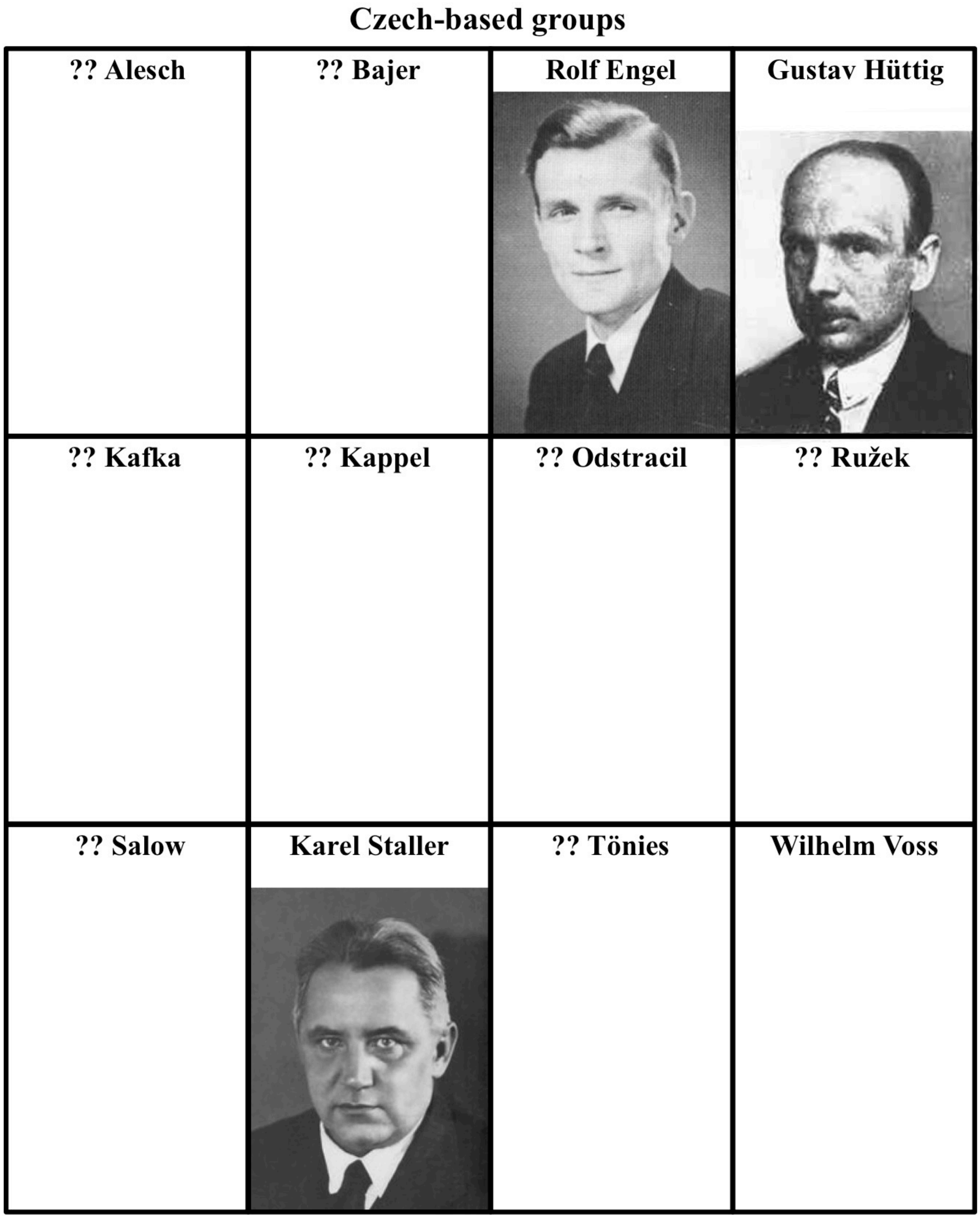


Figure 8.51: Examples of scientists and engineers in Czech-based research groups and companies who played critical roles in the development of nuclear technologies in wartime Germany.

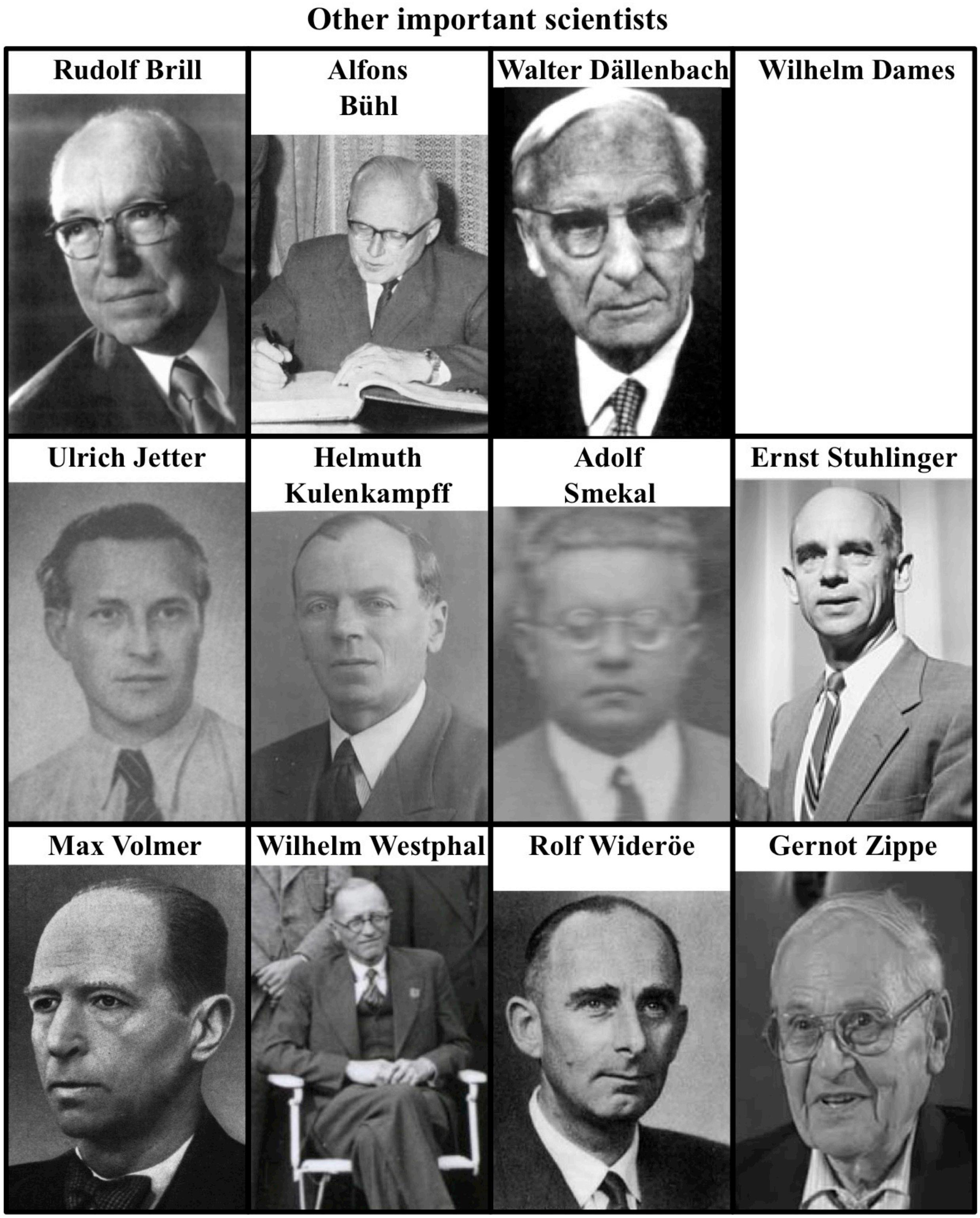


Figure 8.52: Other examples of scientists and engineers who played critical roles in the development of nuclear technologies in wartime Germany.

8.9 Nuclear Engineering in the Soviet Union

German-trained scientists and engineers, as well as German-produced designs, materials, and equipment, made enormous contributions to the postwar Soviet nuclear program.[22]

The Soviet nuclear program employed (at least) many hundreds of German-speaking scientists and engineers. Just the Soviet nuclear institute run by Manfred von Ardenne was staffed with almost 300 Germans [Oleynikov 2000]. At least several hundred more worked at other nuclear institutes and facilities in the Soviet Union.[23] Including German-speaking scientists and engineers in industries that directly supported the nuclear program (geology, chemistry, materials science, electronics, aerospace, etc.), the total number of German-speaking specialists who contributed to the program was likely in the thousands. For examples of some German-speaking scientists who aided the Soviet nuclear program, see Figs. 8.53–8.56. Some of the major contributions included:

- Klaus Fuchs, a German physicist who worked in the U.S./U.K. nuclear program for many years, gave the Soviet Union detailed plans of U.S. nuclear bombs and production systems (which had been designed and developed with the critical contributions of a large number of German-speaking and German-trained scientists, as discussed in Section 8.7).

- Erich Purucker (German, 1893–1957), Hans Kammler's chief assistant in running the wartime German nuclear program, was captured by Soviet troops in May 1945 along with a car full of German nuclear weapons plans, and held in the Soviet Union for the rest of his life. See p. 4960 for more details.

- E. Baroni (German, ??-??), Henry Ortmann (German, 1908–1988), Nikolaus Riehl (German, 1901–1990), Herbert Schmitz (German, ??–??), Herbert Thieme (German, 1902–??), Günther Wirths (German, 1911–2005), and many other German and Austrian scientists processed uranium ore to uranium oxide, uranium metal, and uranium hexafluoride. Joseph Stalin personally awarded Riehl the title "Hero of the Socialist Labor" and gave him a first class Stalin Prize; he gave Thieme and Wirths second class Stalin Prizes.

- Heinz Barwich (German, 1911–1966), Fritz Bernhard (German, 1913–??), Gustav Hertz (German, 1887–1975), Hans Gerhard Krüger (German, 1912–??), Justus Mühlenpfordt (German, 1911–2000), Reinhold Reichmann (German, ??–??), Werner Schütze (German, ??–??), Peter Thiessen (German, 1899–1990), and many other German and Austrian scientists produced gaseous diffusion systems to enrich uranium-235, apparently based on wartime German gaseous diffusion technology. Joseph Stalin gave Thiessen a first class Stalin Prize, and Barwich, Hertz, Reichmann, and Schütze second class Stalin Prizes.

[22] Albrecht et al. 1992; von Ardenne 1990, 1997; Barkleit 2008; Barwich and Barwich 1970; Boch and Karlsch 2011; Fengler 2014; Fengler and Sachse 2012; Goncharov 1996a, 1996b; Goncharov and Riabev 2001; Graham 1993; Heinemann-Gruder 1992; Holloway 1994; Karlsch 2011; Karlsch and Laufer 2002; Karlsch and Zeman 2016; Kozyrev 2005; Kruglov 2002; Maddrell 2006; Mick 2000; Nagel 2016; Naimark 1995; Oleynikov 2000; Pondrom 2018; Riabev 1998, 2002a, 2002b, 2002c, 2002d; 2006a; 2006b; 2006c; Riehl and Seitz 1993; Siddiqi 2009; Sokolov 1955; Wellerstein and Geist 2017; West 2004; Yudin; Zeman and Karlsch 2008; *News Chronicle* 1945-10-15 p. 1; NYT 1945-10-15 p. 4, 1945-10-31 p. 6, 1946-01-29 p. 1, 1946-11-28 p. 16, 1946-12-06 p. 17, 1947-02-24 p. 1, 1948-05-26 p. 3, 1948-12-28 p. 10b; *Spokane Daily Chronicle* 1948-03-16 p. 6; *Sydney Morning Herald* 1946-04-20 p. 2; *Times* 1945-05-15, 1945-05-18; https://nsarchive.gwu.edu/briefing-book/nuclear-vault/2018-04-06/cia-debriefed-soviet-h-bomb-eye-witness-1957

[23] Rainer Karlsch, unpublished Soviet archival list of personnel files.

- Fritz Lange (German, 1899–1987), Rudolf Scheffel (German, 19??–19??), Max Steenbeck (German, 1904–1981), Eberhard Steudel (German, 1906–19??), Gernot Zippe (Austrian, 1917–2008), and many other German and Austrian scientists produced gas centrifuges to enrich uranium-235, apparently based on wartime German gas centrifuge technology.

- Manfred von Ardenne (German, 1907–1997), Werner Schütze, Max Steenbeck, and many other German and Austrian scientists produced electromagnetic separators to enrich uranium-235, apparently based on wartime German electromagnetic separation technology.

- Hans-Joachim Born (German, 1909–1987), Alexander Catsch (German, 1913–1976), Nikolai Timoféeff-Ressovsky (Russian but German educated, 1900–1981), Karl Günter Zimmer (German, 1911–1988), and other German and Austrian scientists elucidated the biological effects of radiation, as well as methods to protect against it, based on their earlier research in Germany.

- Victor Karl Bayerl, Ludwig Bewilogua (German, 1906–1983), Werner Czulius (Austrian, 1914–2007), Karl-Hermann Geib (German, 1908–1949), Paul Herold (German, ??–1951), Walter Herrmann (German, 1910–1987), Paul Heylandt (German, 1884–1947), Hans Gerhard Krüger, Hans-Jürgen von Oertzen (German, 1907–??), Heinz Pose (German, 1905–1975), K. Renker (German, ??–??), Ernst Rexer (German, 1902–1983), Gustav Richter (German, 1911–1999), Karl-Heinz Riewe (German, 1907–??), Adrian Rosen (German, ??–??), Herbert Schmitz, Max Volmer (German, 1885–1965), Carl Friedrich Weiss (German, 1901–1981), Hans Westmeyer (German, 1910–??), and many other German and Austrian scientists developed fission reactors for breeding plutonium-239 from natural uranium-238, based on wartime German technology.

- Manfred von Ardenne, Gustav Hertz, Carl Kober (German, 1913–??), Josef Schintlemeister (Austrian, 1908–1971), Werner Schütze, and other German and Austrian scientists developed methods of producing and using lithium and tritium in H-bombs, apparently based on wartime German and Austrian work. (See p. 4385 as well as the rest of Section D.9.) Von Ardenne was awarded two first class Stalin Prizes for his multiple contributions in the Soviet Union, including the purification of lithium-6 for H-bombs.

Even Pavel Oleynikov, a former group leader of the Chelyabinsk-70 nuclear weapons complex in Russia, admitted that German scientists, technologies, ideas, and materials had had a profound effect on the development of nuclear weapons in the Soviet Union [Oleynikov 2000]:

> It is hard to fully explore the German contributions to the Soviet atomic project without performing a detailed examination of the whole Soviet atom bomb effort. What is clear from the available evidence is that German involvement had several very important implications for the Soviet Union and the world:
>
> - German resources jump-started the Soviet program and saved it up to five years of time. If not for this time, the USSR could hardly have been as aggressive as it was in seeking global dominance. Very likely, the USSR could not have wielded its influence in Asia, and the whole course of regional history (e.g., the Korean War) would have been different. [...]

- Participation of German scientists in the development of new uranium enrichment methods revolutionized the whole uranium fuel industry. The work of Max Steenbeck and Gernot Zippe shaped the European and Japanese enrichment plants, and was used by several later proliferators (e.g., Pakistan and Iraq) as well.

> In sum, although the Soviets would have eventually developed nuclear weapons on their own, they benefited considerably from German technology, expertise, and raw materials. The German contributions undoubtedly accelerated the program by several years and enhanced the Soviets' stature on the world stage. An accurate and complete history of the Soviet bomb program must acknowledge the importance of the Germans' contributions.

At a minimum, the contributions of all of those German-trained scientists and all of the nuclear-related materials taken from Germany appear to have accelerated Soviet development of fission and fusion bombs by many years (Figs. 8.57–8.58). Although some historians have studied this area, much more detailed investigations are needed, especially if unrestricted access to former Soviet archives becomes available.

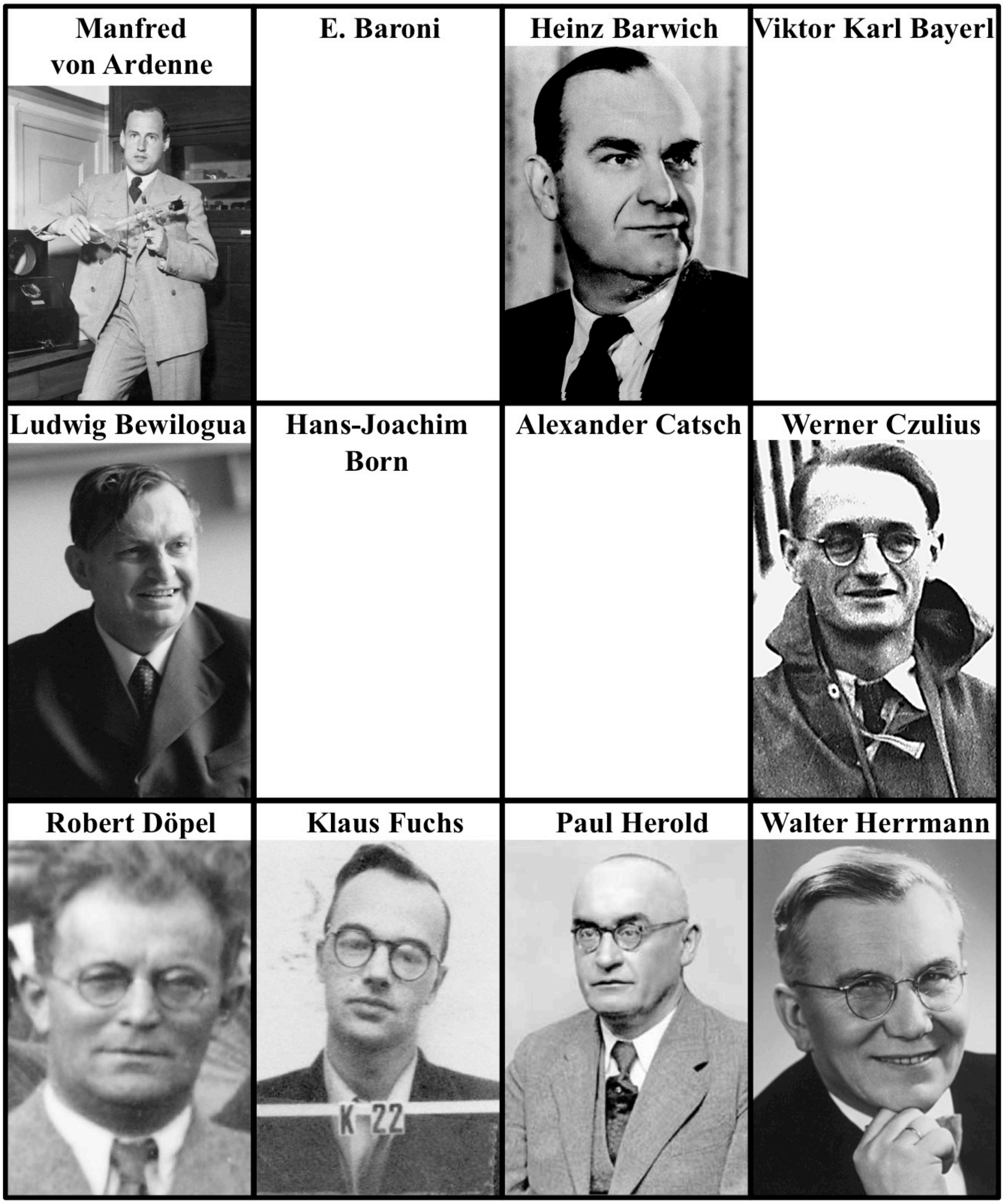


Figure 8.53: Examples of German-speaking scientists who played critical roles in the development of nuclear weapons in the Soviet Union.

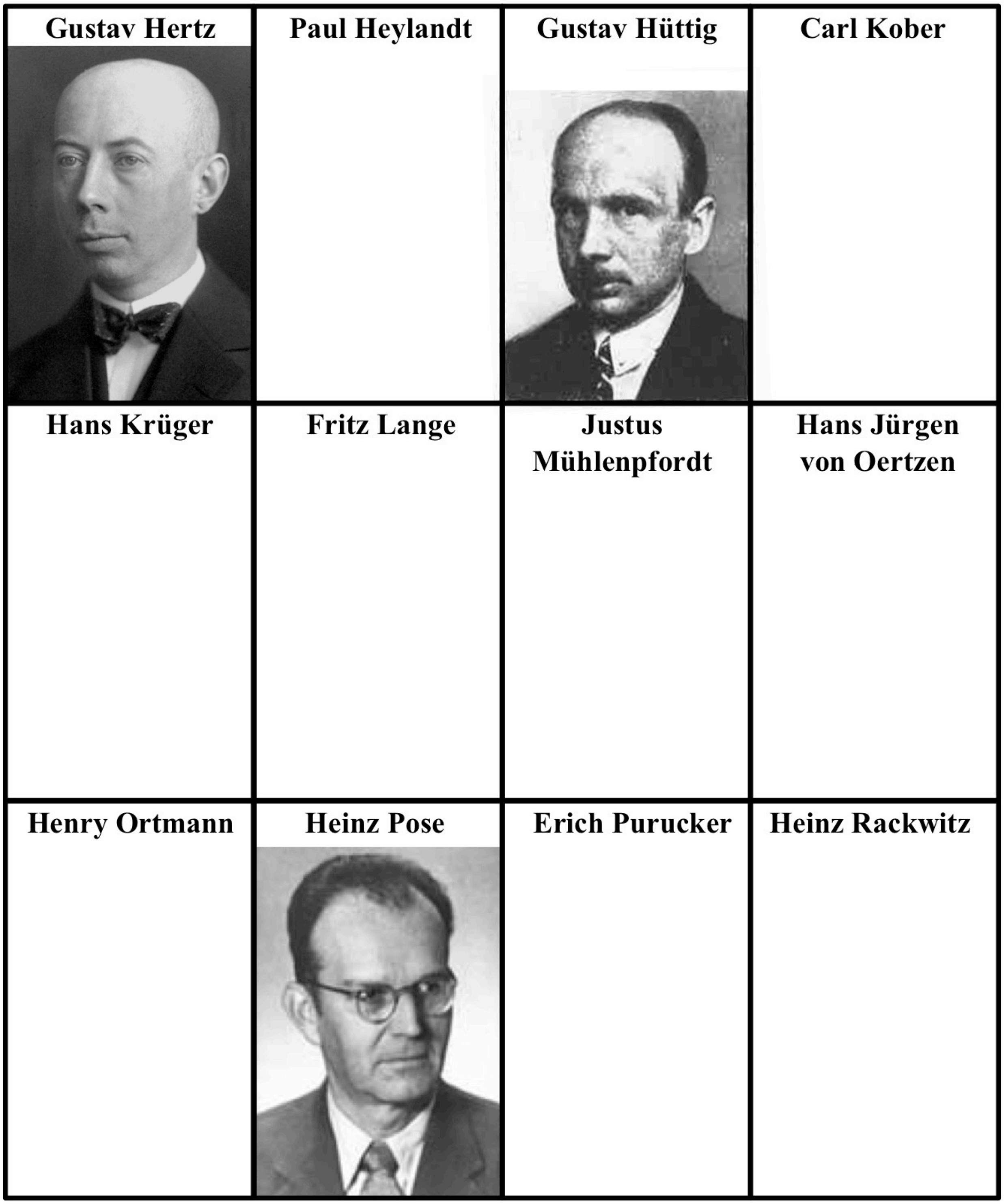


Figure 8.54: More examples of German-speaking scientists who played critical roles in the development of nuclear weapons in the Soviet Union.

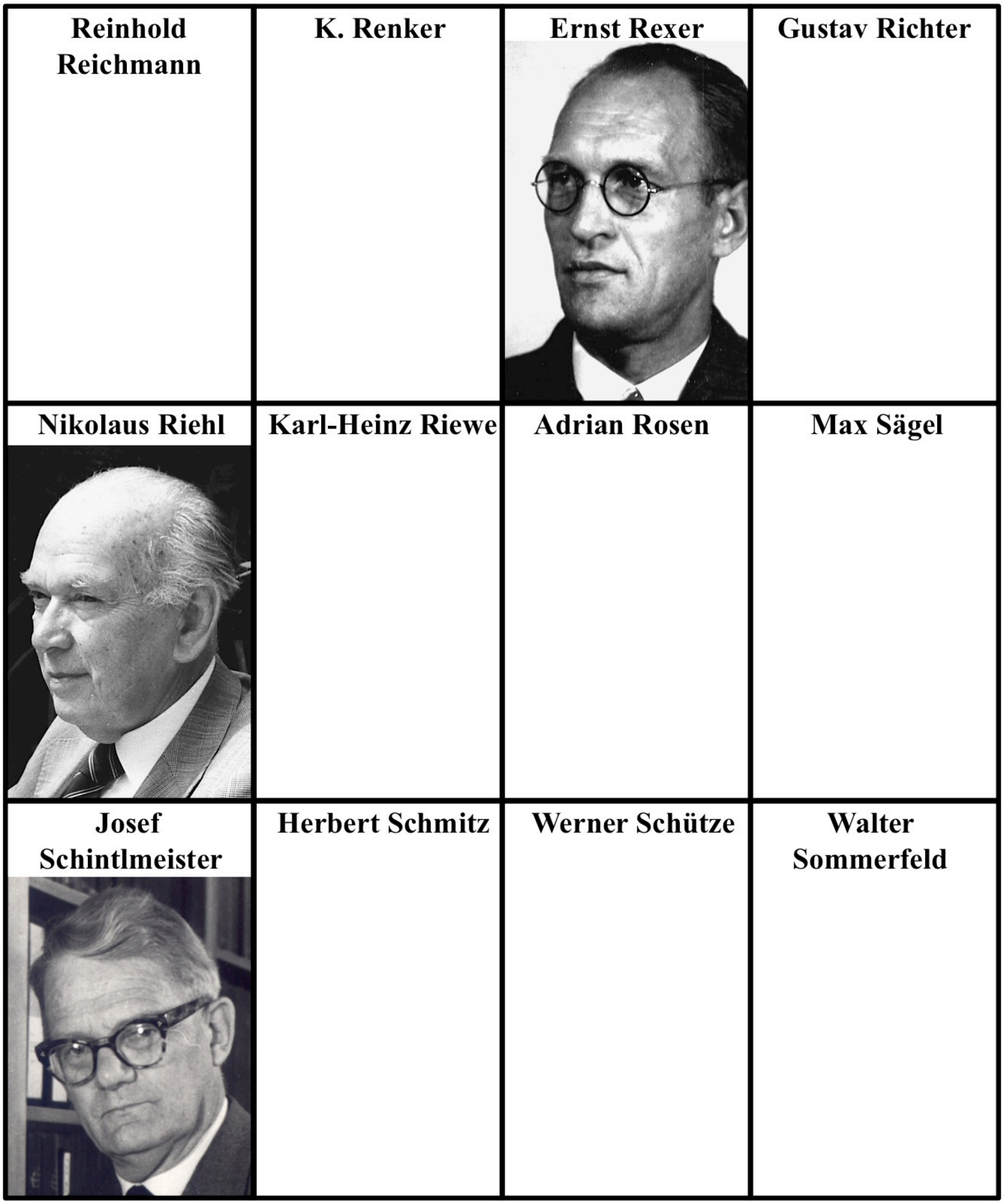


Figure 8.55: More examples of German-speaking scientists who played critical roles in the development of nuclear weapons in the Soviet Union.

Figure 8.56: More examples of German-speaking scientists who played critical roles in the development of nuclear weapons in the Soviet Union.

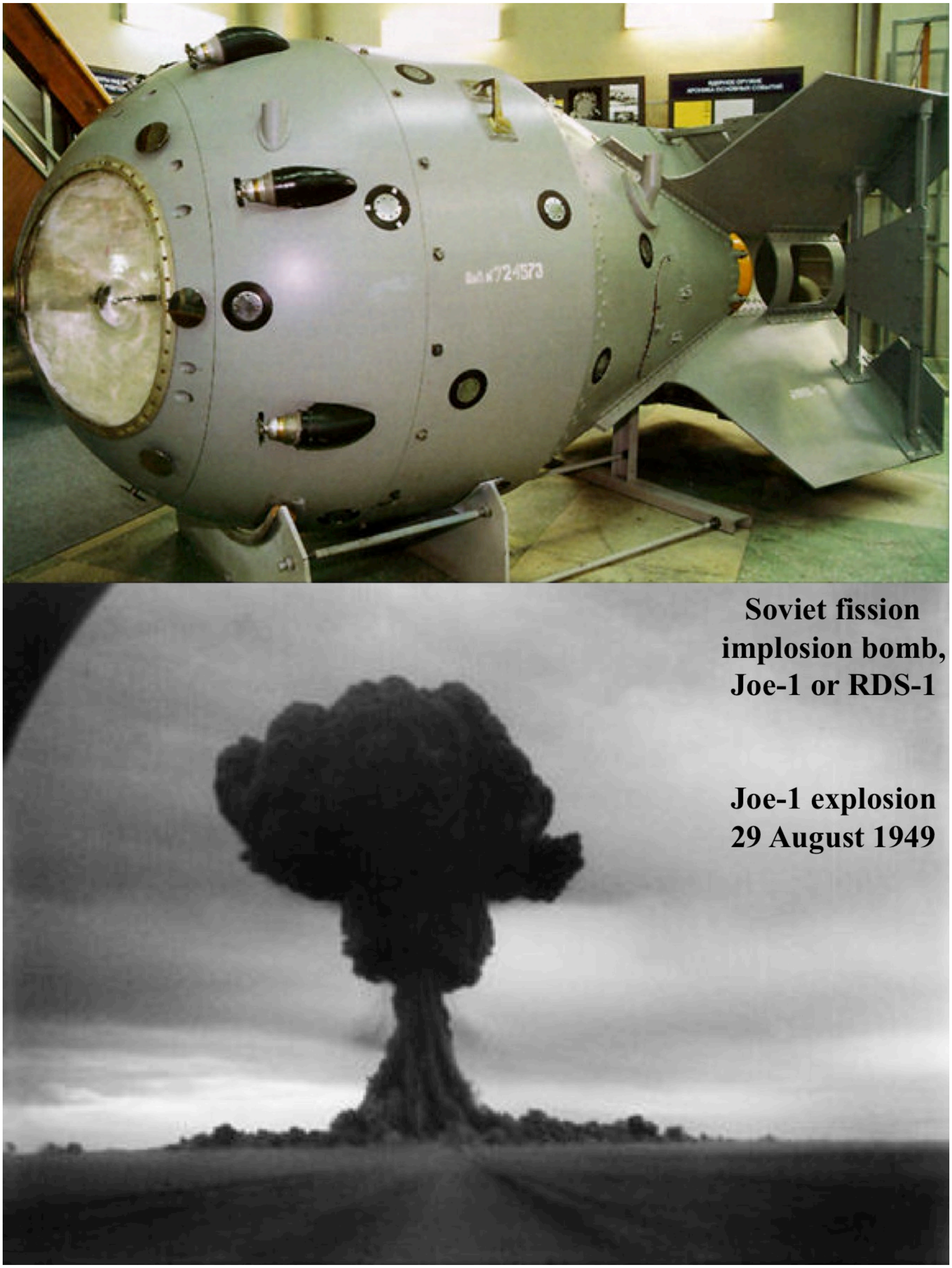
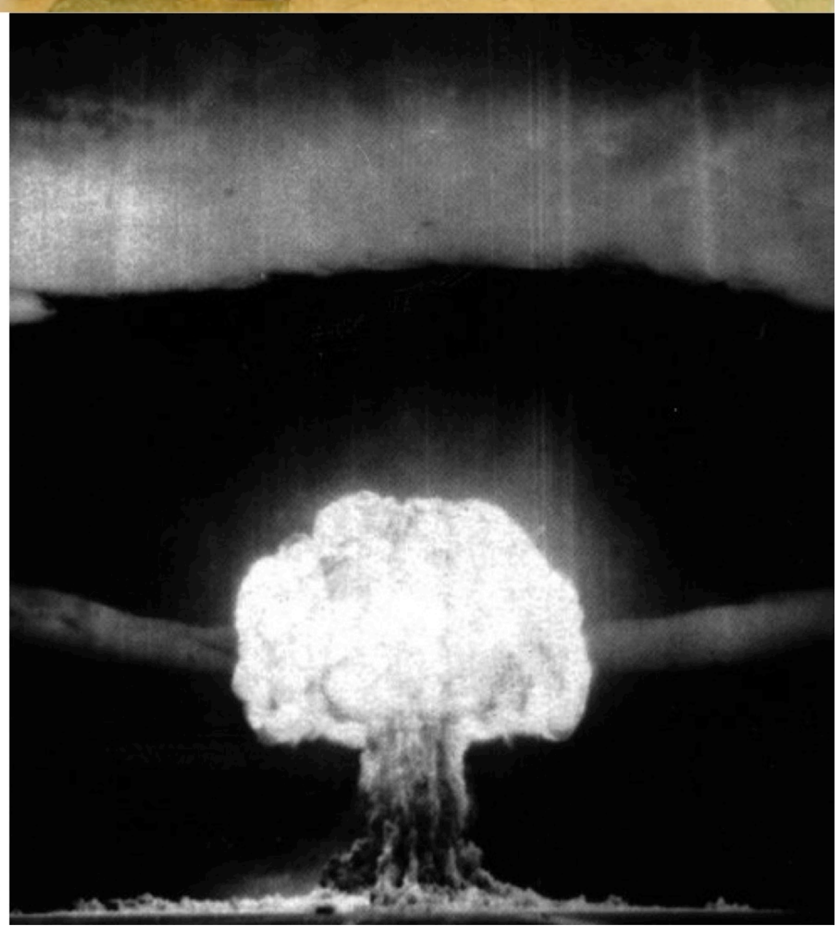


Figure 8.57: Examples of early Soviet nuclear weapons: a replica of Joe-1 or RDS-1, the first Soviet fission implosion bomb, and the explosion of Joe-1 on 29 August 1949.

First Soviet H-bomb,
Joe-4 or RDS-6



Joe-4 explosion
12 August 1953

Figure 8.58: Examples of early Soviet nuclear weapons: a replica of Joe-4 or RDS-6, the first Soviet hydrogen bomb, and the explosion of Joe-4 on 12 August 1953.

Chapter 9

Creators and Creations in Aerospace Engineering

Dieses merkt Euch, Ihr stolzen Männer der Tat. Ihr seid nichts als unbewußte Handlanger der Gedankenmänner, die oft in demütigster Stille Euch all Euer Tun aufs Bestimmteste vorgezeichnet haben.

Mark this well, you proud men of action. You are nothing but the unconscious hands of the men of thought, who have often, in the most humble silence, directed all your actions in advance.

Heinrich Heine. 1834. *Zur Geschichte der Religion und Philosophie in Deutschland* [*History of Religion and Philosophy in Germany*] Book III, paragraph 3.

This chapter gives an overview of some innovations in aerospace engineering that have played major roles in the modern world and that were invented or discovered by scientists and engineers who were trained in the predominantly German-speaking central European research world in the nineteenth and early twentieth centuries.[1]

[1] In addition to specific references that are cited in different areas throughout this chapter, this chapter makes use of general biographical and project information from: ACLS 2000; Albrecht et al. 1992; Ash and Söllner 1996; Bar-Zohar 1967; Bower 1987; Bunch and Hellemans 2004; Challoner 2009; Cornwell 2003; Crim 2018; EB 1911, 2010; Gillispie 1970–1990; Gimbel 1990a; Glatt 1994; Hall 2019a; István Hargittai 2006, 2011; Linda Hunt 1991; Impey et al. 2008; Jacobsen 2014; Koertge 2007; Kurowski 1982; Lasby 1971; Lusar 1956, 1971; Medawar and Pyke 2000; Mick 2000; Murray 2003; Nachmansohn 1979; NDB 1953–2020; Neufeld 2012; Nouzille and Huwart 1999; O'Reagan 2014, 2019; Porter 1994; Charles Walker 1946; Peter Watson 2010; Weitensfelder 2009.

For general overviews of large portions of the history of aerospace engineering in the German-speaking world, see: Benecke and Quick 1957; von Braun et al. 1985; Coats and Carbonel 2002; Freeman 1993, 2008; Griehl 1990, 2003, 2004, 2005, 2015; Hirschel et al. 2004; Kay 2002; Lommel 2000, 2002, 2005; Jürgen Michels 1997; Myhra 1998a, 1998b, 2000a, 2000b, 2001, 2002, 2003; Michael Neufeld 1995, 2002, 2003, 2004, 2007, 2012; Ordway and Sharpe 1979; Samuel 2004, 2010; Smith and Creek 1982, 1992, 2001; Smith and Kay 2002; Stüwe 1999, 2014, 2015; Trischler 1992a, 1992b; Trischler and Schrogl 2007; Frank Winter 1983, 1990.

Creators from the German-speaking world made major contributions to:

9.1. Lighter-than-air craft

9.2. Aerodynamics and aircraft design

9.3. Jet engines and jet aircraft

9.4. Parachutes and ejection seats

9.5. Helicopters

9.6. Small missiles and smart bombs

9.7. Large liquid propellant rockets

9.8. Submarine-launched and solid propellant rockets

9.9. Rocket planes and space planes

9.10. Space exploration

9.1 Lighter-Than-Air Craft

Lighter-than-air craft use low-density gas (hot air, hydrogen, or helium) rather than powered engines to stay aloft. The simplest lighter-than-air craft is a balloon, and the French brothers Joseph-Michel and Jacques-Étienne Montgolfier are believed to have conducted the first piloted hot-air balloon flights in 1783. By the late nineteenth century, balloons were a well developed and widely utilized technology. However, their greatest weakness was that they were at the mercy of the prevailing winds and nearly impossible to guide.

I have deliberately left a blank space where images of some creators or creations should go. Those are people or projects that I felt were important enough that they should definitely be shown in this book, yet I have not yet been able to locate a suitable image that I have permission to use, despite my searches in Europe and in the United States. If readers have any relevant images and could send them to me, I would be very grateful and will include them in future editions of this book. Even where a suitable photo cannot be located, I believe that leaving a blank space pays tribute both to the scientific importance of that creator or creation and to how that historical fact has been very nearly forgotten.

German-speaking creators played leading roles in transforming spherical, unpowered balloons that could not be guided into long, aerodynamic, internal-combustion-engine-powered, propeller-driven airships that could follow any desired course, even between continents [Danelek and Davis 2011; Hirschel et al. 2004].[2]

Those German-speaking creators developed:

1. Non-rigid airships, in which the giant envelope holding the low-density gas is simply an inflatable sack like a balloon.

2. Semi-rigid airships, in which the envelope is partially supported by a skeleton of light-weight materials such as aluminum or wood to hold its shape.

3. Rigid airships, in which the envelope is fully supported by a stiff skin of light-weight materials such as aluminum or wood to hold its shape regardless of gas pressure.

Some of the earliest German-speaking pioneers of powered airships are shown in Fig. 9.1:

- Paul Haenlein (German, 1835–1905) built and tested a small semi-rigid airship with an internal combustion engine in 1872.

- Hermann Ganswindt (German, 1856–1934) was a very creative inventor who experimented with early forms of both lighter-than-air and heavier-than air flying machines; see pp. 1810 and 1965.

- Georg Baumgarten (German, 1837–1884) and Friedrich Wölfert (German, 1850–1897) built and tested a series of non-rigid airships 1880–1897. They probably would have had a much greater ultimate impact, but Baumgarten died along the way, and Wölfert died in the crash of the final airship.

David Schwarz (Austro-Hungarian/Croatian, 1850–1897), his wife Melania Kaufmann Schwarz (Austro-Hungarian?, 1858–19??), and Carl Berg (German, 1851–1906) developed the first rigid airship, the Schwarz II, which first flew in Berlin in 1897; see Fig. 9.2. David Schwarz died of heart failure only months before the first flight of his invention, but Melania Schwarz and Carl Berg finished the project. Berg, who had developed and supplied aluminum alloys for that project, continued to do so for other airships.

After Count Ferdinand von Zeppelin (German, 1838–1917) retired from the German army in 1890, he wanted to realize the full potential of airships, which had so far only been small, unreliable prototypes. Along with Heinrich Müller-Breslau (German, 1851–1925), Theodor Kober (German, 1865–1930), Carl Berg, and other engineers, he developed a series of increasingly sophisticated rigid airships or Zeppelins, beginning with the LZ 1, which first flew in 1900, as shown in Fig. 9.3. Examples of later Zeppelins depicted in Fig. 9.4 included the LZ 3 (first flight 1906, and here shown over Berlin in 1909), LZ 72 (first flight 1916), and LZ 129 *Hindenburg* (first flight in 1936 and destroyed in 1937).

[2] There were some French engineers who tested early airships that used other power sources which were too weak and/or short-lived to be practical: Henri Giffard (1825–1882) with his steam-powered airship (1852), and Arthur Krebs (1850–1935) and Charles Renard (1847–1905) with their battery-powered airship (1884).

Encyclopedia Britannica explained the progression of Zeppelin's team from initial prototypes to a working fleet [EB 2010]:

> He retired in 1890 and devoted the rest of his life to the creation of the rigid airship for which he is known.
>
> Zeppelin struggled for 10 years to produce his lighter-than-air craft. The initial flight (July 2, 1900) of the LZ-1 from a floating hangar on Lake Constance, near Friedrichshafen, Ger., was not entirely successful, but it had the effect of promoting the airship to the degree that public subscriptions and donations thereafter funded the count's work. The German government was quick to perceive the advantage of airships over the as yet poorly developed airplanes, and when Zeppelin achieved 24-hour flight in 1906, he received commissions for an entire fleet. More than 100 zeppelins were used for military operations in World War I. A passenger service known as Delag (Deutsche-Luftschiffahrts AG) was established in 1910, but Zeppelin died before attaining his goal of transcontinental service.

In addition to his work on airships, Heinrich Müller-Breslau made many other important contributions to structural engineering and the theory of stress and strain.

As shown in Fig. 9.5, Johann Schütte (German, 1873–1940) and Karl Lanz (German, 1873–1921) rivaled Zeppelin with their own series of increasingly sophisticated airships that tended to use wood instead of aluminum.

Hans Groß (German, 1860–1924) and Nikolaus Basenach (German, 1875–1951) developed a series of semi-rigid airships, such as the Groß-Basenach M I airship (first flight in 1908 and enlarged in 1913, Fig. 9.6).

August von Parseval (German, 1861–1942), August Riedinger (German, 1845–1919), and Rudolf von Sigsfeld (German, 1861–1902) developed increasingly sophisticated non-rigid airships, such as the Parseval Versuchsluftschiff (1907) and PL19 airship (1914), as shown in Fig. 9.7.

Auguste Piccard (Swiss, 1884–1962) and Paul Kipfer (Swiss, 1905–1980) created and tested high-altitude balloons and used them to make measurements of the upper atmosphere and of cosmic rays. Jean Piccard (Swiss, 1884–1963), Auguste Piccard's twin brother, also invented and tested many high-altitude balloon designs. See Fig. 9.8.

See also some of the early balloonists and pioneers of aerospace medicine and meteorology on pp. 394 and 784–785.

Figure 9.1: Some of the earliest German-speaking creators of airships were Paul Haenlein, Hermann Ganswindt, and Georg Baumgarten and Friedrich Wölfert.

David Schwarz (1850–1897)

Melania Schwarz (1858–19??)

Carl Berg (1851–1906)

First flight of a rigid airship, the Schwarz II (Berlin, 1897)

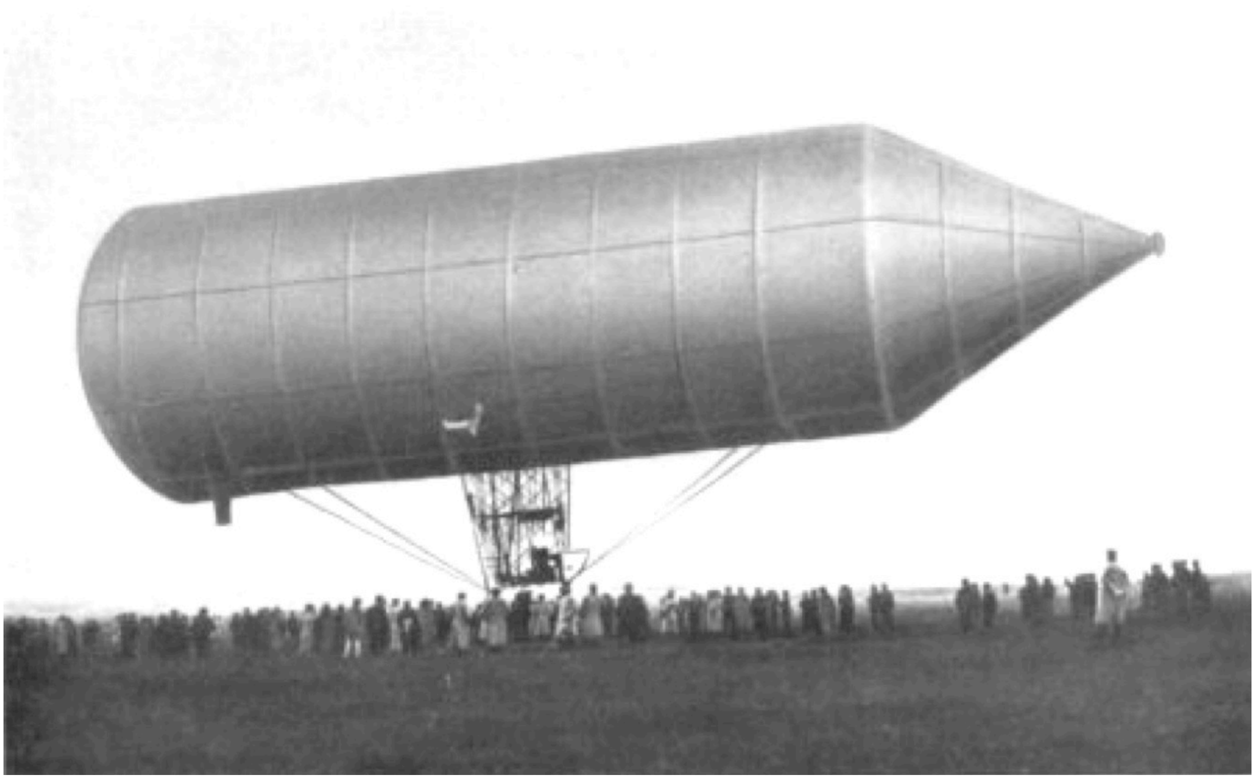
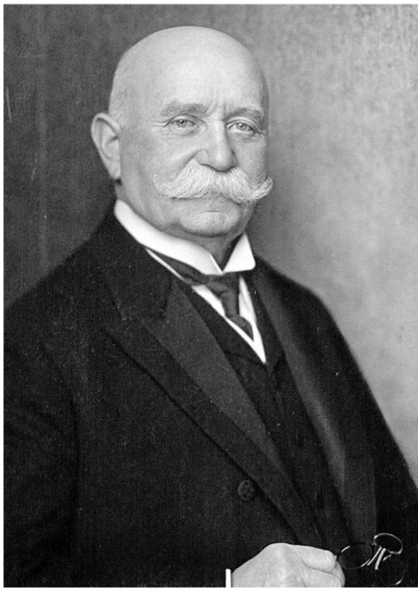


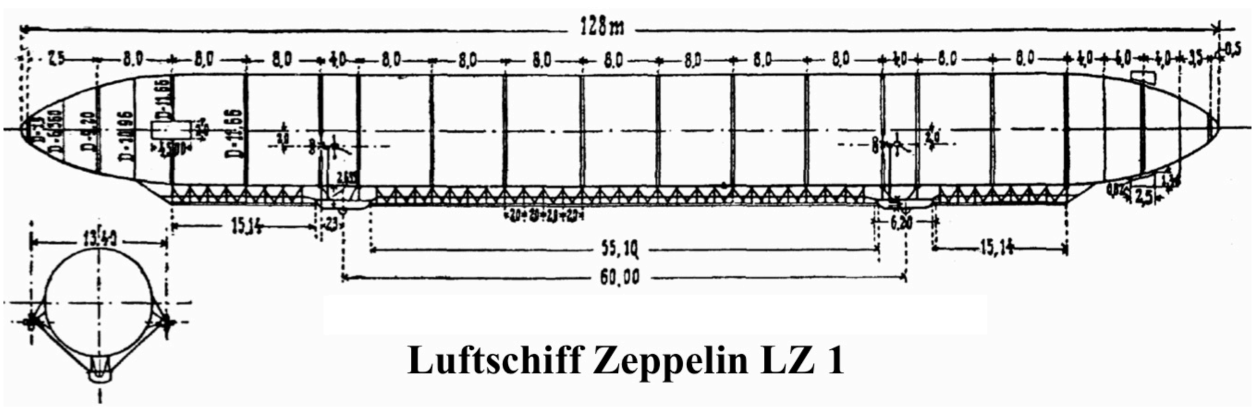
Figure 9.2: David Schwarz, his wife Melania Kaufmann Schwarz, and Carl Berg developed and demonstrated the first rigid airship, the Schwarz II, in Berlin in 1897.

Ferdinand von Zeppelin (1838–1917)

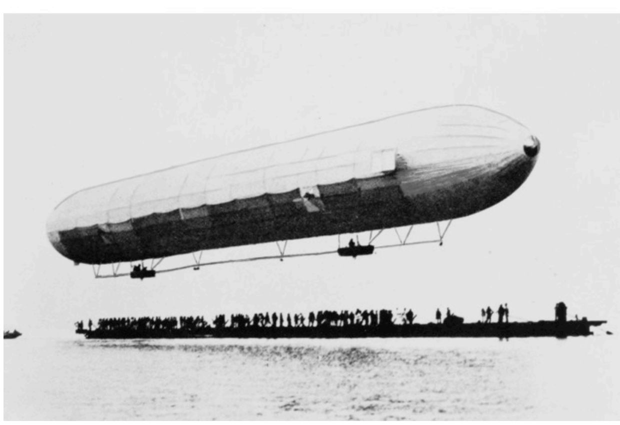


Heinrich Müller-Breslau (1851–1925)

Theodor Kober (1865–1930)



First flight of Zeppelin LZ 1 (1900)



One of LZ 1's Daimler engines

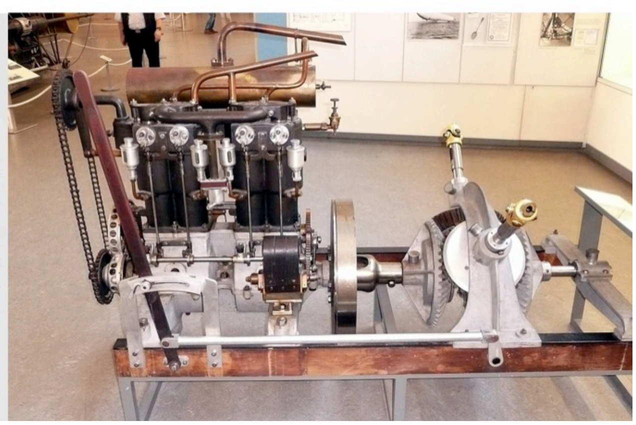
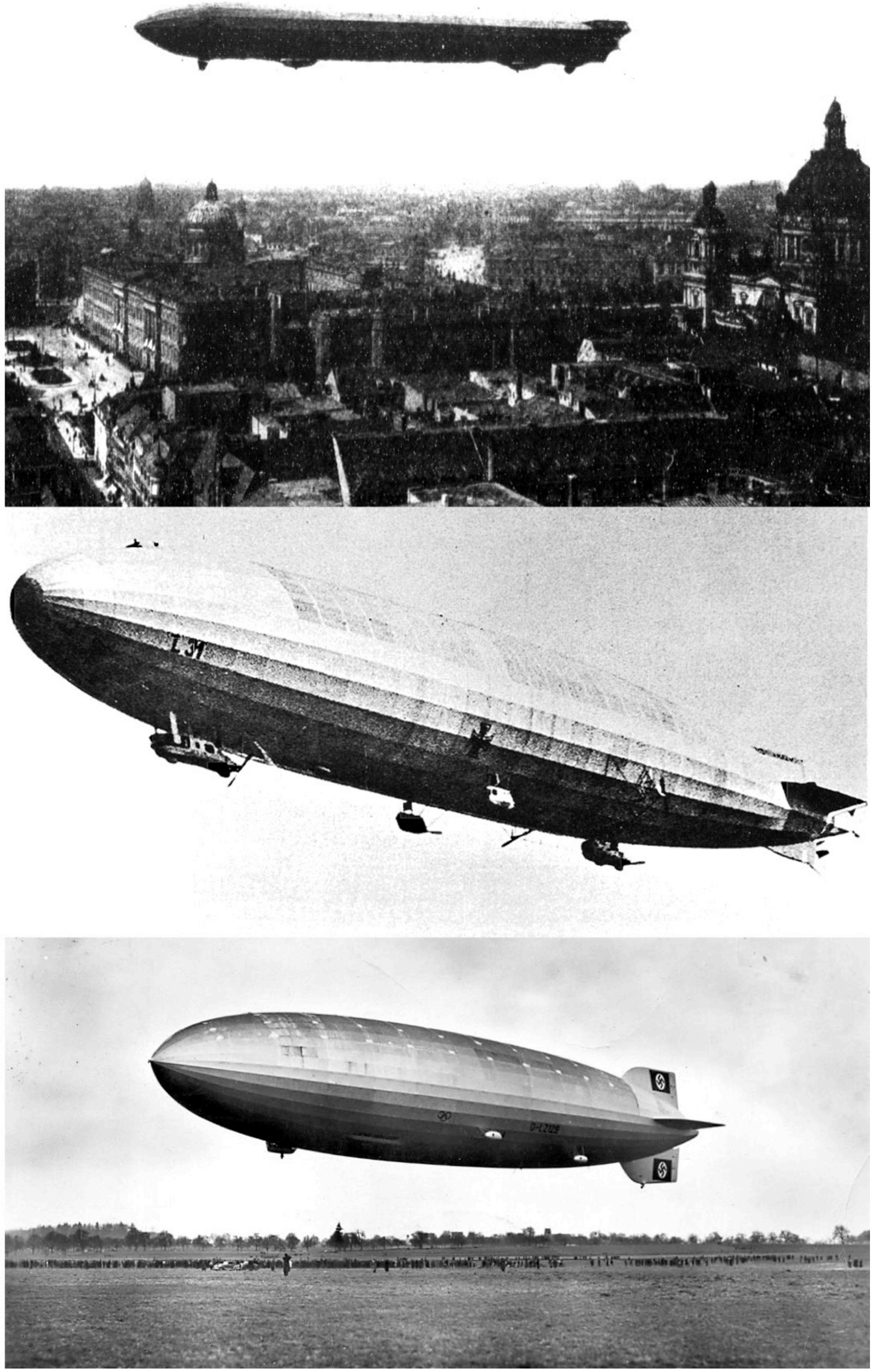


Figure 9.3: Ferdinand von Zeppelin, Heinrich Müller-Breslau, Theodor Kober, and Carl Berg developed a series of increasingly sophisticated rigid airships or Zeppelins, beginning with the LZ 1, which first flew in 1900.



Zeppelin LZ 3 over Berlin (1909)

Zeppelin LZ 72 (1916)

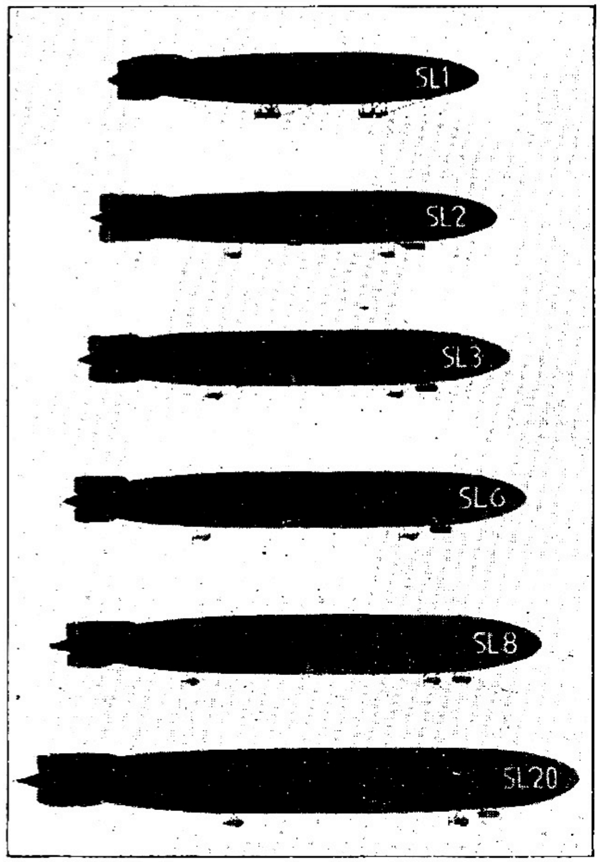
First flight of the LZ 129 *Hindenburg* (1936)

Figure 9.4: Examples of later Zeppelins included the LZ 3 (first flight 1906, and here shown over Berlin in 1909), LZ 72 (first flight 1916), and LZ 129 *Hindenburg* (first flight in 1936 and destroyed in 1937).

Johann Schütte (1873–1940)

Karl Lanz (1873–1921)

Schütte-Lanz rigid airships



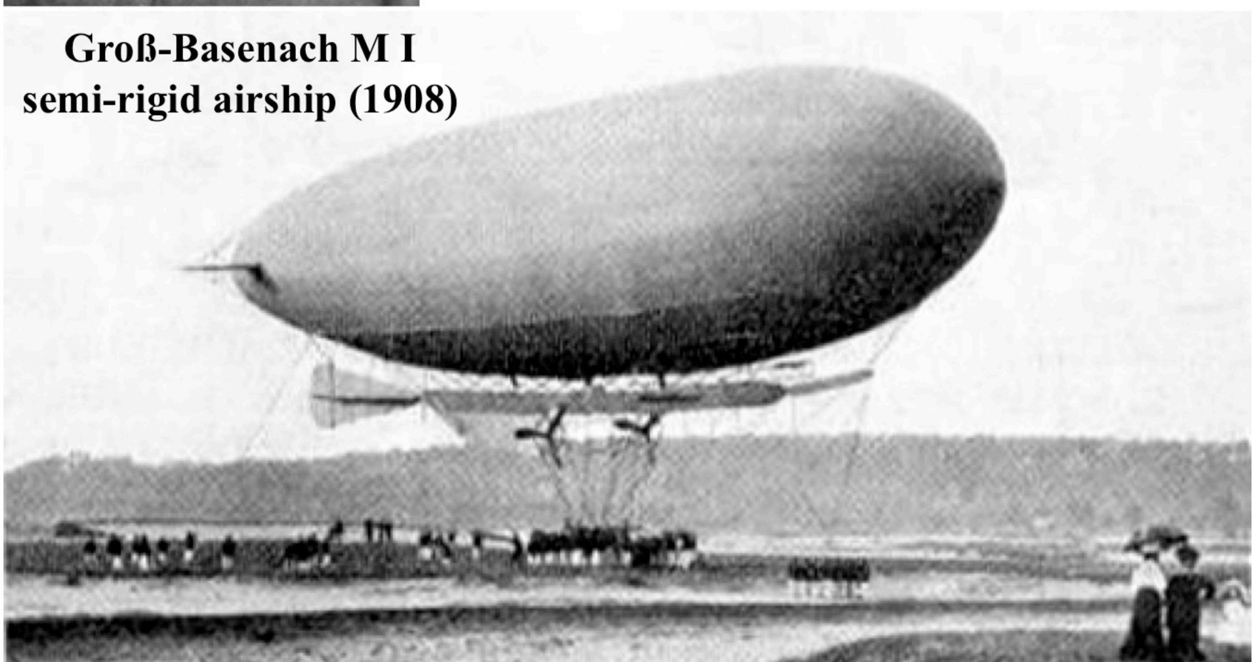
1911
1914
1915
1915
1916
1917

SL22 rigid airship (1918)

Figure 9.5: Johann Schütte and Karl Lanz rivaled Zeppelin with their own series of increasingly sophisticated airships that tended to use wood instead of aluminum.

Hans Groß
(1860–1924)

Nikolaus
Basenach
(1875–1951)



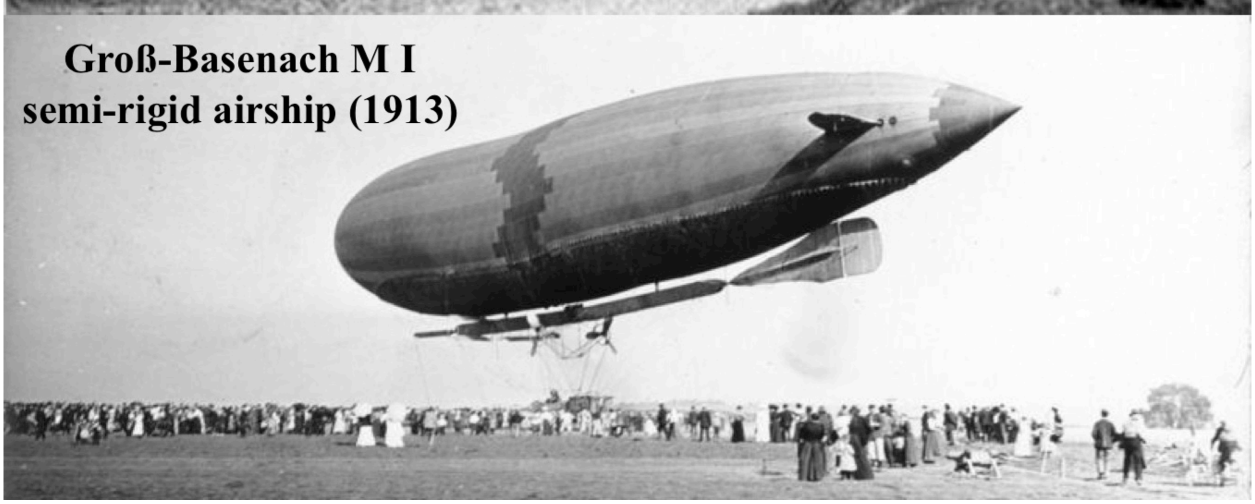


Figure 9.6: Hans Groß and Nikolaus Basenach developed a series of semi-rigid airships, such as the Groß-Basenach M I airship (first flight in 1908 and enlarged in 1913).

August von Parseval (1861–1942)

August Riedinger (1845–1919)

Rudolf von Sigsfeld (1861–1902)

Parseval *Versuchsluftschiff* non-rigid airship (1907)

PL19 non-rigid airship (1914)

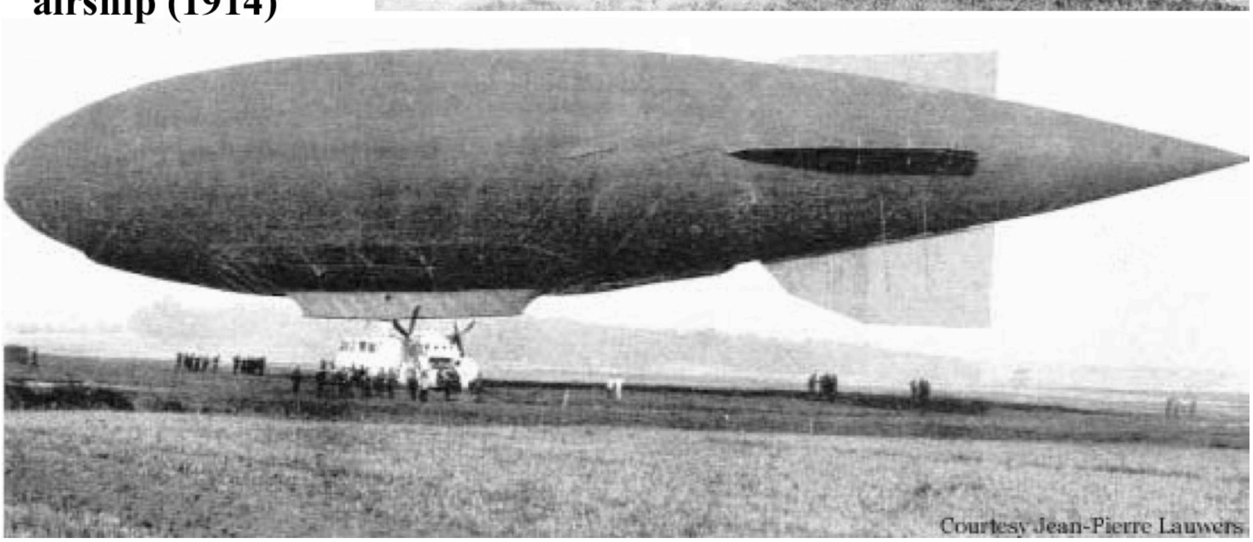


Figure 9.7: August von Parseval, August Riedinger, and Rudolf von Sigsfeld developed increasingly sophisticated non-rigid airships, such as the Parseval Versuchsluftschiff and PL19 airship.

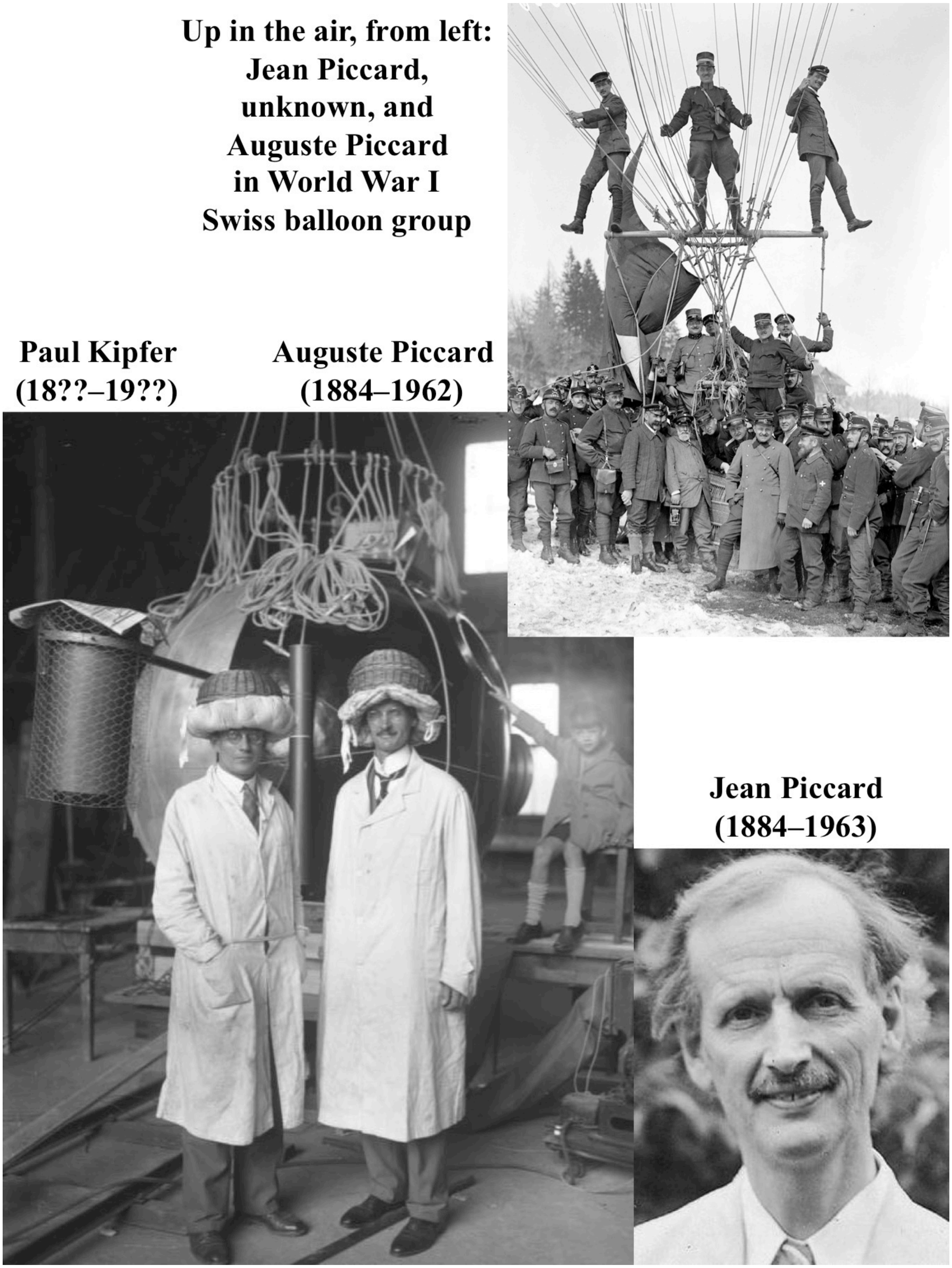


Figure 9.8: Paul Kipfer and Auguste Piccard, as well as Auguste's twin brother Jean Piccard who later worked separately, created and tested very high-altitude balloons.

9.2 Aerodynamics and Aircraft Design

German-speaking creators played such a dominant role for nearly a century in the development of aerodynamics and aerodynamics-guided aircraft designs that only a few examples of those creators and their creations can be mentioned here, representing the following areas:[3]

9.2.1. First aircraft

9.2.2. Aerodynamics experiments and theory

9.2.3. Specialized aircraft

9.2.4. High-speed aircraft design

For closely related contributions by German-speaking creators to jet engines and jet aircraft, see Section 9.3.

9.2.1 First Aircraft

George Cayley (English, 1773–1857) built the first known successful piloted glider in 1853. Although Cayley does not fall within the scope of this book, he deserves to be studied and remembered far more in his own right [Dee 2007]. Cayley's demonstration caught the attention of people around the world, and especially engineers in rapidly industrializing Germany.

As shown in Fig. 9.9, Otto Lilienthal (German, 1848–1896) developed and flew very innovative gliders with improved lift and maneuverability. He would likely have gone on to make the first powered airplane flights if he had not died from a glider crash in 1896 [Harsch et al. 2008; Heinzerling and Trischler 1991]. Oxford University's *Biographical Dictionary of Scientists* described Lilienthal's importance in the history of flight [Porter 1994, p. 432]:

> Lilienthal [...] was a German engineer whose experiments with gliders helped to found the science of aeronautics. But for his premature death in a flying accident, he might well have beaten the Wright brothers to the achievement of powered flight. [...]
>
> Lilienthal flew the first of his famous series of gliders in 1891, and continued, until his final fatal glide in 1896, to hold to his fundamental conviction that the key to eventual powered flight was in glider-flying, in which pilots could master the elements of control and design. [...] The step to powered flight was a straightforward progression from advanced gliding. The Wrights' breakthrough was a simple extension of their own work with gliders, which in turn was greatly helped by Lilienthal's many glides and careful observations. Among other things, he had demonstrated the superiority of cambered wings over flat wings—the principle of the aerofoil.

Gustav Weisskopf (German, 1874–1927) very closely studied the work of Lilienthal, then moved to the United States, where he became known as Gustave Whitehead. Weisskopf settled in Connecticut, where he built a long series of powered aircraft prototypes. There is considerable evidence that

[3] E.g., see: Amtmann 1988; Anderson 1997; Beauvais 2002; Bohr 2013; Brinchman 2015; Budrass 1998; Butler 1994, 2007; Chant 1999; Danelek and Davis 2011; Eckert 2017; Gorn 1992; Griehl 1990, 2004, 2005, 2015; Hanle 1982; Heinzerling and Trischler 1991; Herwig and Rode 2000, 2003; Hirschel et al. 2004; von Kármán 1945, 1967; Krehl 2009; Lommel 2000, 2002; Hans-Ulrich Meier 2010; Myhra 1998a, 1998b, 2000a, 2000b; Rotta 1990; Samuel 2004, 2010; Schick and Meyer 1997; Smith and Creek 1982, 1992, 2001; Smith and Kay 2002; Stüwe 1999, 2014, 2015; Trischler 1992a, 1992b; Trischler and Schrogl 2007; Vajda and Dancey 1998; Wegener 1996; CIOS XXVIII-47.

Weisskopf successfully conducted the first piloted flights of a powered airplane in 1901, covering a distance of approximately half a mile on the first flight, and several miles in subsequent flights:

1. Multiple witnesses reported that Weisskopf's airplane flew.

2. Many contemporaneous newspaper articles reported that his airplane flew.

3. Many contemporaneous newspaper articles reported that there were photographs showing Weisskopf's airplane flying (although the photographs cannot be located now).

4. Modern replicas of his aircraft successfully flew in tests made in the 1980s and 1990s.

If those claims are true, Weisskopf's first piloted, powered flight occurred over two years before the Wright Brothers' far more famous first flight, was much longer than the Wright Brothers' first flight, and was subsequently improved and repeated several times.

The details of Weisskopf's claims and the details of the evidence are still hotly debated.[4] Nonetheless, they seem to deserve far more open-minded and serious historical attention than they have generally received.

Surprisingly, the major relevant museums and scholars in the United States are legally forbidden from just that sort of open-minded and serious evaluation of the historical evidence. In 1948, the estate of the Wright family donated the Wright brothers' 1903 airplane to the Smithsonian Institution and the United States under extraordinary conditions that were agreed to in a legally binding contract (Figs. 9.11–9.12). That contract stipulated that the Wright airplane must be displayed immediately inside the museum entrance—accompanied by specific language stating that it was the first airplane—and that the museum and any affiliated organizations were legally forbidden to question whether there might have been any earlier successful airplanes:

> [...] Neither the Smithsonian Institution or its successors nor any museum or other agency, bureau or facilities, administered for the United States of America by the Smithsonian Institution or its successors, shall publish or permit to be displayed a statement or label in connection with or in respect of any aircraft model or design of earlier date than the Wright Aeroplane of 1903, claiming in effect that such aircraft was capable of carrying a man under its own power in controlled flight.
>
> 3. The title and right of possession to be transferred by the Vendors hereunder shall remain vested in the United States of America only so long as there shall be no deviation by the Vendee from the requirements of the foregoing paragraph[...]

Thus the major science history museums, curators, historians, and scholars of the United States are legally obligated to ignore any evidence that Gustav Weisskopf or anyone else may have been successful before the Wright brothers, or else they will lose the world-famous exhibit that hangs in the very center of the National Air and Space Museum in Washington, D.C. This 1948 contract was the culmination of many decades of action by the Wright family and their powerful allies against the relatively undefended and impoverished legacy of Gustav Weisskopf, which might also explain why some of the documentary evidence for Weisskopf's flights (such as numerous photographs that were described in contemporaneous accounts) disappeared over the years.

[4] Brinchman 2015; Brown 2016; Crouch 2002, 2013; Danelek and Davis 2011; O'Dwyer 1978; Randolph 1966; Schlenoff 2014; NYT 2015-04-18 p. A15; http://gustavewhitehead.info.

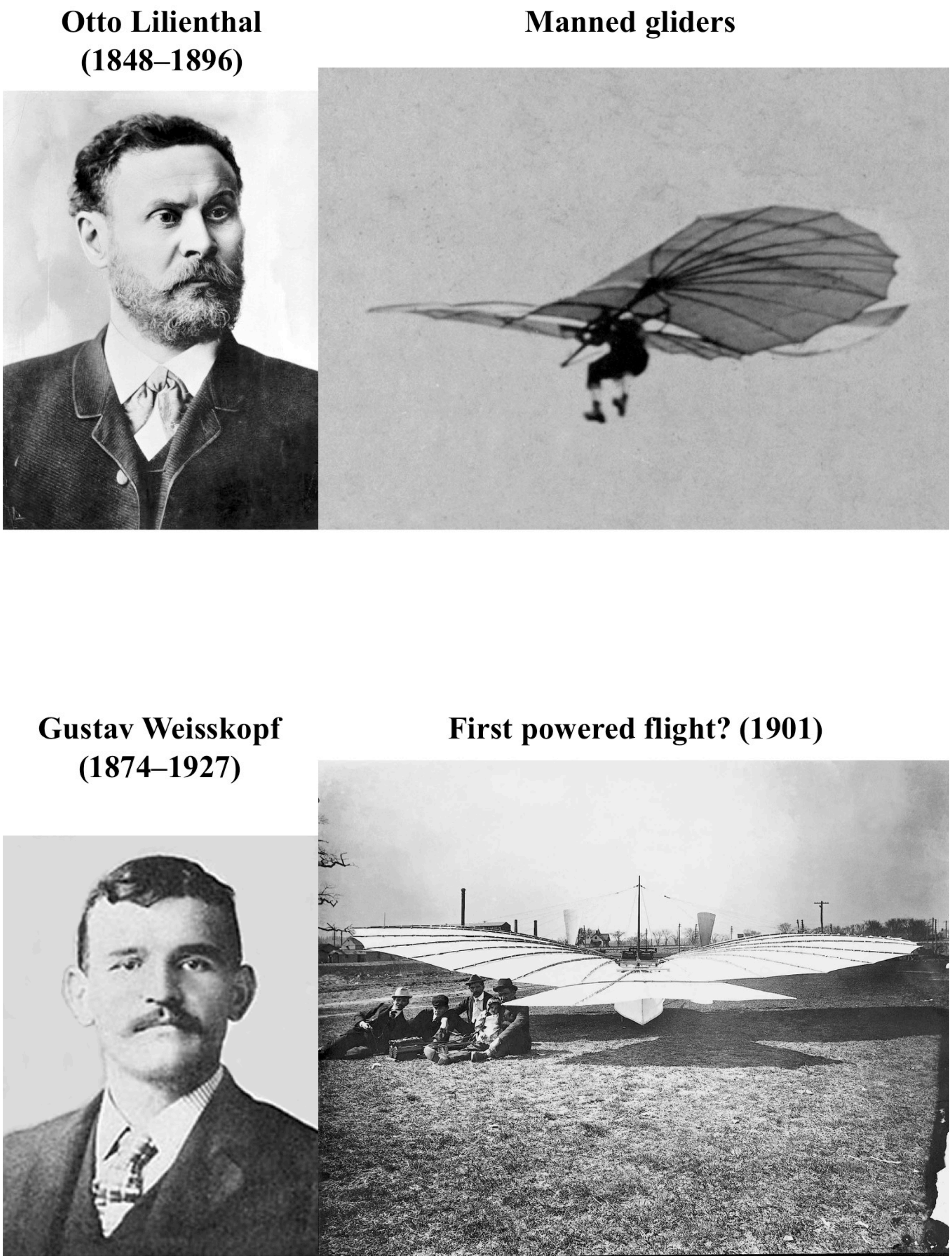
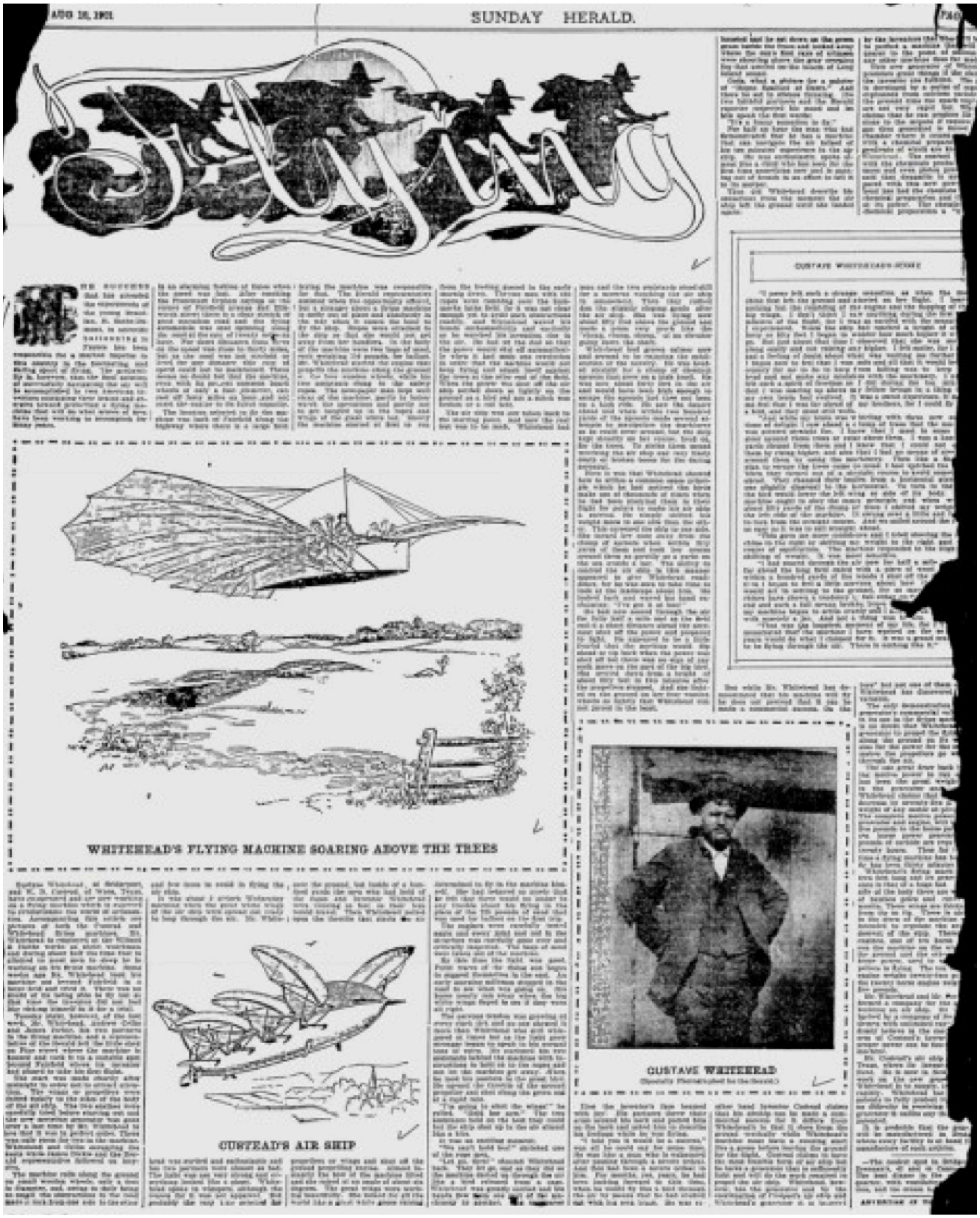


Figure 9.9: Otto Lilienthal developed and flew gliders, and there is significant evidence that Gustav Weisskopf/Gustave Whitehead conducted the first powered flight in 1901.



AUG 18, 1901 SUNDAY HERALD.

Flying

GUSTAVE WHITEHEAD'S STORY

WHITEHEAD'S FLYING MACHINE SOARING ABOVE THE TREES

CUSTEAD'S AIR SHIP

GUSTAVE WHITEHEAD

Figure 9.10: Many local Bridgeport, Connecticut newspaper articles reported that Gustav Weisskopf/Gustave Whitehead successfully conducted the first powered flights in 1901 [see this and many other examples of 1901 newspaper articles at http://gustavewhitehead.info].

AGREEMENT

THIS AGREEMENT made by and between HAROLD S. MILLER and HAROLD W. STEEPER as Executors of the Last Will and Testament of Orville Wright, deceased, hereinafter called the Vendors, Parties of the First Part, and THE UNITED STATES OF AMERICA, hereinafter called the Vendee, Party of the Second Part, W I T N E S S E T H:

WHEREAS there is included in the residuary estate of Orville Wright the Wright Aeroplane of 1903, invented and built by Wilbur and Orville Wright and flown by them at Kitty Hawk, North Carolina on December 17, 1903, and

WHEREAS it is in the public interest that said plane be preserved for all time and made available as a public exhibit in an appropriate place and under proper auspices, and

WHEREAS the Probate Court of Montgomery County, Ohio, having jurisdiction over the administration of said estate, after full hearing in a proceeding to which all persons and institutions having any interest under the will of Orville Wright were parties and had submitted themselves to the jurisdiction of the Court, has officially found that the known wishes of Orville Wright will be carried out and the highest and best interest of the estate will be served by recognizing the public interest and has accordingly authorized and directed the Vendors to enter into this Agreement,

NOW, THEREFORE, THIS AGREEMENT WITNESSETH:

1. For the consideration hereinafter set forth the Vendors agree to sell and do hereby sell to the United States of America, and agree to deliver to the United States National Museum, Washington, D.C., within the current fiscal year ending June 30, 1949, and subject to the terms of this Agreement, the original Wright Aeroplane of 1903.

2. In consideration thereof the Vendee agrees to pay to the Vendors the sum of One ($1.00) Dollar in cash and to comply with the following requirements:

(a) Said aeroplane is to be displayed as a public museum exhibit in the Metropolitan Area of the United States National Capital only, and except as hereinafter provided in paragraph (b) is to be housed directly facing the Main Entrance in the fore part of the North Half of the Arts and Industries Building of the United States National Museum. It shall never be removed from such public exhibition except as may be required temporarily for maintenance or protection.

(b) If the proper authorities of the Smithsonian Institution or its successors (acting for the United States of America) at any time in the future desire to remove said aeroplane to any other building in the Metropolitan Area of the national capital, such removal shall be permitted on the following conditions:

1. That the substituted building shall have equal or better facilities for the protection, maintenance and exhibition of the aeroplane.

2. That the Wright Aeroplane of 1903 be given a place of special honor and not intermingled with other aeroplanes of later design.

3. That such building be not a military museum but be devoted to memorializing the development of aviation.

(c) There shall at all times be prominently displayed with said aeroplane a label in the following form and language:

The Original Wright Brothers' Aeroplane
The World's First Power-Driven Heavier-than-Air Machine
in Which Man Made Free, Controlled, and
Sustained Flight
Invented and Built by Wilbur and Orville Wright
Flown by Them at Kitty Hawk, North Carolina
December 17, 1903
By Original Scientific Research the Wright Brothers Discovered
the Principles of Human Flight
As Inventors, Builders and Flyers They Further Developed the Aeroplane
Taught Man to Fly and Opened the Era of Aviation
Deposited by the Estate of Orville Wright.

"The first flight lasted only twelve seconds, a flight very modest compared with that of birds, but it was nevertheless the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in free flight, had sailed forward on a level course without reduction of speed, and had finally landed

2.

Figure 9.11: As a condition for possessing the Wright Brothers' 1903 airplane, the U.S. Smithsonian Institution and related organizations are legally forbidden from questioning whether Gustav Weisskopf/Gustave Whitehead or others may have succeeded before the Wrights [see http://gustavewhitehead.info/smithsonian-conspiracy-to-deny-whitehead-flew-first/ for this and additional related documents and information].

without be[illegible] wrecked. The second and th[illegible] flights were a little longer, and the fourth lasted 59 seconds covering a distance of 852 feet over the ground against a 20 mile wind."

Wilbur and Orville Wright
(From Century Magazine, Vol. 76, September 1908, p. 649.)

(d) Neither the Smithsonian Institution or its successors nor any museum or other agency, bureau or facilities, administered for the United States of America by the Smithsonian Institution or its successors, shall publish or permit to be displayed a statement or label in connection with or in respect of any aircraft model or design of earlier date than the Wright Aeroplane of 1903, claiming in effect that such aircraft was capable of carrying a man under its own power in controlled flight.

3. The title and right of possession to be transferred by the Vendors hereunder shall remain vested in the United States of America only so long as there shall be no deviation by the Vendee from the requirements in the foregoing paragraph, and only so long as neither the Estate of Orville Wright nor any person having an interest therein is required to pay and does bear without indemnity an estate or inheritance tax, assessed by the State of Ohio, the United States or any other taxing authority, based upon a valuation of property of the Estate which includes said aeroplane at a value in excess of One ($1.00) Dollar.

4. Upon the failure of the Vendee to remedy any deviation from the requirements set forth in paragraph 2, within twelve months after written specification thereof shall have been given to the Smithsonian Institution on behalf of the United States or upon (a) the final assessment of any state or federal inheritance, succession or estate tax whereby the Estate of Orville Wright or any person or persons having an interest therein shall be required to pay a higher tax by reason of a valuation of said aeroplane for tax purposes in excess of One ($1.00) Dollar, and (b) the omission of the United States or others on behalf of the United States within twelve months of written notice of the final assessment by the person assessed to provide for the payment thereof by appropriations or otherwise, title to and right of possession of said aeroplane shall automatically revert to the Vendors, their successors and assigns.

5. In the event of a termination of title in the United States by reason of an omission on the part of the United States to provide for the

3.

payment [illegible] a tax assessment as aforesai[illegible] [illegible]he United States shall have an option to repurchase the plane at any time within five years of the tax payment by reimbursing the taxpayer in the amount paid with interest thereon at six per cent from the date of payment. Upon the exercise of such option, this Agreement, in all of its terms, shall automatically again become of full force and effect.

WITNESS the due execution hereof in duplicate this 23rd day of November 1948.

Harold S Miller (SEAL)
Harold [illegible] Stecker (SEAL)
Executors of the Estate of
Orville Wright, deceased

UNITED STATES OF AMERICA

BY A. Wetmore
Secretary of the Smithsonian Institution

4.

Figure 9.12: As a condition for possessing the Wright Brothers' 1903 airplane, the U.S. Smithsonian Institution and related organizations are legally forbidden from questioning whether Gustav Weisskopf/Gustave Whitehead or others may have succeeded before the Wrights [see http://gustavewhitehead.info/smithsonian-conspiracy-to-deny-whitehead-flew-first/ for this and additional related documents and information].

9.2.2 Aerodynamics Experiments and Theory

Two brilliant Swiss mathematicians laid the foundations for the mathematical theory of fluid mechanics and aerodynamics in the 1700s:

- Daniel Bernoulli (Swiss, 1700–1782) developed the Bernoulli equation for incompressible, inviscid fluid flow, and published it in 1738 (Fig. 9.13). The Bernoulli equation is useful for designing barometers, finding the aerodynamic lift of aircraft wings, calculating the aerodynamic drag on vehicles and parachutes, explaining meteorological phenomena, and analyzing other applications. Bernoulli also made important contributions to mathematics and to the theory of flexible beams.

- Leonhard Euler (Swiss, 1707–1783) developed the more general Euler equations for fluid flow, which greatly extend the Bernoulli equation for many other conditions and applications, and published them in 1757 (Fig. 9.14). He also made extensive contributions to calculus, complex number theory, topology and graph theory, mechanical stress and strain calculations, astronomy, optics, logic, and other topics [Calinger 2015; Richeson 2008].

As illustrated in Fig. 9.15, Ernst Mach (Austrian, 1838–1916), his son Ludwig Mach (Austrian, 1868–1951), and Peter Salcher (Austrian, 1848–1928) conducted the first experiments to visualize shock waves around a bullet traveling faster than the speed of sound through air. The speed of an object compared to the speed of sound is now called the Mach number.

Ernst Mach excelled both at experimental technique—as demonstrated by his ability to capture detailed images of a bullet in flight without any electronic timing equipment—and at finding the correct theoretical interpretation of the new phenomena that he observed. He made many contributions to aerodynamics and aerodynamic measurements, as listed by science historian Peter Krehl [Krehl 2009, p. 1118]:

> Ernst Mach, who had planned supersonic ballistic experiments several years before Prof. Peter Salcher, an Austrian physicist at the Imperial Navy, eventually succeeded in photographing them (1886). Mach immediately gave a correct interpretation of the head wave and the lines emanating from projectile surfaces. These supersonic flow phenomena were later connected with his name, such as the *Mach angle*, *Mach cone*, *Mach head wave*, *Mach line*, and *Mach wave*. Furthermore, Mach also studied the oblique interaction of shock waves, thereby discovering irregular reflection (*Mach reflection effect*) and the origin of a new shock wave (*Mach disk*, *Mach front*, *Mach stem*), which since the 1940s has stimulated worldwide research activities to better understand this puzzling "Mach effect."

In addition to his work in aerodynamics, Ernst Mach made important contributions to many other unrelated fields, as explained by aerodynamics expert and historian John D. Anderson, Jr. [Anderson 1997, pp. 375–376]:

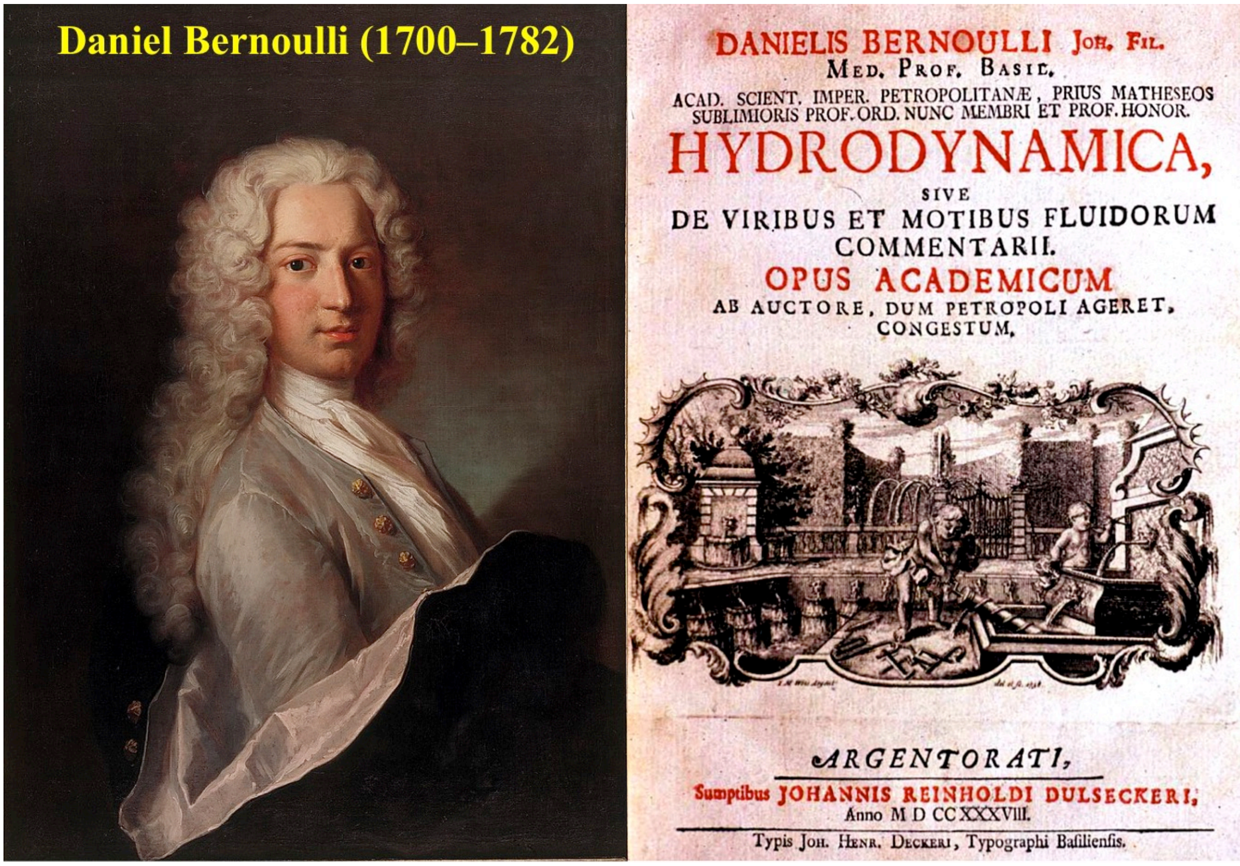
> Mach entered the University of Vienna, where he excelled, spurred by interest in mathematics, physics, philosophy, and history. In 1860 he received a Ph.D. in physics, with a thesis entitled "On Electrical Discharge and Induction." By 1864 he was a professor

> of physics at the University of Graz. (The variety and depth of his intellectual interests were attested by the fact that he was offered, but turned down, a chair in *surgery* at the University of Salzburg, preferring to go to Graz.) In 1867, Mach became a professor of experimental physics at the University of Prague, a position he would occupy for the next 28 years.
>
> In the modern technological world, engineers and scientists are virtually forced to concentrate their efforts in narrow areas of specialization, but in Mach's time one could still contemplate the Renaissance man, and Mach was a supreme generalist. A listing of Mach's contributions and writings would include works on physical optics, the history of science, mechanics, philosophy, the origins of relativity theory, supersonic flow, thermodynamics, the sugar cycle in grapes, the physics of music, and classical literature. He even wrote on world affairs: one of Mach's papers commented on the "absurdity committed by the statesman who regards the individual as existing solely for the sake of the state," which provoked strong criticism from Lenin. We can only regard him with awe and envy, for Mach, in the words of the American philosopher William James, knew "everything about everything."

For some of Ernst Mach's other accomplishments, see pp. 300, 309, 882, and 886. For some of his son Ludwig Mach's other accomplishments, see p. 1038.

Like Ernst Mach, Ludwig Prandtl (German, 1875–1953) was enormously talented at both experimental methods of measuring aerodynamic effects and theoretical methods of explaining those effects. Yet whereas Mach divided his time among several other unrelated fields, Prandtl spent his long career focused on aerodynamics, building the most advanced wind tunnels in the world from 1907 onward, and discovering and calculating a wide range of aerodynamic phenomena (Figs. 9.16–9.17, 9.42). *Encyclopedia Britannica* labelled Prandtl the "father of aerodynamics" [EB 2010]:

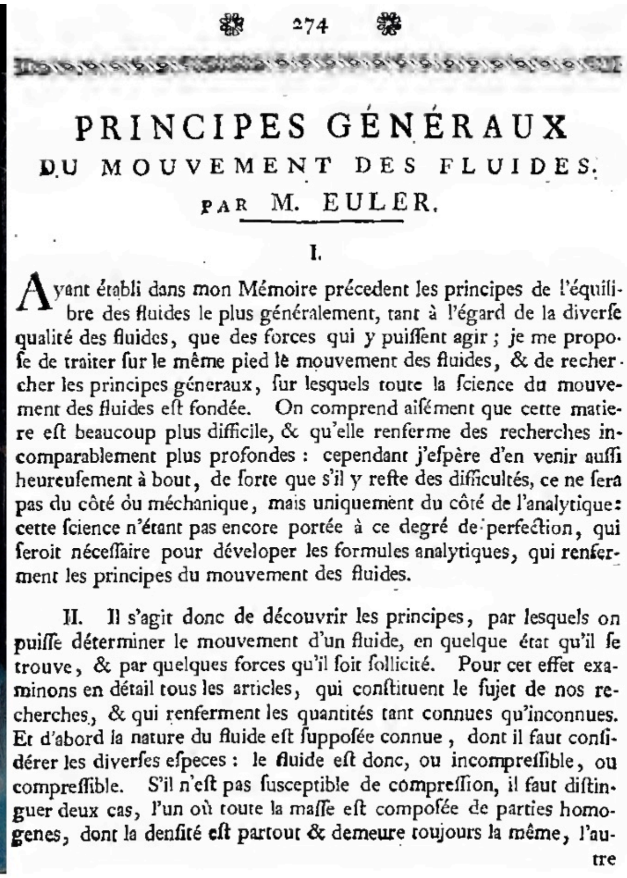
> German physicist who is considered to be the father of aerodynamics. [...]
>
> Prandtl made decisive advances in boundary-layer and wing theories, and his work became the fundamental material of aerodynamics. He was an early pioneer in streamlining dirigibles, and his advocacy of monoplanes greatly advanced heavier-than-air aviation. He contributed the Prandtl-Glauert rule for subsonic airflow to describe the compressibility effects of air at high speeds. In addition to his important advances in the theories of supersonic flow and turbulence, he made notable innovations in the design of wind tunnels and other aerodynamic equipment. He also devised a soap-film analogy for analyzing the torsion forces of structures with noncircular cross sections.



Bernoulli equation for incompressible, inviscid fluid flow

$$\overbrace{\frac{1}{2}\rho v^2}^{\substack{\text{Kinetic energy}\\ \text{per volume}}} + \overbrace{\rho g H}^{\substack{\text{Gravitational}\\ \text{potential energy}\\ \text{per volume}}} + \overbrace{p}^{\substack{\text{Pressure}\\ \text{potential energy}\\ \text{per volume}}} = \overbrace{\text{constant (along a streamline)}}^{\substack{\text{Total energy}\\ \text{per volume}}}$$

Figure 9.13: Daniel Bernoulli developed the Bernoulli equation for incompressible, inviscid fluid flow, and published it in 1738.



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PRINCIPES GÉNÉRAUX
DU MOUVEMENT DES FLUIDES.
PAR M. EULER.

I.

Ayant établi dans mon Mémoire précedent les principes de l'équilibre des fluides le plus généralement, tant à l'égard de la diverſe qualité des fluides, que des forces qui y puiſſent agir; je me propoſe de traiter ſur le même pied lè mouvement des fluides, & de rechercher les principes géneraux, ſur lesquels toute la ſcience du mouvement des fluides eſt fondée. On comprend aiſément que cette matiere eſt beaucoup plus difficile, & qu'elle renferme des recherches incomparablement plus profondes: cependant j'eſpère d'en venir auſſi heureuſement à bout, de ſorte que s'il y reſte des difficultés, ce ne ſera pas du côté du méchanique, mais uniquement du côté de l'analytique: cette ſcience n'étant pas encore portée à ce degré de perfection, qui ſeroit néceſſaire pour développer les formules analytiques, qui renferment les principes du mouvement des fluides.

II. Il s'agit donc de découvrir les principes, par lesquels on puiſſe déterminer le mouvement d'un fluide, en quelque état qu'il ſe trouve, & par quelques forces qu'il ſoit ſollicité. Pour cet effet examinons en détail tous les articles, qui conſtituent le ſujet de nos recherches, & qui renferment les quantités tant connues qu'inconnues. Et d'abord la nature du fluide eſt ſuppoſée connue, dont il faut conſidérer les diverſes eſpeces: le fluide eſt donc, ou incompreſſible, ou compreſſible. S'il n'eſt pas ſuſceptible de compreſſion, il faut diſtinguer deux cas, l'un où toute la maſſe eſt compoſée de parties homogenes, dont la denſité eſt partout & demeure toujours la même, l'au-
tre

Euler equations for fluid flow

$$\overbrace{\frac{\partial \rho}{\partial t}}^{\text{Change in mass}} + \overbrace{\nabla\cdot(\rho\mathbf{v})}^{\text{Mass outflow}} = \overbrace{0}^{\text{Conserved}}$$

Continuity equation (differential form)

$$\overbrace{\rho\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v}}^{\text{Mass}\,\times\,\text{acceleration}} = \overbrace{\rho\mathbf{g}}^{\substack{\text{Gravitational}\\\text{force}}} - \overbrace{\nabla p}^{\substack{\text{Pressure}\\\text{force}}} + \overbrace{\mathbf{F}_{\text{viscous}}}^{\substack{\text{Viscous}\\\text{forces}}}$$

Momentum equation (differential form)

$$\overbrace{\frac{\partial}{\partial t}\left[\rho\left(u + \frac{v^2}{2} + gH\right)\right]}^{\text{Change in energy}} + \overbrace{\nabla\cdot\left[\rho\left(u + \frac{v^2}{2} + gH\right)\mathbf{v}\right]}^{\text{Energy outflow}}$$
$$= \underbrace{\dot{q}_{\text{input}}}_{\substack{\text{Input heat}\\\text{energy}}} + \underbrace{\dot{w}_{\text{input}}}_{\substack{\text{Input work}\\\text{energy}}} - \underbrace{\nabla\cdot(p\mathbf{v})}_{\substack{\text{Output work energy}\\\text{by expanding pressure}}} + \underbrace{\phi_{\text{viscous}}}_{\substack{\text{Input energy from}\\\text{friction with surroundings}}}$$

Energy equation (differential form)

Figure 9.14: Leonhard Euler developed the more general Euler equations for fluid flow, and published them in 1757.

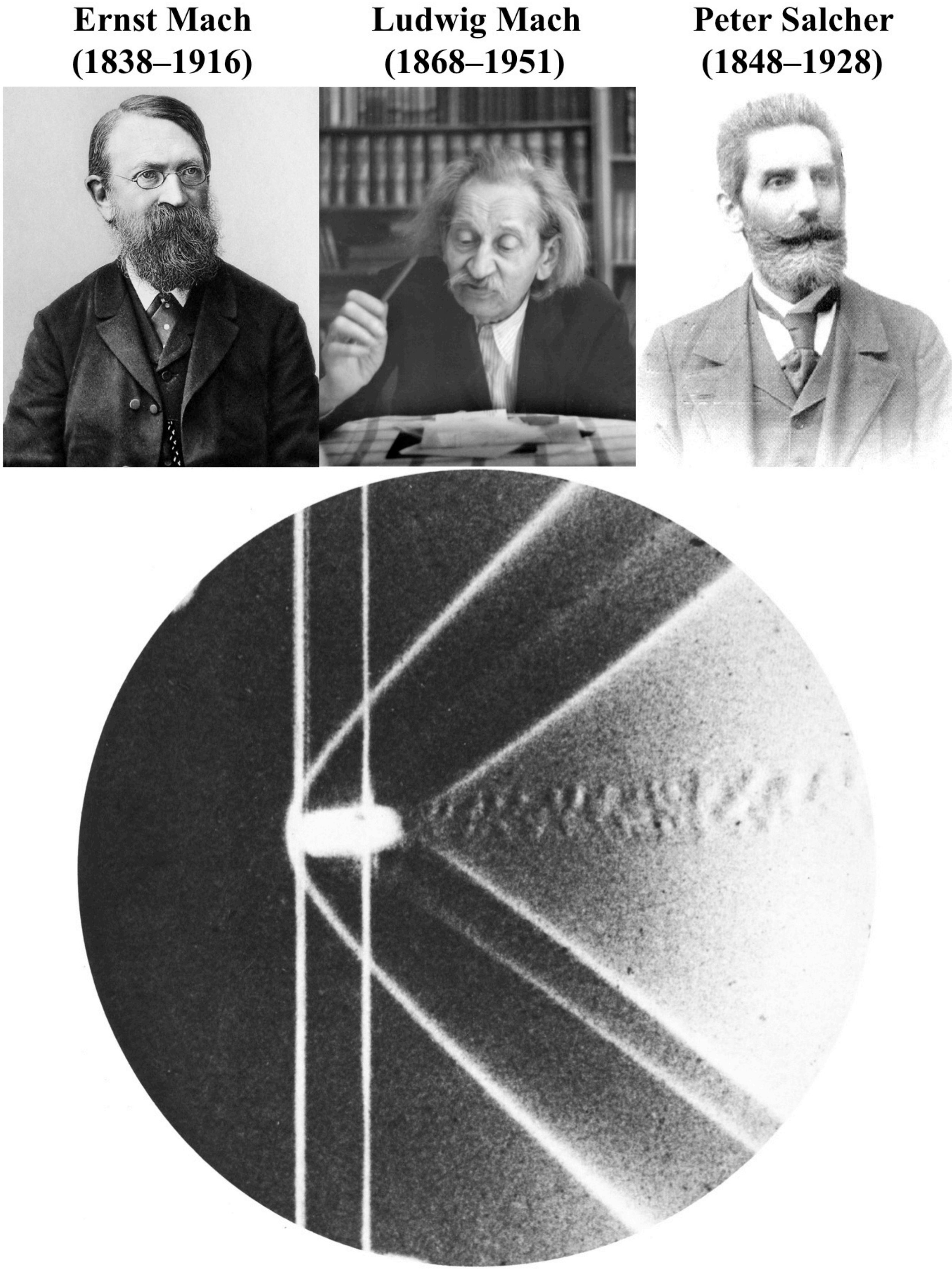


Figure 9.15: Ernst Mach, his son Ludwig Mach, and Peter Salcher conducted the first experiments to visualize shock waves around a bullet traveling faster than the speed of sound through air.

Ludwig Prandtl (1875–1953), the "father of aerodynamics"

Photographed in 1904 with a water canal for fluid mechanics measurements, shortly before he began building a series of world-leading wind tunnels

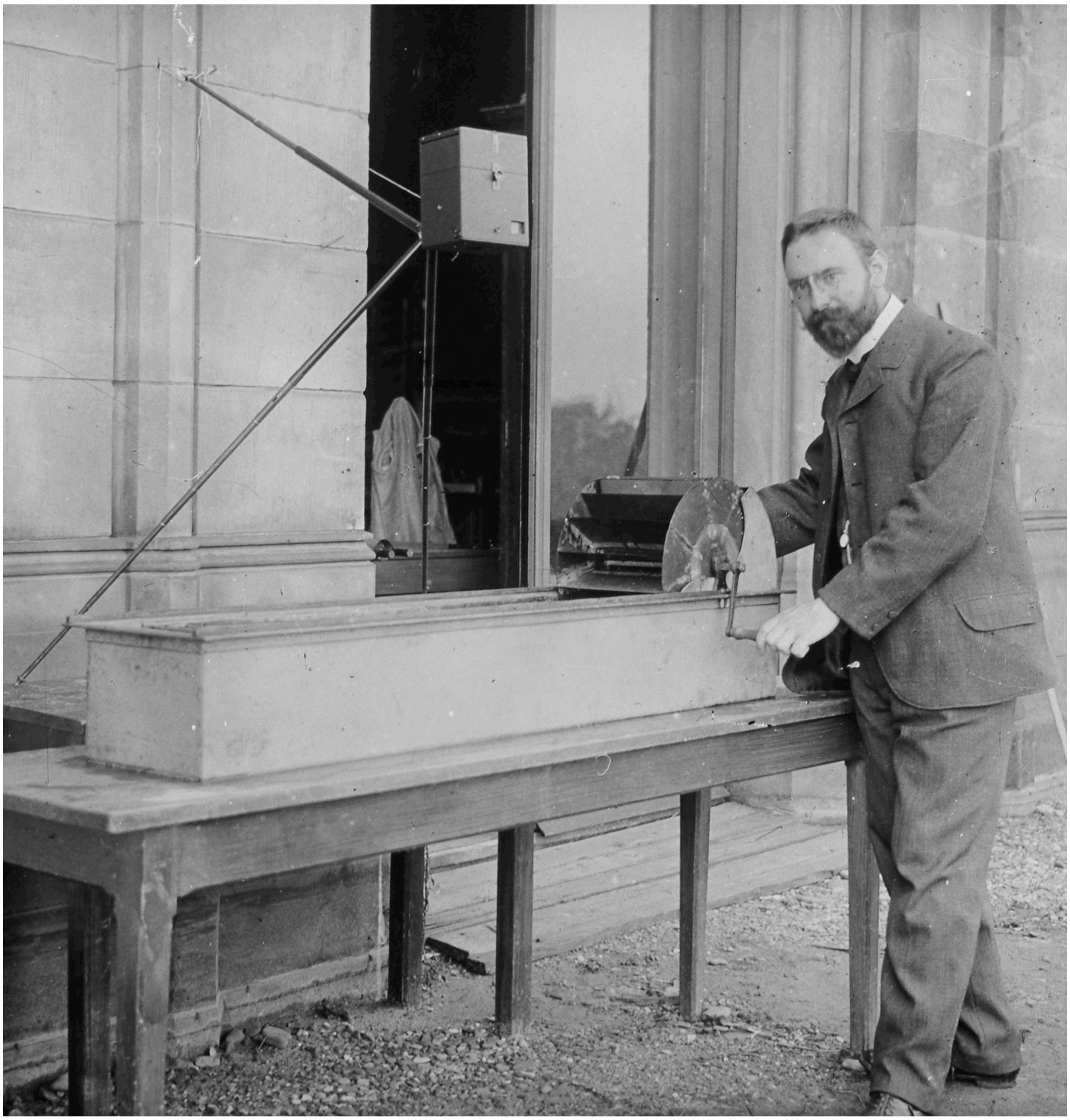


Figure 9.16: Ludwig Prandtl was the "father of aerodynamics." In this 1904 photograph, he was using a water canal for fluid mechanics measurements, shortly before he began building a series of world-leading wind tunnels.

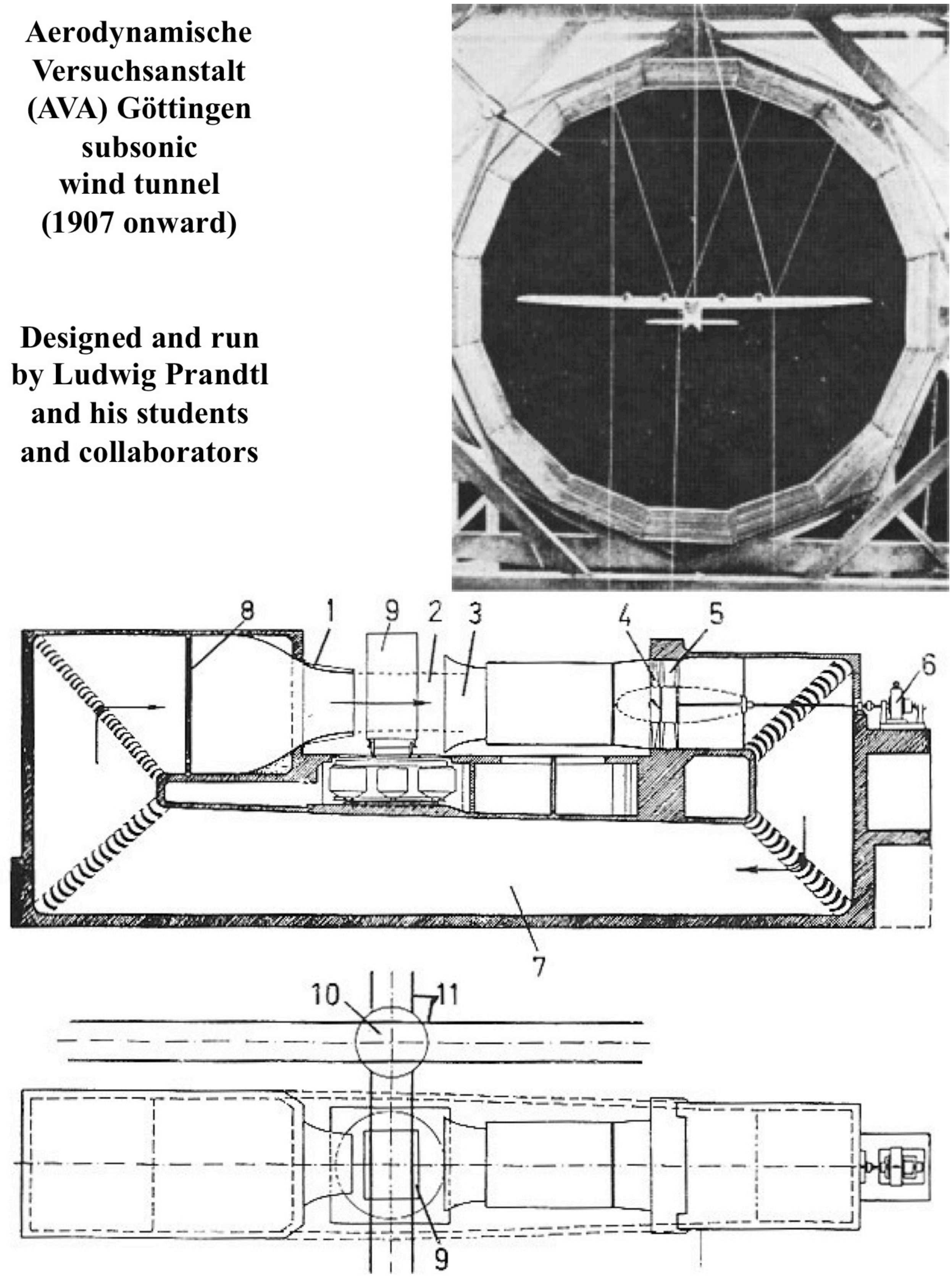


Figure 9.17: Ludwig Prandtl and his students and collaborators designed and operated the Aerodynamische Versuchsanstalt (AVA) subsonic wind tunnel at Göttingen from 1907 onward [http://www.histaviation.com].

During his several decades at the Aerodynamische Versuchsanstalt (AVA) at Göttingen University, Prandtl was also a prolific teacher and mentor for countless students and lab assistants who themselves went on to make major contributions to aerodynamics, wind tunnel experiments, and other aspects of aerospace engineering. Looking at all the resulting innovators and innovations, one gets the impression that most of the field of aerodynamics can be traced to Prandtl and/or his students.[5] [See Eckert 2017 for much more information on Prandtl.]

Albert Betz (German, 1885–1968) was one of Prandtl's students, continued to work with Prandtl at the AVA after that, and eventually succeeded Prandtl as director of the AVA. In 1919, Betz applied the principles of aerodynamics to calculate the efficiency of power-producing wind turbines and to design wind turbine blades with the highest possible efficiency (Fig. 9.18). Such wind turbines are now used all over the world. Betz made many other contributions to aerodynamics over his career, including working on the AVA wind tunnels, testing and implementing Adolf Busemann's designs for swept-back aircraft wings (p. 1708), and developing axial flow compressor blades for jet engines (p. 1745).

The early wind tunnels that were constructed by Ludwig Prandtl and his students were subsonic, producing wind speeds slower than the speed of sound (Fig. 9.17). Subsonic wind tunnels have continued to be used worldwide to test the aerodynamics of subsonic aircraft, automobiles, models of buildings, etc. For example, Fig. 9.19 shows the Deutsche Forschungsanstalt für Luftfahrt (DFL) subsonic wind tunnel at Braunschweig-Völkenrode that began operation in 1940. It was so large that whole aircraft could be tested in it, instead of subscale models.

Max Munk (German, 1890–1986) studied aircraft wing (airfoil) design and wind tunnel design under Ludwig Prandtl and graduated from Göttingen University in 1918 with two Ph.D. degrees, in both physics and mathematics. In 1920, he moved to the United States. In 1921, he designed the Variable Density Tunnel at the NACA (later NASA) Langley Research Center (Fig. 9.20). He completed that subsonic wind tunnel in 1923 and oversaw its operation for several years. Munk's wind tunnel was so advanced compared to other apparatus then available in the United States that it was used until the 1940s, when it was superseded by new German-designed wind tunnels.

[5] One should also note the work of Frederick Lanchester (English, 1868–1946), a contemporary of Prandtl who had some similar insights in aerodynamics but unfortunately was not able to find much support for them within the British system at the time.

Albert Betz (1885–1968) maximized the efficiency of wind turbines (1919)

$$\dot{E}_{in}-\dot{E}_{out}=\Delta\dot{E}_{system}$$

$$\dot{E}_{in}=\dot{E}_{out}$$

$$\dot{m}h_{in}+\tfrac{1}{2}\dot{m}v_1^2+\dot{m}gz_1=\dot{m}h_{out}+\tfrac{1}{2}\dot{m}v_2^2+\dot{m}gz_1+\dot{W}_{out}+\dot{Q}_{out}$$

$$\tfrac{1}{2}\dot{m}v_1^2=\tfrac{1}{2}\dot{m}v_2^2+\dot{W}_{out}$$

$$\dot{W}_{out}=\tfrac{1}{2}\dot{m}(v_1^2-v_2^2)$$

$$\dot{m}=\rho vA$$

$$\text{let } v=\tfrac{1}{2}(v_1+v_2)$$

$$\dot{m}=\tfrac{1}{2}\rho A(v_1+v_2)$$

$$\dot{W}_{out}=\tfrac{1}{4}\rho A(v_1+v_2)(v_1^2-v_2^2)$$

$$\dot{W}_{out}^{max}=\dot{E}_{in}=\tfrac{1}{2}\rho Av_1^3$$

$$C_p=\dot{W}_{out}/\dot{W}_{out}^{max}=\tfrac{1}{2}\left[1-\left(\frac{v_2}{v_1}\right)^2\right]\left[1+\left(\frac{v_2}{v_1}\right)\right]$$

$$y=\tfrac{1}{2}(1-x^2)(1+x)$$

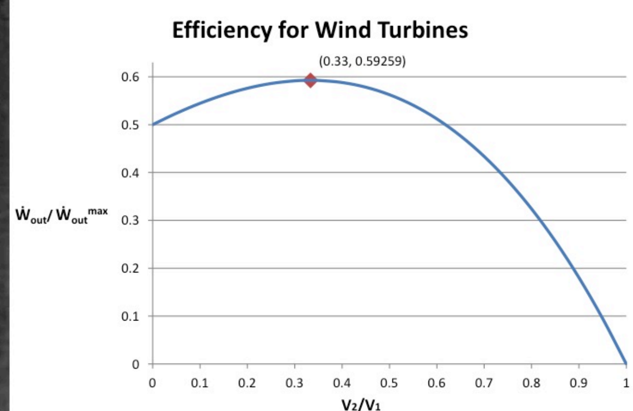


Figure 9.18: Albert Betz maximized the efficiency of wind turbines in 1919. His innovations have become increasingly important as larger amounts of electricity are generated from wind power worldwide.

Deutsche Forschungsanstalt für Luftfahrt (DFL)
Braunschweig-Völkenrode subsonic wind tunnel (1940)

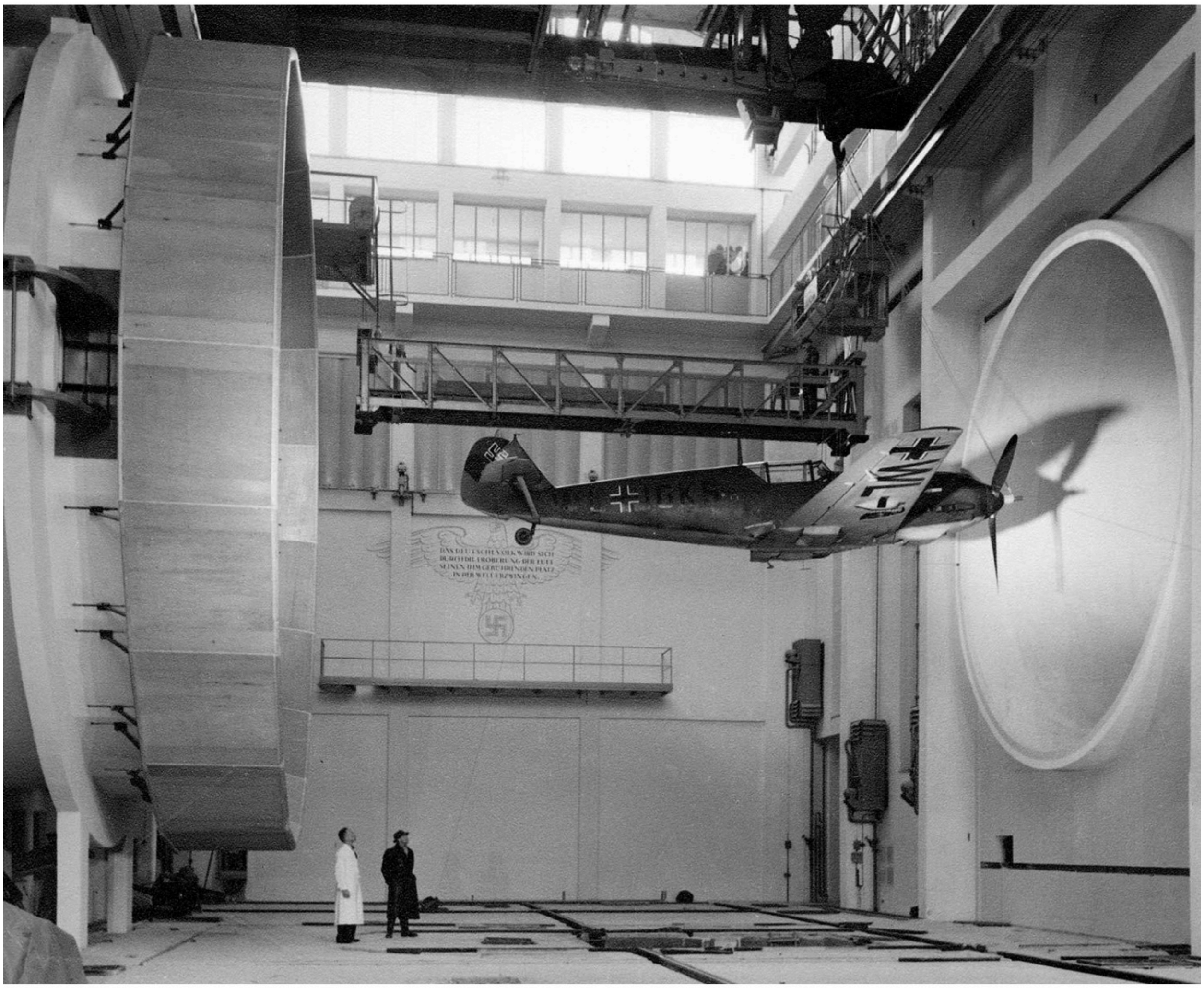


Figure 9.19: The Deutsche Forschungsanstalt für Luftfahrt (DFL) wind tunnel at Braunschweig-Völkenrode began operation in 1940. It was so large that whole aircraft could be tested in it, instead of subscale models.

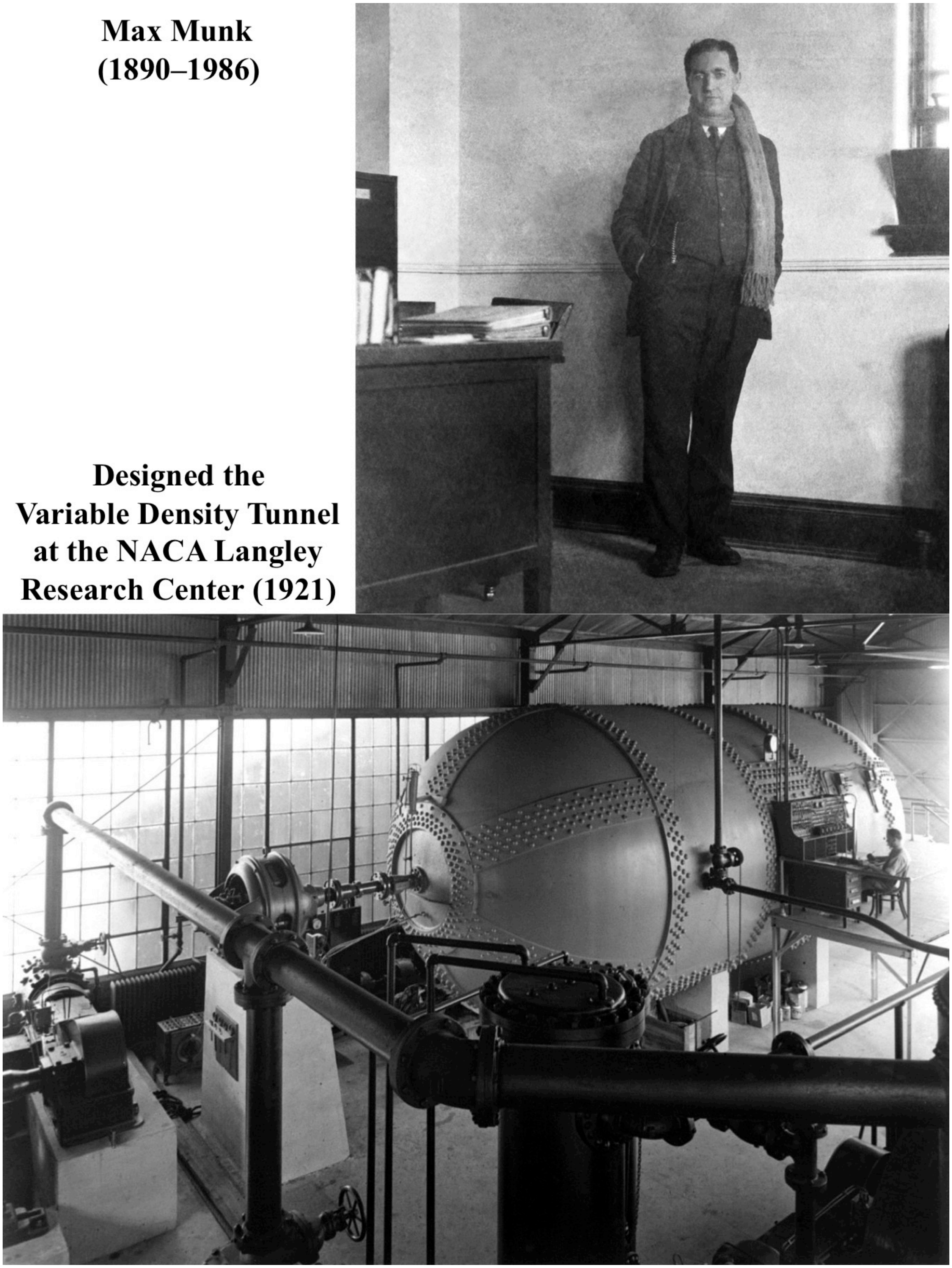


Figure 9.20: Max Munk, one of Prandtl's former students and assistants, immigrated to the United States. In 1921 he designed the best U.S. wind tunnel at that time, the Variable Density Tunnel at the NACA Langley Research Center. It began operation in 1923 and was used until the 1940s, when it was superseded by new German-designed wind tunnels.

In 1917, Prandtl designed the first supersonic wind tunnel, capable of producing wind speeds faster than the speed of sound. Unfortunately World War II and the financial impacts of Allied reparations payments in the 1920s prevented Prandtl from immediately finding the support and resources necessary to build supersonic wind tunnels. When more funding became available in the early 1930s, there was a boom in building supersonic wind tunnels in the German-speaking world.

Jakob Ackeret (Swiss, 1898–1981, p. 1708), one of Prandtl's protégés, began operating a supersonic wind tunnel at ETH Zurich in 1933. It was initially capable of attaining wind speeds up to Mach 2. The ETH Zurich wind tunnel facility has been repeatedly upgraded over the years and is still in operation.

Rudolf Hermann (German, 1904–1991, Fig. 9.24) and Carl Wieselsberger (German, 1887–1941, Fig. 9.25), former students of Prandtl, built a wind tunnel at the Technical University of Aachen that could achieve wind speeds up to Mach 3.

In 1936, Rudolf Hermann designed the Heeresversuchsanstalt (HVA) supersonic/hypersonic wind tunnel for the German army's rocket program (Fig. 9.21). The HVA wind tunnel was the most advanced facility of its type in the world at that time. It was run by Hermann Kurzweg (German, 1908–2000, Fig. 9.24) and his team at Peenemünde during the period 1939–1943, moved to Kochel for 1943–1945 to avoid Allied bombing, and taken to the U.S. Naval Ordnance Laboratory in 1945. The HVA tunnel could attain a range of speeds up to Mach 5.2. In 1944, it attained Mach 9.5 after being modified. Rudolf Hermann's wind tunnel was critically important for the development of rockets such as the A-4 (V-2), and he was rewarded for it along with Wernher von Braun and other top members of the rocket team (p. 5452).

Prandtl and his collaborators began operated a supersonic wind tunnel at the AVA in 1938. In 1955 at the AVA, Hubert Ludwieg (German, 1912–2000, Fig. 9.24), yet another former student of Prandtl, created what became known as the Ludwieg tube, a wind tunnel capable of speeds from Mach 3 to Mach 12.

At the end of World War II, the very advanced Zitteraal wind tunnel was under construction at Ötztal, Austria, as shown in Fig. 9.22. After the war, it was taken to Modane, France, where it formed the basis of the ONERA (Office National d'Etudes et de Recherches Aérospatiales) wind tunnel laboratory. It is still in use there and still the largest of its kind.

In all, there were over 70 subsonic, transonic, supersonic, and hypersonic wind tunnels in the greater German-speaking world at the end of World War II. Many aircraft companies, military laboratories, and universities had important wind tunnel facilities. Most of those wind tunnels were seized by Allied forces and taken to the United States, United Kingdom, France, and Soviet Union, along with vast amounts of aerodynamic information and most of the experts on aerodynamics and wind tunnels.

As presented in Figs. 9.23–9.25, some other creators who developed wind tunnels and/or analyzed their results included:

Hans Amtmann (German, 1906–2007), aircraft and rocket design

Paul Richard Heinrich Blasius (German, 1883–1970), boundary layers

Carl Cranz (German, 1858–1945), ballistics and high-speed diagnostics

Siegfried Erdmann (German, 1916–2002), supersonic and hypersonic wind tunnels

Irmgard Flügge-Lotz (German, 1903–1974), aerodynamic control systems

Kurt Otto Friedrichs (German, 1901–1982), fluid dynamics and theory of elasticity

Georg Fuhrmann (German, 18??–19??), subsonic wind tunnel design/measurements

Erich Groth (German, 19??–19??), high-speed aerodynamics and aircraft design

Axel Kolb (German, 1917–2009), aerodynamics and wind tunnels

Klaus Oswatitsch (Austrian, 1910–1993), hypersonic aerodynamics

Hermann Schlichting (German, 1907–1982), boundary layers

Walter Tollmien (German, 1900–1968), boundary layers

Otto Walchner (German, 19??–19??), supersonic and hypersonic aerodynamics

Peter Wegener (German, 1917–2008), supersonic and hypersonic wind tunnels

Theodor Wilhelm Zobel (German, 1906–1953) worked on high-speed aerodynamics, wind tunnels, tests of Otto Frenzl's supersonic area rule (p. 1713), and Schlieren interferometry measurement systems for wind tunnels, first in Germany during the war and then in the United States after the war (Fig. 9.26). Hans Amtmann, another German aerospace expert who came to the United States in Operation Paperclip, eulogized Zobel [Amtmann 1988, pp. 115–116]:

> Dr. Theodor Zobel, former chief of the high-speed aerodynamic section of the Aerodynamic Research Center in Brunswick. He developed the Schlieren Interferometer, an optical measuring device to measure the flow of air around an airfoil without disturbing the flow. This was one of the most important contributions to supersonic research. His work saved the United States several years of expensive research time.

Theodore von Kármán (Hungarian, 1881–1963) earned his Ph.D. under Prandtl in 1908, worked on aerodynamics in Germany and Austria until 1930, and then moved to the United States. From then until the end of his life, Von Kármán was a tireless advocate trying to persuade the United States to improve its funding and level of research for wind tunnels, aerodynamics, and other aspects of aerospace engineering (Fig. 9.27). At the end of World War II, he served as a top U.S. government advisor guiding the transfer of German-speaking scientists and technologies to the United States, working closely with U.S. Army Air Forces General Henry Arnold (p. 2216).

In February 1963, near the very end of von Kármán's life, President John F. Kennedy awarded the first U.S. National Medal of Science to von Kármán (Fig. 9.27) and praised the importance of his work [https://www.jfklibrary.org/asset-viewer/archives/JFKPOF/042/JFKPOF-042-040]:

> Gentlemen, Dr. von Kármán, it is a great pleasure for me to select you as the first recipient of the National Medal of Science. I know of no one else who more completely represents all of the areas with which this award is appropriately concerned—science, engineering, and education.
>
> This Nation, and indeed the entire free world, holds you in the highest esteem and respect for your devoted service, for your scientific achievements, and for your warmly human gifts as a teacher and counsellor. Your assistance to the United States Air Force and to the NATO Advisory Group for Aeronautical Research and Development have been outstanding. We also are deeply indebted to you for your continuing efforts in the promotion of international cooperation in science and in engineering.
>
> It is hard to visualize what the world would be like without aircraft and jet propulsion, or without the vision we have, just entering the realm of reality, of exploring space. I am especially glad to present this first National Medal of Science to one of the pioneers who has helped make all of this new and exciting age possible.

Many creators who were primarily mathematicians also made important contributions to methods of solving complex aerodynamics equations. See for example:

Martin Wilhelm Kutta (German, 1867–1944), p. 838

Richard von Mises (Austro-Hungarian, 1883–1953), p. 839

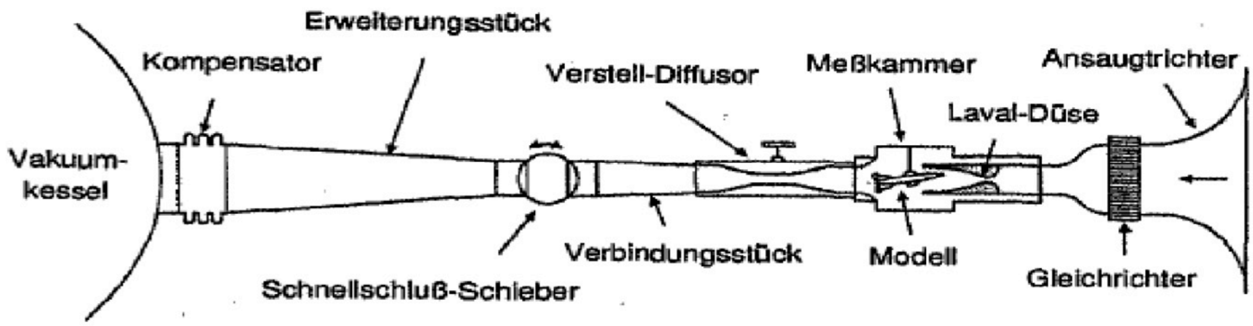
John von Neumann (Hungarian, 1903–1957), p. 839

Carl Runge (German, 1856–1927), p. 841

Karl Hermann Amandus Schwarz (German, 1843–1921), p. 841

Heeresversuchsanstalt (HVA) supersonic/hypersonic wind tunnel
Variable speeds up to Mach 5.2
Attained Mach 9.5 in 1944 after modifications

Designed by Rudolph Hermann in 1936
Operational at Peenemünde 1939–1943
Moved to Kochel for 1943–1945
Taken to U.S. Naval Ordnance Laboratory in 1945



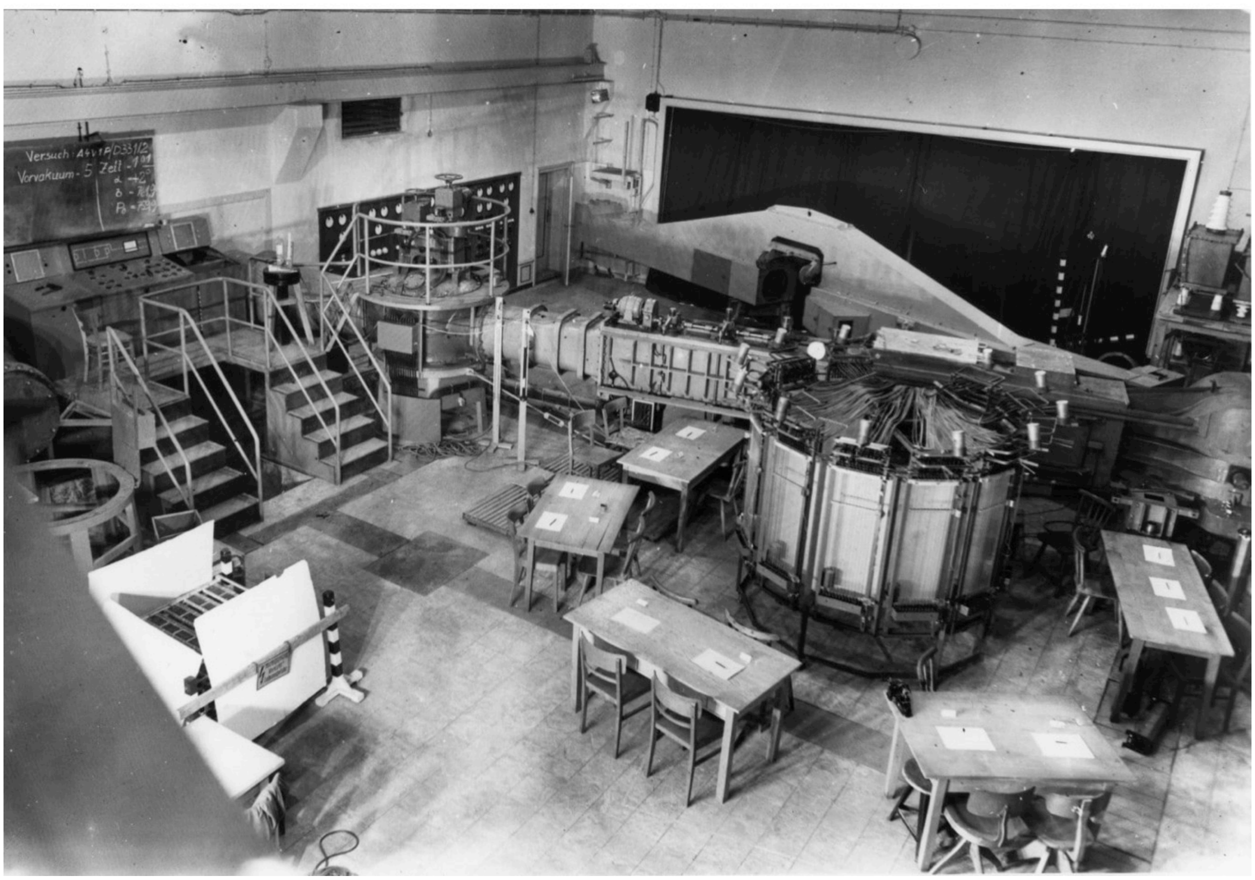


Figure 9.21: The Heeresversuchsanstalt (HVA) supersonic/hypersonic wind tunnel could attain a range of speeds up to Mach 5.2. In 1944, it attained Mach 9.5 after being modified. The HVA wind tunnel was designed by Rudolf Hermann in 1936. It was operational at Peenemünde 1939–1943, moved to Kochel for 1943–1945, and taken to the U.S. Naval Ordnance Laboratory in 1945.

NARA Still Pictures, RG 111 SCA---Records of the Chief Signal Officer. Prints: U.S. Army Signal Corps Photographs of Military Activity During WW II and the Korean Conflict, 1941-1954. Captured German Equipment, German, Box 3344, Book 5, SC 209555.

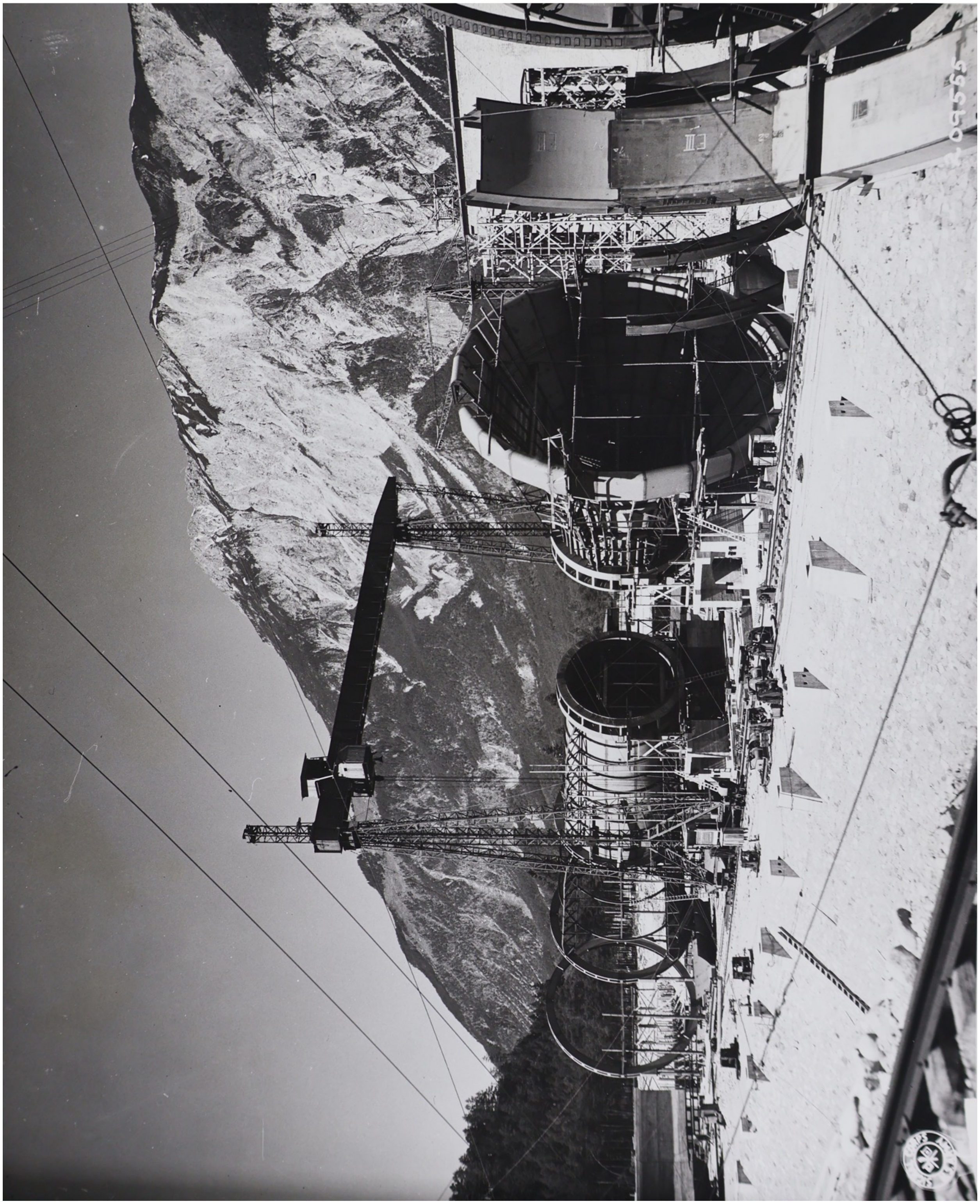


Figure 9.22: The Zitteraal wind tunnel at Ötztal, Austria, was under construction at the end of World War II. After the war, it was taken to Modane, France, where it formed the basis of the ONERA wind tunnel laboratory. It is still in use there and still the largest of its kind. [NARA Still Pictures, RG 111 SCA—Records of the Chief Signal Officer. Prints: U.S. Army Signal Corps Photographs of Military Activity During WW II and the Korean Conflict, 1941–1954. Captured German Equipment, German, Box 3344, Book 5, SC 209555.]

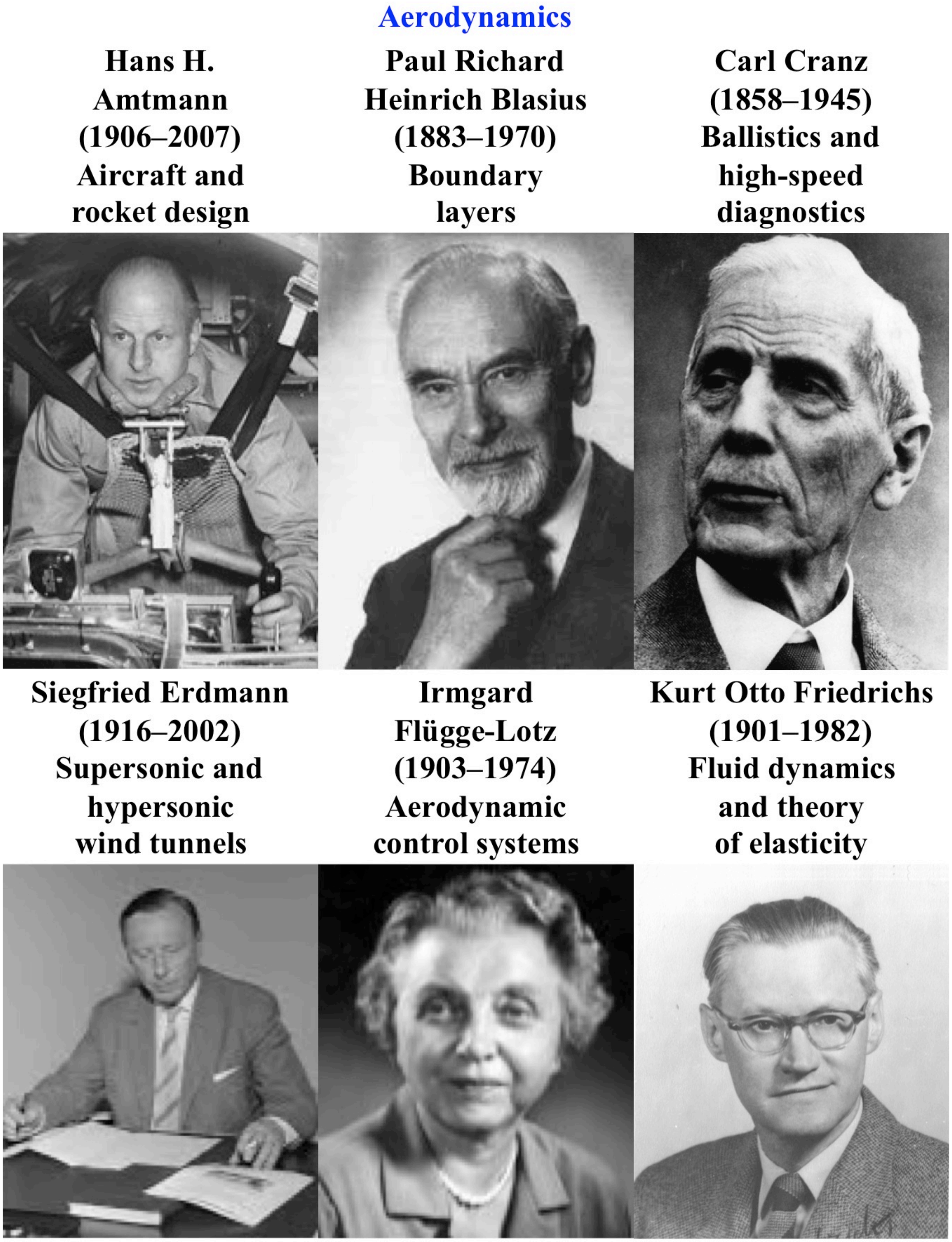


Figure 9.23: Other creators who developed wind tunnels and/or analyzed their results included Hans Amtmann, Paul Richard Heinrich Blasius, Carl Cranz, Siegfried Erdmann, Irmgard Flügge-Lotz, and Kurt Otto Friedrichs.

Aerodynamics

Georg Fuhrmann
(18??–19??)
Subsonic wind tunnel design/ measurements

Erich Groth
(19??–19??)
High-speed aerodynamics and aircraft design

Rudolf Hermann
(1904–1991)
Supersonic and hypersonic wind tunnels

Axel Kolb
(1917–2009)
Aerodynamics and wind tunnels

Hermann Kurzweg
(1908–2000)
Supersonic and hypersonic wind tunnels

Hubert Ludwieg
(1912–2000)
Supersonic and hypersonic wind tunnels

Figure 9.24: Other creators who developed wind tunnels and/or analyzed their results included Georg Fuhrmann, Erich Groth, Rudolf Hermann, Axel Kolb, Hermann Kurzweg, and Hubert Ludwieg.

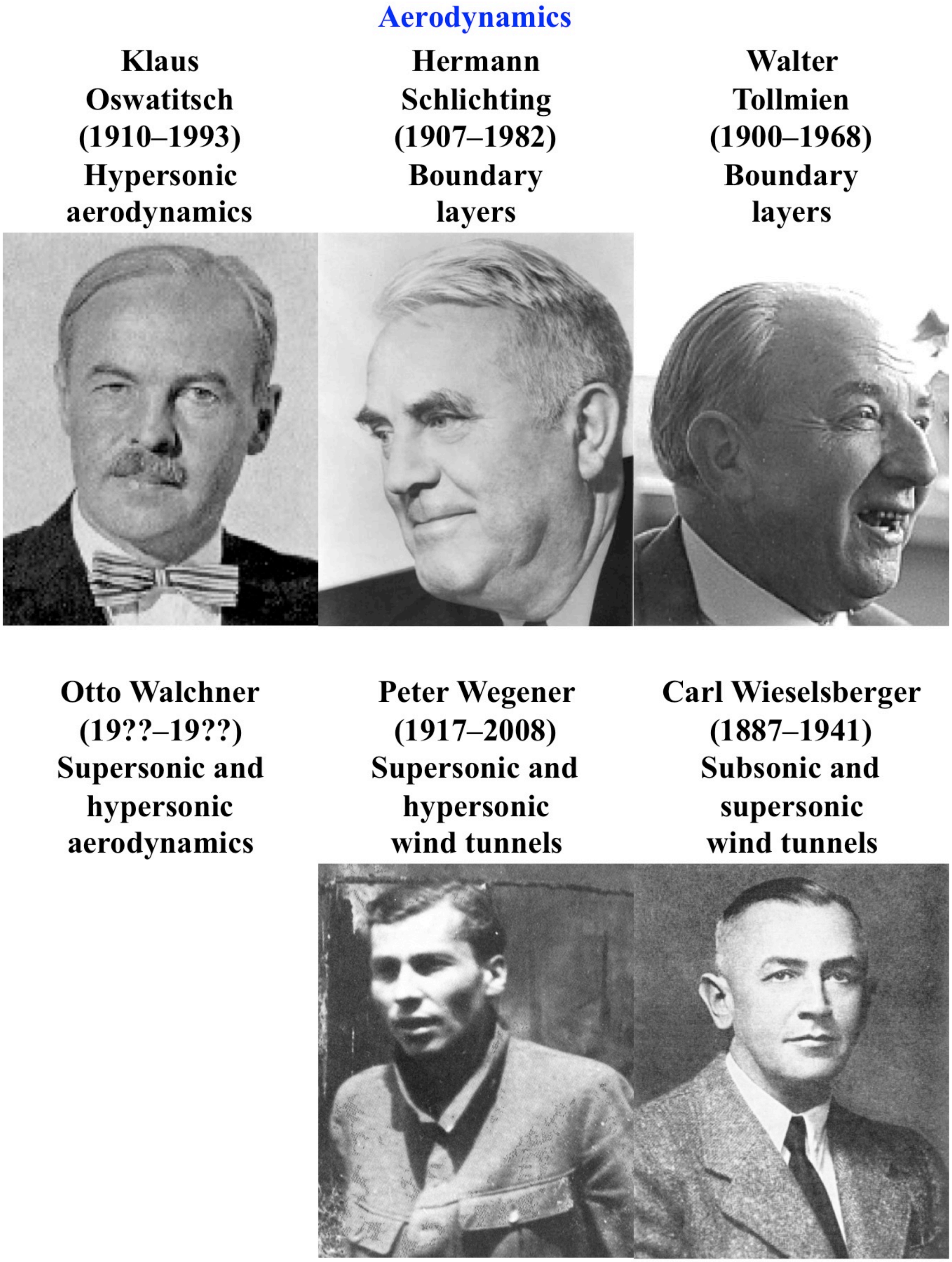


Figure 9.25: Other creators who developed wind tunnels and/or analyzed their results included Klaus Oswatitsch, Hermann Schlichting, Walter Tollmien, Otto Walchner, Peter Wegener, and Carl Wieselsberger.

Dr. Theodor Zobel, former chief of high speed aerodynamics unit, Brunswick, Germany, explains operation of device to measure airflow.

Theodor Wilhelm Zobel
(1906–1953)

Worked on high-speed aerodynamics, wind tunnels, the area rule, and Schlieren interferometry

Dr. Zobel's apparatus for measuring airflow—a Schlieren-Interferometer—brought here because materials were not available in U. S.

Figure 9.26: Theodor Wilhelm Zobel worked on high-speed aerodynamics, wind tunnels, the area rule, and Schlieren interferometry, first in Germany during the war and then in the United States after the war [*Dayton Daily News*, 8 December 1946, p. 55].

Figure 9.27: Aerodynamicist Theodore von Kármán directing work at the U.S. Jet Propulsion Laboratory in 1940 (above), and receiving the National Medal of Science from President Kennedy in 1963 (below).

9.2.3 Specialized Aircraft

Using the principles of aerodynamics, German-speaking engineers developed a wide range of aircraft that were specialized for various applications, and aircraft following those general designs have been used around the world. This section only presents a few examples, although many more could be cited.

Some major aircraft designers are shown in Figs. 9.28–9.29.

Claude Dornier (German, 1884–1969, Fig. 9.28) was most famous for his company's 12-engine Dornier Do X flying boat (first flight 1929), which had multiple decks, luxury accommodations, and room for over 150 people (Fig. 9.30). He also designed the Dornier Do 17 light bomber (1934) and numerous other aircraft throughout his long career. After World War II, Dornier worked in France, Spain, Switzerland, and West Germany.

German-speaking engineers invented dedicated ground-attack aircraft with the pilot and engines protected inside an armored "bathtub":

- In 1917, Otto Mader (German, 1880–1944, Fig. 9.29) and Hugo Junkers (German, 1859–1935, Fig. 9.28) created the first armored ground-attack aircraft, the Junkers J.I (Fig. 9.31). Hugo Junkers built a wide range of aircraft until his death, and his company played a major role in the development of jet engines after his death.

- The Henschel company introduced the Hs 129 armored ground-attack aircraft in 1939, and ultimately equipped it with a 7.5 cm automatic antitank gun in 1944 (Fig. 9.32). In this final configuration, the Hs 129 was the most powerful tank-killing aircraft in the world at the time.

- The Junkers company appears to have designed an even more advanced armored ground-attack aircraft to succeed the Hs 129 [Herwig and Rode 2003, pp. 36–37]. Aviation historians should thoroughly search archives to find more information on this design, how far it progressed during the war, and how much it (and the Hs 129) influenced the U.S. A-10 Thunderbolt II three decades later.

During World War I, Anton Fokker (Dutch, 1890–1939) and Reinhold Platz (German, 1886–1966) designed and mass-produced very effective early fighter aircraft, including the Fokker Eindecker E.III monoplane (1915), Doppeldecker D.VII biplane (1918), and Dreidecker Dr.I triplane (1917). See Fig. 9.33.

Robert Thelen (German, 1884–1968), the chief designer of Albatros-Flugzeugwerke, also created biplane fighter aircraft during World War I (Fig. 9.34). Today the Albatros and Fokker fighters are best remembered as the preferred vehicles of the "Red Baron" Manfred von Richthofen (German, 1892–1918).

As shown in Fig. 9.35, Willy Messerschmitt (German, 1898–1978) and Robert Lusser (German, 1899–1969) developed the Messerschmitt Bf 109 piston-propeller fighter aircraft by 1935. The Bf 109's performance and features were a major step beyond earlier fighters, and the Bf 109 was extensively used by Germany until 1945.

The Messerschmitt Bf 109 seems to have strongly influenced the design of the British Supermarine Spitfire, which appeared as a first prototype in 1936 and began production in 1938. Beverley Shenstone, the head aerodynamics expert for the Spitfire design, had previously worked in Germany [Cole 2012, 2015].

Edgar Schmüd (German, 1899–1985), an aircraft designer, immigrated to the United States in 1931 and went to work for North American Aviation. Using his knowledge, details of the German Bf 109 and the German-inspired Spitfire, and other German design information, Schmüd developed the North American P-51 Mustang piston-propeller fighter in 1940. Subsequently the P-51 was widely used by the United States and United Kingdom during the war. The extreme similarity of Schmüd's 1940 P-51 design to Messerschmitt's 1935 Bf 109 design is evident in Fig. 9.35. In fact, the P-51 so closely resembled the Messerschmitt Bf 109 that at least one P-51 was shot down by Allied forces who mistook it for a Bf 109, and the other P-51s had to be painted with yellow bands on the wings to distinguish them from Bf 109s [Ray Wagner 2000, p. 94]. The resemblance throughout the design was so uncanny that even one of the P-51's own test pilots mistakenly believed that Schmüd must have been one of the designers of the original Bf 109 [Ray Wagner 2000, p. 104].

In 1947, Schmüd likewise developed the North American F-86 Sabre jet fighter based directly on the wartime Messerschmitt Me P.1101 and Focke-Wulf Ta 183 jet fighters (see p. 1787). Schmüd also developed the North American F-100 Super Sabre (1953), the Northrop F-5 Freedom Fighter (1959), and the Northrop T-38 Talon trainer (1959, widely used by NASA for astronaut training) [Ray Wagner 2000].

German-speaking engineers developed specialized gliders for military troops and cargo. Due to the gliders' speed, agility, and low noise, they were used for a number of highly creative and successful assaults during World War II. Some major examples included (Fig. 9.36):

- The Deutsche Forschungsanstalt für Segelflug DFS 230, which was designed by Hans Jacobs (German, 1907–1994, Fig. 9.28) and first flew in 1937.

- The Gotha Go 242, which was designed by Albert Kalkert (German, 1902–1977, Fig. 9.29) and first flew in 1941. (There is some evidence that suggests that Kalkert may have been involved in building or trying to build a Horten H.XVIII flying wing intercontinental bomber during the war—see pp. 5281–5285).

- The Messerschmitt Me 321 Gigant, which first flew in 1941.

The Arado Ar 232, first flown in 1941, was the world's first special-purpose cargo aircraft, establishing now-standard features such as a rear cargo ramp, low boxy fuselage, high wing, high tail, and rugged landing gear. It was followed in 1942 by the Junkers Ju 290, designed by Konrad Eicholtz (German, 18??–19??, Fig. 9.28), and the Messerschmitt Me 323 Gigant (the largest land-based cargo aircraft in the world at the time—only the Blohm & Voss BV 238 flying boat was larger). See Fig. 9.37.

German-speaking creators also produced aircraft with highly creative airframe designs. Two examples (among many others that could be cited) were the asymmetrical Blohm & Voss BV 141 reconnaissance aircraft (1938), designed by Richard Vogt (German, 1894–1979, p. 1694), and the twin-boom Focke Wulf Fw 189 Uhu reconnaissance aircraft (1938), designed by Kurt Tank (German, 1898–1983, p. 1694). See Fig. 9.38. Vogt was famous for the wide range of unusual aircraft designs he produced during the war, and he worked for the U.S. Air Force, Curtiss-Wright, and Boeing after the war. Tank designed fighter aircraft at Focke-Wulf during the war, and after the war developed a wide range of aircraft and missiles in Argentina, India, and West Germany.

Even German designs that were not actually built during World War II continued to exert a strong influence on aircraft that were built long after the war. For example, Richard Vogt's 1944 design for the Blohm & Voss P 202 oblique wing aircraft directly inspired the design of the NASA AD-1 oblique wing aircraft, which was first flown in 1979 (Fig. 9.39). As shown in Fig. 9.40, Vogt's 1945 outboard tail swept-wing design for the Blohm & Voss P 212 (and the rest of his P 208–215 design series from 1944–1945) similarly appears to have directly inspired the design of the Virgin Galactic SpaceShipTwo, which made its first suborbital flight in 2018.

Claude Dornier (1884–1969)

Konrad Eicholtz (18??–19??)

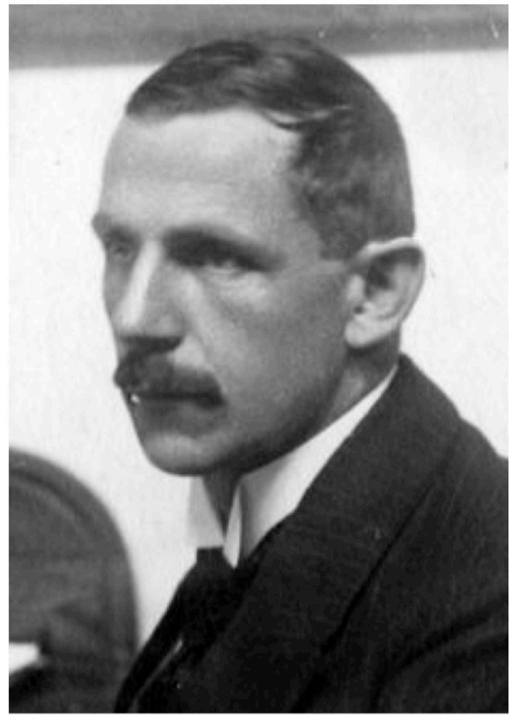
Hans Jacobs (1907–1994)

Hugo Junkers (1859–1935)

Figure 9.28: Some major aircraft designers included Claude Dornier, Konrad Eicholtz, Hans Jacobs, and Hugo Junkers.

Albert Kalkert (1902–1977)

Otto Mader (1880–1944)



Kurt Tank (1898–1983)

Richard Vogt (1894–1979)

Figure 9.29: Other major aircraft designers included Albert Kalkert, Otto Mader, Kurt Tank, and Richard Vogt.

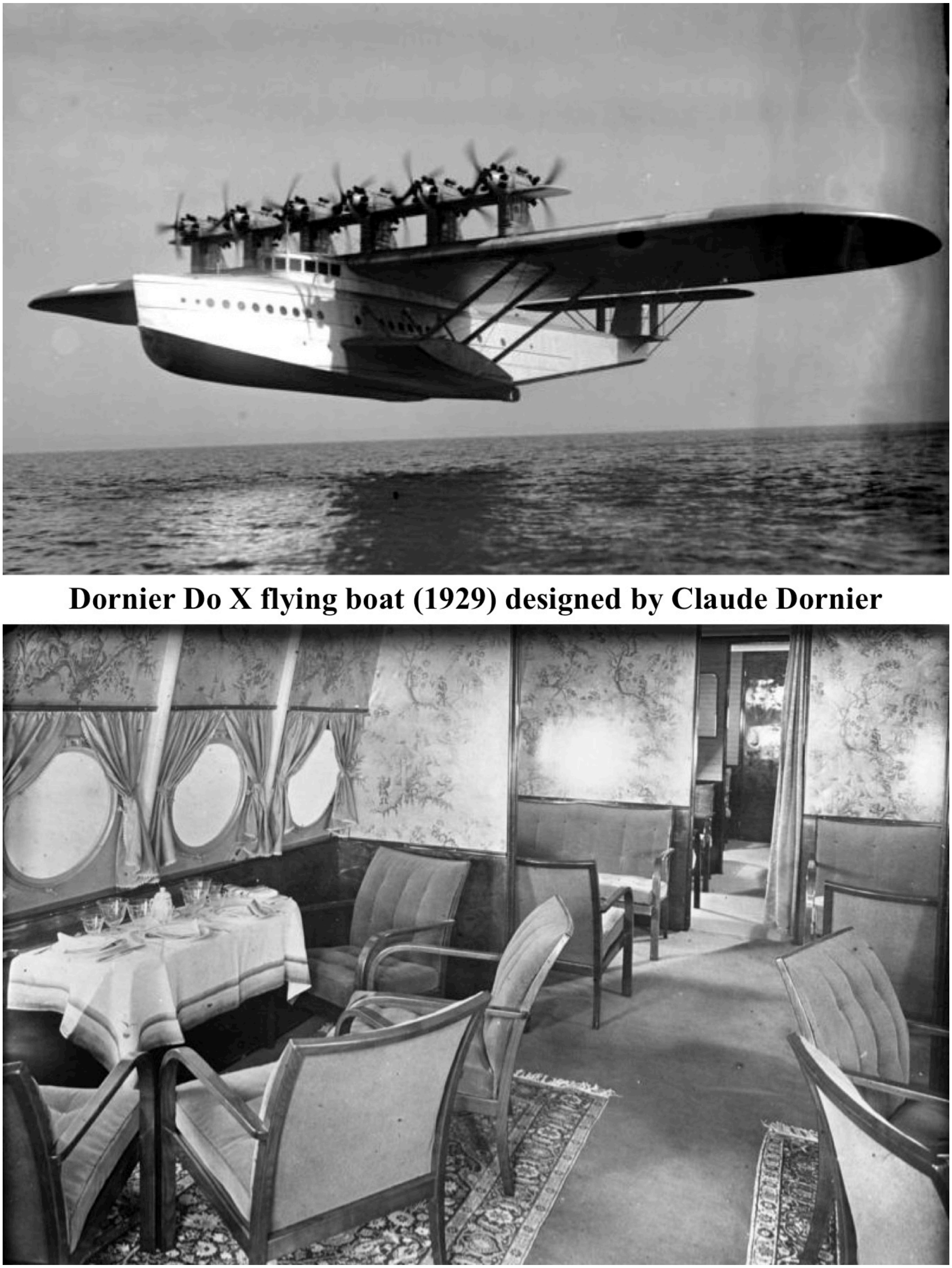


Figure 9.30: In 1929, Claude Dornier created the Dornier Do X flying boat, which had multiple decks, luxury accommodations, and room for over 150 people.

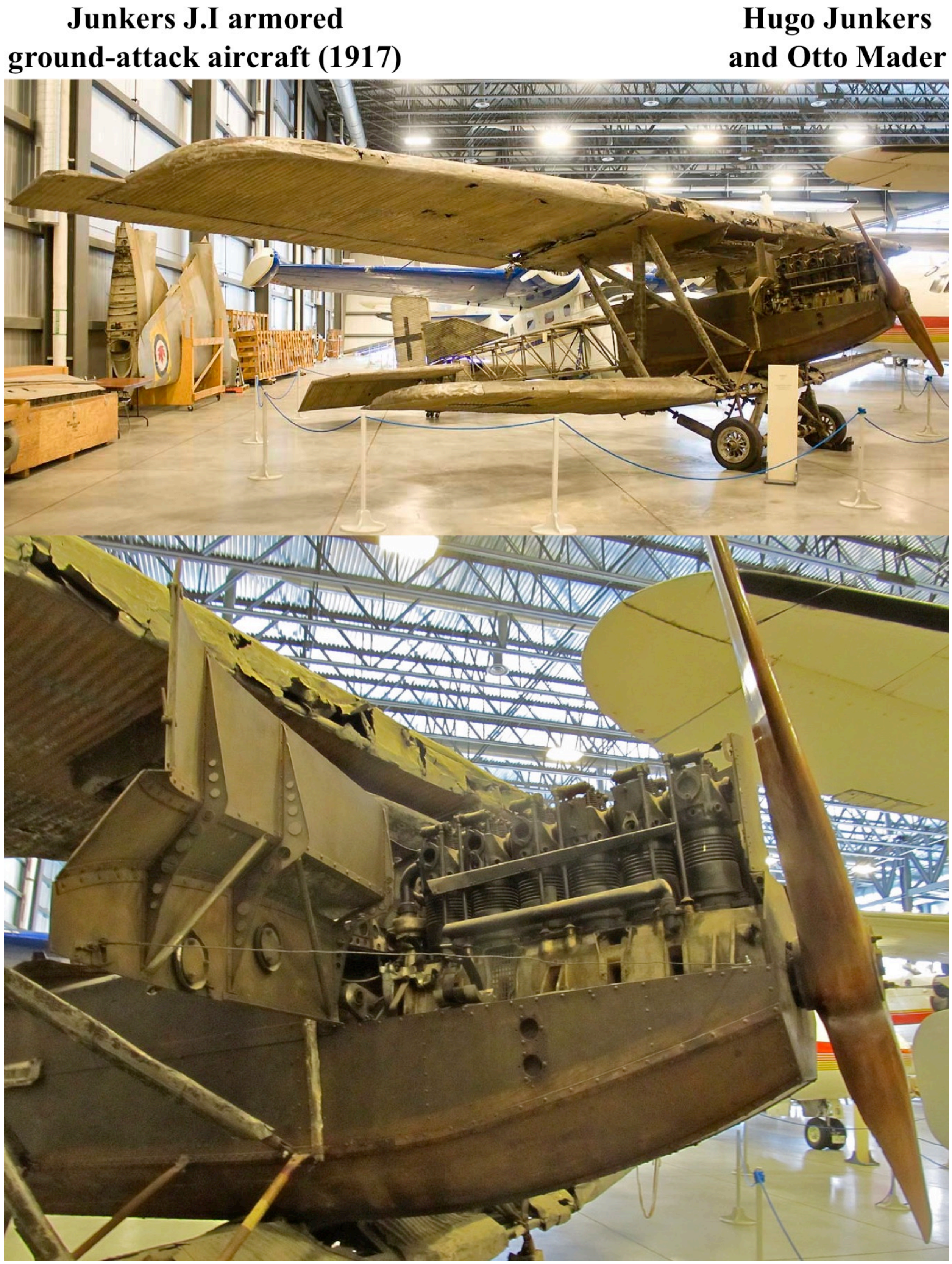


Figure 9.31: In 1917, Otto Mader and Hugo Junkers created the first armored ground-attack aircraft, the Junkers J.I.

Henschel Hs 129 armored ground-attack aircraft (1939)

Equipped with 7.5 cm automatic antitank gun (1944)

Figure 9.32: Henschel introduced the Hs 129 armored ground-attack aircraft in 1939, and equipped it with a 7.5 cm automatic antitank gun in 1944.

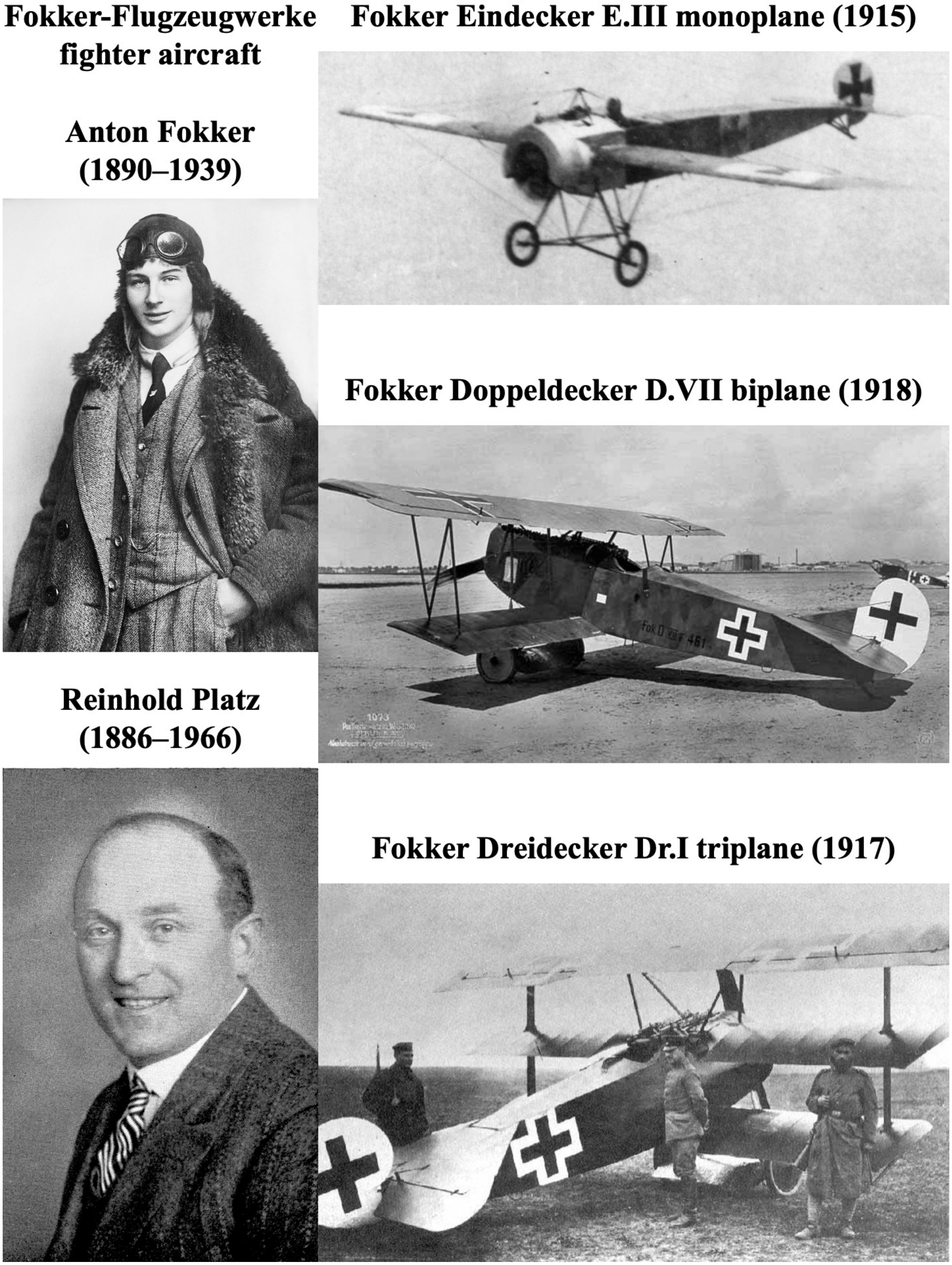


Figure 9.33: Anton Fokker and Reinhold Platz created monoplane, biplane, and triplane fighter aircraft during World War I.

Figure 9.34: Robert Thelen, the chief designer of Albatros-Flugzeugwerke, created biplane fighter aircraft during World War I.

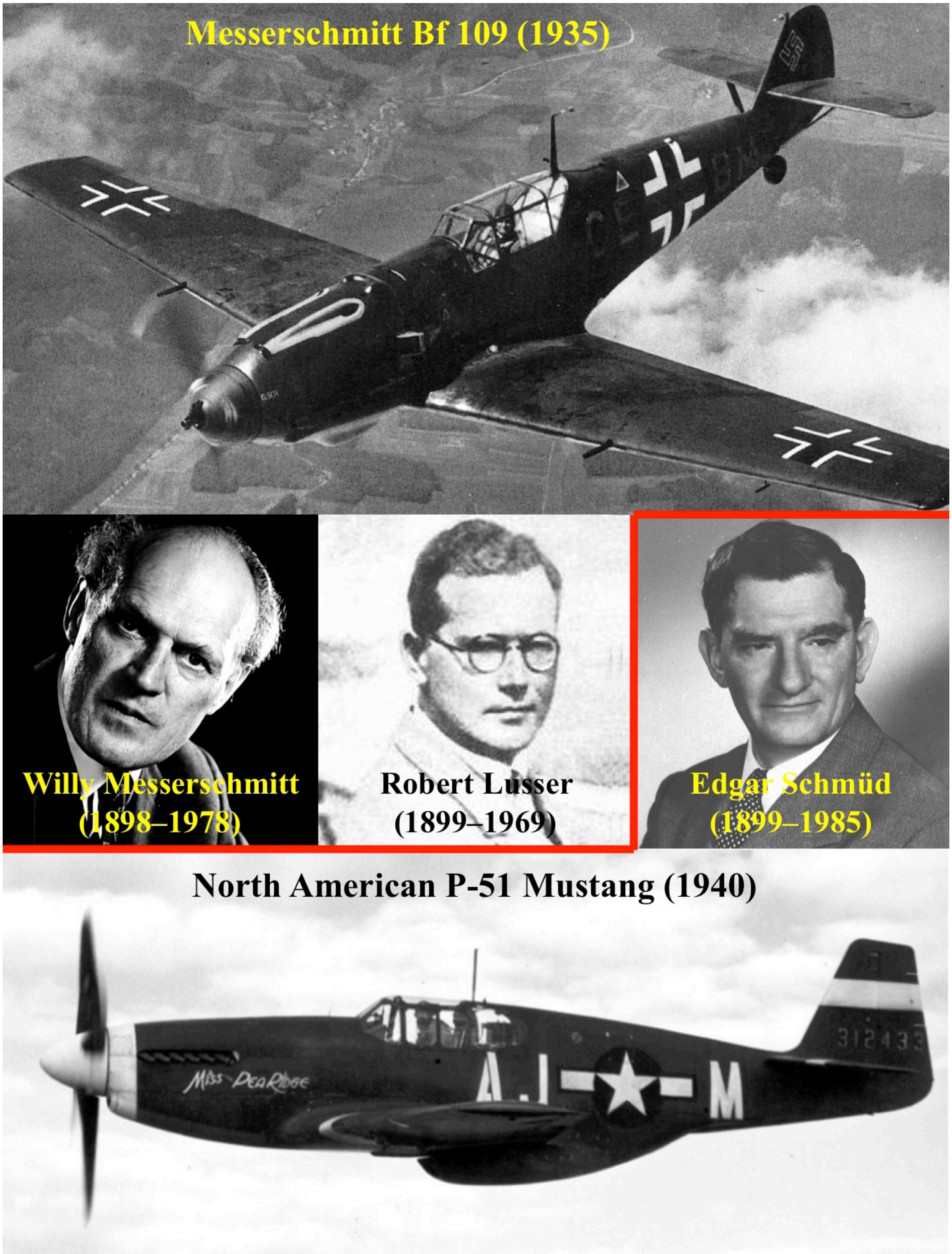


Figure 9.35: Willy Messerschmitt and Robert Lusser developed the Messerschmitt Bf 109 fighter (1935), which was extensively used by Germany until 1945. Edgar Schmüd, a German aircraft designer, immigrated to the United States. Using his knowledge, details of the Messerschmitt Bf 109, and other German design information, Schmüd developed the North American P-51 Mustang (1940), which was widely used by the United States and United Kingdom during the war.

DFS 230 troop glider (1937) Hans Jacobs

Gotha Go 242 troop glider (1941) Albert Kalkert

Messerschmitt Me 321 Gigant cargo glider (1941)

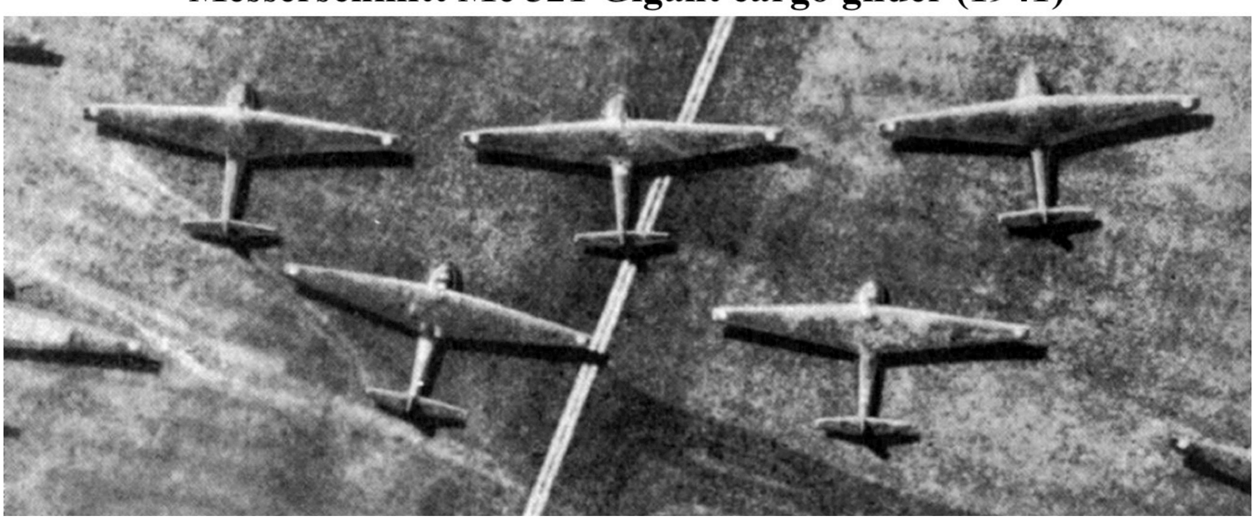
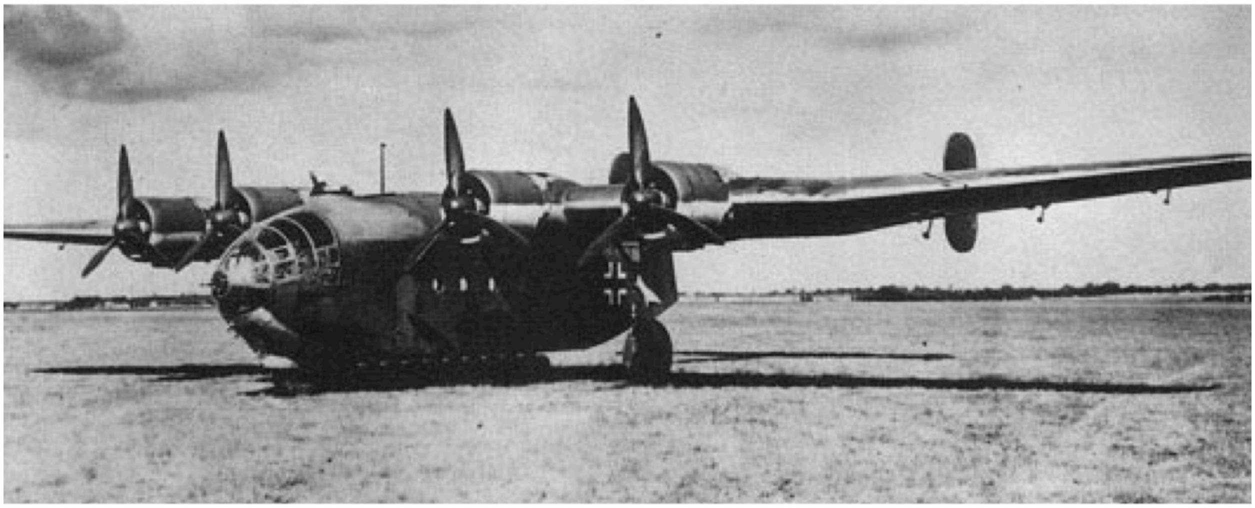


Figure 9.36: German-speaking engineers developed specialized gliders for military troops and cargo, such as the Deutsche Forschungsanstalt für Segelflug DFS 230, Gotha Go 242, and Messerschmitt Me 321 Gigant.

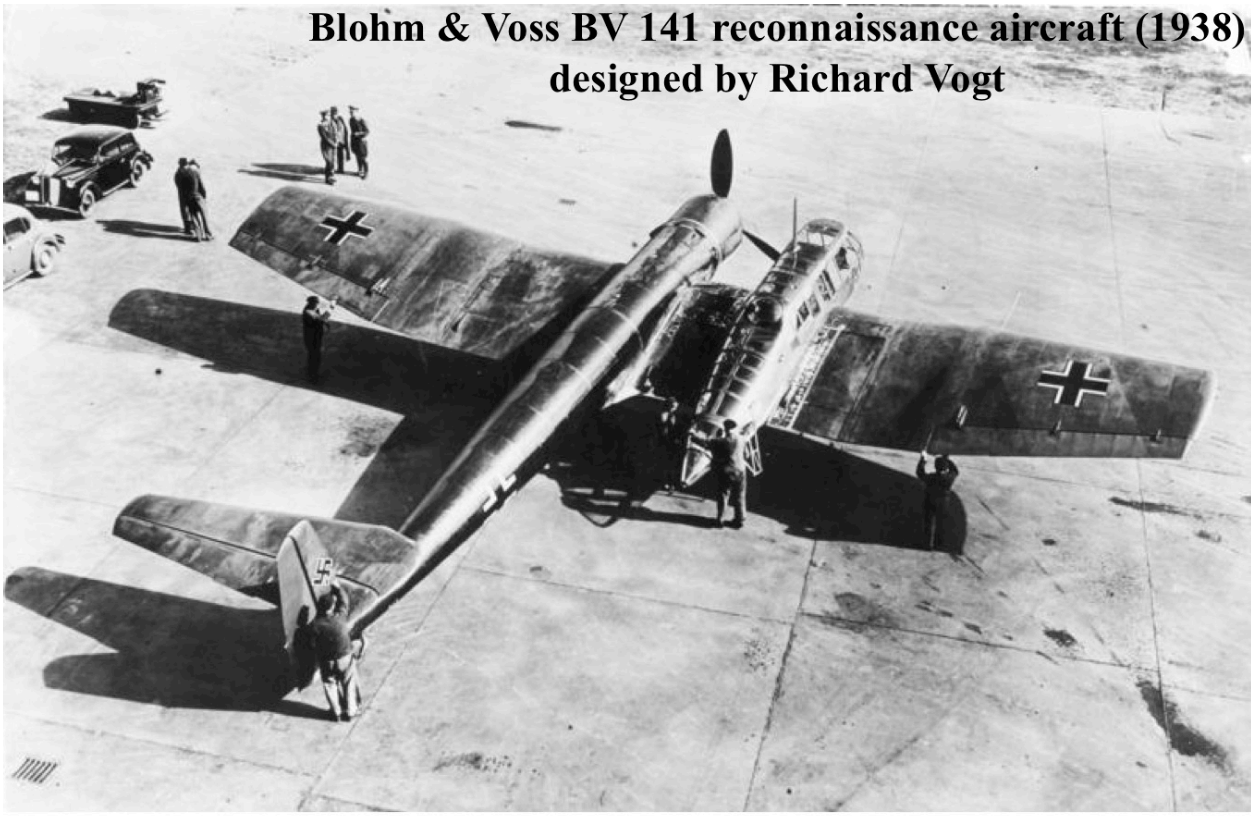
Arado Ar 232 cargo aircraft (1941)



Junkers Ju 290 cargo aircraft (1942) **Konrad Eicholtz**

Messerschmitt Me 323 Gigant cargo aircraft (1942)

Figure 9.37: The Arado Ar 232 was the world's first special-purpose cargo aircraft, and was followed by the Junkers Ju 290 and Messerschmitt Me 323 Gigant.



**Focke Wulf Fw 189 Uhu reconnaissance aircraft (1938)
designed by Kurt Tank**

Figure 9.38: Examples of aircraft with highly creative airframe designs include Richard Vogt's Blohm & Voss BV 141 reconnaissance aircraft (1938) and Kurt Tank's Focke Wulf Fw 189 Uhu reconnaissance aircraft (1938).

**Blohm & Voss P 202 oblique wing aircraft
(designed in 1944 by Richard Vogt)**

NASA AD-1 oblique wing aircraft (1979)

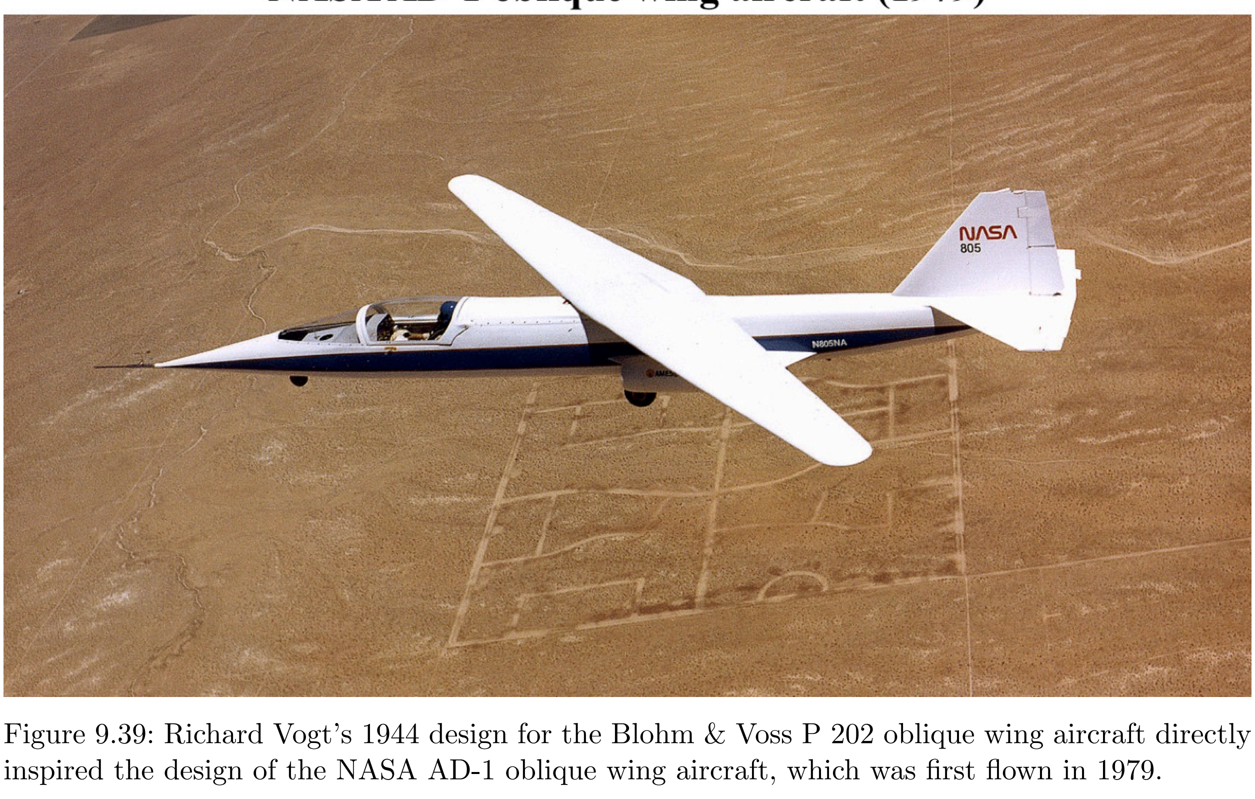


Figure 9.39: Richard Vogt's 1944 design for the Blohm & Voss P 202 oblique wing aircraft directly inspired the design of the NASA AD-1 oblique wing aircraft, which was first flown in 1979.

Blohm & Voss P 212 (designed in 1945 by Richard Vogt)

Virgin Galactic SpaceShipTwo (first suborbital flight 2018)

Figure 9.40: Richard Vogt's 1945 outboard tail swept-wing design for the Blohm & Voss P 212 appears to have directly inspired the design of the Virgin Galactic SpaceShipTwo, which made its first suborbital flight in 2018.

9.2.4 High-Speed Aircraft Design

Much of the German-speaking work before, during, and after World War II focused on the best aerodynamic shapes of aircraft wings and bodies. The best shapes and their performance characteristics depend on the speed of aircraft through the air, or equivalently the speed of airflow around the aircraft.

An airfoil is a cross-section through an aircraft wing along the direction of incoming flow (Fig. 9.41). Airfoils are usually cambered, with asymmetric upper and lower surfaces. For an angle of attack α between a surface and incoming flow, the force normal to the surface may be separated into drag and lift components. A cambered airfoil produces zero lift at a negative angle of attack $\alpha_{L=0}$, linearly increasing lift for increasing angles of attack, and decreasing lift (stalling) above α_{stall}. Its drag is much smaller but increases parabolically.

At very low speeds, airflow is not especially compressible—its density remains approximately constant. However, at higher and higher speeds, airflow becomes more and more compressible; the air gets squished when it suddenly runs into an object. No later than 1922, based on wind tunnel data and his own theoretical derivations, Ludwig Prandtl discovered mathematical rules that describe compressible flow around subsonic aircraft (Fig. 9.42). In 1928, Hermann Glauert (English, 1892–1934) independently (apparently) rediscovered Prandtl's equations for compressible flow around subsonic aircraft, so in the English-speaking world those equations are often called the Prandtl–Glauert transformation or method. (Incidentally, although Glauert was born in England, his parents were both German.)

In 1925, Jakob Ackeret (Swiss, 1898–1981), who was one of Prandtl's assistants at that time, found a way to extend Prandtl's compressible flow equations to cover supersonic speeds. Ackeret himself had a long and distinguished career in aerodynamics and wind tunnel experiments.

In 1935, Adolf Busemann (German, 1901–1986) used the compressible flow rules to design swept-wing aircraft. Busemann realized that the faster an aircraft goes, the more swept-back its wings should be, in order to maximize the aerodynamic lift and minimize the drag from the wings. Hubert Ludwieg confirmed the efficiency of the swept-wing design in wind tunnel tests, and then Albert Betz incorporated swept-back wings into several Messerschmitt aircraft. By the end of World War II, numerous German aerospace vehicles employed the swept-wing design (see for example pp. 1782, 1785–1787, 1854, 1924, 1934, 1938–1943), in stark contrast to Allied aircraft that continued through 1945 to use less efficient wings that stuck straight out to the sides. After the war, Busemann and other German-speaking aerodynamics experts helped to produce swept-wing aircraft, supersonic aircraft, and spacecraft in the United States.

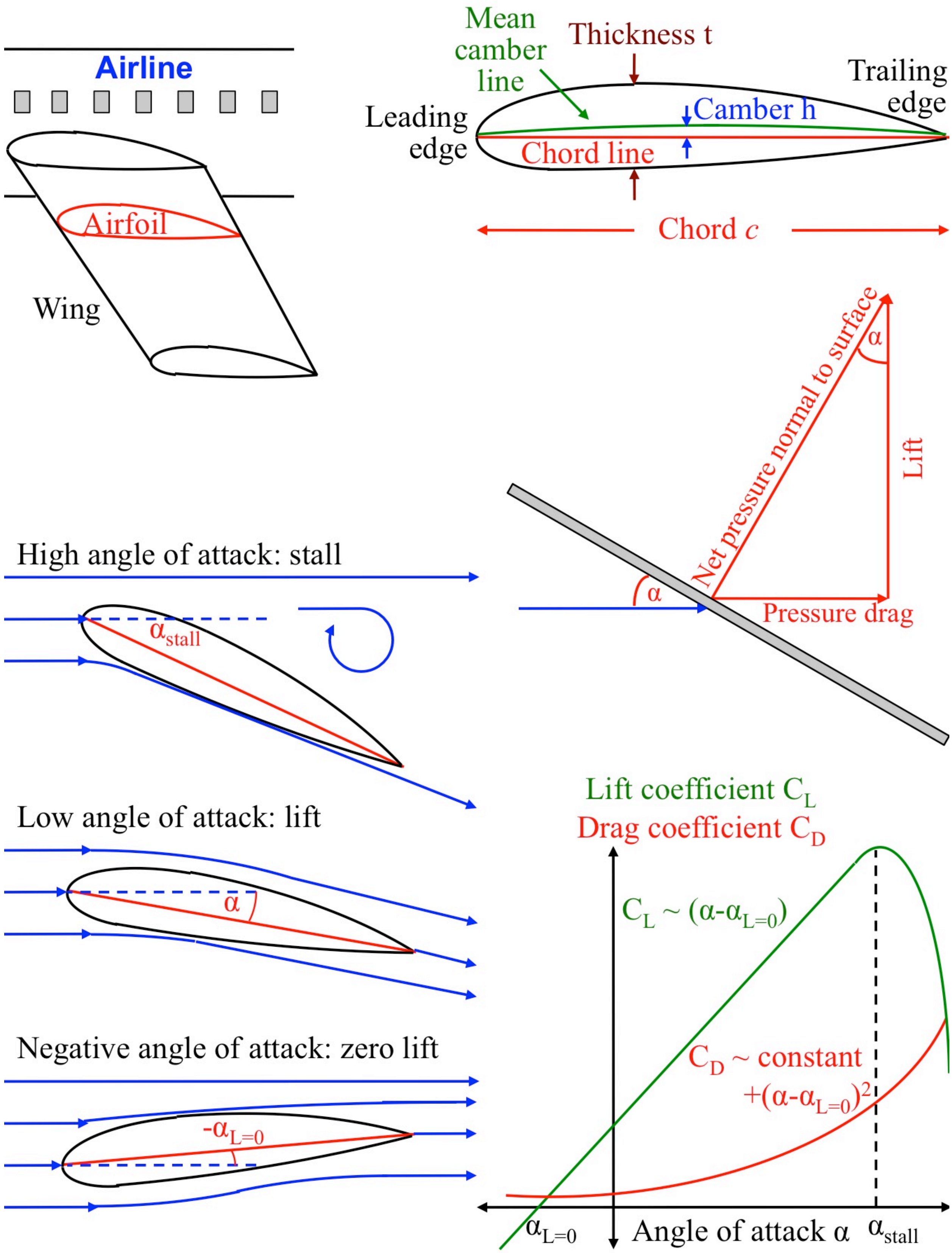


Figure 9.41: An airfoil is a cross-section through an aircraft wing along the direction of incoming flow. Airfoils are usually cambered, with asymmetric upper and lower surfaces. For an angle of attack α between a surface and incoming flow, the force normal to the surface may be separated into drag and lift components. A cambered airfoil produces zero lift at a negative angle of attack $\alpha_{L=0}$, linearly increasing lift for increasing angles of attack, and decreasing lift (stalling) above $\alpha_{\rm stall}$. Its drag is much smaller but increases parabolically.

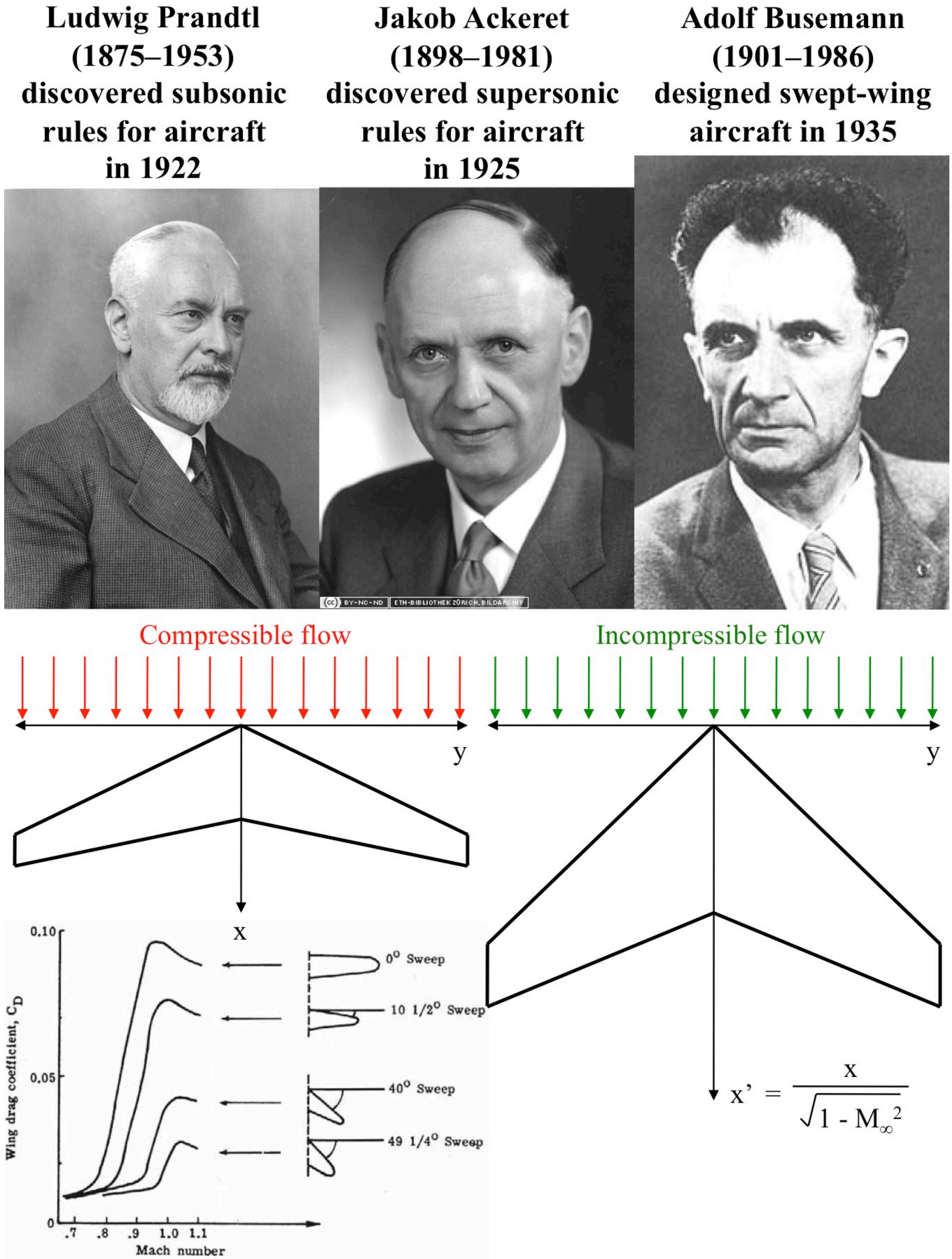


Figure 9.42: Ludwig Prandtl discovered subsonic compressible-flow rules for aircraft in 1922, Jakob Ackeret extended them to supersonic speeds in 1925, and Adolf Busemann designed swept-wing aircraft in 1935.

Winglets (wing tips bent up and/or down) improve the efficiency of wings by reducing wing-tip vortices, the undesirable leakage of higher-pressure air below the wing to the lower-pressure region above the wing. The abstract idea of winglets dates back to even before powered flight (e.g., they are mentioned in an 1897 patent by Frederick Lanchester), but most of their experimental development and demonstration appears to have been conducted in the German-speaking world in the 1920s through the early 1940s. They were actively utilized in German aircraft such as the Hamburger Flugzeugbau Ha 137 (designed by Richard Vogt, first flown in 1935) and the Heinkel He 162 jet fighter (designed by Alexander Lippisch and others, first flown in 1944). See Figure 9.43. Some other examples of early German aircraft or aircraft designs with winglets included the Espenlaub-Lippisch E2 (1921), Fieseler F 3 Wespe (1932), DFS 193 (1936), Gotha Go 147 (1936), Lippisch Delta I (1930), Lippisch Delta III (1934), Lippisch Delta IV (1936), Lippisch Delta V (1937), etc.[6]

In 1940, Bernhard Göthert (German, 1907–1988) and K. A. Kawalki (Polish?, 19??–19??) developed and demonstrated supercritical airfoils or wings that enabled aircraft to travel at higher speeds with less drag, and ultimately to break the sound barrier with less difficulty (Fig. 9.44). Normally, the curvature of an airfoil makes airflow above the wing faster than flow below it, which in turn makes the air pressure lower above the airfoil that below it, creating a net upward lift force on the airfoil that keeps the aircraft aloft. For aircraft at high subsonic speeds, this effect can accelerate air above the wings to the speed of sound, creating a strong shock wave, a separated boundary layer, and higher drag. By making the upper surface of the wings flatter or supercritical, aircraft can travel closer to the speed of sound before high-drag transonic flow occurs. After the war, Göthert came to the United States, where he became chief scientist of the Air Force Systems Command and helped to develop everything from the Saturn V rocket to the F-111 fighter [https://www.latimes.com/archives/la-xpm-1988-04-01-mn-489-story.html].[6]

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[6]Despite abundant documentation for the invention, development, and demonstration of winglets, supercritical airfoils, and the area rule by these German-speaking creators, many history books [e.g., Anderson 1997] erroneously assign credit for all of these creations to a much later American, Richard Whitcomb (1921–2009). Whitcomb only had a bachelor's degree in engineering, but he seems to have had great ambitions to advance in his career. Whitcomb took a job at the NACA (later NASA) Langley Research Center where many of the German-speaking aerodynamics experts worked or visited after the war, and he stayed there until he chose early retirement in 1980.

After the war, Adolf Busemann worked at the Langley Research Center and gave detailed presentations summarizing earlier German work and knowledge about supersonic aerodynamics. Whitcomb is known to have attended at least one of Busemann's major talks on that topic in 1951. It appears that Whitcomb learned of the area rule from Busemann (or other German sources, such as the huge amount of documentation that NACA received on wartime German work—e.g., p. 1714) and then wrote a paper in 1952 announcing it as his own new discovery [Mack 1998, p. 138]. The principle has been known as the "Whitcomb area rule" ever since. Proper credit was not given to Frenzl and his colleagues who had actually developed and tested it a decade earlier, or even to scientists such as Busemann and Theodore von Kármán who guided the transfer of German aerodynamics knowledge to the United States.

Whitcomb also claimed and received credit for first developing supercritical airfoils in the 1960s. Recognition was not given to Göthert and Kawalki who had actually invented and demonstrated supercritical airfoils over 20 years earlier, or to the other German-speaking aerodynamics experts involved in transferring the information to the United States.

Then in the 1970s, Whitcomb claimed and received credit for developing winglets. Once again, no recognition was given to the German-speaking aerodynamics experts who had actually conducted or transferred that work.

For all of his alleged inventions, Whitcomb was showered with national awards and became a department head at the Langley Research Center. Most of the German-speaking creators who had actually developed, demonstrated, and transferred those technologies died in obscurity.

Downward folding wingtips for compression lift appear similar to winglets but serve a different purpose. Folding wingtips (such as those on the XB-70 Valkyrie, pp. 1766–1767) catch part of the shock waves of a supersonic aircraft and increase the under-wing pressure to increase lift. Officially that was discovered in the United States in the 1950s. Yet that feature was already present in wartime German jet designs (e.g., Heinkel He P.1078 A and B versions, p. 5278) and it resurfaced in the XB-70, which was heavily reliant on German expertise (p. 1762). More archival research should be conducted to determine how much work on compression lift was conducted in wartime Germany, and how much that work influenced postwar projects in the United States and other countries.

Otto Frenzl (Austrian, 1909–1996) discovered the area rule for supersonic flight in 1943 and filed a patent on it with aircraft designers Heinrich Hertel (German, 1901–1982) and Werner Hempel (German, 1910–??). If airflow moving near or above the speed of sound longitudinally down a vehicle encounters a sudden change in the vehicle's cross-sectional area, the flow cannot easily move out of the way; it is forcibly compressed or rarified and may separate from the vehicle's surface or create a shock wave. By keeping the cross-sectional area relatively constant down the length of a vehicle, one can avoid such effects and thereby minimize the drag coefficient. For example, an aircraft's body should begin to narrow at the point where wings begin, as shown in Fig. 9.45. This was a critical discovery for creating aircraft that could easily break the sound barrier to move from subsonic to supersonic speeds. After the war, Frenzl and Hertel developed aircraft in France and West Germany, and Hempel worked for the Soviet Union. Theodor Zobel confirmed the area rule in wartime Germany and continued his work in the United States after the war (Fig. 9.26).[6]

The advantages of blunt leading surfaces for atmospheric reentry, in order to create detached shock waves and reduce vehicle heating, were discovered, analyzed, and advocated by Rudolf Hermann (German, 1904–1991, Fig. 9.24), Adolf Busemann (Fig. 9.42), and Gottfried Guderley (German, 1910–1997, Fig. 8.37) during World War II [NARA RG 319, Entry NM3-82, Box 1568, HEC 842]. This information was transferred to U.S. and U.K. officials in 1945–1946 interrogations of the German experts, and it was subsequently exploited in postwar U.S. and U.K. aerospace programs. See Figs. 9.46–9.47.[7] Most conventional English-language histories erroneously ascribe the original discovery of these principles to Harry Julian Allen, an American bureaucrat at NACA, in the 1950s [e.g., Anderson 1997], long after the actual discovery and official transfer.

Sighard Hoerner (German, 1906–1971, Fig. 9.48) conducted aerodynamics research in Germany during World War II and in the United States after the war. He strongly promoted the use of advanced German aerodynamics insights and aircraft design principles in the postwar United States.

Alexander Lippisch (German, 1894–1976, Fig. 9.49) applied high-speed aerodynamics to aircraft design and had an enormous impact over his long career. He proposed and strongly advocated for delta-wing designs, winglets, and tailless aircraft, and he influenced other wartime designs (such as those of the Horten brothers, pp. 1780, 1785–1786) and postwar designs (such as the Avro Vulcan, p. 5280). He also invented and demonstrated rocket planes (pp. 1932, 1934–1935, 1938).

Similarly, Hans Multhopp (German, 1913–1972, Fig. 9.49) applied the principles of high-speed aerodynamics to develop very advanced prototype jet aircraft (such as the Focke-Wulf Ta 183, p. 1787) in Germany during the war, and jet fighters and lifting bodies (subscale prototypes for the later U.S. Space Shuttle—see p. 1945) in the United States after the war.

Dietrich Küchemann (German, 1911–1976) and Johanna Weber (German, 1910–2014), shown in Fig. 9.50, also did extensive work on supersonic aerodynamics during World War II. After the war, they both moved to the United Kingdom and played key roles in the postwar development of supersonic aircraft such as Concorde passenger plane and Victor jet bomber, as well as subsonic aircraft such as the Airbus A300.

[7] Figures 9.46–9.47 show excerpts from HEC 842, rough notes made by the Allied interrogators of the German experts. The German experts clearly specified a blunt nose with a detached shock, and the Allied interrogators revealed their own ignorance by continuing to draw a sharp nose. Can the more polished final Allied reports be found? Can the original German documents be found? The initial German discovery was Rudolf Hermann's experimental measurements of the best reentry vehicle shapes for German long-range missiles in the hypersonic wind tunnel of the Heeresversuchsanstalt. Adolf Busemann and Gottfried Guderley provided the theoretical analysis and applications of those results.

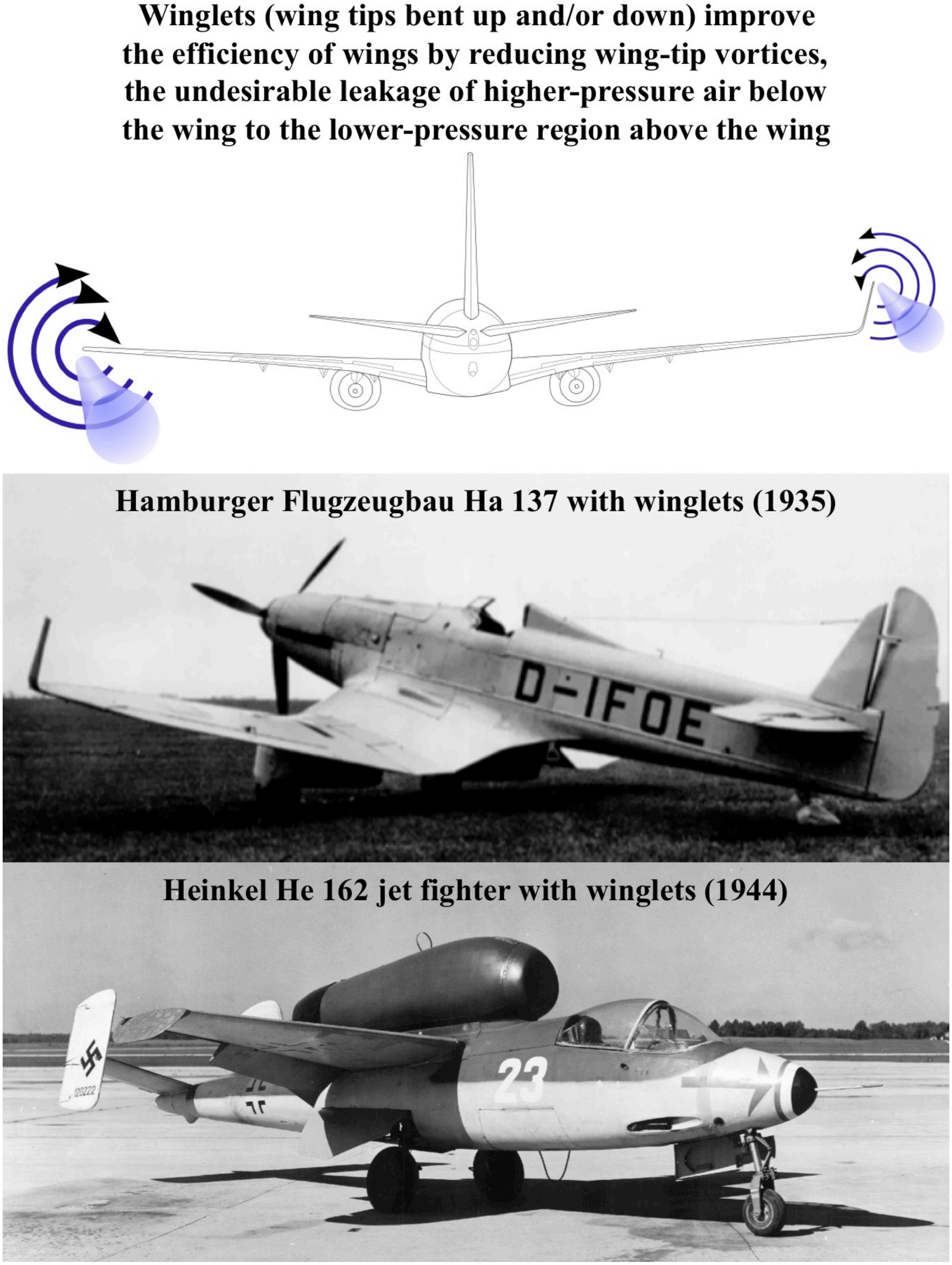
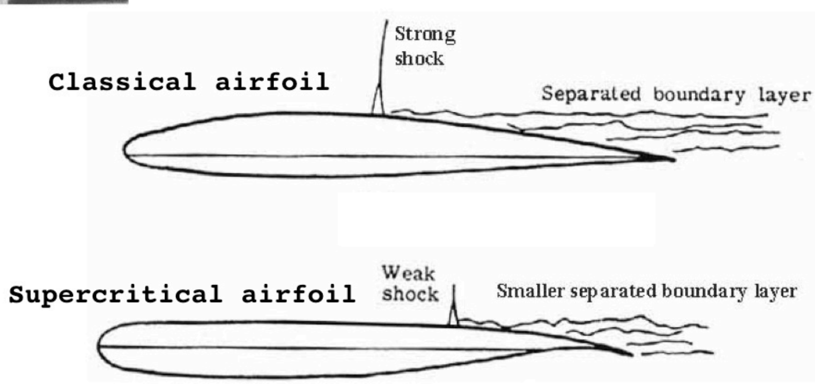


Figure 9.43: Winglets (wing tips bent up and/or down) improve the efficiency of wings by reducing wing-tip vortices, the undesirable leakage of higher-pressure air below the wing to the lower-pressure region above the wing. Examples of German aircraft that employed winglets included the Hamburger Flugzeugbau Ha 137 (1935) and the Heinkel He 162 jet fighter (1944).

Bernhard Göthert (1907–1988) **K. A. Kawalki (??–??)**

Developed supercritical airfoils for high speeds 1940–1944



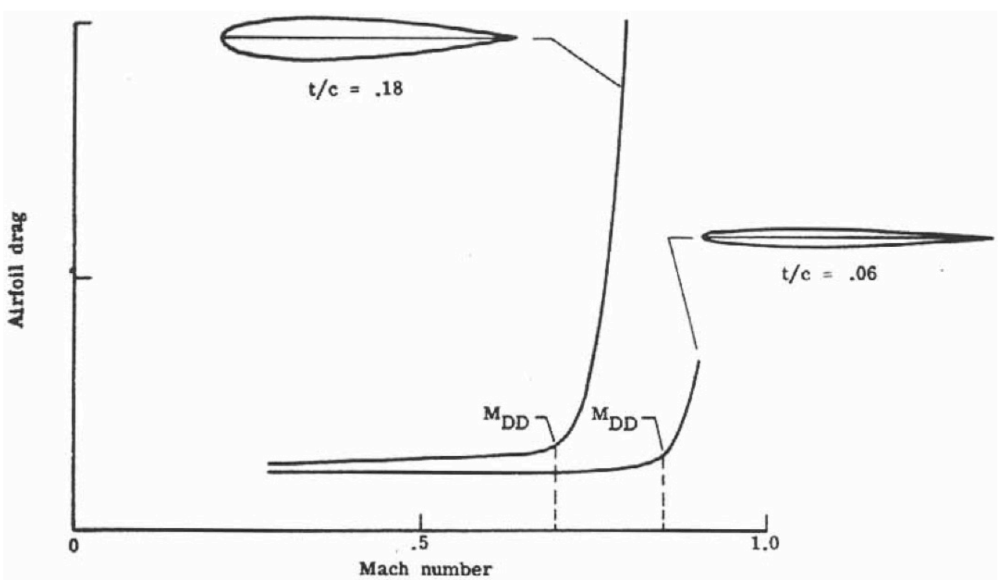


Figure 9.44: Bernhard Göthert and K. A. Kawalki developed supercritical airfoils for high-speed aircraft in 1940.

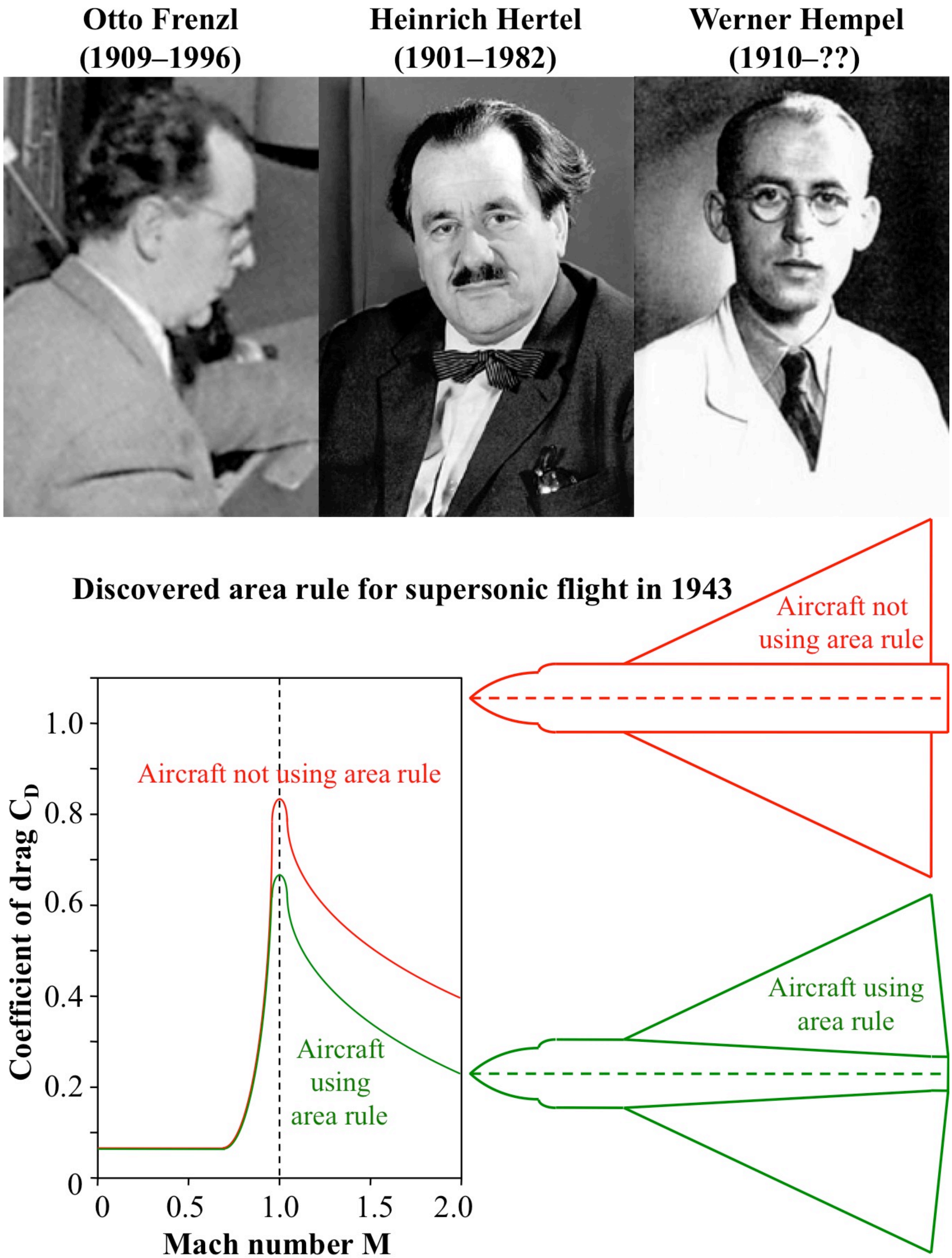


Figure 9.45: Otto Frenzl discovered the area rule for supersonic flight in 1943 and filed a patent on it with aircraft designers Heinrich Hertel and Werner Hempel.

HALSTEAD EXPLOITING CENTRE

ROUGH NOTES TAKEN WHILE INTERVIEWING PROF. LUTZ, DR. KNACKSTEDT, ING. WINKLER, PROF. BUSEMAN, DR. GUDERLEY, DR. SCHMIDT, PROF. SCHLICHTING FROM THE HERMANN GÖRING STEEL WORKS.

NOTE

This is a copy of the rough notes taken while interviewing the persons noted herein. A complete and final report will be written subsequently.

The interviewers were :

Dr.	Francis	H. Clausen
Dr.	Clenn	H. Peebles
Dr.	Robert	W. Krueger
Dr.	K.R. Osman	

PUBLICATION : BIOS / Gp. 2 / HEC 842.

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B.I.D.No. 1000.1200 (4)
M.I.G.No. 804.050
Report No. R5418-46

By authority of
M. A. London
11/12.46 C.E.M. CEM

CEM/lah

INTELLIGENCE REPORT

From The Military Attache, London, England. DATE 11 Dec. 1946.

Subject GERMAN RAM JET RESEARCH.

Source Halstead Exploitation Center Publication BIOS/Gp.2./HEC 842. Eval. B-2

Area Reported On - Germany.

329947

SUMMARY: This document consists of rough notes taken by a number of American scientists while interviewing a number of German scientists working in the field of jet propulsion. Some of the subjects covered are theory of the aero-pulse engine (such as the propulsion of the V-1 "flying bomb"), design and combustion theory of ram jets, ram jet-assisted shells and supersonic aerodynamics.

COMMENTS - Among the German scientists interviewed was Dr. Busemann. He is now at the National Physical Laboratory in U.K. (working under British supervision), where Mr. Hayes of the North American Aviation Company recently interviewed him. Mr. Hayes' comments on Busemann's work were forwarded in M.A.London R4414-46. A translation of Busemann's review of ballistics theory was forwarded in M.A.London R5126-46.

Although the attached report is unclassified this report is classified "Secret" because of the information in the above comments.

This report will be of interest to the Ordnan ce Ballistic Research Laboratory, GALCIT - ORDCIT, Army Air Forces, U.S.Navy Bureaus of Ordnance and Aeronautics and N.A.C.A.

1 Incl. as above,
five copies.

C. E. Martinson
C. E. MARTINSON,
Major,Ord.Dept.

Approved and Forwarded,
For the Military Attache:

S. W. DON,
Lt.Col.,FA
Executive Officer.

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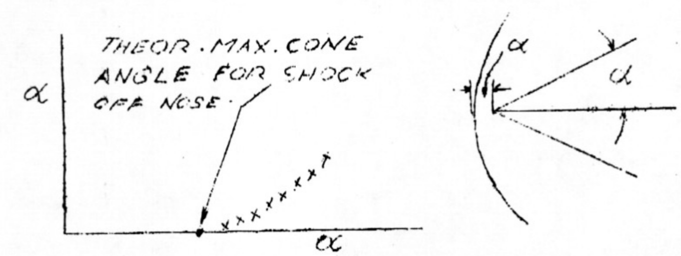
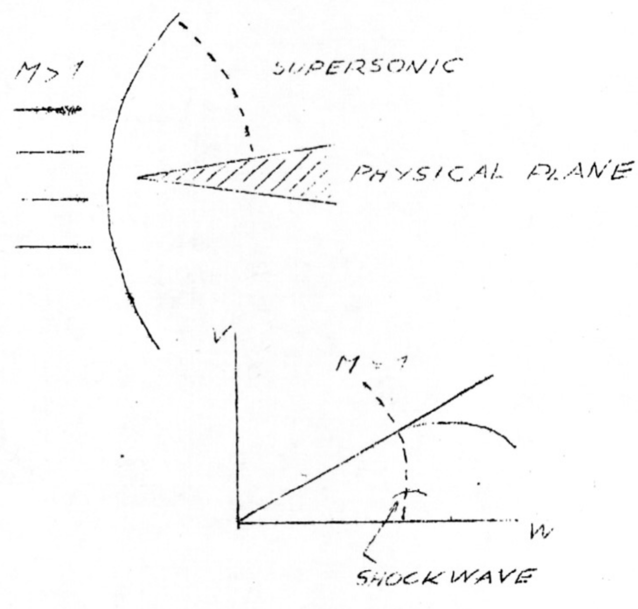
NARA RG 319, Entry NM3-82, Box 1568, HEC 842

Figure 9.46: The advantages of blunt leading surfaces for atmospheric reentry, in order to create detached shock waves and reduce vehicle heating, were discovered, analyzed, and advocated by Rudolf Hermann, Adolf Busemann, and Gottfried Guderley during World War II, then transferred to the U.S. and U.K. after the war [NARA RG 319, Entry NM3-82, Box 1568, HEC 842].

In connection with the problem of the curved shock wave existing in front of a cone that has a blunt angle, Hermann made tests at Peenemuende and plotted the distance; the shock was ahead of the point against the cone angle for various constant M'nos. and found that the extrapoled curve did not point at a zero distance for the predicted maximum angle at which the shock would come off the nose as it had for the wedge. Busemann has calculated a much more complete set of cases for the Taylor-Me. Call cone presented in the memorial issue of the "Luftfahrtforschung" for a Mr. Wieselsberger.



Guderley believes that he can solve the problem of the flow behind a curved shock ahead of a blunt profile by obtaining a solution in the hodograph plane for the sub-sonic portion in an expansion of a hypergeometric function and continuing the supersonic flow by the method of characteristics.



NARA RG 319, Entry NM3-82, Box 1568, HEC 842, pp. 10, 17

Figure 9.47: The advantages of blunt leading surfaces for atmospheric reentry, in order to create detached shock waves and reduce vehicle heating, were discovered, analyzed, and advocated by Rudolf Hermann, Adolf Busemann, and Gottfried Guderley during World War II, then transferred to the U.S. and U.K. after the war [NARA RG 319, Entry NM3-82, Box 1568, HEC 842, pp. 10, 17].

Figure 9.48: Sighard Hoerner (1906–1971) conducted aerodynamics research in Germany during World War II and in the United States after the war [http://hoernerfluiddynamics.com]. He was an important conduit for the transfer of advanced German knowledge about aerodynamics and aircraft design.

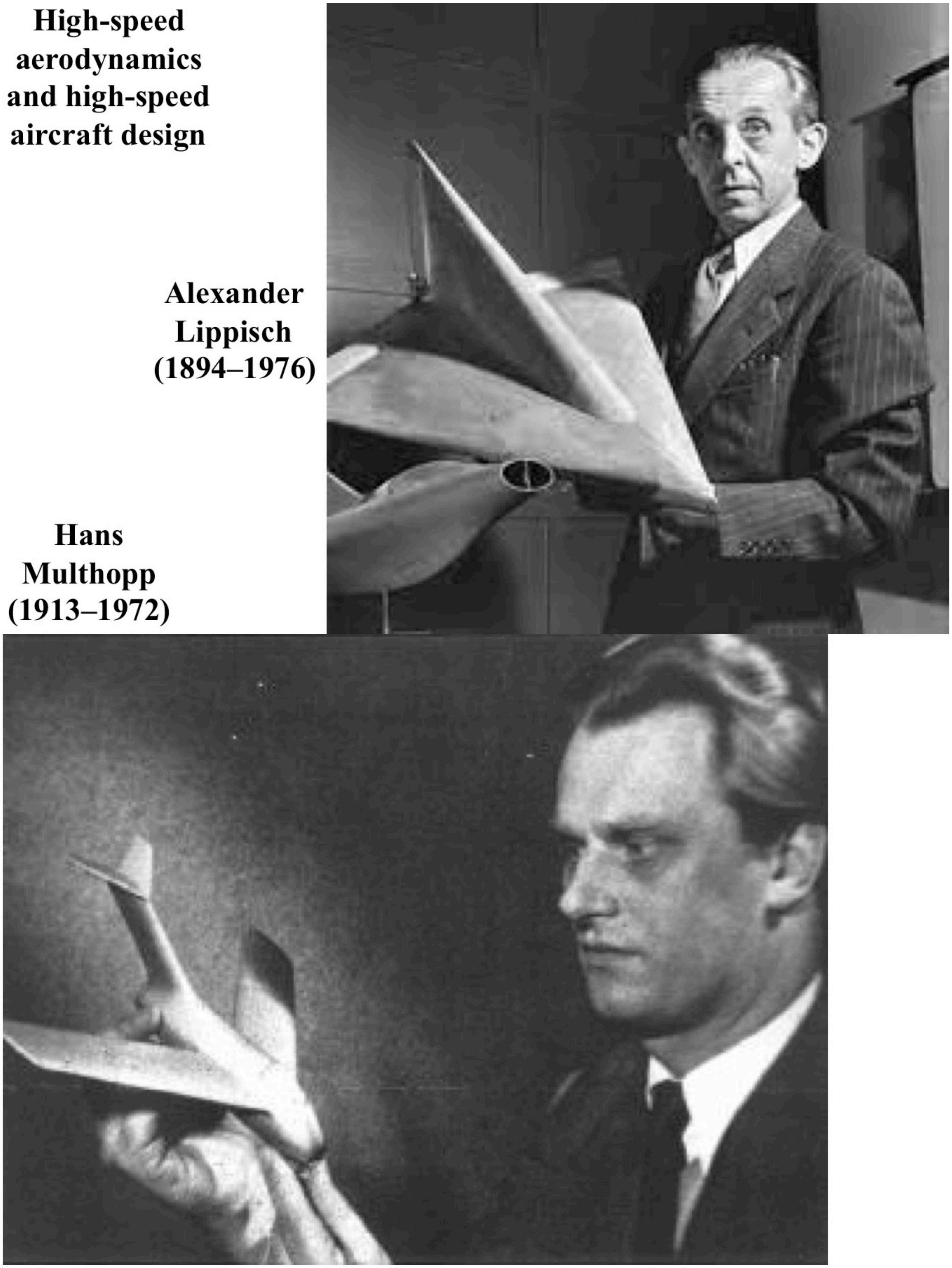


Figure 9.49: Alexander Lippisch and Hans Multhopp made many major contributions to high-speed aerodynamics and high-speed aircraft design.

Figure 9.50: Dietrich Küchemann and Johanna Weber studied supersonic aerodynamics during World War II and played key roles in the postwar development of supersonic aircraft such as Concorde.