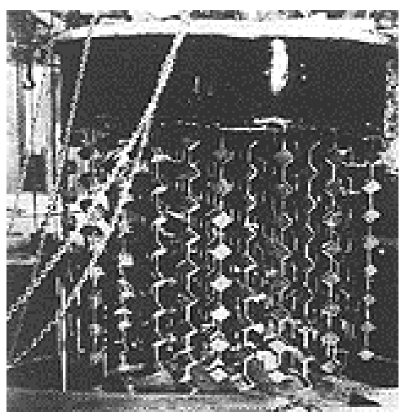
David Irving

The Virus House

GERMANY'S ATOMIC RESEARCH AND ALLIED COUNTER-MEASURES



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FOCAL POINT

To Pilar

DAVID IRVING is the son of a Royal Navy commander. Imperfectly educated at London's Imperial College of Science & Technology and at University College, he subsequently spent a year in Germany working in a steel mill and perfecting his fluency in the language. In 1963 he published The Destruction of Dresden. This became a best-seller in many countries. Among his thirty books (including three in German), the best-known include Hitler's War; The Trail of the Fox: The Life of Field Marshal Rommel; Accident, the Death of General Sikorski; The Rise and Fall of the Luftwaffe; Göring: a Biography; and Nuremberg, the Last Battle. The second volume of Churchill's War appeared in 2001 and he is now completing the third. His works are available as free downloads at www.fpp.co.uk/books.

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Author's Introduction

WAS THERE A WARTIME German atomic research program? It seems hard to believe, for twenty years have passed and there is little reference to it in the established chronicles of the Second World War. In fact, there has up to now been no history of the German atomic research effort between 1938 and 1945, simply because of the thoroughness with which the Allied Intelligence mission under Dr. Samuel A. Goudsmit divested liberated Europe of almost every vestige of evidence that such a program had ever existed. For a historian it would have been — and initially it *was* — something of a nightmare to piece the story together from such scraps as remained. I can now understand the French Professor Joliot's feelings when, having insisted that the German nuclear physicists at Hechingen should produce for him every remnant of the uranium metal that they must surely have concealed, he was solemnly handed a lump of uranium the size of a sugar cube that had been used for laboratory tests. (The British and American officers had removed all the documents and uranium from the French zone of Germany even before the war ended.)

In the end, I went to the United States and searched for the missing documents there; and I ran them to earth in abundance, lying unused and neglected in a warehouse of the U.S. Atomic Energy Commission at Oak Ridge, Tennessee. I am grateful to Mr. Robert L. Shannon and Mr. James M. Jacobs for their assistance to me there. The most important German files, particularly on the political history, were provided to me by Dr. Goudsmit, to whom I am indebted for his hospitality at Brookhaven National Laboratory, New York; I must also thank his assistant, Mrs. Peggy Homan, who took care of many arrangements for me during my American investigations.

Too many participants in these events have assisted me — in conversations, correspondence, and commenting upon various sections of the draft manuscript — for me to be able to thank them all here. I have named all of them in my Notes on Sources. But three I must particularly thank: Lieutenant-Colonel Knut Haukelid, DSO, MC, who aided me during my researches in Norway into the SOE operations against heavy-water production; Professor Werner Heisenberg, who made time for several very lengthy conversations with me, and who has read the whole manuscript in draft; and Sir Patrick Linstead, FRS, who kindly permitted me to make use of the extensive facilities of the Imperial College physics library in South Kensington. Without their help it would have been exceedingly difficult to present in detail the story that follows.

DAVID IRVING
London, August 1966

CHAPTER ONE

Solstice

THE HISTORY of the German nuclear research program during the war can best be begun at the end, for it was a program which — lacking strong military direction like that in America — was beset by the personalities of its main scientists and nowhere do the characters of the ten leading German atomic scientists come more closely to the surface than in the records relating to the events of August 6, 1945.

During the evening the BBC Home Service broadcast the first news that an atomic bomb had been dropped on Hiroshima some hours before. The 6:00 P.M. bulletin announced that the bomb had contained as much explosive power as two thousand of the RAF's ten-ton bombs, and that President Truman had disclosed that the Germans had worked feverishly to "find a way to use atomic energy," but had failed. In Farm Hall, a country house near Huntingdon, languished the man who had made the atomic bomb possible, with nine of his fellow countrymen: he was the German chemist Professor Otto Hahn, the man who had discovered the fission of the uranium nucleus.

Some minutes after the first news was broadcast, Major T. H. Rittner, the British officer in charge, asked for Hahn to be brought to his office and broke the news to him. The elderly German was horrified: he felt personally responsible for the deaths of thousands of people. He told Rittner that he had had the worst forebodings when he had first seen the potentialities of his discovery, six years before; but he had never thought it would come to this. Rittner fortified him with a strong drink and tried to calm him. Together they waited for the bulletin to be repeated at seven o'clock.

The other captives — all of whom had worked on Germany's nuclear project during the war* — had already sat down to supper when Hahn's absence was noted. Dr. Karl Wirtz went to Rittner's office to fetch him. Wirtz came in just as the 7:00 P.M. was beginning; he listened with Hahn and Rittner, then returned to the dining room and shocked the others into silence with the announcement.

Uproar broke out. British Intelligence officers listening through concealed microphones heard with satisfaction that even the most eminent of the Germans were sure that such a bomb had not been made. Professor Werner Heisenberg — one of the most famous names in theoretical physics and a Nobel Prize winner of long standing — suggested that it was a bluff. Professor Gerlach, Göring's last Plenipotentiary for Nuclear

* The ten German scientists detained at Farm Hall were: Dr. Erich Bagge, Dr. Kurt Diebner, Prof. Walther Gerlach, Prof. Otto Hahn, Prof. Paul Harteck, Prof. Werner Heisenberg, Dr. Horst Korsching, Prof. Max von Laue, Prof. Carl-Friedrich von Weizsäcker and Dr. Karl Wirtz.

Physics, wrote in his diary afterward: "Heisenberg energetically disputes the possibility that the Americans have this bomb."

The Americans were no better than the Nazis, said Heisenberg; they had just developed some new explosive and had given it this fancy name.

The possibility that the Americans had even had a uranium project seemed remote. Heisenberg had himself asked Dr. Goudsmit, the head of the American Intelligence mission which had taken him prisoner in May, whether the Americans had been working on the same lines as he had in Germany, and Goudsmit, a fellow physicist who was not likely to mislead a colleague, had assured him that they had not. Professor Heisenberg had begun to drop hints about being ready to advise the Americans should they wish to start a uranium project of their own and Goudsmit had not ridiculed him. Nor was that all: it seems that when the Germans' last uranium pile laboratory was captured in April by the American mission, the German scientists there — and von Weizsäcker and Wirtz in particular — had been tricked into revealing the location of their uranium and heavy-water stocks, with a promise that these would be needed when the Germans resumed their research elsewhere; so how could the Americans have an atomic bomb? In fact, the Americans' object was to insure that the materials did not fall into the hands of Professor Joliot and the French, in whose zone the pile laboratory lay.

Heisenberg still could not believe that a fellow scientist like Goudsmit — with whom he had stayed in America in 1939 — would have misled him. So this talk of "atomic bombs" must be bluff. Hahn, who had now rejoined them, said that he hoped Heisenberg was right. If the Americans had used what is now called plutonium — a process which the Germans had themselves mooted as being less expensive than using uranium-235 —

it would still have been an extremely complicated business. As Hahn pointed out at once: "For [plutonium] they must have a pile which will run for a long time."

To camouflage his distress at the news, he found malicious pleasure in the discomfort of his good friend Heisenberg. "If the Americans have the uranium bomb, then you're all second-raters. Poor old Heisenberg!" Professor Heisenberg hotly asked him: "Did they use the word *uranium* in connection with this 'atomic' bomb?"

Hahn said, "No."

"Then it's got nothing to do with atoms," said Heisenberg.

Otto Hahn refused to let him off. "At any rate, Heisenberg, you're just second-raters and you may as well pack up."

Professor Heisenberg persisted that the bomb probably used some unconventional chemical concept, like atomized hydrogen or oxygen, or something; anything was easier to believe than that Goudsmit had deliberately misled him. But Professor Paul Harteck, a physical chemist from Hamburg, gently reminded them that the bulletin had apparently spoken of one bomb's being equivalent to 20,000 tons of TNT. This touch of realism was typical of Harteck, an outstanding scientist with a well-developed bachelor sense of humor; with his small mustache he bore some similarity, when he tried, to their late Führer, and this had been hilariously exploited at the urge of his fellow professors on one occasion already, when the British newspapers had begun to hint that Hitler was still at large. But nobody was in the mood for practical jokes today.

Von Weizsäcker, one of Heisenberg's younger physicists, cautiously asked his mentor what he could say to the "20,000 tons." Heisenberg answered more circumspectly, but was still reluctant to believe that the Allies had made an atomic bomb.

Professor Gerlach and the legendary Max von Laue pointed out that the main news bulletin would be broadcast at nine o'clock.

In the two hours that followed, the discussion developed still further. Dr. Korsching and Dr. Wirtz asserted that the Americans must have made the bomb by separating uranium-235 by diffusion — a process which they had canvassed themselves. "It was anyway obvious that it must have been done by isotope separation," wrote Dr. Bagge, an isotope-separation expert, "if it was going to work as a bomb."

Dr. Wirtz said: "I'm glad we did not have it." Von Weizsäcker agreed: "I think it is dreadful for the Americans to have done it. I think it is madness on their part." From across the dinner table, Heisenberg intervened: "One can't say that. One could equally well say that it's the quickest way of ending the war . . ."

"That," said Otto Hahn, "is what consoles me." And after a time he added, "I think we'll bet on Heisenberg's suggestion that it is a bluff."

At nine o'clock all ten scientists clustered round the wireless in the drawing room.

"Here is the news," began the announcer. "It's dominated by a tremendous achievement of Allied scientists — the production of the atomic bomb. One has already been dropped on a Japanese army base . . ." After a while, further details were given: "Reconnaissance aircraft couldn't see anything hours later because of the tremendous pall of smoke and dust that was still obscuring the city of once over 300,000 inhabitants." The Allies had spent £500 million on the project; up to 125,000 people had helped to build the factories in America and 65,000 people were running them now. Few of the workers had known what they were producing: "They could see huge quantities of materials going in, and nothing coming out — for the size of the explosive charge is very small." Then came the final confirmation: the American Secretary for War had announced that "uranium" was used in making the bomb.

As the story unfolded in all its detail — a long statement from Downing Street followed the main news bulletin — the captive German scientists agreed that for the initiated there could be no doubt that the Allies had perfected the uranium bomb. "A very difficult situation [develops] in our small circle," wrote Gerlach.

The feelings of the Germans were a mixture of horror, disbelief, annoyance and recrimination. Commander Welsh of Intelligence — to whom they referred as the "golden peacock" because of his passion for gold braid — and Dr. Goudsmit had obviously led them deliberately astray. Dr. Erich Bagge complained: "Goudsmit has led us up the garden path!" In his diary he wrote: ". . . and now the bomb has been used against Japan. They say that for several hours afterward the target city was obscured by masses of dust and smoke. There is talk of 300,000 dead. Poor old Professor Hahn!" Hahn had described to them his feelings when he had first learned the frightful implications that his uranium-fission discovery might have: "For a time, he said, he had mooted a plan to throw all the uranium into the sea and ward off the catastrophe like that; but should one at the same time deprive humanity of all the blessings that uranium fission might bestow? And now it has arrived, this dreadful bomb. The Americans and British — Chadwick, Simon, F. A. Lindemann (Lord Cherwell) and many others — have put up huge factories in America and produced pure uranium-235 without hindrance."

Now it began to dawn on the German scientists why they had been detained since the collapse of Germany.

In the hours that followed the news broadcast, an increasingly bitter discussion developed. Dr. Korsching said that the American scientists had obviously cooperated on a tremendous scale: "That would have been impossible in Germany. Each one said the other was unimportant."

"I believe the reason why we didn't do it was that all the physicists didn't want to do it, on principle," asserted von Weizsäcker. And he added: "If we had all *wanted* Germany to win the war, we could have succeeded."

This upset more than one of the others. Had the German uranium project been sabotaged from within? One of the physicists wrote soon after, ". . . and all the time, we had to put up with our powers-that-be jeering at our own isotope-separation efforts, and barely tolerating them at all; and we had to force through our isotope-separation research against the internal opposition of our own best physicists; and even had to see how people like M——, E——, P—— and W—— were either unwilling or incompetent to crook so much as a little finger to work on the isolation of pure uranium-235. It's just too much." Professor Gerlach — who had been Reichsmarschall Göring's Plenipotentiary for Nuclear Physics since the beginning of 1944 — was the most grief-stricken about the German failure. And Dr. Bagge said: "I think it is absurd for von Weizsäcker to say he did not want the thing to succeed: that may be so in his case, but not for all of us."

As Professor von Laue went up to bed that night, long after one o'clock in the morning, he confided to Bagge: "When I was a boy I wanted to do physics and watch the world make history. Well, I have done physics and I have seen the world make history. I will be able to say that to my dying day."

Von Laue could not sleep that night. At two o'clock, he knocked on Bagge's door and told him: "We must do something. I am very worried about Otto Hahn; the news has shocked him terribly, and I fear the worst."

They opened the door leading into Hahn's bedroom, so that they could see him as he lay there, agitated and sleepless. Only when they saw him drifting safely off to sleep did the other German scientists relax their vigil.

[11]

IT WAS SIR GEORGE Thomson* who drew attention to that peculiarity in the world of nature which allows us to derive large amounts of energy, with explosive violence, from the fission of the atomic nucleus; the process depends upon the existence in nature of very heavy nuclei like uranium and thorium which — although fundamentally unstable — have nevertheless contrived to survive the 5,000 million years since the birth of the solar system. Had these nuclei been a little less stable, none would have survived for the great men of science like Enrico Fermi, Otto Hahn, Fritz Strassmann and Sir George Thomson himself to work with; but had they been a little more stable, nuclear fission would not occur.

So often, the phenomena of natural science are such paradoxes; and so often, they are detected by chains of coincidence and chance. Indeed, four years of errors and wrong hypotheses preceded the discovery by Hahn that the uranium nucleus could split. The story had begun in the early 1930s when Enrico Fermi — an outstanding Italian physicist — had suggested that it

* Sir George Thomson, "Nuclear Energy in Britain during the Last War" (The Cherwell-Simon Lecture, Oxford, Oct. 18, 1960).

might be possible to form artificial radioactive isotopes of the heaviest known elements by bombarding them with the neutrons discovered by Professor Chadwick: the neutron, a massive atomic particle carrying no net electric charge, should be able to penetrate the highly charged atomic structure more easily than the helium nuclei — "alpha particles" — with which Frédéric Joliot and Irène Curie were making similar experiments in Paris. Alpha particles carried a positive charge and were difficult to get near the positively charged atomic nucleus of the target element, as the one repelled the other. The neutron, on the other hand, should be able to enter the atomic structure even when traveling at only a drifting rate. In fact, Fermi discovered substantially by chance that if he surrounded the source of his neutrons with a layer of some substance rich in hydrogen, for example paraffin wax, the neutrons' powers of affecting some of the target element were considerably enhanced. He deduced that the normally fast neutrons emitted by the source were being slowed down ("moderated") by collision with the paraffin's light hydrogen atoms, and that these slow neutrons were more easily captured by the target nuclei.

Uranium is the heaviest element existing in nature: in the metallic form, it is a fairly hard white metal, malleable, ductile and with a melting point very much lower than those of the other metals with similar chemical properties — tungsten, chromium and molybdenum. Uranium has the atomic number 92, and the mass number of its most abundant isotope is 238, meaning that its nucleus must consist of 92 protons and a balance of 146 neutrons; but in every thousand parts of natural uranium there are about seven parts of a rather lighter isotope, with the mass number 235. The chemical properties of the two isotopes are the same, but the *physical* properties differ. Were there no such physical difference it would be neither possible nor necessary to separate the uranium isotopes.

When Fermi and his co-workers bombarded natural uranium with neutrons in their Rome laboratory, they found that it became activated in such a way as to suggest that the uranium-238 nucleus had captured a neutron, to become the unstable isotope uranium-239; and that this new atom had then emitted one (negatively-charged) electron and accordingly lost its atomic-number-92 (uranium) identity, to become a new element with the atomic number 93. What had been uranium had apparently been "transmuted" to form a hitherto unknown element beyond even uranium in the atomic table.

To establish that he had indeed created a new, "transuranic" element, Fermi extracted it from his irradiated target solution of uranium compounds, and by chemical precipitation techniques he proved to his initial satisfaction that at least one of the products of the neutron bombardment of uranium was chemically different from all existing elements, or at least all existing elements heavier than lead; as a physicist he could see little point in making comparisons with elements below lead in the atomic table. Fermi reasoned that his new substance must therefore be heavier than the heaviest known element, uranium. It certainly seemed reasonable that no known process of radioactive decay* could have reduced the uranium atom even to a position as low as lead. One German chemist, Frau Ida Noddack, did raise a questioning voice against Fermi's assumption; she suggested tentatively that the uranium might in fact have bodily split up, rather than decayed, under neutron bombardment. She herself

* In a "decay" process, the uranium nucleus would have one or two fragments "chipped off" under intense bombardment by massive atomic particles or in normal radioactive emissions.

did not pursue the suggestion, and it was certainly not heeded by the world of physics.

Fermi's postulation of the existence of a series of "transuranic" elements did not pass unchallenged, and it was the object of some controversy. Immediately after his findings were published in *Nuovo Cimento* and *Nature* in 1934, the Viennese-born physicist Lise Meitner persuaded Otto Hahn, the famous German radiochemist with whom she had worked on the discovery of mesothorium and protactinium in the years prior to 1922, to renew their collaboration in an investigation of these "transuranic" elements Fermi was claiming to have found. Hahn had been joined in his laboratory at the Kaiser-Wilhelm Institute of Chemistry in Berlin-Dahlem by the young Dr. Fritz Strassmann, an excellent inorganic and analytical chemist who was by now well versed in the techniques of radiochemistry.

It would be irrelevant to describe the full program of research which these three scientists now embarked upon in Berlin. It will suffice to say that during the four years preceding the last dramatic weeks of 1938, Hahn, Strassmann and Meitner confirmed Fermi's remarkable findings and built up a complex fabric of apparently transuranic elements, which won them the acclaim of the whole world of science. They detected and described four new elements, which they provisionally christened "eka-rhenium," "eka-osmium,"* "eka-iridium" and "eka-platinum"; rhenium, osmium, iridium and platinum were the elements directly above them in the Periodic System, and the chemical properties of the new elements should accordingly be similar. There were some puzzling inconsistencies, but they were

* "Eka-rhenium" and "eka-osmium" — the elements with atomic numbers 93 and 94 — are now named neptunium and plutonium, respectively.

overlooked in the pious belief that explanations would eventually be found for them.

It was not until 1938 that the first cracks began to appear in this elaborate and dangerous edifice of transuranic elements. Following in Fermi's footsteps, Irène Curie and Pavel Savitch described a new radioactive substance they had obtained by bombarding uranium with neutrons — a strange substance with a radioactive half-life of three and a half hours. At first the Paris physicists suggested that this was an isotope of thorium, two places below uranium in the atomic table: this would be the theoretical consequence of a decay process whereby the uranium nucleus captured the neutron, became unstable, and ejected an alpha particle to become thorium.

Nobody had yet detected the emission of an alpha particle from irradiated uranium, but it was understandable that the pride of the physicists in Otto Hahn's Berlin laboratory should have been injured by this discovery by a rival team. In 1934, Lise Meitner had entertained a belief that thorium might be found, but Strassmann had searched chemically for traces of thorium in their irradiated uranium solutions, and found none.

Lise Meitner took him to task for having failed, while the physicists in Paris had apparently succeeded, although admittedly they had betrayed none of their experimental methods in their published findings. Meitner urged Strassmann to repeat the experiment. Strassmann did so, carrying out a straightforward experiment to separate thorium from uranium and all other elements, using iron as the "carrier." Within a week, a baffled Strassmann was able to assure Lise Meitner that whatever the French team might claim, there was certainly no thorium in the solution.

Otto Hahn's laboratory could have published this finding and caused the Paris laboratory some embarrassment. In fact they chose a more diplomatic approach: a letter was written to the French scientists by Hahn and Meitner, privately warning them to proceed with caution, for they had found no thorium; might not Irène Curie have made some error? Otto Hahn was a radiochemist of thirty years' standing by then, and his voice bore the unmistakable ring of authority. Although he received no reply to the letter, Mme. Curie soon afterward published a further paper in which she admitted that their strange substance was not thorium after all.

Indeed, she now set up an even more adventurous hypothesis, for as a result of further chemical tests which showed that the strange 3.5-hour substance could be precipitated out of solution with lanthanum as a carrier, she and her co-worker were obliged to conclude: "In the final analysis, the properties of the 3.5-hour substance are those of lanthanum, from which it might at present seem to be separable only by means of fractionation." The substance could not of course *be* lanthanum, in their view, for no process of radioactive decay could reduce the uranium nucleus so far. It must be yet another "transuranic" element. Yet how could a place be found for a "transuranic" element with properties similar to lanthanum — a rare earth? To physicists and chemists alike, the problem seemed insoluble.

As the strange substance was thus to be forcibly entered into the ranks of the "transuraniums," which were very much the preserve of Otto Hahn's laboratory, he and his co-workers were obliged to devote a more than casual interest to the properties of this newcomer. It was not until the Paris laboratory published a final paper, in the autumn of 1938, giving a first detailed description of their experimental methods and the strength of their preparations, that the mists began to clear. In the meantime Hahn had lost the benefit of Lise Meitner's advice as a physicist, for in July she had decided to leave Germany because her Austrian passport no longer protected her from religious persecution. It was thus the two chemists of the Berlin laboratory who brought the work to its extraordinary conclusion.


Prof. Otto Hahn

Professor Hahn saw Irène Curie's new paper briefly and passed it on to Dr. Strassmann, commenting that she had now published her experimental methods and was this of any interest to him? Strassmann scrutinized the paper and believed that he saw a fallacy in the French team's conclusions: the latter were trained physicists, of course, and not as familiar with radiochemical methods as the Berlin workers, and this might well result, thought Strassmann, in their having attributed to one strange substance the properties in fact accruing from the presence of *two* new substances in their irradiated uranium solution.

Strassmann told Hahn of his suspicions; the professor laughed at his theory, but added shortly that there might well be something in it. Within a week they had carried out a remarkable series of experiments designed to distinguish the new radioactive substance, or substances, from uranium, protactinium, thorium and actinium on the one hand, and all the transuranic elements on the other. There *was* a mixture of two, and possibly even more, new radioactive substances in the target solution after radiation. What were they?

By using barium as a "carrier" they found they could precipitate one set of three radioactive substances, from which grew a further set of three "daughter" substances which could be precipitated with lanthanum as a "carrier." The only possible conclusion in the light of current theory was that the former were radium isotopes and the latter actinium isotopes; the only alternatives would have been that they were isotopes of barium and lanthanum respectively, and for physical reasons this seemed unthinkable, for barium and lanthanum were way down the atomic table and could not have been reached by any conceivable process of radioactive decay.

When Hahn and Strassmann published, late in 1938, their conclusion that there were three new substances in the irradiated uranium solution — isotopes of radium and actinium — substances created by the progressive decay of the uranium nucleus, many physicists were disinclined to accept even this. What kind of decay process was this, that resulted in the rapid ejection of the two alpha particles necessary for uranium to be reduced to radium, especially since only slow (i.e., low-energy) neutrons had been used to "bombard" the uranium solution? Professor Hahn described their theory to Niels Bohr, the eminent Danish nuclear physicist, during a visit to Copenhagen soon after; Bohr frankly told him that the ejection of two successive alpha particles was "unnatural"; he was inclined to the theory that the substances were in fact transuraniums. From Stockholm Lise Meitner wrote an anxious letter to Professor Hahn warning him that he was beginning to make nonsense; one can imagine her clicking her tongue at the frivolities in which the Berlin chemists were indulging now that the iron hand of the laws of physics no longer restrained them.

Mocked by these distant voices, Hahn and Strassmann resolved to apply themselves anew to the strange 3.5-hour substance.* Strassmann proposed an elegant experiment whereby they would use barium chloride to carry the "parent" radioactive substance out of the irradiated uranium solution. Barium chloride precipitates in perfect crystals which can be relied upon to be clean of any of the numerous transuranic elements also unquestionably produced by the irradiation. The apparatus was simple and inexpensive: a tube containing a uranium compound was exposed to neutrons, emitted by a source comprising one gram of radium mixed with beryllium and slowed down by a block of paraffin wax, a source many times weaker than the cyclotrons at the disposal of foreign countries. The irradiated uranium solution, now containing the mysterious 3.5-hour substance among a host of other elements produced by the neutron bombardment, was mixed with barium chloride; the crystals formed now contained the minute quantities of what were believed to be radium isotopes. The presence of these isotopes was confirmed when the crystals were checked with Geiger–Müller counters whose pulses were amplified by a simple amplifier powered by scores of Pertrix HT batteries stacked under the wooden bench. The amplified pulses triggered clockwork counter-mechanisms, which Hahn, Strassmann and their two assistants read at fixed intervals, to establish the half-lives of the radioactive substances they had produced.†

It was a difficult experiment; the minute quantities of these new radioactive substances were choked by masses of non-radioactive barium chloride crystals, and this led to a routine

* Hahn may have begun to suspect the truth as early as November 1938, for when he lectured in that month to the *Chemisch-Physikalische Gesellschaft* in Vienna he did hint that the "radium" result might have quite a different explanation.

† The original laboratory bench, with the equipment used by Professor Hahn in making his discovery, is on permanent display at the Deutsches Museum in Munich.

attempt to separate the supposed "radium" isotopes from the barium carrier, so that the radioactivity of the isotopes could be examined more conveniently. To separate the "radium," they would use their familiar process of fractional crystallization, the process which had originally been used by Mme. Marie Curie to isolate radium. Hahn and Strassmann had performed this experiment many times before, and were thoroughly familiar with it.

When they applied the method now, however, they found to their surprise that they could achieve no extraction of the supposed "radium" isotopes at all.

Was there some error in their technique? During the third week in December, Hahn decided upon a control experiment: he repeated the fractional crystallization, substituting this time a *known* radioactive isotope of radium — thorium-X — in the solution for their own supposed "radium" isotopes, and diluting the solution until it showed as little radioactivity as their "radium" had. This control experiment went just as it should: a few atoms of the genuine radium isotope could be separated from the barium carrier just as theory had predicted, so there was nothing wrong with their technique.

On Saturday, December 17, Hahn and Strassmann were still thoroughly bewildered by this unexpected turn of events, but the truth was gradually dawning upon them; that day they repeated the two experiments, *simultaneously* this time, with both their artificial "radium" isotope and the natural radium isotope mesothorium-I in the same solution, the latter isotope acting as an "indicator." These radioactive traces were carried out of the uranium solution by the same barium carrier, precipitated and fractionally crystallized together — an extraordinarily complex experiment, confused and fouled at every stage by the production of families of radioactive decay products from all the ingredients. At each stage of the crystallization, samples of the barium crystal were tested for radioactivity: the Geiger–Müller counter showed beyond doubt that the mesothorium — the genuine radium isotope — was concentrating from one stage to the next as it should, while their own artificial "radium" isotope was not. The latter was *uniformly* distributed among the barium crystals sampled at each stage — as uniform as the barium itself. The uniformity was strange, but significant. That night, Hahn wrote in his diary: "Exciting fractionation of radium/barium/mesothorium."

He himself was in doubt no longer: what they had believed to be a radioactive isotope of "radium" could not be separated from barium by any chemical means, because it was in fact a radioactive isotope of *barium*.

The slow-neutron bombardment of uranium — the heaviest naturally occurring element on earth — had yielded barium, an element not much over half its weight. The uranium atom had burst asunder. Despite the costly equipment of the great foreign physical laboratories, it was a German chemist working with the most primitive of equipment who had made the discovery that was to throw the world of physics into pandemonium.

[III]

OTTO HAHN CONTAINED his secret for only a very few days. Over the weekend he busied himself with a private matter, looking after the interests of Lise Meitner now that she had gone. He called on the Inland Revenue office in Berlin, and on Monday morning, before returning to his Institute, he had an interview with Karl Bosch, the president of the Kaiser-Wilhelm Institute, to see whether Meitner's flat could be let to a colleague, Professor Mattauch. It was an unpleasant time for all of them. The

Berlin authorities had opened an exhibition entitled "The Wandering Jew" and, to his annoyance, Hahn had found that somebody with a misguided sense of humor had included him in the exhibition. It was a source of considerable embarrassment to his governors, but it was symptomatic of the times.

When Hahn finally arrived at his laboratory in Berlin-Dahlem on Monday morning, he and Strassmann set up a new experiment, parallel to their earlier one, but designed this time to establish the identity of the second family of radioactive isotopes created by the irradiation of uranium; this was the substance which could be carried out by lanthanum just as their spurious "radium" isotopes had been carried out by barium.

As he and Strassmann took it in turns to watch the Geiger–Müller counters, Professor Hahn began to write a long letter (dated: "Monday evening the 19th, in the laboratory") to Lise Meitner, the woman with whom he had worked over thirty years, and who had been forced to leave them only five months before seeing their work culminate in this extraordinary climax.

After describing his endeavors on her behalf over the weekend, Hahn continued:

> Through all this, Strassmann and I are tirelessly working — as well as we are able — on the uranium substances, with the help of [Fräulein Clara] Lieber and [Fräulein I.] Bohne. It is now just eleven o'clock at night. At a quarter to twelve Strassmann will be coming back so that I can see about going home. The fact is, there is something so odd about the "radium isotopes" that for the time being we are telling only you about it: the half-lives of the three isotopes have been measured with absolute accuracy; they can be separated from all elements with the exception of barium; all the processes are working properly

> with the exception of one — unless there has been some exceedingly strange coincidence. The fractional crystallization is not working. Our "radium" isotope is behaving just like barium.

He recapitulated the experiments he and Strassmann had performed, including the final highly involved "indicator" experiments; he described the impossibility of enriching their artificial "radium" isotopes in the crystals from one stage of the fractionation to the next, while the natural radium introduced as the "indicator" behaved as it should. It was an agonizing moment: "There may still be some extraordinary coincidence behind it all," he repeated. "But we keep coming back to the horrifying conclusion — our 'radium' isotopes aren't behaving like radium, they're behaving like barium." Hahn had agreed with Strassmann to tell only her about their findings as yet; perhaps Frau Meitner as a physicist could put forward "some fanciful explanation" for it all. "We all know that it can't *really* burst asunder to form barium. But now we are going to see whether the 'actinium' isotopes formed by our 'radium' are going in fact to behave like actinium — or like lanthanum. All highly tricky experiments! But we must get at the truth."

Hahn concluded by urging Lise to think whether there was any possible explanation for their findings to accord with existing physical laws; then they might still publish their findings under all three names — an offer characteristic of the warm generosity of Otto Hahn. He concluded: "I have got to get back to the counters now," and posted the letter upon leaving the laboratory that night.

The Christmas vacation was almost upon them now: Tuesday brought the Kaiser-Wilhelm Institute's annual Christmas party, filling Hahn with nostalgia for the many Christmases he had enjoyed with Lise Meitner in Berlin. He had other things on his mind: he and Strassmann had "some very fine graphs" from their experiments, and they were determined to get their findings down in writing before the Institute closed for Christmas.

Within the next two days, the second half of their experiments was complete: the supposed "actinium" isotopes had turned out to be isotopes of *lanthanum*, which was again an element halfway down the atomic table.

Hahn and Strassmann worked feverishly throughout December 22 composing their report on the artificial isotopes they had identified in the first half of their experiments: "As chemists," they wrote, "we are obliged to state that the new isotopes are not of radium but of barium; for there is no question of their being of elements other than radium or barium." But if this was a verdict "contradicting all known tenets of nuclear physics," a verdict which the two radiochemists hesitated to pronounce as final, they still hastened to insure its publication with the utmost dispatch. A telephone call brought Dr. Paul Rosbaud, the editor of the German scientific periodical *Naturwissenschaften* and a close friend of Professor Hahn's, hurrying round to the Kaiser-Wilhelm Institute that same evening. The two chemists had finished writing their paper, claiming proof that the uranium nucleus had "burst asunder," only moments before.

Its importance was at once clear to Rosbaud; the next edition of *Naturwissenschaften* was already in proof, but he ordered another scientific paper of less moment to be struck from the galleys and the Hahn–Strassmann work to be set up in type at once bearing as its date of receipt that day's date — December 22, 1938. It was the solstice: the world's winter had begun.

Dr. Meitner received Otto Hahn's excited letter in Sweden, while spending the Christmas holiday with her nephew — the physicist Dr. Otto Frisch, of Niels Bohr's famous Copenhagen laboratory. Reading Hahn's long letter, she was both amazed and uneasy: could chemists of the caliber of Hahn and Strassmann have made an error? It seemed unlikely. When she tried to tell her nephew of Hahn's suppositions, she had difficulty in distracting his attention from his plans for a large magnet he was working on, and it took some time to get him to believe what she told him.

Frau Meitner's reply to Hahn in Berlin was cautious but congratulatory:

> Your radium results are really very disconcerting: a process using slow neutrons that yields barium?! . . . At present it seems to me very difficult to accept that there is such a drastic breaking-up [of the uranium nucleus] but we have experienced so many surprises in nuclear physics that one cannot dismiss this by saying simply: "It's not possible!"

Soon after, she and Dr. Frisch reconsidered the "liquid-drop" model of the nucleus postulated two years before by Bohr: according to Bohr the "surface tension" stabilized the nucleus in face of minor deformations; but it was not difficult to envisage a uranium nucleus, already almost unstable because of its high electric charge, becoming so unbalanced by its capture of an excess neutron, even a low-energy one, that it became elongated and finally broke up into two smaller "droplets" (i.e., smaller nuclei) approximately equal in size to each other. Each of these nuclei would, of course, be positively charged, so they would repel each other with considerable force. It was calculated that each such "fission" would liberate sufficient energy — about 200 million electron volts — to cause a visible grain of sand to make a visible jump, if the energy could be harnessed to that innocuous purpose.

Once the article by Hahn and Strassmann had appeared in Berlin, on January 6, 1939, there must have been a score of scientists disconcerted by the sudden realization of how close they had themselves been to making the discovery. Of these, Irène Curie's team in Paris had probably come closest, when they wrote in bewilderment of their "3.5-hour substance" that its properties were "those of lanthanum"; for the substance most probably *was* lanthanum. Again, in an experiment designed by Dr. von Droste in Berlin to detect the alpha particles which the then current theory suggested would be ejected by uranium and thorium under neutron bombardment, only the thin metal foils with which he had covered his uranium and thorium samples (to eliminate the naturally ejected alpha particles of low energy) prevented him from finding the very large bursts of ionization caused by fission fragments.

Years later, Fritz Strassmann met an American physicist who told him the most tragic "one-that-got-away" story of them all: about a year before Hahn's discovery, he had irradiated a uranium solution with the very much stronger neutron sources available to the Americans; he had separated the "transuraniums" from the solution and carried what was left in a small glass beaker to another room where he planned to investigate its gamma-ray spectrum. If he had done so, he would at once have detected that the uranium had been joined in the solution by barium and other elements halfway down the atomic table. The floor of the laboratory was, alas, highly polished; the physicist slipped and the beaker with its highly radioactive contents irretrievably smashed. The room had to be sealed off for a period of some weeks, during which he had passed on to other investigations.*

Be that as it may, one is left nevertheless with the strong impression that it was only a team like Hahn's that could have made the discovery when it was made: the delicacy of the experiments they had mastered can be assessed from the quantity of the substances they had identified; in the crystals of barium, only a few hundred atoms of the radioactive isotopes had been present, discernible only by Geiger–Müller counter. It took a man of thirty years' experience in radiochemistry to make the assertions Hahn made with the confidence that he did.

How different history would have been had war broken out in the summer of 1938, as once seemed possible. Would Hahn's discovery ever have been published? Would the United States have reached by 1945 the same stage with their atomic bomb that they were able to reach through the publication of Hahn's discovery in 1939? The United States might never have brought the atomic weapon to such terrible perfection, while the secret might have remained in German hands alone. Hahn and Strassmann are now the first to deny any special claim: "The time was ripe for the discovery," they have said. It was Fortune that ordained that it should be made in Berlin.

[IV]

CONVINCED BY NOW that Hahn and Strassmann were right, Frisch and Meitner had not kept the secret to themselves, and as soon as the Christmas period was past, while Lise Meitner re-

* Regulations concerning the handling of radioactive substances were not known in those days; Hahn now says that if the present regulations had existed in 1938 he would not have been able to make his discovery.

turned to Stockholm, Dr. Otto Frisch traveled back to Copenhagen to tell Niels Bohr in detail of Hahn's discovery (still not published) in Berlin and of the conclusions he and his aunt had reached on the quantity of energy liberated. Bohr left very soon after for a stay of several months in the United States. The secret traveled with him across the Atlantic.

Over the long-distance telephone Otto Frisch and Lise Meitner composed a paper on their findings, which was received by *Nature* in London in the middle of January; this paper, which talked for the first time of a "fission" process, was not published for a further month.

At this time, Professor Josef Mattauch, the leading Viennese physicist whom Hahn had selected to fill the gap left by the irreplaceable Lise Meitner, was traveling back from a lecture tour in Scandinavia. Frisch met him outside Copenhagen, and traveled with him by train the rest of the way into the Danish capital, talking excitedly all the way about the energy calculations that he and his aunt had made. He told Mattauch that he had just proven by physical means what Hahn had proven chemically, using a simple device which clearly recorded the large pulses of ionization caused by each fission. He took Mattauch back to his laboratory at once, and showed him. He said that he had cabled details of the experiment to Niels Bohr in America.

Unaware of Frisch's findings, two Berlin physicists, Dr. Siegfried Flügge and Dr. von Droste, had on January 23 delivered their own report to the *Zeitschrift für Physikalische Chemie*, in which they independently arrived at the same conclusions as Frisch and Meitner. Unhappily for the prestige of either group, Niels Bohr related Otto Hahn's discoveries and the energy conclusions based on them to a conference on theoretical physics in

Washington on January 26.* "The whole matter was quite unexpected news to all present," recounted one physicist. Bohr told the conference that Frish and Meitner had suggested that the high-energy fission fragments should be demonstrable with the simplest of apparatus; and even before Bohr, whose oratory was never of the most audible, had finished speaking several experimental physicists had risen from the audience and hastened — in full evening dress — to their laboratories to repeat and confirm the findings with all possible dispatch.

Within a day or two many national newspapers were reporting their results, and when the scientific papers finally published the findings of Meitner and Frisch and of the Berlin physicists a month later, the laurels were already resting on other heads. The only mention of these momentous events in the serious London newspapers was a small news item in *The Times*, reporting that Columbia University in America had discovered a new process, the "splitting" of the uranium atom: Enrico Fermi, the physicist working by now in the United States, had used the 150,000-pound cyclotron at Columbia University to achieve "the largest conversion of mass into energy that has yet been obtained by terrestrial methods." Fermi had computed that 6,000 million times more energy was liberated by the fission than was necessary to cause it.

Two days after Niels Bohr's Washington meeting, Otto Hahn and Fritz Strassmann delivered a second paper to the same Berlin scientific journal as before. This time they showed by the very wording of their main heading — "Proof of the Formation of Active Barium Isotopes by the Neutron Bom-

* The fifth Washington conference on theoretical physics, sponsored jointly by the George Washington University and the Carnegie Institute of Washington.

bardment of Uranium and Thorium" — that they no longer doubted the validity of their original discovery; but it was with their secondary caption — "Further Active Fragments from Uranium Fission" — that they dropped their second bombshell into the world of physics. What was the nature of the "further active fragments" arising from uranium fission? As it seemed to Hahn that there was no question of fission by atomic *weight*, it seemed more appropriate to think in terms of fission by atomic number; the uranium nucleus (atomic number 92) would fission into nuclei of barium (56) and krypton (36): "There could then simultaneously be a number of neutrons emitted."

This was the key to the golden gate. Hahn and Strassmann, by their tentative proposition that a reaction initiated by neutrons might in itself generate more neutrons, each such reaction liberating large quantities of energy, had shown the way to the New World. It was now seen that the neutrons emitted by one fission might be used to fission further uranium nuclei; and if each such fission resulted in the emission on average of more than one such secondary neutron, there seemed to be no reason why there should not be an avalanche of fissions, each accompanied by the release of energy on a hitherto unsuspected scale.

Poor Otto Hahn: it was some days before this inevitable sequel to his original discovery dawned upon him. Six and a half years later, on the evening when he heard for the first time of the use to which the Western Allies had put his discovery at Hiroshima, he confided to his companions in captivity that as soon as he realized the terrible consequences of his discovery back in 1939, he had been unable to sleep for many days; and he had even deliberated the possibility of taking his own life.

CHAPTER TWO

A Letter to the War Office

PROFESSOR HAHN'S EXPERIMENTS were carefully reproduced by Professor Frédéric Joliot — son-in-law of Madame Curie — at his laboratory in Paris, and by the end of the first week in March 1939 he and the French physicists von Halban and Kowarski had confirmed by physical means the existence of the neutrons suspected by Hahn and Strassmann during the process of uranium fission. In a letter to *Nature*, headed "Liberation of Neutrons in the Nuclear Explosion of Uranium," they pointed out that for a chain reaction to be established it still had to be proven that more than one neutron was produced for each fission; this they now intended to determine, using uranium solutions of varying concentrations.

On April 7, the same three physicists reported from the Collège de France that within limits of error which in no way altered their findings' validity, on average 3.5 neutrons were emitted by the uranium nucleus during fission.* This finally established the possibility of extracting energy from the atomic nucleus by means of a chain reaction — an avalanche of fissions sweeping through a mass of uranium, each fission releasing great bursts of energy, and causing still further fissions until the whole mass of uranium had disintegrated in a fraction of a second. That was how it looked on April 22, when the edition of *Nature* publishing the Paris physicists' letter appeared. Throughout the world of science, the ears of physicists suddenly, as one of them described, "pricked up."

The first faint heartbeats of the embryonic German atomic project could be heard during the very next few days in Göttingen. At the Physics Colloquium, Professor Wilhelm Hanle read a short paper on the employment of uranium fission in an energy-producing reactor. After the colloquium, Hanle's chief, Professor Georg Joos — an experimental and theoretical physicist of some renown — told him that this was a development which they could not keep to themselves: Joos was a civil servant with a traditional Prussian sense of duty to what might be termed the German establishment, and he at once wrote a letter to the Reich Ministry of Education, the authority controlling the universities.

The Ministry acted with surprising promptness.

They deputed Professor Abraham Esau to call an immediate conference. Esau had been an academic physicist at Jena, and was a leading authority on high-frequency electronics; but he was politically active, and had studiously followed the rising star of nationalism in Germany; as a reward for his support for the Party, he had shortly before been appointed president of the

* Approximately 2.5 is the accepted figure now.

Reich Bureau of Standards (*Physikalisch-Technische Reichsanstalt*). In particular, he was head of the Ministry's Reich Research Council physics section.

Prof. Abraham Esau

Esau welcomed the addition of nuclear physics to his ambit of authority. He drew up a short list of scientists to attend the first conference, headed of course by Professor Otto Hahn. Hahn was happy to be able to excuse himself: he had a previous lecture engagement in Sweden. Professor Josef Mattauch, newly arrived in Dahlem from Vienna to take the place of Lise Meitner, deputized for him.

The conference took place in all secrecy on April 29, 1939, at the Ministry's building at Unter den Linden in Berlin.* Dr. Dames, head of the Ministry's research department, voiced his disquiet at the way in which Hahn had been able to publish his vital discovery to the world. Mattauch took up the cudgels on his new chief's behalf with a vehemence that cowed the others into silence, and the reproaches were not repeated. After the two Göttingen professors, Joos and Hanle, had outlined in simple terms the stage reached by nuclear research abroad and in Germany, the practicability of building an experimental uranium reactor — referred to at the time as a "uranium burner" — was examined.

* Those at this first meeting were Professor Esau (chairman); Professors Joos, Hanle, Geiger, Mattauch, Bothe and Hoffmann; and the Ministry's representative, Dr. Dames.

Professor Esau recommended that they secure at once all available uranium stocks in Germany. Furthermore the most important nuclear physicists in the country should be co-opted to a joint research group under his overall administration. For most of those present, this was all they heard of a uranium research project until war broke out.

Esau was not idle, however. The general consensus had been that the first experiments would be with uranium oxide.* A general ban was placed on the export of uranium compounds from Germany, and negotiations were opened with the Reich Ministry of Economics for the provision of radium from the recently captured mines at Joachimsthal (Jáchymov) in Czechoslovakia. The procurement of the necessarily large quantities of uranium in these late spring days of 1939 was more difficult, but thanks to the exertions of the same Ministry enough was obtained. A sample was dispatched to Göttingen for special analysis; the expert analyst was called up almost at once by the War Office. Suspecting nothing, Esau had the tests transferred to his own laboratories instead.

Prof. Paul Harteck

In fact, the War Office had within a very short space of time begun its own uranium research program. Even as the first letter was being written by Professor Georg Joos to the Ministry of Education, a second initiative had been taken: on April 24, two

* This was U_3O_8, subsequently assigned the code name "Preparation 38"; uranium metal then became "38-metal" and was later code-named "Special Metal." No importance was attached to uranium dioxide.

days after the publication of the Paris physicists' letter in *Nature*, the young Hamburg professor, Paul Harteck, and his assistant Dr. Wilhelm Groth had written a joint letter to the War Office, with far-reaching consequences:

> We take the liberty of calling your attention to the newest development in nuclear physics, which, in our opinion, will probably make it possible to produce an explosive many orders of magnitude more powerful than the conventional ones.

After outlining in simple terms the work of Hahn and Strassmann, and the importance of Joliot's discovery, the two physicists continued that while in America and Britain great emphasis was placed on research in nuclear physics, the subject had been neglected in Germany. One thing above all was obvious: "That country which first makes use of it has an unsurpassable advantage over the others." Professor Harteck's name will be found to recur throughout the narrative that follows. He was the driving force behind much of the most farsighted research on the German atomic project during the war years.

[11]

THE REACTION in London to the French physicists' letter was equally prompt. While in public the popular press published lurid accounts of the possibilities of a new super bomb, based on uranium fission, the private anxiety felt in official quarters was acute. Four days after the letter appeared in *Nature*, the British Treasury and Foreign Office were approached with a recommendation from Sir Henry Tizard, chairman of the Committee on the Scientific Survey of Air Defence, that Britain should take preemptive action to deny large sources of uranium to the Germans; for example, the largest stockpile of uranium in Europe was probably in Belgium, which had a sizable industry for extracting radium from uranium ores imported from the Belgian Congo. Tizard's first advice was that the available uranium stockpiles should be either purchased outright or secured by means of a British option on their purchase.

Several days passed before M. Edgar Sengier, the president of the Belgian company concerned, Union Minière, could meet Tizard in London, and when he did, on May 10, the hubbub, both public and private, had largely subsided. The outcome of their meeting was that Tizard was unwilling to advise the purchase of all available uranium stocks (of which we now know there were several thousand tons in Belgium); and the Belgians were unwilling to grant Britain an option on every ton that was produced. As they parted, the Englishman warned Sengier that in his company's hands lay something that might mean a catastrophe for both countries should it fall into enemy hands.

The meeting did produce one positive result: the intelligence that there had been no abnormal demand for the company's uranium from any other source. The British Admiralty concluded that far from a proof of the ignorance of foreign nations, this showed that they either had limited funds to "gamble with," or had decided that the possibility of developing an explosive of unprecedented power from uranium was "so remote as to be negligible."

Professor G. P. Thomson, on the other hand, thought it highly possible that the Germans might suffer the same anxieties about a British uranium bomb, if they were indeed working on such a weapon themselves. He suggested that through secret channels seemingly authentic reports should reach the Germans, indicating that the British had in fact tested uranium bombs of appalling force — so potent that the authorities had stopped the last test for fear of compromising the project completely. A "gross energy available" of five megatons of TNT was mentioned in the report that was to be "planted," together with the cryptic sentence:

> It is therefore of the first importance to complete the arrangements for the island, as we must get some idea of the delay required to give the aeroplanes a reasonable chance of getting clear.

Mr. Churchill urged for his part that any German talk of "super bombs" should be seen to be pure bluff: while at first sight there might seem to be portents of the appearance of new explosives of "devastating power," there was, he argued, no danger that this discovery would lead to results on a large scale for several years. With the hand of his personal scientific adviser, Professor F. A. Lindemann — later Lord Cherwell — guiding his pen, he wrote to the Secretary of State for Air, suggesting that there were several reasons why rumors of some sinister, new secret Nazi explosive were without foundation. Firstly, only a minor constituent of uranium was effective, which it would take "many years" to extract. Secondly, "the chain process can take place only if the uranium is concentrated in a large mass. As soon as the energy develops it will explode with a mild detonation before any really violent effects can be produced." So it was unlikely to be much more dangerous than their present explosives. Thirdly, by their nature the experiments must be on a large scale, and hence detectable; and fourthly, only a comparatively small amount of uranium was under Berlin control, in Czechoslovakia. All in all, Mr. Churchill thought the German uranium threat could be discounted.

Carl-Friedrich
von Weizsäcker

Upon his return to Otto Hahn's institute in Dahlem, after Professor Esau's April conference, Josef Mattauch was subjected to close questioning by Dr. von Weizsäcker and Dr. Flügge, the institute's theoretical physicists. Carl-Friedrich Baron von Weizsäcker was a young (27) but outstanding philosopher and physicist who had published a famous theory concerning the transformation of the elements in the stars: "a man of ascetic rather than practical habits" was how U.S. Intelligence officers later described him. He was not a National Socialist, but his father's position as Secretary of State under Ribbentrop inevitably made him politically more sensitive than the other scientists.

Dr. Siegfried Flügge told Mattauch he had already drafted a semi-popular paper on nuclear energy, but had refrained from publishing it for fear it would be abused by the government. The Esau conference showed that the authorities were aware of the possibilities, however; Flügge and von Weizsäcker decided that the paper should be published to the world. During June, the periodical *Naturwissenschaften* printed the article under the bold title "Can the energy contained in the atomic nucleus be exploited on a technical scale?" Flügge expressed the view that it was not inconceivable that a chain reaction would be unleashed in uranium, which could consume all the uranium in a large block. What this might mean in actual figures, he suggested in graphic form:

> One cubic meter of consolidated uranium oxide powder weighs 4.2 tons and contains 3,000 million-million-million-million molecules, or three times as many uranium atoms. As each atom liberates about 180 million electron volts (about three ten-thousandths of an erg), in other words three million-millionths of a kilogram-meter, a total energy of 27,000 million-million kilogram-meters would be liberated. That means that one cubic meter of uranium oxide would suffice to lift a cubic kilometer of water (total weight: 10 million-million kilograms) twenty-seven kilometers into the air!

The problem was that this enormous energy would be unleashed within one hundredth of a second: was there some means of controlling the reaction, of taming it for peaceful purposes? He thought it would be possible to stabilize the reaction in some future "uranium engine" by adding cadmium salts to the water used to absorb the neutrons' energy inside the machines. Cadmium was a very strong absorber of neutrons, and could be used to shut the machine down altogether if things threatened to get out of hand. It was this article, coupled with an article he wrote for the German national newspaper *Deutsche Allgemeine Zeitung* in the middle of August, that quickened the interest of the German authorities in nuclear research.


15. August 1939

Deutsche Allgemeine Zeitung

Die Ausnutzung der Atomenergie

Professor Mattauch had also mentioned the Ministry of Education's secret nuclear conference to Dr. Paul Rosbaud. Rosbaud's sense of security was not as highly developed as Mattauch's confidence in him might have suggested; he told Cambridge Professor R. S. Hutton about the conference, during the latter's brief visit to Berlin a week later, and Hutton transmitted the news to Dr. J. D. Cockcroft in England soon after.

Neither Professor Harteck nor Dr. Groth had received any reply from the War Office to their letter at the end of April, drawing attention to the possibilities of nuclear explosives, but the authorities had not been idle. The letter had been passed to General Becker's Army Ordnance Department, and thence to the research branch under Professor Erich Schumann. Schumann in turn forwarded it to Dr. Kurt Diebner, the Army's expert on nuclear physics and explosives, and another key figure in this history.

Dr. Kurt Diebner

Diebner was at the time 34 years old. He had read nuclear physics at the University of Halle under Professor Pose, and graduated with a thesis on the ionization of alpha rays late in 1931. For a time he had worked at the Bureau of Standards laboratory on the construction of a new high-voltage particle accelerator for atomic transformations; but in 1934 the Army had appointed him to an Ordnance Department research branch where together with Dr. Friedrich Berkei he had investigated hollow-charge explosives — a development similar to one being undertaken by the air force's Professor Schardin at Berlin-

Gottow. As a nuclear physicist, Diebner had felt ill at ease in this research and had repeatedly urged Schumann to establish a branch — *Referat* — for pure research into nuclear physics.

Although he had his detractors — he subsequently became Commissioner for Norwegian Heavy-Water Production, Provisional Head of the Kaiser-Wilhelm Institute of Physics at Dahlem, and deputy head of the German atomic project — Dr. Kurt Diebner had at this time a growing reputation in nuclear physics with some twenty publications to his name.

Diebner's first reaction on receiving the Harteck–Groth letter was to take it to the famous nuclear physicist Professor H. Geiger for his opinion. Geiger gave them all the encouragement they needed. (He had done the original work in 1911 with Rutherford on the structure of the atom, and was of course father of the Geiger–Müller counter.)

During the summer, with further encouragement from Flügge's articles, and in particular from a patent application by the Viennese Professor Stetter for a process for extracting atomic energy, they obtained the first Army funds to start research on uranium and a laboratory was erected at Gottow, a section of the Army's vast Kummersdorf rocket-projectiles and explosives research establishment outside Berlin. An independent nuclear research office was at last opened in the Army Ordnance Department, and Diebner was put in charge. As he later commented, the parallel initiative taken by Professor Esau had the effect of "accelerating" the War Office's own endeavors in this field; the truth was that in these last weeks before the outbreak of the Second World War, his superiors were by no means convinced of the need for nuclear research. More than once Diebner was reproached: "Nothing will ever come of your nuclear physics." And Professor Schumann, who was scientific adviser to General Keitel, rebuked him: "Can you not finally put not finally put an end to your atomic poppycock?" To be on the safe side, however, Schumann still thought it advisable to take certain steps to promote the activities of Diebner's office. By the time war broke out, Germany alone — of all the world powers — had a military office exclusively devoted to the study of the military applications of nuclear fission.

It seemed an auspicious start.

[III]

THERE WERE TWO rival teams working on small-scale uranium research in Germany when war broke out: Diebner's and Esau's. Of these, one was shortly eliminated by the intrigues of the other. On the very day after Britain and France declared war on Germany, Professor Esau secured an interview with General Becker* and obtained a promise of War Office support. Esau at once opened firm negotiations with the Reich Economic Ministry for the provision of high-grade uranium compounds and radium, to obviate their being requisitioned in their entirety by the Air Ministry for luminous paint manufacture. Becker agreed that Esau should be given an official voucher certifying the military importance of the project for the war effort. He added that Esau was to inform Schumann, head of the military research department, of his decision and ask him to draft the voucher.

Professor Esau and his assistant, Professor Möller, had some difficulty in reaching Schumann. On the same Monday afternoon, September 4, they conferred briefly at the research department offices with Dr. H. Basche — Diebner's immediate su-

* The German source on which this passage is based makes it seem most probable that Becker was the general whom Esau saw.

perior and a senior civil servant. Esau produced a voucher he had drafted, and asked Basche to forward it through Schumann for the General's signature; Basche regretted they could not handle the matter like that, and Esau left empty-handed. All the same, he felt able to promise the Economics Ministry that the voucher would be forthcoming "on the Thursday," i.e., September 7. On Tuesday morning, Möller telephoned Schumann's office to press for the voucher. Soon after, Dr. Basche appeared in person at the Bureau of Standards laboratory. Esau was out. Basche said that he had been directed by Professor Schumann to say that the voucher would not now be issued to Esau; his own department had begun uranium research.

Esau protested to his chief at the Ministry of Education, Professor Rudolf Mentzel; Mentzel informed the astonished Esau that the Army Ordnance Department had ordered the Bureau of Standards to cease uranium research experiments forthwith. Esau "had to comply."

The energetic steps taken by Esau seem to have stimulated the War Office team to intensify their own efforts. On September 8, a young physicist at the Leipzig Institute of Theoretical Physics was ordered to the Army Ordnance Department in Berlin; at a convention in Breslau in May, this physicist, Dr. Erich Bagge, had been approached by Professor H. Pose, who had told him that he might be able later to assist the War Office who, he said, had clearly defined plans in nuclear physics. Bagge had thought no more about it, and returned to Leipzig. As the ominous buff envelope containing orders to report to the War Office in Berlin now reached him, his feelings can be imagined.

Dr. Bagge packed into a small suitcase a few last precious possessions — family photographs, comfortable underwear and reading matter for the inevitable journey to the front. All the greater was his relief to be confronted by Diebner at the

Hardenberg Strasse office in Berlin, and told why he had been sent for. Together with Professor Schumann, Diebner explained that Bagge had been sent for to help the War Office arrange an immediate secret conference to decide on the feasibility of a uranium project. Between them, Diebner and Bagge drew up a short list of the physicists and chemists most clearly concerned, including Professor Walther Bothe, Professor Geiger, Professor Stetter, Professor Hoffmann, Professor Mattauch, and Drs. Bagge, Diebner and Flügge. Otto Hahn was also summoned to attend. Bagge had read the letter written to *Nature* in April by the three French physicists; but Flügge's article in *Naturwissenschaften* had escaped him. He took copies of the last numbers back to Leipzig to read more closely.


Dr. Erich Bagge

The jottings in Otto Hahn's diary reflect the quickening tempo during the last few days before the meeting:

> *Thursday, 14th September:* constant discussions on uranium.
> *Friday, 15th September:* discussions with von Weizsäcker. (Schumann, Esau.)

The first secret conference was on September 16: "Schumann conference. Nuclear physicists present, but not Schumann. Fixing a program. Esau telephoned, going to call on me. (Von Laue, Debye, Heisenberg.)"

That Professor Schumann was in fact absent from the conference was itself illuminative; a descendant of the composer Schumann, he was himself no mean composer of military music and had grown rich on the royalties of marches he had composed. But apart from the similarity of the pronunciation of *Physik* and *Musik* — a rhyme of which his enemies made much in private — his contact with physics had been slight. This had not prevented him from being appointed to his present post; he had even been given a Chair of Military Physics at Berlin University. A small session attended by high-caliber nuclear physicists was indeed the very last milieu in which Schumann would choose to be.

The call-up papers went out during the next few days to the scientists. Bagge received his on the fourteenth, and he knew what was behind it. The others did not, and suffered the same apprehensions upon being ordered to report to the War Office on September 16. On that day a trickle of young and old eminent German men of science passed the doorway of No. 12 Hardenberg Strasse, all clutching pathetic little suitcases and fearing the worst.

Professor Esau learned quite by chance that Schumann had "summoned a particularly important conference by telegram and telephone"; when he asked his chief, Mentzel, to complain about this, the latter merely assured him that he knew all about it, and that he had asked Dr. Diebner to talk the project over with him before the conference began. "I waited in vain for him," Esau complained. "But, as I was able to observe on the day of the conference — quite by chance I met professors who had been at the conference on April 29, 1939, in the [Education] Ministry — a number of leading experts took part who had committed themselves even then to our joint project." Esau was being pushed further and further aside.

If it struck them as odd that Esau had not been invited, none of the professors remarked on this when the conference began. Basche explained that the German Foreign Intelligence

Service had learned that uranium research had been started abroad, and they had been summoned to give a considered opinion on whether the War Office should support a similar project. Basche stressed that this should not be dismissed out of hand; it was as vital to Germany's interests for them to reach a negative conclusion — as this meant that the enemy would not be able to develop atomic weapons either — as it was for them to decide that such a project really would lead either to an exploitable source of power or to a super bomb.

A lively discussion ensued on the character of a uranium "engine," and whether it would work. A few days before, Niels Bohr and J. A. Wheeler had published in the American *Physical Review* — a journal avidly read by all the German physicists throughout the war — a fine theoretical proof that it was the light uranium isotope, uranium-235, in which fission most probably occurred. But natural uranium contains only seven parts of uranium-235 in every thousand. If it were to become a question of extracting uranium-235 Otto Hahn now said, the project would present virtually insoluble difficulties. All this was already stretching to the extreme the theory outlined by Flügge. Dr. Bagge suggested that the most obvious step now was to call in Professor Heisenberg, his chief at Leipzig, to work out the theory of a uranium chain reaction.

The suggestion was not greeted with universal acclaim: between the experimental and the theoretical physicists there was an element of rivalry, even disdain; this was a conference of experimentalists, and Heisenberg was the doyen of the theoreticians. Bothe and Hoffmann in particular spoke out against Heisenberg's being dragged in. Bagge was able to persuade Dr. Diebner after the meeting, however, and the Leipzig theoretician was co-opted to the next conference. As Professor Geiger said, if there was even the slightest chance of liberating energy from the atomic nucleus, it was of vital importance that they follow it up. Schumann recommended to General Becker that a "Nuclear Physics Research Group"* be formally established under Ordnance Department auspices. For security reasons, according to Doctor Berkei, the project would be referred to as "the creation of new energy sources for R. [rocket] propulsion." Dr. Kurt Diebner was appointed to direct this group.

In the fragmentary diary which he had begun for the first time in his life a week before — sensing that he was embarking on a project of great historical importance — Dr. Bagge wrote:

> *16th September 1939.* Summoned to report to Army Ordnance Department, Berlin. Discussion with Dr. Diebner. Participated in conference about an important matter. Returned to Leipzig.

The "important matter" was now a state secret. From this stage on, all reference to the possibilities of uranium reactors and atomic bombs was suppressed. The first instance came soon after: a Siemens physicist submitted an article for release by a German news agency; it was passed to the military authorities for clearance. It contained a detailed description of what might lie in store, thanks to a "discovery by German researchers." Referring to the power in the uranium nucleus, it said that there was "enough to blast the ruins of a giant city up into the stratosphere. What terrific powers of annihilation an air force would have if it could fight an enemy with bombs like these!" Experiments with steadily increased masses of uranium were, the writer claimed, already in hand, while stringent precautions had been taken so that there would be no unpleasant surprises; the tem-

* "*Arbeitsgemeinschaft Kernphysik.*"

perature of the uranium was measured, the writer explained, under neutron bombardment. The author, who submitted the paper under a pseudonym, foresaw applications of the process for driving turbines and power stations. When the military authorities checked his credentials they learned that he was assistant director of the "Siemens institute of atom smashing" in Berlin. The article was totally suppressed, and in general nothing else appeared in print in Germany until 1942 when the impatient nuclear scientists were given permission to publish some of their lesser research papers, provided that no mention of their context was made.

The discussions after the Berlin conference on the sixteenth had reached no firm conclusion as to which uranium isotope was fissioned by neutron capture, although it was strongly suspected to be uranium-235. The clearest course of action was to separate the isotopes and study their behavior under neutron bombardment; this task was allocated initially to Professor Harteck, who had already demonstrated the possibility of using a process developed by Clusius and Dickel to separate the isotopes of other elements, including xenon and mercury. The process, called "thermal diffusion," involved placing a gaseous uranium compound between two vertical surfaces held at different temperatures; the lighter isotope, uranium-235, should then according to theory concentrate near the hotter surface and rise through normal convection processes; a separating apparatus might then consist of two concentric tubes, the inner one being hotter than the other. The process seemed deceptively uncomplicated.

It was soon apparent to Harteck and his colleagues that the trials would have to be performed using the highly aggressive compound, uranium hexafluoride, as the working gas: the gas was very corrosive and would attack most of the materials from which they might construct the apparatus; and it solidified at temperatures below 50ϒor if allowed to come into contact with very many materials, including water. Professor Harteck needed about one liter of this ugly gas, weighing some twelve grams.

The properties of uranium hexafluoride had been extensively described by Professor O. Ruff; on September 25, with the fighting in Poland already over and German troops beginning to move to the west, Harteck wrote a friendly letter to Ruff, as from one scientist to another, asking for advice on procuring the quantity he needed. Within two weeks, the German chemical combine I. G. Farben had agreed to manufacture the required amount, and arrangements were made to supply 100 grams of uranium to them to work on. In Harteck's Hamburg laboratory, the principal parts of the Clusius–Dickel separation apparatus were already waiting.


Prof. Werner Heisenberg

On the same day as Harteck was writing to Professor Ruff, Professor Heisenberg was in conference with Dr. Bagge in Leipzig, planning an experimental apparatus to establish how many neutrons were liberated during uranium fission. When he traveled to Berlin next day, September 26, for the second conference of nuclear physicists at the Ordnance Department, it was clear to him that there were two quite distinct possibilities of extracting energy from the uranium nucleus: either in controlled amounts in some kind of uranium furnace or in the uncontrolled violence of an explosion. The first would involve mixing the uranium with some substance capable of slowing down the fast (high-energy) neutrons emitted during the fission process, without absorbing them: for technical reasons, neutrons of a certain energy band were particularly liable to capture by uranium-235; so if they were not to be lost, the fission neutrons would have to be rapidly slowed down past this "region of resonance absorption" by some kind of braking substance, or "moderator."

The second possibility, that of the explosive, involved the extraction of the rare isotope uranium-235, which was felt with growing certainty to be the isotope that fissioned with thermal neutrons.

In Hamburg, Professor Harteck discussed the possible design of a uranium reactor with his colleague Dr. Hans Suess, grandson of a famous Austrian geologist. Suess proposed, on the spur of the moment, that they should use "heavy water" as moderator in the reactor. Harteck was at first aghast; five years before he had worked under Rutherford at the Cavendish laboratory and the first task the great English physicist had assigned him was the production of a minute quantity of heavy water, with which, incidentally, Oliphant, Harteck and Rutherford were the first scientists to demonstrate experimentally the thermonuclear fusion processes which are the basis of the modern hydrogen bomb.* Harteck had designed and built a very small electrolytic cell, about twelve inches high, through which he passed electric current for many weeks; after he had reduced very many gallons of water to only a minute quantity, he established that it was almost pure heavy water. And now Suess was

* Cf. M. L. E. Oliphant, P. Harteck, and Lord Rutherford, *Proc. Roy. Soc., A*, Vol. 144 (1934), "Transmutation Effects Observed with Heavy Hydrogen." This was another of that long catalogue of scientific papers which came before their time. In retrospect their paper can be seen to have been of little less moment than Hahn's and Strassmann's 1939 paper on the fission of the uranium nucleus.

suggesting that they should use heavy water in the uranium reactor? Harteck realized that such a reactor would require *several tons* of the fluid, not just a few cubic centimeters, and it was unlikely that the Reich government would finance the project on such a scale. All the same, he traveled to the Berlin conference armed with a report he had specially written on "A Layer Arrangement of Uranium and Heavy Water to Avoid Resonance Absorption in Uranium-238." Most important of his deductions was that in their uranium furnace, or "pile," the uranium fuel and the moderator — for which he agreed heavy water possessed ideal characteristics — should not be mixed, as in a paste, but should be physically separated from each other in alternate layers.

The tasks facing the German scientists after this second meeting were thus twofold: they had to develop processes for the large-scale separation of the uranium-235 isotope; and they had to ascertain, by measuring the "effective cross-sections" of all the substances of possible use as moderators, how far the slow-neutron uranium pile was feasible.* Professor Heisenberg was commissioned to investigate theoretically whether a chain reaction in uranium was possible, given the known neutron diffusion and uranium fission characteristics. Dr. Erich Bagge was returned to Leipzig and assigned the task of measuring the collision cross-section of the heavy-hydrogen nucleus. Professor Harteck was asked to continue with his attempts to extract the uranium-235 isotope, using the Clusius–Dickel thermal diffusion process, and to set up an apparatus for measuring the depend-

* The "cross-section" of a nucleus is a useful concept expressing that nucleus' likelihood of capturing a neutron. It can be compared with the size of a target at which some projectile is fired. The larger the "cross-section," the greater the probability of neutron capture. In general, nuclear cross-sections are larger for slow (thermal) than for fast neutrons.

ence of neutron multiplication on the design of the uranium pile. Each scientist was given a field of research in accordance with a general program drafted by Diebner and Bagge some days before.* They were all assured of the necessary funds.

At the same time, Professor Schumann announced the War Office's intention of taking over the building of the Kaiser-Wilhelm Institute of Physics at Dahlem, with its magnificent equipment, and using it as the new center for the Nuclear Physics Research Group. All scientists participating in the project were to transfer to this one central institute and work under one roof.

In itself the plan was logical and necessary; but it collapsed against the obstinacy of almost all the scientists, who preferred to remain the star figures of their smaller provincial institutes rather than to become minor planets in some super galaxy in Berlin. One by one the scientists agreed to join the project, but declined to move to Berlin. Harteck wrote the War Office: "I shall have to stay in Hamburg. But it will always be possible for me to provide for a visit to Berlin for a day or two each week." Hamburg in those days was only two hours from Berlin; but the other distant centers of nuclear research, at Heidelberg, Munich and Vienna, were less accessible. The group of leading physicists which eventually assembled at the Berlin-Dahlem Institute comprised von Weizsäcker, Wirtz, Bopp, Borrmann and Fischer.

The motives which moved the scientists to work at all on the project were different from those of their colleagues overseas. Apart from their natural curiosity, and a desire to be "at hand" as great discoveries were made, there were other reasons. Mattauch explains: "We were delighted, as it gave us a chance of

* Dated September 20, 1939, the program was titled: "Preparatory Working Plan for Initiating Experiments on the Exploitation of Nuclear Fission."

protecting our young men from call-up, in order to continue scientific research in the manner to which we were accustomed." Professor von Laue agreed: this was their most vital mission now. As one of the young physicists concerned, von Weizsäcker admits that he accepted the military research contract from the War Office in 1939 because his other research commitments would not have kept him out of the forces.

[I V]

THE BERLIN FIRM with the highest reputation for the processing of rare earths, the Auer Company, was awarded a War Office contract for the manufacture of a few tons of refined uranium oxide. The company had a long experience of processing monazite sands to extract the thorium compounds used mainly in the well-known Auer gas mantles; their industrial work on the isolation of radioactive mesothorium had caused them to establish a very efficient Radiological Department to control the various processes, as part of the company's Central Laboratory. The laboratory's director was Dr. Nikolaus Riehl, a 38-year-old chemist born in St. Petersburg; he had studied under Otto Hahn and Lise Meitner in Berlin, and had then been largely responsible for building up Auer's control of the market in luminous compounds.

After the occupation of Czechoslovakia earlier in the year, Auer had been one of the first firms to exploit the uranium mines at Joachimsthal. As a by-product of the extraction of the radium, the company now had a small stockpile of uranium in the form of unrefined sodium uranate and uranium oxide. Dr. Riehl sensed that the uranium project was to prove of far-reaching importance, and assumed personal control of the company's uranium production. He directed this until the end of the war.

Within a few weeks of receiving the War Office contract, Riehl had erected a small plant at Oranienburg, with a production capacity of about one ton of refined uranium oxide every month. Although Auer had successfully purged the oxide of all traces of rare-earth impurities, it now seems that its boron content was undesirably high (boron is a strong absorber of neutrons). Even so, the first ton of extremely pure uranium oxide was delivered to the War Office in the first few weeks of 1940.

Until then, it seems that the only available uranium oxide was in the hands of Professor Esau. Two months after the first conference in Berlin, the institutes of physics and chemistry at Dahlem had still received no uranium compounds to begin their experiments. Esau certainly had some, for he had secured it from the Economics Ministry before war broke out. But he was very aggrieved by the War Office's having poached upon what he regarded as his own preserve. He may have regarded it as merely unfortunate when the War Office called up his expert uranium analyst in Göttingen; but when the Göttingen physicists, including Joos, Hanle and Mannkopf, who had all been working for Esau's "Uranium Club," were all suddenly called up too — Professor Hanle even being hauled out of bed in the middle of the night — Esau divined that it could be coincidence no longer. He urgently telegraphed Hanle, but the telegram was withheld by the military authorities. The Göttingen research team collapsed.

In the middle of November, Esau appealed to his chief at the Ministry of Education, Professor Mentzel, to intercede on his behalf. Mentzel offered him no support, even claiming that the Army Ordnance Department had been working on its uranium project "several years," and suggesting that Esau had purloined the idea from them. An enraged Professor Esau wrote that same day to General Becker* protesting that the problem had "only emerged since January this year," so Mentzel's claim was ludicrous. Esau stressed that it was not a question of one body or another controlling the project; what was vital was for it to be a cooperative effort. The initiative to procure and analyze the necessary uranium had been his alone. The "brutal take-over" of his experimental project by the War Office had, he suggested, done grave damage to the physics sections of the Reich Research Council (of which Mentzel himself was director) and to Esau's reputation as head of the physics section. Becker's withers were unwrung. Esau's uranium hoard was placed at the institutes' disposal, and their experimental research finally began.

Early in December, Dr. Erich Bagge met Heisenberg in the corridor of his institute in Leipzig, and the learned professor called him into his room, unable to contain his excitement. Up to now, he had been exercised by the problem of stabilizing the slow-neutron chain reaction once it began. Now he had solved it for, as he showed Bagge with a few equations chalked on the blackboard, as the temperature of the reaction increased, the fission cross-section of uranium would decrease; so the reaction would tend to slow down automatically at a certain temperature, which would depend only on the size of the reactor — probably of the order of hundreds, rather than thousands, of degrees. On present evidence, he believed that if 1.2 tons of uranium and a ton of heavy water were mixed into a paste and enclosed in a sphere of 60 centimeters radius, surrounded by water as a

* See the footnote on p. 39.

reflector shield, it would stabilize at a temperature of about 800 degrees centigrade.

Professor Heisenberg reported to the German War Office on December 6 that adopting Harteck's suggestion of separating the uranium and the moderator would lead to a very much smaller reactor; such reactors would give up just as much energy as could be extracted from them, until such time as a large part of the uranium had been consumed or the fission products so poisoned the uranium fuel that the temperature fell off.*

The last paragraph of Heisenberg's report shows the great advances the Germans had made within just two months of starting their project:

> *Conclusion:* the uranium fission processes discovered by Hahn and Strassmann can on present evidence be used for large-scale energy production. The surest method for building a reactor capable of this will be to enrich the uranium-235 isotope. The greater the degree of enrichment, the smaller the reactor can be made. The enrichment of uranium-235 is the only way of making the reactor's volume small compared with a cubic meter.
>
> It is, moreover, the only method of producing explosives several orders of magnitude more powerful than the strongest explosives yet known.
>
> For the generation of energy, however, even ordinary uranium can be used, without enriching the uranium-235, if the uranium is used in con-

* The scale on which fission products could poison large uranium reactors was not realized by the Americans until the huge plutonium-producing piles at Hanford were commissioned, only to close down one after another within a very few days because of the xenon-135 produced by the fission of titanium. Although this isotope occurred only in a low concentration, it had an unexpectedly large absorption cross-section for thermal neutrons.

> junction with another substance which will slow down the neutrons from the uranium without absorbing them. Water is not suitable for this. Heavy water and very pure graphite would, on the other band, suffice on present evidence. Minute impurities can always prevent the generation of energy.

Professor Heisenberg warned that the reactor would be a very powerful source of harmful neutron and gamma radiation, too.

The "heavy water" to which reference has now several times been made was for technical reasons ideal for slowing down fast neutrons to energies where they would not be captured by uranium-238, but could still fission uranium-235. As its name implies, it is heavier than natural water by about 11 per cent, as the atoms of hydrogen in H_2O have been replaced by atoms of "heavy hydrogen," deuterium, making D_2O. The deuterium nucleus consists of one proton and one neutron, instead of just one proton. Heavy water freezes at 3.81 degrees, and under normal pressure it boils at 101.42 degrees instead of 100 degrees — the difference being even more marked at low pressure.

As war broke out there was only one firm producing heavy water on a commercial scale, the Norwegian Hydro-Electric company, as a by-product of their hydrogen-electrolysis plant at Vemork, near Rjukan in southern Norway. The American scientist H. C. Urey had shown in 1932 that the hydrogen given off during the electrolysis of water contains five or six times less heavy hydrogen — deuterium — than the water left in the cells; in fact, if 100,000 gallons of water were to be decomposed in one stage into hydrogen and oxygen, until there was just one gallon left in the cell, that gallon would contain about 99 per cent pure heavy water. This was the basic principle of the Vemork plant. In a granite powerhouse built on the side of a rockface below the huge Rjukan Foss waterfall, German-built D.C. generators produced 120,000 kilowatts of cheap electric power, much of which was fed straight into the adjacent electrolysis building standing on the same outcrop of rock.

If the simple process outlined above was employed, much of the heavy hydrogen would be given off and wasted during the later stages of the concentration; in 1934 the firm had accordingly modified the last three stages of their nine-stage hydrogen-electrolysis plant so that the hydrogen given off would be burned in oxygen, to make water, and this water would be fed back into the earlier stages where the heavy water had the same concentration. The unburned hydrogen of the first six stages was fed to a synthetic-ammonia plant, the first stage in Norway's important fertilizer-manufacturing industry. Altogether the nine stages produced water with its deuterium content concentrated to about 13 per cent; at this point a high-concentration plant — specially designed by the Norwegians Professor Leif Tronstad and Dr. Jomar Brun — took over, a microcosm of the main plant in which the heavy water was electrolytically concentrated to over 99.5 per cent purity. The whole plant was described by a German scientist sent to inspect it after the fall of Norway as "a masterwork of Norwegian engineers and scientists."

The Vemork plant began operating at the end of 1934, and between then and 1938 had produced only forty kilograms of heavy water. By late 1939 heavy-water production was only ten kilograms per month. Within the German sphere of influence there were no heavy-water plants at all, and the largest hydrogen-electrolysis plant rated only 8,000 kilowatts. The question was, would the Norwegians cooperate in supplying the German needs?

During November and December 1939, Professor Paul Harteck's laboratory in Hamburg adopted two lines of research. A continuous-flow laboratory apparatus had been built by Professor Knauer and Dr. Suess to measure neutron concentrations in a circulating solution of uranyl nitrate; this experiment would establish the average number of neutrons generated during uranium fission, as a factor of several variables. At the same time work had begun on a Clusius–Dickel apparatus, using uranium hexafluoride as the working gas: a pilot experiment had already been set up, using the Clusius–Dickel separation tube to separate the isotopes of xenon — a heavy gas with the separation of whose isotopes by other means Harteck's institute was thoroughly familiar. The problem was, would uranium hexafluoride gas behave like xenon in the apparatus?

While I. G. Farben's Leverkusen factory, which had supplied the original hexafluoride to Harteck, began corrosion tests to find a metal capable of withstanding the ravages of uranium hexafluoride, the Hamburg laboratory began the erection of a larger separation tube — twenty-five feet tall and heated by steam — specially for the uranium-235 separation project. In the middle of December, Professor Schumann authorized Harteck to expend up to 6,000 Reichsmarks until a proper contract was awarded him.

Over Christmas 1939, Harteck traveled south and visited Professor Clusius himself in Munich. Clusius was working — without any official backing as yet — on the possibility of separating the 235 isotope using a liquid uranium compound and a process based on Nernst's "distribution law." Briefly, he hoped to separate the 235 and 238 isotopes by using two immiscible liquids: the lighter isotope would concentrate in one, and the heavier in the other.* They agreed that both schemes were worth pursuing.

The German War Office's decision to requisition the Kaiser-Wilhelm Institute of Physics at Dahlem ran into difficulties soon after. The Institute's director was the famous Dutch experimental physicist Peter Debye. The military authorities faced him now with the alternative of dismissal or adopting German nationality, as the Institute was to work on a secret project. Debye refused to yield his Dutch nationality, and a fortunate compromise was reached at the last moment whereby he accepted an invitation to "lecture" in neutral America. He left Germany in January 1940, and did not return.

Schumann's nominee to replace Debye was Dr. Diebner, but this nomination met with the resolute opposition of the Kaiser-Wilhelm Foundation (president: Albert Vögler). Diebner was not considered to be of the same caliber as Debye; he was finally introduced as the Dahlem Institute's "provisional head," during Debye's absence abroad. The rift between Diebner and the Heisenberg group, which seems to have emasculated the later uranium research effort in Germany, can be traced to the day on which the War Office physicist took up office at the Dahlem Institute.

Dr. Karl Wirtz observed to von Weizsäcker that all of a sudden they now "had Nazis in the institute": what should they do? It was Wirtz who supplied the answer: somehow, they would intrigue to get Heisenberg into the institute, and once in he could be engineered into the position of director, over Diebner's head. Von Weizsäcker went into Diebner's office and suggested

* Also called the partition law. It states that a substance divides itself between two phases in such a way that the ratio of its concentrations in each phase is constant, provided it is present in each phase in the same molecular species.

that Heisenberg should be invited to join the institute as adviser; Diebner, unsuspecting, agreed. Von Weizsäcker went straight to his fellow conspirator, Dr. Wirtz, and told him that Diebner had suspected nothing, and Heisenberg could come. The famous professor would live with his family in Leipzig and travel once a week up to Berlin.

In July 1940 the planning of a small wooden laboratory building in the grounds of the Kaiser-Wilhelm Institute of Biology and Virus Research, next to the Institute of Physics at Dahlem, was begun. It was here that the first subcritical German uranium pile would be built.

The laboratory was code-named “The Virus House” to keep unwanted visitors away.

CHAPTER THREE

The Plutonium Alternative

DURING THE FIRST WINTER of the war, it became clear that if the Germans were to reach the ultimate goal of a uranium bomb the construction of a uranium reactor was an obvious intermediate stage. This would serve two purposes: it would provide a means of testing in practice what had been established by theory so far; and more important, it would offer tangible promise of success to the governmental and military authorities, for by now it was clear that the manufacture of the bomb as such would be hedged round by formidable and costly difficulties. During the next two years, the German record showed few and guarded references to the uranium bomb, as effort was concentrated on the intermediate goal, the uranium reactor. This by no means meant — as has been suggested — that the idea of a bomb had been virtuously banished from their minds.

It had been recognized during the very first meetings in Berlin that two courses of action were open to them. They could employ uranium or uranium compounds in various configurations with various moderator substances, and observe what happened; this purely empirical approach had its advantages. On the other hand it was hazardous and did imply the immediate availability of the ingredients. The second course of action was reliance on theory: reasonably accurate deductions about chain reactions in uranium could be made, provided that one could accurately measure the various "nuclear constants" — the cross-sections of the materials to be used, for various energies of neutron bombardment. The measurement of these constants would consume time and require great skill; but they could be made with relatively small quantities of material — an important factor in 1940, when uranium, pure carbon, beryllium and heavy water were all exceedingly scarce. In Germany — as in other western countries — a mean was struck between theory and experiment.

The year 1940 saw small-scale experiments in Leipzig, Berlin, Heidelberg, Vienna and Hamburg to measure the nuclear constants of the materials concerned; in June, Professor Bothe in Heidelberg measured the diffusion length of thermal neutrons in graphite; later that summer in Leipzig, Heisenberg and Döpel — the latter aided by his wife — measured the same constant in heavy water and, during the autumn, in uranium oxide. Bothe's carbon measurement was perhaps the most important, for carbon was certainly more abundant than heavy water; he found that if purer carbon could be obtained, of more uniform quality than he had used, it might just be usable as a moderator. The Leipzig physicists found that heavy water would be even more suitable than they had earlier believed and confirmed that theoretically a heavy-water reactor was possible using ordinary uranium. In several other universities and institutes research was pressed ahead on the investigations of the masses and energies of the products of uranium fission.

While the measurements of these constants progressed, the measurement of the variables — and in particular the effect of reactor design — was begun in Berlin. The theoretical physicists under von Weizsäcker at Dahlem's Kaiser-Wilhelm Institute of Physics examined several possible configurations, and concluded late in February that for a reactor, or pile, built in layers as Harteck had suggested, they would need about two tons of uranium oxide and about half a ton of heavy water. These materials would be stacked in five or six layers in a pile about 70 or 90 centimeters tall.

Alternatively, a spherical pile could be built with concentric spherical layers of heavy water and uranium oxide, of which only about 320 liters and 1.2 tons would then seem to be needed; obviously the latter design would be technically more difficult to adopt. The physicists further calculated that if a carbon reflector shield were provided around the pile, to reflect back into the pile any neutrons emerging from its surface, then its dimensions would be reduced still further. In the meantime, Professor Bothe had suggested to Heisenberg that some of the theory in his December 1939 report to the War Office was wrong, and when two months later Heisenberg wrote a detailed mathematical analysis of his earlier report, he unfortunately concluded that pure graphite was less suitable as the moderator in a uranium pile than had at first seemed. Helium gas was also ruled out as such a pile would have to be impossibly large. The applicability of heavy water was still unchallenged.

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ALL THE INDICATIONS were, during January 1940, that given sufficient heavy water a chain reaction could be induced in a pile using ordinary uranium. Professor Harteck wrote a friendly letter to Heisenberg on the fifteenth, stressing that he thought the production of heavy water was every bit as vital as that of uranium. "As the burden of the execution of these experiments is to fall upon the shoulders of us poor experimenters," he wrote, "may I ask you who — if anybody — is working on the production in Germany of heavy water?" He added: "From my own experience of our War Office, the production of large quantities of heavy water will certainly take several years if we leave it to them; but I can well imagine that if I personally take this up with the right gentlemen in our heavy industry the time could be cut to a mere fraction of that."

In fact, there had already been a conference about this nine days before in Dr. Diebner's office in Berlin; Heisenberg had attended, with the physicist Karl Wirtz and the physical chemist Karl-Friedrich Bonhoeffer. It was clear that the War Office was unhappy about heavy-water production. Diebner had asked Heisenberg whether he would advise building a full-scale heavy-water plant in Germany immediately; Heisenberg had wisely replied that he would prefer to measure the neutron absorption with a small amount of heavy water first. This need not take long once he had a few liters of liquid. Diebner promised to procure about ten liters very shortly from Norwegian-Hydro. Professor Heisenberg told him that once they knew for certain that heavy water was suitable, a full-scale plant should then be built; but its construction would have to be left to the physical chemists, "whose province it was," as he wrote to Harteck on January 18; he advised him to have a talk with Bonhoeffer about heavy-water production processes. He clearly regarded the execution of the first heavy-water pile experiments as the "province" of the physicists.

It seemed unlikely that the Norwegians would meet all the requirements of the German project. Both Professor Harteck and Dr. Suess had been occupied with the development of a new heavy-water process, "catalytic exchange," several years before; but when the Norwegian factory had begun production, the need for German sources had disappeared and research had been dropped. Harteck wrote to the War Office on the twenty-fourth, suggesting that the catalytic exchange process should now be reexamined, because Heisenberg's calculations suggested that the reactor would probably need about equal quantities of uranium and heavy water; in other words many *tons* would be needed.

If Norway refused to supply their needs, the only present alternative would be to use steam-generated electricity to electrolyze water: to produce one ton of heavy water like this would cost 100,000 tons of coal. The War Office was suitably shaken by this estimate, but sternly rebuked Harteck for his temerity in communicating directly with Heisenberg. The project was "covered by security regulations," they reminded him: "the transmission of such reports direct from one institute to another is in future forbidden. In each case they will be forwarded through the Army Ordnance Department." They told him that the large-scale manufacture of heavy water in Germany had already been provided for, during the conference at the beginning of January.

The Harteck–Suess process promised to be far cheaper than electrolysis. If ordinary hydrogen was passed through water in the presence of a hydrogenation catalyst, an equilibrium would be reached in which over three times as much heavy hydrogen was in the liquid as in the gas. Harteck proposed that a pilot plant be built, and suggested a discussion with Professor Bonhoeffer at Leipzig. The War Office agreed, and Harteck took up his idea of appending a catalytic exchange plant to an existing hydrogenation plant with Professor Bonhoeffer soon after. At the end of February the latter wrote — in a letter marked "Destroy after reading" — that he had discussed the idea with I. G. Farben's ammonia plant at Merseburg and they were "all in favor of the idea." This Leuna works generated six million cubic feet of hydrogen an hour, and there were no objections in principle. As Bonhoeffer said: "The whole idea stands or falls by the catalyst."

The German government had in the meantime approached Norwegian-Hydro direct. According to the Norwegians, a representative of I. G. Farben, which had a financial interest in the firm, called on the Rjukan factory and tried to persuade them to part with their entire stock of heavy water — 185 kilograms of 99.6 and 99.9 per cent pure stock. The German promised that an important order would be following for heavy-water production from his company. The difficulty was that production was running at only 10 kilograms per month and the Germans wanted 100 kilograms per month; the Norwegian firm asked what Germany planned to use the substance for. The Germans avoided direct reply. In February 1940, Norwegian-Hydro regretted that they could not comply with the German order for heavy water.

The French team of physicists under Frédéric Joliot in Paris had continued during the summer of 1939 a series of experiments logically following upon their confirmation of the possibility of chain reactions in uranium. With uranium oxide as the "fuel," they had attempted to build working piles using water, carbon and solid carbon dioxide as moderator; during August, they had erected a rough sphere of uranium oxide blocks, and soaked it in water as a kind of moderator. This showed the first faint stirrings of a weak and short-lived chain reaction: but the ordinary water was still absorbing more neutrons than it usefully slowed down. One of the team's leading physicists was drafted to a searchlight battery when war broke out. In Paris, von Halban tackled the Minister of Munitions, M. Raoul Dautry, and secured ten tons of graphite for further experiments. Finally, during February, Professor Joliot himself approached Dautry and asked whether heavy water could be procured in quantity as that seemed "the most interesting ingredient" to mix with uranium oxide; he learned that the entire stock available at Rjukan was 185 kilograms, which would be just enough to carry out a crucial experiment.

M. Dautry sent to Oslo a remarkable intermediary, M. Jacques Allier, a lieutenant in the French secret service and an important personality in the French bank owning a controlling interest in Norwegian-Hydro; Allier was also attached to the explosives department of the French Ministry. He decided to "appeal to the better judgment" of the Norwegian managing director, Dr. Axel Aubert, and succeeded to such an extent that within a very few days an agreement had been signed placing at France's disposal the entire heavy-water stock, at no cost, and assuring France of priority in claim on the next year's output. When the agreement had been signed, Allier confided to the Norwegian the possible outcome of the French research; Aubert asked him to convey his good wishes to M. Daladier, the French Premier, and "say that our company will accept not one centime for the product you are taking, if it will aid France's victory." The precious cans of heavy water were secretly flown out of Norway, and some days later they were in Paris, where the French physicists were waiting for them.

An obvious conclusion from Heisenberg's observation that a chain reaction would be damped down by rising temperature, was that it would be favored by low temperature. On April 8 — at about the time that the French physicists were setting up their first experiment with the hard-won heavy water — Professor

Paul Harteck, the Hamburg physical chemist, visited the Leuna ammonia works at Merseburg and outlined to Dr. Herold, the firm's Nazi research director, a plan for an experimental uranium pile built of uranium oxide embedded in solid carbon dioxide — "dry ice" — an easily handled substance that would keep at minus 78ϒ for relatively long periods, evaporating only slowly. It had the added advantage of being available in a very pure state.

It would have been a beautiful experiment. That Professor Harteck had thought of it at all could be attributed only to his having worked under Lord Rutherford, one of the greatest experimental physicists, six years before. Harteck had returned to Germany convinced that unless German experimental technique could be improved to match that in British laboratories, Germany's scientific future was in grave doubt. Not surprisingly his thesis found little currency among his country's physicists.

Herold, whose firm was obviously interested in the uranium reactor's commercial prospects, offered the whole consignment of carbon dioxide free of charge for the experiment, and proposed at first that it should be held at the Leuna works; but I. G. Farben's Dr. Bütefisch subsequently ruled that it should be at Hamburg.

It was still spring, and until the end of May there would be little demand for dry ice in Germany. Told that his entire order could be processed and dispatched in one day, Harteck began at once to prepare the basement where the experiment was to be set up. He wrote to Diebner asking for between 100 and 300 kilograms of uranium; the War Office confirmed that a railway wagon would be provided to rush the frozen carbon dioxide across Germany to Hamburg; and Dr. Basche promised him that there was "a possibility" of his being lent at least 100 kilograms of uranium oxide for a short time.

The difficulty was that each scientist wanted to be the one to make the first critical uranium-pile experiment. Professor Heisenberg asked the War Office for 500 to 1,000 kilograms of uranium oxide, and Diebner told him that he was not the first. For the time being, there were only 150 kilograms available, which would rise to 600 kilograms by the end of May and a ton by the end of June. Diebner suggested that Heisenberg should come to some internal arrangement with Harteck. The Nobel Prize winner wrote to Harteck, implying that the latter was in no hurry for the oxide, as he would certainly have to make other measurements to prepare the ground for the experiment; he asked for several hundred kilograms first, therefore. "Of course," he added, "if there is for any reason any urgency in your experiments, you can go first by all means. But I should like to suggest that for the time being you content yourself with just 100 kilograms."

This was infuriating. Harteck pointed out that within a very few weeks ten tons or so of solid carbon dioxide would be arriving by rail in Hamburg for him; and from June onward the manufacturers' entire output was needed for foodstuffs refrigeration purposes. Professor Knauer had already provided the necessary instrumentation for the experiment: "All we lack is the 38-preparation [uranium oxide] to enable us to perform a decisive experiment. The block of carbon dioxide will not keep much more than one week, so we will soon be finished with our measurements. We would need the oxide only from May 20 to June 10 at the very most." The only reason he had asked Diebner for between 100 and 300 kilograms was that he had thought that was the total amount available. "It is surely obvious that the more the uranium with which the experiment can be performed, the more unequivocal the results will be. So I would be highly indebted to you if you could arrange to lend us as much as possible of the oxide."

By the end of the first week in May 1940, the site for the experimental pile had been prepared, and Diebner promised "some hundreds of kilograms" of uranium oxide. Harteck begged Dr. Herold in Merseburg to delay the delivery of the promised carbon dioxide as long as commercially possible, to give time for Professor Heisenberg to part with his uranium hoard. During a trunk call to Berlin on the sixth, he warned Diebner that 600 kilograms was the minimum quantity of uranium oxide germane to a pile experiment on such a scale. Three days later he wrote to Diebner to inquire how much he might finally expect, "so that I can work out the optimum geometrical configuration." He reassured Diebner that he anticipated a conclusive result.

It was the last week in May before the uranium oxide arrived, and it was considerably less than he had hoped, barely a quarter of the "minimum quantity" he had specified to the War Office. The Kaiser-Wilhelm Institute of Physics parted grudgingly with "some of what they had." Professor Pose wrote: "On the Army Ordnance Department's instructions we are forwarding to you 50 kilograms of the oxide of 38-preparation. Heil Hitler!" A few days later rather over 100 kilograms was brought personally to Hamburg by Auer's Professor Riehl. But that was all.

Harteck was warned by the War Office in a stern letter not to let the uranium oxide become contaminated during his experiments — rather like the British admiral warned by his First Sea Lord not to let his two borrowed battle-cruisers get scratched during what became a famous First World War engagement. There the parallel ended: that admiral had returned a month later and reported in a nonchalant telegram to his superiors the sinking of virtually the whole of von Spee's China Squadron. The scratches had been overlooked.

Alas for the German nuclear research project: Harteck had been sent to do battle with the laws of physics in a frigate, and when the smoke cleared and all was done, the grand problems were still afloat — battle-scarred but seaworthy.

By the first week in June, a final total of not only 185 kilograms of uranium oxide, but also fifteen tons of carbon dioxide ice, had arrived at his laboratory. Professor Harteck built the ice up into a block about seven feet tall and six feet square, and distributed the uranium in five shafts cut into the pile, in the center of which he inserted a standard radium-beryllium source of neutrons. On June 3, he told the War Office that they were already making measurements on the pile, and all would be finished within a week. He knew already that the experiment was hopeless with so little uranium oxide. The net result was that there was no observable neutron multiplication at all. His physicists had to content themselves with using the experiment to measure the diffusion length of neutrons in solid carbon dioxide and the absorption of neutrons in uranium, on which they wrote a definitive report in August. In general, it seemed that a uranium reactor would have to be larger than had been estimated before. Although they announced a further pile experiment, using a five-meter (sixteen-foot) cube of dry ice and one or two tons of uranium oxide, Harteck was so discouraged by the opposition from the true physicists that the experiment was unfortunately never performed.

The German invasion of Norway in April 1940, and the capture of the world's only heavy-water factory intact, changed the complexion of the project at once. The Norwegians had put up a fanatical resistance around Rjukan, with its huge Vemork hydrogen-electrolysis plant 5 miles west of Oslo; Kongsberg, the nearest large town, had fallen on April 13, just three days after the German invasion. But M. Allier brought to Rjukan orders that the town was to be "defended with all means," and it was the last town to surrender in southern Norway. German troops marched in on May 3. Negotiations with the heavy-water factory began at once, on a different footing than during January; but now the Germans learned that the entire stock of heavy water had been evacuated some weeks before to France. If this was a disappointment, it was also a warning, for the Allied interest in uranium research could hardly be expected to remain academic. Professor Harteck later (1944) described: "Contact with the firm Norwegian-Hydro, the only *SH.200* [code name for heavy water] producers in the world, established that the firm was able to supply only minute quantities of *SH.200* at present. But the firm itself volunteered that it could increase its top output to 1.5 tons a year by the appropriate expansion of their Vemork electrolysis plant."

[III]

IT WILL BE INSTRUCTIVE at this point to glance briefly at the other arm of the crossroads along which the two opposing sides in the growing conflict were now progressing. "At the time I was brought into the picture," General L. R. Groves, appointed executive head of the American bomb project in 1942, was to write, "research on the uses of atomic energy had been going on at a gradually accelerating rate since January 1939, when Lise Meitner explained that the atom could be split."

The discovery opened up two divergent paths of investigation. Most physicists realized that nuclear fission could be used either to generate power or to build super bombs; in general, however, it was the scientists with personal experience of Hitler's

New Order who first became interested in the possible military uses of atomic power. The native American physicists were, like their British counterparts, unaccustomed to applying scientific research to military needs; it was the Jewish émigrés from the Axis countries who were most active in awakening the Americans to the possible dangers of German nuclear research. Of the five scientists who provided the necessary stimulus for the American project in 1939 — Szilard, Wigner, Teller, Weisskopf and Fermi — all were foreign born, as the Smyth *Report* pointed out, and all except Fermi (whose wife was Jewish) were Jews. In Britain, too, it was the refugees from Hitler who formed the backbone of the project.

On March 17, 1939, at least a month before the first approach was made by German scientists to the War Office in Berlin, Fermi conferred at his own request with U.S. Navy Department officials in Washington, on the possibility of achieving a controllable chain reaction in uranium using slow neutrons, or an explosive one using fast neutrons; he particularly alerted the officials to the dangers of German possession of nuclear weapons. The officials were by all accounts unmoved. During the summer, the tireless Fermi enlisted the aid of Albert Einstein, and together with Szilard and Wigner discussed the possibility of government support with Alexander Sachs, a Wall Street economist with access to the president. Sachs drafted a letter to the president and Einstein signed it.

Dated August 2, the letter warned Roosevelt of the possibility of constructing bombs of this new explosive capable of destroying whole cities; America herself disposed only low-grade uranium ores, the most important sources being in the Congo, Czechoslovakia and Canada. "I understand that Germany has actually stopped the sale of uranium* from the Czechoslovakian mines which she has taken over," Einstein added. "That she should have taken such early action might perhaps be understood on the grounds that the son of the German Undersecretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm Institute in Berlin, where some of the American work on uranium is now being repeated."

Roosevelt appointed an Advisory Committee on Uranium, under Dr. L. Briggs, who was head of his country's Bureau of Standards laboratory, like Esau in Germany; in November 1939 this committee recommended government financial support, and the procurement of four tons of graphite and fifty tons of uranium oxide, so that measurements of the absorption cross-section of carbon could be made. No large sums of money were in fact made available and for the next six months interest waned in America.

On March 7, 1940, Albert Einstein addressed a second letter to President Roosevelt, again warning urgently of danger looming in Germany:

> Since the outbreak of war, interest in uranium has intensified in Germany. I have now learned that research there is being carried out in great secrecy and that it has been extended to another of the Kaiser-Wilhelm Institutes, the Institute of Physics. The latter has been taken over by the government and a group of physicists, under the leadership of C.-F. von Weizsäcker, who is now working there on uranium in collaboration with the Institute of Chemistry. The former director was sent away on leave of absence apparently for the duration of the war.

* This was presumably on the initiative of Professor Esau.

There seems little doubt that it was this "former director," Dr. Debye, who had started the scare about uranium research at the Kaiser-Wilhelm Institute at Dahlem. At the end of April, Debye finally reached America; he privately told journalists there of the circumstances of his departure from Dahlem. The authorities had informed him that his laboratory was needed for "other purposes"; he had made discreet inquiries and learned that a large part of the Institute was to be devoted to uranium research. The result of his disclosures was a very large article in *The New York Times* some days later, reporting in tones of greatly exaggerated alarm how in Germany every physicist, chemist and engineer available had been ordered to "drop all other researches and devote themselves to this work alone. All these research workers, it was learned, are carrying out their tasks feverishly at the laboratories of the Kaiser-Wilhelm Institute at Berlin."

By this time similar news of German uranium research had reached Britain through a different route. In Britain a number of British and alien scientists had pursued lines of scientific investigation similar to those in America, Germany and France; in the middle of 1939, the Air Ministry had supplied a quantity of uranium oxide to Professor G. P. Thomson at Imperial College in South Kensington, and various fast- and slow-neutron experiments had been performed there with both water and paraffin wax as moderators. All the experiments had failed to achieve a chain reaction. In Liverpool, Professor J. Chadwick was convinced from *his* experiments that both fast and slow neutrons could be used in explosive chain reactions; part of the Imperial College uranium oxide was transmitted to him. Early in 1940, about 250 kilograms of the oxide was also sent to Birmingham, where Dr. Otto Frisch — who had just moved for a short time to England when war broke out — had now decided to stay.

Frisch had only just expressed the view in a scientific journal that a super bomb would be "if not impossible, then at least prohibitively expensive." In Birmingham, however, Frisch had begun to live with another émigré, Professor Rudolf Peierls; and before long his thinking on the bomb issue had undergone a marked change. The two physicists now reasoned that if instead of merely enriching the uranium-235 isotope by a factor of ten, a lump of *pure* uranium-235 could somehow be separated — a lump greater than the "critical size" — then this would of itself explode with colossal violence. They wrote two concise memoranda, of which the first was a three-page report on the "construction of a super bomb": in it they suggested that a bomb containing five kilograms of pure uranium-235 would explode with a force equivalent to "several thousand tons of dynamite" if assembled in one piece.

The obvious obstacle was the large-scale separation of the rare uranium-235 isotope in bulk. Like the German War Office late in 1939, they now thought that the Clusius–Dickel thermal-diffusion process would overcome this difficulty. This process, repeated over 100,000 stages, should produce about 90 per cent pure uranium-235, they thought.

In their second memorandum, circulated at the same time, Frisch and Peierls described in simple detail the mechanics of a uranium-235 bomb, and touched upon its strategic advantages and disadvantages.

They warned furthermore that since all the theory had been published, it was "quite conceivable" that Germany was in fact developing the weapon: this would be difficult to prove, because an isotope-separation plant need not, they thought, be of such a size as to attract attention. Their advice was that it would be informative to investigate how far the uranium mines under German control were being exploited, and whether uranium was being purchased from abroad; on the isotope-separation plant, they commented: "It is likely that the plant would be controlled by Dr. K. Clusius (Professor of Physical Chemistry in Munich University), the inventor of the best method for separating isotopes; and therefore information as to his whereabouts and status might also give an important clue."

The two émigré physicists added that as it was conceivable that nobody in Germany had recognized that the separation of uranium-235 would make a super bomb possible, it was vital to keep their report secret; even rumors of some connection between uranium-isotope separation and a bomb might set the Germans thinking along the right lines. There was no realistic shelter defense against uranium bombs; the only defense would be the deterrent effect of possessing such bombs oneself. There was every reason to commence work on the bomb at once, whether or not firm evidence of German activity came to hand.

The two memoranda were still under consideration by a British government committee appointed to report on "the possibilities of producing atomic bombs during this war" when the French Lieutenant Jacques Allier arrived in London, bringing a warning of German work on nuclear research. He informed the British government of Germany's attempts to place orders with the Norwegian heavy-water factory early that year — a figure of two tons being mentioned — and at the British committee's first meeting, on April 10, he removed any last doubts about the reason for Germany's interest in heavy water; the Norwegians had told him that the German representatives had expressed an interest in French progress on the uranium bomb.

Allier had also brought with him a list of the German nuclear scientists — the result of his work in the French secret service; he recommended that their present whereabouts should be investigated. The list was shown to Sir Henry Tizard, who subsequently minuted the War Cabinet Offices that although M. Allier seemed "very excited," he still remained a skeptic: "On the other hand it is of interest to hear that Germany has been trying to buy a considerable quantity of heavy water in Norway." This might indicate merely that the Germans were trying to corner the whole world supply of heavy water as a precaution; on the other hand, it would seem appropriate to ask the Belgian firm of Union Minière whether Germany had displayed a similar interest in uranium purchases. So far he had heard nothing from the company in that vein.

The Ministry of Economic Warfare, whose department it was, was requested to attempt to deprive the Germans of the stockpiles of uranium oxide in Belgium; Tizard opposed the outright purchase of the thousands of tons of uranium oxide there, and proposed that it should merely be moved to the United Kingdom. The Ministry acted with ponderous precision, and when the German armies fell upon Belgium a month later, by far the greater part of the uranium was still there.

Up to June 1940, Union Minière had sold no more than about a ton of the various compounds to Germany each month; the company now received an immediate order for sixty tons of refined uranium compounds, to be supplied to the Auer company in Berlin. During the next five years, the Germans seized 3,500 tons of uranium compounds from the Belgium stockpiles, and shipped it under the general supervision of Dr. Egon Ihwe*

* General Manager of Auer's subsidiary, the Oranienburg Rare Earths Factory; and an agent of the *Reichsstelle Chemie*, the Reich Chemicals Authority.

back to central Germany, where it was stacked in the surface buildings of the old salt mines at Stassfurt, owned by the Industrial Research Association (*WiFo*). It was from this huge stockpile of sodium and ammonium uranate that the Auer company would now meet its requirements.

During May, the Ministry of Economic Warfare in London learned that Germany had directed Norwegian-Hydro to increase heavy-water production at Vemork to 1,500 kilograms a year. The Ministry of Supply now began to study the effects of the detonation of a German uranium bomb in the heart of a large British city.

Immediately after the occupation of Paris, at the end of June 1940, Dr. Kurt Diebner and Professor Erich Schumann descended on Professor Frédéric Joliot's laboratory at the Collège de France. The most important item of equipment there was the half-finished American cyclotron. All the French physicists of note, with the exception of Joliot, had hurriedly left Paris for London. Diebner secured Joliot's cooperation and an agreement that the Germans should be allowed to bring the cyclotron into service and use it. Work began on this during July and shortly a "Paris group" was formed under Professor Wolfgang Gentner.

The Germans were able to reconstruct much of the work the French team had been engaged on. The Frenchmen had prepared a small experiment, using 100 liters of heavy water mixed into a paste with uranium oxide when they felt compelled to leave France. Of greater significance for the Germans was the French conclusion, parallel to that of Harteck in Germany, that uranium and moderator should be kept separate in a uranium "furnace." The French suggested introducing "cubes or spheres" of the moderator substance into the uranium mass (not vice versa). Using paraffin-wax cubes (paraffin, being rich in hydrogen, was a relatively good moderator) interspersed through the sphere of uranium oxide they had used previously, they had achieved distinctly encouraging results. They had been planning further such experiments, using uranium oxide and if possible even uranium metal, with graphite and heavy water as moderators, when circumstances had obliged them to depart for England. Dr. Diebner was the first German to put the cube configuration to the test in a uranium pile; but in his experiment, it was the uranium that was cubed, not the moderator.

By the end of June 1940, therefore, when the sound of firing had once again died away on the European continent, Germany's position in the nuclear race was impressive and alarming: she had little heavy water, but she had the heavy-water factory; she had thousands of tons of very high-grade uranium compounds; she had a cyclotron nearing completion; she had a body of physicists, chemists and engineers as yet unweakened by the demands of total war; and she had the greatest heavy chemical engineering industry in the world.

Up to that month, she had been able to benefit too from the open publication in the American scientific periodicals of the results of physical investigations vital to a uranium bomb project — results which Germany herself had not then the means to obtain. It had been publicly confirmed that uranium, thorium and the ultra-rare protactinium could all be fissioned by neutrons — the first by fast or slow neutrons, and the latter two by fast neutrons alone. Thanks to notes published in the American *Physical Review* during March and April 1940, it was now known in Germany that there was experimental proof that slow neutrons actually had a greater probability of fissioning uranium-235, and that neutrons of a certain energy were very likely to be captured by uranium-238, producing uranium-239.* On June 15, just before the final censorship was imposed on such scientific disclosures, two American physicists completed the picture with a lengthy letter to the same journal: they had used the great Berkeley cyclotron to prove the existence of a new "transuranic" element, now known as plutonium, created by the emission of a beta ray from the unstable element, Number 93, produced from uranium-239. Just how stable was plutonium, was shown by the letter's authors: "If alpha particles are emitted, their half-life must be of the order of a million years or more." The publication of this final letter caused great anguish in Britain, for if the theory propounded by Bohr and Wheeler was reliable — and all these experiments in the United States had served only to prove how valid the theory was — then this new element, Number 94, or plutonium, must be fissionable like uranium-235. This occurred to several scientists at once, as they read the letter published in *Physical Review*; in the circumstances it was regrettable that such a letter should have been published at all. On Sir James Chadwick's representations, the British authorities sent a letter of protest to America.

When the British authorities inquired what progress the Americans had made, they were assured that uranium research was unlikely to have much military relevance. While it was admitted that some physicists in Germany were working on uranium research, it was believed that they had succeeded in misleading the German government about the rate at which re-

* Thus in a letter on March 3, Alfred O. Nier, of the University of Minnesota, and three physicists of Columbia University, New York, wrote to *Physical Review* that they had isolated small quantities of uranium-235 by means of a mass spectrometer, and established that "uranium-235 is the isotope responsible for slow neutron fission"; on April 3, the same physicists wrote to the same periodical, reporting similar tests on "considerably larger samples of separated uranium isotopes" obtained by the same method.

search could be put to practical use, in order to be left to work in peace on more congenial problems.

To some extent this was true: the responsible scientists, for various reasons, had as yet made no active effort to interest the German government in a uranium bomb. But the physicists were working along those lines nonetheless. Carl-Friedrich von Weizsäcker, the theoretical physicist, was an avid reader of the American *Physical Review*; during his commuting journeys between home and laboratory, he several times startled curious passengers in the Berlin underground railway by his habit of reading the periodical in public, oblivious of his fellow passengers' suspicious glances. In July, before the previous month's edition got to him, he reached theoretically much the same conclusions about the decay products of uranium-238 as had the two American physicists using experimental methods. In fact, von Weizsäcker was sitting in an underground railway carriage when the realization first came to him that by capturing neutrons, the uranium-238 nuclei might themselves be transmuted into a new element as fissionable as uranium-235 — with the important difference that being *chemically* different, the new element could be separated by relatively simple chemical means from the irradiated uranium inside an atomic pile. Von Weizsäcker's theory was wrong in one detail: he believed at this stage that the decay process would stop at element Number 93 (neptunium), and it was to this element that he assigned the fissionable and explosive characteristics important in uranium-235; in fact the Americans, and two Cambridge physicists, quickly proved that neptunium decayed to yet another element, Number 94 (plutonium), and this was the stable explosive. Both neptunium and plutonium were identified virtually simultaneously by the Viennese physicists J. Schintlmeister and F. Hernegger during June, but they reported their findings only at the end of 1940. In the meantime von Weizsäcker had written a five-page report to the War Office "on the possibility of extracting energy from uranium-238," in which he mentioned that the new element produced by the irradiation of uranium in reactors could be used in three ways, one of which was "as an explosive."

[IV]

UNTIL THE REALIZATION of the plutonium alternative dawned on them, the Germans maintained a realistic attack on the problem of separating the uranium-235 isotope in bulk. Hope centered mainly, as Frisch and Peierls had foreseen, on the Clusius–Dickel gaseous diffusion process. If one now marvels at the many false starts which were made in the isotope-separation field, one must bear in mind that even as late as 1940 no large-scale separation of isotopes had been achieved by any means, except of course of the hydrogen isotopes; and even this latter was possible only because of the great difference in atomic weight — a factor of two.

During May, Professor Harteck and Dr. Groth in Hamburg had investigated the excessively corrosive habits of very pure uranium hexafluoride gas: samples of steel, light alloy and nickel were exposed to the gas for fourteen hours at a time, at 100ϒ, and their weight gain measured; the nickel's weight was unchanged, and even when the experiment was repeated at 350ϒ it was the least affected of the metals. Steel was quite unsuitable. Nickel was, of course, one of the scarcest metals in Germany at the time — another instance of the perverseness of the whole uranium problem. The German War Office wrote to isotope-separation expert Professor Karl Clusius in Munich on July 10 asking if he could suggest any alternatives to uranium hexafluoride. Clusius answered eight days later that the only known volatile uranium compound worth any attention was uranium pentachloride — and with this the difficulties promised to be even more formidable than with the hexafluoride. A uranium carbonyl, possibly either hydrogenated or chlorinated, might be feasible. In the meantime, there seemed to be no choice but to continue working with uranium hexafluoride. I. G. Farben's Leverkusen works — which had wide experience of fluorine compounds — set up a large plant for producing the noxious gas.

Sensing that all was not well with the Clusius–Dickel method, one or two scientists were already proposing more exotic methods of separating or enriching the uranium-235 isotope in Germany. Clusius himself proposed that a process using a liquid, rather than gaseous, uranium compound should be developed. He advised the War Office: "With our experience of volatile uranium compounds to date, only a process working in the liquid phase offers any breakthrough." At about the same time, the Heidelberg physicist R. Fleischmann made a similar proposal — suggesting a modification of the process used by Urey to concentrate the nitrogen-15 isotope. Based, like Clusius's, on the Nernst distribution law, Fleischmann's method would involve mixing a solution of uranium nitrate in water, with a solution of uranium nitrate in ether. Theoretically, the uranium-235 isotope ion would concentrate more in the ether, and could then be separated by physical means.

In fact, Clusius had been experimenting in Munich since January 1940 on this principle: in May he had been able to report "promising results" from pilot experiments to separate sodium and lithium ions in this way; but when he and M. Maierhauser had proceeded to ions of greater similarity, those of the "rare earths," they had met with failure and had abandoned the simple experiment in favor of a more complicated "countercurrent" principle. A metal column and then a glass one were set up in their Munich laboratory, and experiments began to find which was the most promising uranium salt.

Pilot experiments using the "rare-earth" salts neodymium and yttrium perchlorate certainly suggested that the liquid process had some prospect of success.

At a special conference on isotope separation held during the Bunsen Scientific Convention at Leipzig in October 1940, the manifold difficulties of adapting any existing process for the mass production of uranium-235 were stressed. W. Walcher described an electromagnetic method of separating minute quantities of the isotope, using the mass spectroscope; and Professor H. Martin outlined the work his institute in Kiel had already done on a new process, involving an ultracentrifuge coupled with a special "multiplication" technique. Martin had been telephoned by the War Office in the very early days of the war and ordered to tell the Ordnance Department of his progress in the field of isotope separation, as there was a "nuclear research interest" in this; he had been ordered to complete his first prototype as soon as possible, but even now there were still technical problems to overcome. Neither method seemed capable of producing uranium-235 in any great quantities. After the Bunsen Convention, the physicists applied themselves to the problem afresh.

The greatest hindrance to the pace of German research was the attitude of the government to science. During the first year of war, the whole German economy had been geared to lightning war; the sudden and overwhelming impact of conventional arms had proven itself in Poland, in Norway and now in France. What equipment the laboratories had not possessed at the outbreak of war, they seemed unlikely now to receive for a long time.

Most telling among their deficiencies was the lack in Germany of a cyclotron, the basic weapon of attack on the atomic nucleus. It was with the cyclotron that the Americans had produced minute quantities of plutonium, enabling them to measure its constants long before the first uranium pile began to function. Not until 1938 had the Kaiser-Wilhelm Institute of Physics at Heidelberg, under Bothe, been able to issue the first contracts for a cyclotron; but shorn of labor and material priorities, its construction dawdled until it finally came into operation only at the end of 1943. Early in 1940, Baron Manfred von Ardenne, an outstanding technician in this particular field, tried to persuade Otto Hahn's instrumentation and equipment specialist, Professor Philipp, to apply for a subsidy from General Göring for the construction of large "atoms-mashing" installations. Philipp replied that it would be tactless to go over the heads of the Kaiser-Wilhelm Foundation, and complained in general that Minister Bernhard Rust, the Minister of Education, was completely unsympathetic toward nuclear research.

Von Ardenne cast around for a source of large-scale funds, and learned that the Post Office had a large and rich research department. He called personally on the Minister of Posts, Ohnesorge, and in general terms explained how Hahn's discovery made uranium bombs now possible; he called particular attention to hints about "powering ships with uranium reactors" dropped in a commentary to the U.S. naval construction program. In personal exchanges between the Dahlem laboratories and his own laboratory in Lichterfelde, von Ardenne had asked both Hahn and Heisenberg outright how much pure uranium-235 was necessary for an atomic explosion. He was told it would be only a few kilograms. "During these discussions," von Ardenne describes, "I expressed an opinion that it was technically quite feasible, by means of high-yield electromagnetic mass-separators (which we already had on our drawing boards) to make quantities of a few kilograms of uranium-235 available, if only the Reich government would resolve to direct the talents of the big electrical combines to that end."*

Minister Ohnesorge was so impressed by von Ardenne's argument that he secured an audience with Adolf Hitler soon after, and informed him of the uranium bomb. The Führer certainly had other pre-occupations in late 1940 and, with what seemed to be total victory only a few months ahead, he was disinclined to accord to the subject the serious attention it was winning from the governments of his enemies. In any event, he is said to have jeered that while the other Ministers present were worrying about how to win the war, it was his Minister of Posts who had to bring him the solution.

Von Ardenne saw Ohnesorge return angry and disappointed, but not defeated; he resolved to support von Ardenne's project within the framework of German Post Office research. There were thus now three factions in the nuclear research effort: the scientists allied to Dr. Diebner — including Berkei, Czulius, Herrmann, Hartwig and Kamin — at the Army Ordnance Department's Gottow laboratory; the scientists attracted to von Ardenne's laboratory; and the institutes of physics of the Kaiser-Wilhelm Foundation.

The established laboratories viewed the emergence of von Ardenne with suspicion and disfavor: his background and methods were unorthodox. He had read physics, mathematics and chemistry for four semesters in Berlin, but he was not an academic; and he was not one of the exalted theoretical physi-

* From the unpublished manuscript of Professor M. von Ardenne's memoirs, *Ein glückliches Leben für Forschung und Technik*, to be published by Verlag der Nation, East Berlin, in about 1972.

cists of the group surrounding Heisenberg. Possibly at the latter's instigation, Carl-Friedrich von Weizsäcker visited von Ardenne's laboratory on October 10, and "very emphatically" declared that he and Heisenberg believed atomic bombs were not feasible for a technical reason: as the effective cross-section of uranium would decrease with rising temperature, the chain reaction would prematurely shut down. Von Ardenne had no alternative but to believe him and for the rest of the year he concentrated on stressing to his Minister the importance of constructing "atom smashing" installations in Germany. Before 1940 had expired, Ohnesorge had provided funds for erecting within the next year a 1-million-volt Van de Graaff electrostatic machine at von Ardenne's Lichterfelde laboratory; he had established a second Post Office nuclear research establishment at Miersdorf, outside Berlin, where a Philips Cascade Generator was installed and at both sites work had begun on 60-ton cyclotrons, using Post Office funds. Until they could be completed, the Germans were obliged to rely on the cyclotron built by Frédéric Joliot in Paris. In September 1940, Professor Wolfgang Gentner, Germany's leading authority on cyclotron operation, who had worked with Lawrence in California, transferred to Paris to assist Joliot in completing the device's construction.

[V]

AMONG THE MATERIALS captured in Belgium was a large quantity of sodium uranate. Two tons of this were taken to Berlin, and used as the basis of an experiment conducted by G. von Droste. The compound contained inevitable impurities and was very damp; it was packed into 2,000 paper containers, which were built up into a solid cube three feet high — an experiment not unlike that performed by Harteck in Hamburg four months before, only von Droste believed that the paper and water would act to a certain extent as moderator, while Harteck had used dry ice. Nothing was learned from the Berlin experiment, except the importance of using uranium as free of impurities as possible for constructing a pile.

The reactor pit and alloy vessel in the Berlin-Dahlem bunker laboratory — the Virus House

This was the last intermediate experiment, for by early October 1940 the "Virus House" at Dahlem was ready for use. Built under the direction of Dr. Karl Wirtz, the laboratory was housed in a wooden barracks in the grounds of the Institute of Biology and Virus Research, next to the Institute of Physics. If anything went wrong, it was explained, this would avoid the whole institute's being contaminated. The main feature of the Virus House was a circular pit — six feet deep and lined with brick — at the back of the laboratory. All power and water came from the Institute's virus growth laboratory. The reactor pit could be filled with ordinary water as a reflector and shield, and high-speed pumps could empty it in about an hour should need arise. A portal crane was installed to lift the heavy reactor vessel in and out of the pit. Other rooms contained the pumping machinery, a laboratory and testing equipment, and a safe store for the neutron source. The possibility that despite all precautions, and despite calculations to the contrary, a uranium pile might get out of hand, was only marginally considered by the laboratory's designers, although they considered it just as well that the building's roof and walls were of light, fragile material should the worst ever happen. After one similar hazardous gamble, all the American piles were built in sparsely occupied terrain; the Virus House was in the heart of Berlin.

The Berlin scientists were aware of the dangers of handling uranium oxide, however. While it was virtually non-radioactive, it was highly toxic; the scientists had to don special overalls, footwear, goggles and breathing-masks before entering the Virus House. It was here, in December 1940, that Professor Heisenberg, Dr. von Weizsäcker, Dr. Wirtz and two other physicists began to build their first uranium pile. A slightly domed aluminium cylinder, 1.4 meters tall and of the same diameter, was stood upright and packed with thick layers of uranium oxide, separated by thin layers of paraffin wax as moderator. The whole assembly was immersed in the water in the pit, which acted as a neutron shield. They did not know quite what to expect. K. H. Höcker's latest calculations suggested that a uranium oxide pile would show neutron production even using paraffin alone as a moderator. A neutron source was lowered down a tube into the heart of the pile, while measurements of neutron intensity at various distances throughout the pile were made. No kind of chain reaction was observed: the neutrons emitted by the radium/beryllium source were absorbed by the pile and lost. Some weeks later the pile experiment was repeated, with 6,800 kilograms — over six tons — of uranium oxide arranged in two different piles, still using paraffin wax as moderator, inside the same slightly domed cylinder as before. Neither configuration produced a better result than the first. It was established by Heisenberg that no uranium oxide pile could be built using light water or paraffin; with heavy water — still not available in quantity — it might be possible.

Professor Heisenberg continued to divide his time between Leipzig and Berlin. In Leipzig, Professor Döpel had constructed a similar uranium-oxide/paraffin experiment, only Döpel had arranged the four alternate layers in his pile concentrically, each layer being separated from the next by an aluminium sphere. This difficult experiment had been planned since June 1940. Döpel met with as little success as the Berlin team. The most useful results of this period came from Heidelberg, where Professor Walther Bothe and Dr. Flammersfeld mixed nearly 4_ tons of black uranium oxide with water (435 kilograms) in a large earthenware vat, and measured the neutron-multiplication factor and "resonance absorption" of neutrons in these substances to a high degree of accuracy. They too found that a uranium pile should theoretically be possible using uranium oxide, if heavy water was used as moderator.

Although by the end of 1940 no suggestion to this effect seems to have been put forward by the German nuclear scientists, the War Office on its own initiative decided that the final, decisive experiments would be using metallic uranium, instead of uranium oxide. The Berlin Auer company, who had supplied the refined oxide, had no facilities for reducing the oxide to uranium metal, so Dr. Riehl turned for assistance to Dr. Bärwind, director of an associate company with a high reputation for processing rare metals — the German Gold and Silver Extraction Corporation, *Degussa*. Auer had dealt with this Frankfurt firm since the thirties, when the latter had succeeded in reducing thorium oxide to metal for them; Auer thereupon had found commercial application for this ductile metal, and *Degussa* had set up under a Dr. Weiss a small thorium reduction plant at its Number 11 Works, at 215 Gutleut Strasse. Just over 200 kilograms of thorium metal had been produced here between 1938 and December 1940.

The importance of this thorium plant will shortly be seen, for it was to *Degussa* that Auer now issued an urgent contract for a very large amount of metallic uranium, under the code name "Special Metal." Because of the similarity of the reduction processes, *Degussa* was able to use the existing thorium plant: the refined uranium oxide supplied free by Auer was reduced at 1,100ϒby means of calcium metal, with a calcium chloride flux, in an atmosphere of the inert gas argon. The *Degussa* product still contained impurities, although the Germans preferred this thermic reduction to the more conventional electro-metallurgical processes used abroad, in the belief that the uranium metal so produced was of the highest purity attainable. In fact the uranium metal contained more impurities than the original oxide, largely emanating from the calcium used in the reduction process. During the months that followed, attempts were made to manufacture purer uranium, for example by the electrolytic process; Dr. Horst Korsching, working in Berlin, managed to produce some small quantities of metal in this way, but Auer's Dr. Riehl considered the process uneconomical.

The Frankfurt firm supplied all the uranium metal that was produced in Germany during the war. By the end of 1940, the first 280.6 kilograms of the heavy, dangerous black powder had been produced by laboratory methods and shipped to Auer's headquarters in Berlin for the German nuclear research project.

If in these paragraphs too much stress may seem to have been laid on the uranium production aspect, the reader should bear in mind: this was the end of 1940, and (powdered) uranium metal production was already in hand in Germany, with a rated maximum output of one ton per month. Yet in America, almost no uranium metal was available until the end of 1942, when the first six tons became available for the famous uranium pile built by Enrico Fermi. By the time Fermi's Chicago pile was making history, the *Degussa* plant in Frankfurt had manufactured over seven and a half tons of uranium metal, and 99 per cent of this had been made available for the German nuclear scientists. It was not her industry that had failed Germany; it was her scientists. The manner in which they failed, during 1941, will now be seen.

CHAPTER FOUR

An Error of Consequence

THE YEAR 1941 brought crisis to Germany's scientific attack on the uranium nucleus. In the same months as Germany was publicly losing the Battle of Britain, her scientists were privately realizing that their hopes of attaining an easy separation of the uranium-235 isotope were not well-founded. In the same month as Germany's Axis partner was unleashing a conflict in the Balkans that was to have the gravest of consequences for German strategy in eastern Europe, the scientists were wrestling with the appalling new problems cast up by a Heidelberg professor's calculation that graphite could not, after all, be used as moderator in a uranium pile. While at the end of 1940 the military exploitation of nuclear energy had seemed only a matter of months away, in the first months of the new year it was recognized that what had seemed from afar like the end of the road was only a bend: the new road opened up endlessly into the distance ahead of them.

The graphite result, reported in January 1941, was an error. About seven months before, the physicist responsible for the measurement of graphite's nuclear constants had performed a simple experiment, and determined the diffusion length of thermal neutrons in carbon as 61 centimeters. Professor Bothe had confidently expected that if the impurities could be removed, the figure would increase to more than 70 centimeters, indicating that pure graphite was thoroughly suitable as a cheap and plentiful moderator for uranium reactors. The Army Ordnance Department had issued a contract for the supply of carbon of the highest purity.

By January 1941 the new Heidelberg measurements were complete. Somewhere, something had gone very wrong, for the new experiment, using a 100-centimeter sphere of Siemens electro-graphite of apparently the highest purity, had shown the diffusion length to be not the expected 70, but only about 35 centimeters. Professor Bothe concluded that unless the uranium-235 could be very much enriched in the fuel, pure graphite was probably out of the question as a pile moderator. He strongly doubted whether impurities — hydrogen or nitrogen, for example — in the carbon he used had caused the result.*

During the previous year, Professor Joos had attempted in Göttingen to produce extremely pure carbon, free of the boron

* It is very likely that impurities — probably nitrogen from the air — were the cause of the low diffusion length. It was not until 1945, during experiment *B-VIII* at Haigerloch, where graphite blocks were used as a reflector, that the physicists realized that Bothe's measurements must have been wrong. See Chapter 11. A less significant error was the measurement of the capture cross-section of natural uranium for slow neutrons, put by Volz and Haxel at between 0.1 and 0.2 10^{24} cm^2, whereas in reality it was as large as 3.5 10^{24} cm^2. The discrepancy was recognized during the war, and taken into account by adding what was euphemistically referred to as an "additional absorption" cross-section of 2.8 10^{24} cm^2 to the theoretical value: a nice example of scientific book-cookery, which is perhaps permissible in war.

traces which had contaminated earlier samples; he had heated various carbohydrates, including various sugars and potato flour, obtaining carbon of the highest purity. But Bothe's experiment showed that even the purest carbon would not work, so all further experiments on graphite and carbon were stopped. There was a parallel error in Cambridge: von Halban and Kowarski, the expatriate French physicists who had cornered the world stock of heavy water a year before, had performed experiments using very pure graphite to determine whether a chain reaction was possible. Their results were also unfavorable.

Had the German physicists not discouraged Professor Paul Harteck, the Hamburg physical chemist, from continuing his large-scale experiments with carbon dioxide and uranium oxide in 1940, the real neutron absorption of carbon of unchallengeable purity would almost certainly have been known then.

As it was, Bothe's regrettable error was not challenged by his peers. And while carbon and graphite were thus rejected in Germany, in America two years later the first uranium reactor in the world went critical using graphite; and the plutonium-producing factory piles at Hanford in the United States were graphite-moderated as well. The whole German project was now tied to the ponderous trickle of heavy water reaching the Reich from the Vemork High Concentration Plant at Rjukan.

Dr. Karl Wirtz, a leading physicist at the Kaiser-Wilhelm Institute of Physics in Berlin-Dahlem, was instructed by the Army Ordnance Department to inspect the heavy-water plant at Vemork. Wirtz had entered the uranium project because of his specialization before the war on heavy water — determining its physical constants and particularly its specific gravity. A tall, dome-headed physicist with a nervous, rapid manner of speech, he was to become one of the leading uranium-project scientists in Germany. He had known by name the Vemork plant's chief engineer, Dr. Jomar Brun, for some time; together with Professor Leif Tronstad, Brun had written the standard work on heavy water's density.

Wirtz's purpose was to ascertain how far the plant's output could be increased. Norwegian-Hydro's heavy-water production had hitherto been geared only to the demands of the world's laboratory technicians, and was clearly incapable of meeting the demand for the many tons which the German War Office now knew would be necessary. Wirtz reported that the heavy water was being produced in a most uneconomic manner, involving the re-oxidation of the enriched hydrogen and its re-electrolysis. He had ascertained, moreover, that even under ideal conditions it required 100 kilowatt hours of electricity to produce one gram of heavy water. As this would cost one Reichsmark in Germany, any prospect of erecting a plant in the Reich was out of the question, even if the German power economy had been able at this stage to find capacity for such a load.

The impact of the faulty graphite measurement would have been less had the Germans still known a viable process for enriching uranium-235 — that is, increasing the concentration of uranium-235 in uranium — for with this rare isotope enriched in the fuel, even ordinary water could be used as moderator in a reactor. Early in 1941, however, Harteck and Jensen were forced to admit defeat: the Clusius–Dickel gaseous separation process was unworkable with uranium hexafluoride. In their Hamburg laboratory they had set up a fourteen-foot double-walled nickel tube, heated the inner tube with superheated steam, and cooled the outer tube; between the two they had passed the hexafluoride, but to no avail. They had built an even larger separation tube, eighteen feet tall, at I. G. Farben's Leverkusen works and gone over the experiment again. Their apparatus worked with xenon gas, and it managed to enrich the carbon-13 content of methane gas. But with uranium hexafluoride, at the temperatures they were using, the thermal-diffusion factor was virtually nil. It took over seventeen days to obtain just one gram of the hexafluoride with double the normal uranium-235 content — a separation effect of less than 1 per cent. The Munich physical chemist L. Waldmann suggested that a possible cause of this disappointing result was that the hexafluoride decomposed at the high temperatures involved, but this was not so. So far, there was no alternative gas, however: uranium pentachloride had proven unsuitable, as foreseen by Clusius, as even when no water was present the substance had broken down into the tetrachloride and chlorine gas.

As late as the end of 1940, R. Fleischmann, who had set up a similar experiment in Heidelberg using a heated wire in a glass tube, had held out strong theoretical hopes that the process could be used for separating the uranium isotopes. Now, as the winter turned into the spring of 1941, all hope had vanished. As no difficulties had been foreseen, no serious alternative had been considered, except the elegant liquid process in which Clusius and his associates had invested some effort in Munich. They reaffirmed their belief in their "countercurrent" principle, but warned that a suitable soluble compound still had to be found.

It was a gloomy prospect that faced the main scientists when they met in late March. Professor Paul Harteck reported to the War Office on the impasse they had now reached:

> The conference has shown that two problems need to be worked on more urgently than any others:
>
> 1. The production of heavy water
> 2. The separation of the uranium isotopes

> Of these two problems, the former seems the more realistic for the immediate future, as current theory suggests that a reactor will operate with heavy water, even without enriched uranium. And quite apart from this, the quantity production of the heavy water for a uranium reactor is incomparably cheaper and simpler than enriching the uranium-235 isotope by the two or three times necessary for us to get away with using ordinary water [as moderator].

Referring to the second of the problems facing them, Professor Harteck concluded that, unless in the meantime a better method of separating uranium isotopes could be found, this would probably come into consideration "only for special applications in which cheapness is but a secondary consideration." By this, Harteck meant atomic explosives.

During May, he and Dr. Wirtz paid a further visit to the Vemork plant in Norway, to see how far Wirtz's proposals for expanding output could be effected. They met Dr. Brun, the chief engineer, for the first time. Brun found the Germans very secretive about the use to which the heavy water was to be put, but gathered that it was considered of the greatest importance.

The Germans still had to solve the apparently insuperable problem of enriching uranium-235. This time, the War Office decided to back several projects, of which the first was proposed by Dr. Erich Bagge, the assistant at Heisenberg's Leipzig institute who had aided Dr. Diebner in the first weeks of the uranium project.

A month after the October 1940 Leipzig conference on isotope separation (Chapter 3, section IV) Bagge had written a paper on what seemed a most novel possibility of enriching rare isotopes, at a relatively high rate. In simple terms, his suggestion involved producing a narrow "molecular beam" of the substance concerned, and passing this through a system of two shutters rotating at speeds carefully predicted, so that their slits would enable one "packet" of molecules to be stopped, while another passed. According to Maxwellian velocity-distribution theory, the lighter molecules would travel faster in the "beam" than the heavier, so that after a certain time, the lighter isotopes would be ahead of the slower ones. In the case of uranium, this lighter-isotope "packet" would be cut off by the rotating shutter, and pumped into a suitable receptacle. It seemed rather a "Heath–Robinson" device.

Early in April, Dr. Bagge had been summoned to a conference with Diebner at the Army Ordnance Department in Berlin. This was just before Harteck had made his report. Diebner had transferred him to the Kaiser-Wilhelm Institute of Physics at Dahlem, and dispatched him on the twenty-third to help Joliot and Gentner on the reconstruction of the Paris cyclotron. Before leaving for Paris, Bagge handed in his paper on what he called his "isotope-sluice" invention. He was still in France at the end of July, when Diebner hastened to Paris with the news that the isotope-separation side of the project had reached an impasse.

In the interval, after the crisis had emerged, Dr. Basche — Diebner's immediate superior at the Ordnance Department — had forwarded Bagge's paper to Harteck in Hamburg with a request for an opinion. Now Bagge was to return to Germany at once. On August 2, Bagge was already in Munich, conferring with Professor Clusius, the isotope-separation specialist: "He considers the [isotope-sluice] device quite workable," wrote Bagge.

For the next month he shuttled between Berlin, Leipzig, Berlin again and Kiel, as he consulted the experts appropriate to his invention, particularly those who could advise him on a suitable vaporization furnace for heavy metals, the heart of his apparatus. On September 11, he was called before Professor Schumann, chief of military research, in Berlin: "Conference, together with Dr. Basche," wrote Bagge in his diary. "The whole thing like an interrogation, with an apparently favorable outcome." It was probably on this occasion that he learned the reason for this continuing interest in uranium-isotope separation. He overheard Diebner and Basche discussing the mounting cost of the whole project: how could they subscribe to the continued tying down of manpower and money on isotope separation if, as seemed so likely, a uranium reactor could be designed to run with natural uranium, with heavy water as moderator? Diebner replied at once that even if the separation of uranium-235 was not vital for reactor purposes, it was necessary for its exploitation as an explosive. It was Bagge's first introduction to this possibility.

Diebner sent him back to Paris, "until mid-October." But it was late in November before Bagge was again in Berlin, outlining for a final time his isotope-sluice project to all the experts in this field — Harteck, Clusius, Bonhoeffer, Korsching and Wirtz — and to Basche and Diebner once again. Now the firm decision was taken to go ahead with the construction of the machine, "without fail," as Harteck said. Bagge arranged with Bamag-Meguin, a Berlin firm, to build most of the prototype. Twelve months to the day had passed since he had written his first paper.

At the same time, Dr. Wilhelm Groth, one of Harteck's best project scientists at Hamburg, was beginning a development that was to prove one of the most far-sighted of the uranium research program in Germany: an ultracentrifuge to enrich the uranium-235 isotope. Three years before, the American physicist J. W. Beams had published in *Review of Modern Physics* a description of a gas centrifuge; like Professor H. Martin at Kiel, Groth now proposed the adaptation of this American invention to work with uranium hexafluoride gas. This time the thermal-diffusion factor was not involved; indeed, the centrifuge's special advantage was that its separation factor depended on the *difference* of the masses of the two atoms being separated — 235 and 238 — their absolute mass playing no role at all. It took Groth some weeks to find a firm capable of constructing the prototype ultracentrifuge.

Early in August, he began negotiations with Dr. K. Beyerle, chief research technician of Anschütz & Co., a Kiel firm specializing in gyroscope manufacture; and a week later a contract was issued to Anschütz for the construction of a prototype ultracentrifuge. On October 10 the first blueprints reached Hamburg and, after a further conference in Kiel nine days later, the final blueprints were finished by the twenty-second of the same month; the firm had already built the electric motor for the machine, capable of speeds up to 60,000 R.P.M. Two days later, when Harteck, Basche and Diebner met at the Army Ordnance Department to talk through the whole concept in much the same way as Bagge's "isotope sluice," they agreed that a letter of commendation should go to Anschütz for the remarkable effort they had made. Beyerle put the prototype's cost at between twelve and fifteen thousand Reichsmarks.

Other firms were less accommodating. The Hamburg team had originally planned to have the centrifuge's rotor — which would have to withstand enormous stresses — built of an extremely strong steel alloy; but Krupps, who were to have delivered the raw material, demanded eight months for this, so the team had to use a light alloy instead. The United Light Alloy

Works of Hanover promised to supply the alloy — "Bondur" — by mid-December. To accelerate the ultracentrifuge project still further, the Hamburg institute would build the rotor and vacuum chamber in its own workshops, while Anschütz concentrated on the drive; both sections would be complete by the end of February. As with the ill-fated Clusius–Dickel process experiments, they planned to run the first pilot trials with xenon gas, rather than hexafluoride. "Theoretically," reported Groth in December 1941, "the ultracentrifuge will deliver more than two kilograms of hexafluoride a day, in which [the uranium-235 element] is more than seven per cent enriched."

It is a measure of the German inventiveness that, whereas they had entered the year of 1941 relying solely on the Clusius–Dickel process, they had no fewer than seven different processes under investigation for enriching uranium-235 as the year went out: the mass spectrograph at von Ardenne's laboratory; thermal diffusion; the separation column — a variation of thermal diffusion; "washing out" — the application of Nernst's distribution law, using liquid uranium compounds; Dr. Bagge's isotope sluice; the diffusion of isotopes in carrier metals; and now the ultracentrifuge. But there was no intention of using the gaseous diffusion of uranium hexafluoride through porous barriers — the process originally developed by the German Gustav Hertz and destined to be used to such effect by both British and Americans. Study of the German records shows that the possibility was entirely overlooked.

It was in the summer of 1941 that German attention was again drawn to the plutonium alternative. During the previous autumn, the Berlin-Lichterfelde laboratory of Baron Manfred von Ardenne had received an important and unorthodox new worker, Professor Fritz Houtermans. He had had a checkered career: he had emigrated to Russia after the National Socialist election victories of 1933, and after several years lecturing in physics had ended up in one of Beria's prison cells; after the Russo-German pact he was amnestied and conveyed to the German secret police authorities, who imprisoned him in Berlin. After three months, Houtermans had been paroled, but was not allowed to work in a government laboratory. Professor Max von Laue used his influence with von Ardenne to persuade him to take the hapless Houtermans under his wing at Lichterfelde.

The arrangement was considerably to von Ardenne's profit. Houtermans had taken up his new position on the first day of 1941. The first task set him was to investigate the cost efficiency of the various isotope-separation methods; then he began the measurement of the effective cross-sections for slow neutrons of various substances. He was obliged to rely on weak natural neutron sources, as work was only just beginning on the construction of two Post Office cyclotrons.

Eight months later, his most important investigation was complete, a report "on the question of unleashing chain reactions." In 39 pages of typescript, he surveyed the whole theory of the project so far, and for the first time made explicit calculations on fast-neutron chain reactions and the critical mass of uranium-235 — i.e., that mass which, when assembled, would result in a spontaneous fast-neutron chain reaction and a violent explosion.

Various historians have since stated that the Germans did not apparently investigate the critical size of a mass of uranium-235 or ponder the importance of fast-neutron chain reactions. Houtermans certainly did both. Siegfried Flügge, in a September 1942 paper on the possibility of fast-neutron reactions, explicitly referred to the importance of separating uranium-235 for "uranium bombs." At about the same time, Heisenberg himself, when talking of the possibility of uranium bombs, said, in reply to a question, that such bombs would be "the size of pineapples." At a lecture a year later, Heisenberg used a diagram schematically illustrating the fast-neutron process inside a mass of uranium-235, and he improved on Houterman's criticality theory on the basis of 1943 fast-neutron fission cross-section measurements of uranium-235, made by the Viennese physicists Jentschke and Lintner.

Houtermans's report concentrated primarily on the importance of the plutonium alternative. Early in February 1941, H. Volz and O. Haxel had believed they could show experimentally that neutron absorption in uranium-238 was much lower than had been believed; the corollary of this, as the authors pointed out, would be that von Weizsäcker's suggestion that the decay product of uranium-239 could be extracted as a fissionable material would have to be reconsidered because of the small amounts actually produced.

Houtermans was rightly unimpressed by this line of reasoning, and argued that at this stage less attention should be paid to isotope separation than to the design and geometry of uranium reactors: because in natural uranium there were 139 times as much of the 238 isotope as of the 235, it was clearly far more profitable to concentrate on means of exploiting the abundant uranium-238, rather than the rare uranium-235. "Every neutron which, instead of fissioning uranium-235, is captured by uranium-238 creates in this way a new nucleus, fissionable by thermal neutrons," Houtermans wrote.* Thus,

* The exact identity of the new fissionable nucleus had been established some months earlier by the Viennese J. Schintlmeister, who showed that this theoretically explosive transformation element, which could be extracted chemically from a chain-reacting uranium pile, was almost certainly element 94 (now known as plutonium) rather than 93 (neptunium).

any chain-reacting uranium pile could be regarded as an "isotope-transformation machine" far superior to the most efficient isotope separators that could be devised. It would remain only to discover chemical means of extracting the new element from the irradiated uranium inside the pile.

Houtermans's lucid argument can be seen as a first turning point in the story of the German uranium research effort: now there seemed to be a sound basis for waiting until a heavy-water reactor could be built. And now, while there was never an express decision to this effect, the urgency for an isotope-separation process for uranium-235 had gone.

[11]

THE STRIKING FEATURE of grand scientific progress is its essential universality. Never is this more apparent than in time of war, when the various arms of the international scientific community are compelled to proceed independently, ignorant of each other's particular achievements. The parallel progress made by both Axis and Allied scientists in the fields of radar and jet engine development bear witness to the accuracy of this maxim.

During the summer of 1940, scientists working in a number of Allied universities had narrowed the field of possible methods of uranium-isotope separation down to one major contender, after several had been considered. The electromagnetic process used by Nier to isolate uranium-235 in minute quantities had been ruled out as prohibitively expensive. Of the alternatives — thermal diffusion, centrifuging and the diffusion of gases through a porous barrier — only the latter process had promised any success. Thermal diffusion — referred to by the Germans as the Clusius–Dickel process — had been abandoned "because no uranium compound is known with which it will work."

The gaseous-diffusion process adopted in Britain involved passing a gaseous uranium compound — the unpleasant uranium hexafluoride being the only one suitable — through a membrane under a finely adjusted pressure. The uranium-235 atoms would diffuse through the barrier with greater facility than the atoms of the heavier isotope. The process would have to be repeated many, many times to enrich the uranium-235 to the required degree; the gaseous diffusion plant would thus consume considerable quantities of power in the pumping machinery. The principle was not new; it had been tried by Aston in the early isotope investigations, and modified by Gustav Hertz, the German physicist, in the early 1930s as a means of separating the neon isotopes.

In December 1940, a British team under the refugee scientist F. Simon designed a large-scale plant based on Hertz's apparatus, capable of producing one kilogram of 99 per cent pure uranium-235 each day; it would sprawl across forty acres and consume some 60,000 kilowatts of electric power. In the same month, Imperial Chemical Industries were awarded a contract for the production of a first working stock of uranium hexafluoride (a gas of which large quantities had already been produced in Germany).

In general, the work in the United States was behind that in Britain at this stage, although work on the plutonium alternative was being pressed ahead by physicists working with the giant Berkeley cyclotron in California. Alarmed by the exaggerated reports of the work in hand at the "Virus House" at the Kaiser-Wilhelm Institute in Berlin, the American uranium committee had embarked on an ambitious research program in the early summer of 1940, under the auspices of Dr. Vannevar Bush's National Defense Research Council. Bush had obtained presidential approval to compare notes with the British scientists, and in March 1941 British scientists had begun to receive from Washington the first research reports. On the basis of these, Professor Peierls reported that the critical mass of uranium-235 would probably be eight kilograms or less. Two months later, a contract for the construction in Britain of a 20-stage, pilot gaseous-diffusion plant for separating uranium-235 was awarded to Metropolitan-Vickers. The Cambridge work on plutonium was gradually dropped, largely because of the lack of a cyclotron in Britain.

Several authoritative British scientists expressed doubts whether plutonium would prove suitable for bombs. Its production would in any case have been dependent, it seemed, on the manufacture of enough heavy water for a reactor, and this was scarcely a more attractive problem than the separation of uranium-235.

In July 1941, the British research was summarized in the report of the Ministry of Aircraft Production's MAUD Committee — the special government committee appointed for the project. It was concluded that an effective uranium bomb could be made, containing about 25 pounds of uranium-235 and equivalent to 1,800 tons of TNT. The Committee further warned:

> We know that Germany has taken a great deal of trouble to secure supplies of the substance known as heavy water. In the earlier stages we thought that this substance might be of great importance for our work. It appears in fact that its usefulness in the release of atomic energy is limited to processes which are not likely to be of immediate war value, but the Germans may now have realized this, and it may be mentioned that the lines on which we are now working are such as would be likely to suggest themselves to any capable physicist.

On the evidence at present available, it seemed that the material for the first atomic bomb could be available in Britain by the end of 1943.

Would Germany get a bomb before then? A number of obvious Intelligence precautions were taken. The most direct lead to the German uranium research program lay through the heavy-water factory at Rjukan, and any references to heavy water in Intelligence reports were closely followed up. When a telegram reached London from Trondheim during the summer, reporting that the Germans were increasing heavy-water production at Rjukan still further, this finally triggered off the main British investigation, as it was clear now that the German effort had to be taken seriously.

One copy of the telegram reached Dr. R. V. Jones, the young scientific Intelligence officer attached to the Intelligence Service. Jones telephoned the officer running the Norwegian section of the Intelligence Service, Lieutenant-Commander Eric Welsh, a First World War minesweeper officer who had later managed the International Paint Company's factory in Norway. Welsh, who had married a Norwegian, had a modest scientific background which was an advantage for the Intelligence task that was to come to him. Welsh told R. V. Jones that he had seen the Trondheim telegram, but who had heard of this stuff called "heavy water"? Jones outlined to him the grave significance of the telegram, and asked Welsh to dispatch a request for detailed information on Norwegian-Hydro's present production.

When the reply came back from Trondheim, it was an unexpected jolt: the information was refused, with an explanation redolent of the suspicion of ulterior Allied motives in Norway. The Trondheim agent asked whether Imperial Chemical Industries — a peacetime competitor of Norwegian-Hydro — was behind the inquiry. "Remember," he added, "blood is thicker even than heavy water." Jones suppressed his curiosity about the anonymous wit who had contrived this remarkable telegram; he met its author in the autumn. In the meantime, Commander Welsh, the only pure Intelligence Service officer with some scientific knowledge, gradually assumed control of the Intelligence attack, to the inevitable consternation of the established scientific Intelligence officers attached to the Service. During the early years, Welsh's position was impregnable because of the importance of the Norwegian theater for Intelligence operations; later he was to become indispensable.

America was still not at war, and American physicists were not yet "pointing their research toward war." Even in the middle of 1941, the emphasis in the big laboratories was on the exploitation of uranium as a source of power, and it was only when a draft copy of the British MAUD Committee's report, couched as it was in such unambiguous terms, became unofficially available in Washington that the tempo changed. At the same time, the first voice was raised in query; the senior British scientific representative in Washington wrote to the chairman of the Cabinet's scientific advisory committee, to point out that an urgent question would seem to arise if it should prove possible to manufacture a uranium bomb — should it be used? "For example, are our own prime minister and the American president and the respective general staffs willing to sanction the total destruction of Berlin and the country round, when, if ever, they are told it could be accomplished at a single blow?"

The moral question was answered by the Official Historian of the British atomic research effort in the war years. The truth was that in this early stage there was no dilemma for British scientists: all except the convinced pacifists were deeply committed to the war and to the defeat of Germany. "The refugees from

Europe who played such an important part in the development of the bomb were the most deeply committed of all."

At the time, there still seemed a real possibility that Germany might make a uranium bomb; while many of the best scientists had left, many more had stayed on, determined — like Heisenberg, Wirtz, Hahn and many others — not to desert a country which had done so much for them. Scanty though the detail was, there were indications from the Ministry of Economic Warfare, from Swiss sources and from people in America that all pointed to the same danger. The Ministry thought that the Germans were taking an increased interest in Portuguese uranium ores, and that the uranium from a certain mine was going to Germany. Above all, the Ministry had information that suggested the Germans were ordering large numbers of fans of a type suitable for a gaseous diffusion plant, for the enrichment of uranium-235.

Most of these reports were paper ghosts thrown up by the scavenger hunt of the Intelligence investigation, but the second-order clues could not be so easily ignored. Why else should the Germans have ordered an *increase* in heavy-water output? Aided by the German émigrés who had fled their country to work for Britain, a search began for the whereabouts and activities of their colleagues and rivals of only a few months before — the nuclear scientists who had stayed loyal to their fatherland. Professor Peierls and his colleagues compiled for British Intelligence a list of all the names they thought important: the "Kaiser-Wilhelm" establishment figured prominently among them.*

* The sixteen scientists mentioned were Heisenberg, Hoffmann, Hahn, Strassmann, Flügge, von Weizsäcker, Mattauch, Wirtz, Geiger, Bothe, Fleischmann, Clusius, Dickel, Hertz, Harteck and Stetter. All of these, with the exception of Hertz, who had been excluded on racial grounds, were indeed working on the German uranium project.

The Intelligence services had insufficient agents in Germany to follow each of these scientists, but an adequate substitute seemed to be a close study of the German scientific periodicals and lecture lists, and of the behavior patterns of these main scientists. Gradually a consistent picture of their activities emerged.

The MAUD Committee had recognized all along that without the active support of the prime minister, such a vast and questionable enterprise would be stillborn; the committee had taken considerable care to ensure that Professor Lindemann, the prime minister's scientific adviser and confidant, was enamored of their arguments. A copy of the MAUD report accordingly found its way to him.

On August 27, Lindemann wrote a private six-page letter to Mr. Churchill, telling him of the "super-explosive" about which he had already frequently spoken to him, something like a million times more powerful than chemical explosives: "A great deal of work has been done here and in America, and probably in Germany, on this, and it looks as if bombs might be produced and brought into use within, say, two years." He graphically reduced the calculations reproduced by the MAUD report to a conjecture that one airplane should be able to carry one somewhat elaborate bomb weighing about a ton, exploding with a violence equal to about 2,000 tons of TNT. Lindemann advised the prime minister that the Allies already had plenty of uranium in Canada and the Belgian Congo: "The Germans have less (in Czechoslovakia) but I fear sufficient."

If all went well, a factory producing one bomb a week would cost up to £5 million, and some diversion of manpower from the engineering industry, probably of the type used in the manufacture of turbines. Lindemann candidly concluded: "People who are working on these problems consider the odds are ten-to-one on success within two years. I would not bet more than two-to-one against, or even money. But I am quite clear we must go forward. It would be unforgivable if we let the Germans develop a process ahead of us by means of which they could defeat us or reserve the verdict after they had been defeated."

The decision to proceed with large-scale research in Britain had thus in effect already been taken, when the War Cabinet's scientific advisory committee met late in September to formulate its recommendations to Mr. Churchill. In reading its report, it must be borne in mind that even now Britain's only enemies were the European Axis powers. Urging that the program should be initiated, the committee stressed: "The destructive power of the weapon which would thus be created, and the ultimate importance of the issues at stake, need no emphasis. Moreover, we have to reckon with the possibility that the Germans are at work in this field, and may at any time achieve important results. It is known that one eminent German physicist [*sic*] in particular, Professor Hahn, has made a study of uranium disintegration for some years past. Although steps were taken beforehand to induce the Belgian company to reduce stocks of uranium oxide, some of which are now in Canada, some eight tons* are believed to have fallen into the hands of the Germans when Belgium was invaded."

All these reasons argued strongly for the development under high priority of a uranium bomb in Britain. Mr. Churchill and the Chiefs of Staff had already acted on the basis of Lindemann's explanatory letter: a minister of Cabinet rank, Sir John

* Margaret Gowing, *Britain and Atomic Energy 1939–1945*, quoting the committee's report, drew attention to this error and said that it was discovered that the Germans had acquired the equivalent of 600 tons of uranium oxide; but Professor N. Riehl has informed the author that it was in fact very much more.

Anderson, was appointed to direct the project at ministerial level; and on September 3 the Chiefs of Staff agreed that no time, labor, materials or money be spared in promoting the manufacture of the bomb. Soon after, a senior ICI director, Mr. Wallace Akers, was appointed to head the administrative side of the project. His deputy, Mr. Michael Perrin, moved with him into the new offices of the British atomic project (code name: "Tube Alloys Directorate") in the DSIR's headquarters at 16 Old Queen Street. From here part of his responsibility was, with Commander Welsh, to direct the Intelligence attack on the German research program. One of their first visitors in this connection was the Trondheim agent who had warned that the Germans were stepping up heavy-water production, and had expressed grave suspicions that ICI might be at the back of the subsequent request for more details.

The agent was Professor Leif Tronstad, the 37-year-old chemist who with Jomar Brun had created Norwegian-Hydro's heavy-water plans years before. Tronstad soon after became head of Section IV of the Norwegian High Command in London, responsible for intelligence, espionage and sabotage, with the rank of major; and it was in this service that he was to meet his death in Norway just over three years later.

In the United States, the possibility of separating plutonium from a chain-reacting uranium pile, and of using this plutonium as an atomic explosive, had also been recognized. In fact during March 1941 the first minute quantities of plutonium-239 were prepared in the great Berkeley cyclotron, and in the same month a laboratory confirmed experimentally that the new element could be fissioned as readily as uranium-235. In December the American government approved an extensive Chicago research project for the design and operation of a plant for extracting plutonium, even though no uranium pile had yet gone critical. That month, even as the first qualms were being expressed by the German War Office about the point of their uranium research effort, a new top policy group was established under Roosevelt to control the future of the U.S. atomic project.

With the American entry into the war that month, all non-military uranium research was stopped to enable effort to be concentrated on the manufacture of an atomic bomb. "The policy adopted and steadily pursued by President Roosevelt and his advisers was a simple one," the American Secretary of War later explained. "It was: to spare no effort in securing the earliest possible successful development of an atomic weapon. The reasons for this policy were equally simple: the original experimental achievement of atomic fission had occurred in Germany in 1938, and it was known that the Germans had continued their experiments.

"In 1941 and 1942," Stimson continued, "they were believed to be ahead of us, and it was vital that they should not be the first to bring atomic weapons into the field of battle."

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DURING THE LATE SUMMER of 1941, the German program had made less progress than might have been expected. The Army research department had now given Norwegian-Hydro a contract for the supply of 1,500 kilograms of heavy water, and between October 9, 1941, and the end of the year the first 361 kilograms had been delivered. By the end of the year German industry had manufactured over two and a half tons of powdered uranium metal, and the Frankfurt factory had a maximum capacity of a further ton of the metal each month. Yet when Professors Heisenberg and Döpel came to build their second uranium pile experiment, using the first heavy water now arriving from Norway, they were still using the uranium oxide which had proven so disappointing at the beginning of the year in Berlin, Leipzig and Heidelberg. Again their "pile" was contained in an aluminum sphere, 75 centimeters in diameter, filled with 164 kilograms of heavy water, and with 142 kilograms of uranium oxide in two layers surrounding the neutron source in the center. The whole pile was immersed in a tank of water in Döpel's Leipzig laboratory.

There was still no neutron increase measurable; but when they repeated their calculations, taking into account the neutrons that would have been absorbed by the aluminum separating the concentric layers, they *just* reached a figure showing that there had been a positive neutron production coefficient of about 100 per second. Now they began to "feel it in their bones" that they were on the right track; no one day can be stated, between the late summer of 1941 and the first weeks of 1942, when the final realization of their ultimate success dawned on them. As the series of Leipzig experiments progressed, and the readings were repeated, their confidence increased. The physicists began to talk of success, to discuss and eliminate one by one all possible sources of error which might be occasioning false hopes. The private excitement increased, until by the end of the summer Professor Heisenberg was sure that their next pile configuration would give them a positive coefficient, even with the aluminum supporting material.

"It was from September 1941," Heisenberg now says, "that we saw an open road ahead of us, leading to the atomic bomb."

This was the culmination of a great debate behind the scenes of German science. Many of the physicists were by now beset with grave anxieties about the moral propriety of working on the uranium project — predominant among them being Heisenberg, von Weizsäcker and Fritz Houtermans.

At the end of October, Heisenberg traveled to Denmark to see Professor Niels Bohr, to ask for his advice on the human issue. As Professor P. Jensen aptly put it, Heisenberg, the "high priest" of German theoretical physics, was going to seek absolution from his Pope. Heisenberg asked the Danish physicist whether a physicist had the moral right to work on the problems of atomic bombs in wartime. Bohr countered with a question of his own: was the military exploitation of atomic fission possible, in Heisenberg's view, therefore? Heisenberg sadly replied that he now saw that it was. Heisenberg had intended asking Bohr whether he thought it feasible that all the scientists would agree not to direct the efforts of their governments toward the construction of atomic bombs, if he or they could be satisfied that the German physicists were also abstaining from such work. Unfortunately he does not appear to have formulated his proposal as clearly as this.

In any event, to Heisenberg's considerable amazement Bohr replied that military research by physicists was inevitable everywhere and was thus proper too; he refused to be drawn into discussion on the German's proposal, apparently suspecting a German attempt at demolishing the feared American supremacy in nuclear physics, for which the enforced emigration of so many German physicists was largely to blame. Their conversation left a deep legacy of shock in Bohr, and a conviction that Germany was on the threshold of making a uranium bomb.

CHAPTER FIVE

Item Sixteen on a Long Agenda

"THE NEEDS OF the German national economy are to give way to the necessities of the armaments economy." With this policy decision by Adolf Hitler, the winter of 1941 was ushered in. Even as late as the autumn of that year, the German economy had been geared to "short wars with long respites," during which latter the materials and manpower exhausted during the hostilities could be replenished; but now the German armies had met their match and as winter closed in they were still outside the gates of Moscow, and the end of the war seemed further off than ever before.

On December 3, Munitions Minister Fritz Todt informed Hitler that sixty armaments experts had warned that the war economy was at breaking point, and that from then on any expansion in one sector must be balanced by reduction in another. Hitler drafted and signed a decree outlining a number of clear economy measures to enable the necessary production increases elsewhere. Two days after Hitler's meeting with Todt, the director of military research, Professor Schumann, wrote to all the institutes working on the uranium project, warning their directors that "the work on the project undertaken by the Research Group is making demands which can be justified in the current recruiting and raw materials crisis only if there is a certainty of getting some benefit from it in the near future."

All the institute directors were ordered to attend a conference at the Army Ordnance research department early on the sixteenth. When the conference was over — each of the main scientists having delivered carefully prepared speeches on the status of the work to date and their future timetables — a detailed report was submitted by Schumann to General Leeb, chief of Army Ordnance, with a request for a high-level decision on the War Office's future attitude toward the project. The depressing outcome was a decision that the German Army should gradually relinquish control to the Reich Research Council, a weak agency still controlled by the Reich Ministry of Education under the incompetent Bernhard Rust. It was also decided that there should be a further conference of all the main project scientists at the end of February in Berlin.

By the beginning of 1942, all was confusion. The academic scientists were delighted that they no longer carried the stigma of working on a German Army project. But the Reich Research Council had merely delegated its physics section's head to control this new enterprise — Professor Abraham Esau, whom we have already met in 1939. The research team financed by the Army research department was continuing its program as before, under Dr. Diebner, and there was still a certain element of War Office control. The seriousness of the shortages which now began to afflict the program can be realized from a letter circulated to all the institute directors, asking them to provide five —

or if possible ten — carbon copies of all research reports in future to facilitate their distribution, as the shortage of photographic materials now made it impossible to photostat them *en masse*. Soon after, Schumann gave permission for the most important nuclear research papers to be circulated in mimeographed volumes, *Secret Research Reports*, but these excellent publications were few and irregular in appearance.

On January 24, Schumann circulated all the institute directors that a second research conference was to be held, on February 26 and 27, with a limited number of participants, and in the middle of February the special security passes to the conference, to be held at the Kaiser-Wilhelm Institute of Physics under conditions of great secrecy, were issued. Only one agenda was given to each institute director, and all other participants had to wait until the day itself when they could borrow and sign for one inside the conference room itself. This was hardly surprising, as to an expert even a study of the titles of the various papers would have provided a great insight into the status of German research. The four-page agenda listed twenty-five highly complicated scientific papers — fifteen-minute dissertations on “diffusion lengths,” “fission cross-sections,” “pile configurations,” “isotope enrichment” and a host of similar topics, bewildering to the layman but of great significance to the scientists.

It is now that this story takes an unexpected turn. The Reich Research Council decided to hold a special convention themselves, and at the end of the second week in February sent out advance invitations to a wide circle of officers of the High Command, the SS, and the world of science. Their convention would be held at the “House of German Research” — the council’s headquarters — on February 26, the same day as the Ordnance Department's conference was to begin. It was not intended as a rival attraction; the intention was that the *scientists* who attended the Research Council's popular lectures on nuclear physics might proceed to the more detailed and complicated scientific conference beginning later in the day. "A number of important problems of nuclear physics is to be discussed," the Research Council told its invitees, "work on which has been kept largely secret because of their importance for the nation's security."

When, on February 21, the invitations to Speer, Keitel, Himmler, Raeder, Göring, Bormann and a galaxy of others were finally sent out, there had, however, been an administrative mistake. Instead of the agenda listing eight brief popular talks, beginning with one by Professor Schumann on "Nuclear Physics as a Weapon," and including ten-minute speeches by Hahn, Heisenberg, Bothe, Geiger, Clusius, Harteck and Esau, many of the guests — including Himmler — were accidentally sent the long list of highly complex scientific papers to be read over three days in the related conference at the Kaiser-Wilhelm Institute.*

Confronted with this unintelligible agenda, Himmler replied to Rust: "As I will not be in Berlin at the time in question, I regret I will not be able to attend the event." Field-Marshal Keitel diplomatically assured Rust of the great importance he attached to "these scientific problems," but he too regretted that the burden of his commitments made it impossible to attend. Raeder promised to send Admiral Witzell as his representative. None of the senior personalities accepted the invitation.

* The Reich Research Council culprit was a certain secretary. In late 1943, when she should have circulated Göring's decree replacing Esau as head of the project, she again put the wrong document in the envelopes; apologizing for this some days later, she said she was enclosing the correct document, but it was as wrong as the first.

At 11:00 A.M. on February 26 the Reich Research Council's convention began, with Schumann's address on nuclear weapons; Education Minister Bernhard Rust presided. After Otto Hahn had talked for the prescribed ten minutes on the principles of uranium fission, it was Heisenberg's turn. He had entitled his talk "The theory of extracting energy from uranium fission." It was a masterpiece of clear exposition, and even now it is hard to fault. His main point was that the energy produced by nuclear fission was "about 100 million times" greater than chemical energy produced from the same fuel; but such chain reactions could be sustained only if more neutrons were produced during fission than were absorbed in non-fission processes, and for this reason natural uranium by itself was unsuitable.

Heisenberg drew a happy parallel: "The behavior of neutrons in uranium can be compared with the behavior of a human population sample — taking the fission process as analogous to 'marriage' and the capture process as analogous to 'death.' In natural uranium, the 'death rate' exceeds the 'birth rate,' with the result that any given population is bound to die out after a short time." This could be remedied, Heisenberg continued, either by raising the number of children per marriage or by lowering the mortality rate. The mean birth rate of neutrons per fission was an unalterable constant in nature; but if the percentage of the rare uranium-235 isotope could be increased in the uranium fuel, the neutron "mortality rate" would drop. Moreover, if pure uranium-235 could be isolated altogether, mortalities of neutrons would cease altogether:

> If one could assemble a lump of uranium-235 large enough for the escape of neutrons from its surface to be small compared with the internal neutron multiplication, then the number of

> neutrons would multiply enormously in a very short space of time, and the whole uranium fission energy — 15 million-million calories per ton — would be liberated in a fraction of a second. Pure uranium-235 is thus seen to be an explosive of quite unimaginable force.

Heisenberg admitted that this explosive was extremely difficult to extract, and a large part of their work at present for the Army Ordnance Department was devoted just to this, as Professor Clusius would later describe to the audience. But, as Heisenberg warned, "the Americans seem to be pursuing this line of research with particular urgency."

Returning to his human-population simile, Heisenberg explained that there was a second proven possibility of lowering the "mortality rate" of the neutrons. The most recent research had proven beyond doubt that neutrons "died" — that is, underwent capture — only when traveling at quite clearly defined energies; they had thus investigated several substances capable of rapidly braking the neutrons to energies below the lowest that would invite capture, without capturing the neutrons themselves. The best such moderator would have been helium gas, as this absorbed no neutrons at all; but it was too light to be practicable. That left only heavy water, as investigations had shown both graphite and beryllium to be unsuitable.

The most obvious application of a reactor comprised of layers of uranium fuel and moderator would be to generate heat to drive a turbine. That the engine would consume no oxygen and allow an enormous radius of action would particularly favor its employment in U-boats, for example; but there was more to a uranium reactor than that. "As soon as such a pile begins to operate, the question of producing the explosive receives a new twist: through the transmutation of uranium inside the pile a new element is created (atomic number 94*) which is in all probability as explosive as pure uranium-235, with the same colossal force." This element would be far easier to obtain than uranium-235, as it could be extracted chemically from the irradiated uranium fuel.

At about the same time as Heisenberg was speaking in Berlin-Steglitz, the second conference was just beginning at the Kaiser-Wilhelm Institute's Harnack Building in Berlin-Dahlem. Dr. Berkei stood guard on the main entrance and checked the passes as the scientists and guests streamed in. A stranger arrived and, introducing himself as "Herr Eckart," told Berkei that Heisenberg had authorized him to attend the conference; Berkei regretted that he would have to clear the matter with his superiors first. He telephoned Diebner. The latter, more militarily conscious than his deputy, told Berkei to apprehend the stranger at once, if necessary by force, until his identity could be established.

When Berkei returned to the door, however, the stranger had vanished the way he had come. Neither Heisenberg, nor any other scientist, had authorized "Herr Eckart" to attend the conference.

Virtually all the project scientists read papers during the next three days at this main atomic energy conference. Professor Bothe reported on his Heidelberg group's measurements of the various nuclear constants. Von Weizsäcker described his improved theory of resonance absorption in a reactor. There were several papers on the behavior of fast neutrons in uranium, on the characteristics of neptunium and of plutonium-244.

Professor Döpel told the conference of the latest Leipzig pile experiment — *L-III* — and Wirtz described the experiments in

* Plutonium.

the Virus House a few hundred yards away from their conference chamber, in Berlin.

The Army Ordnance Department subsequently circulated a 131-page report on the conference, discussing the prospects in detail more explicit than many of the scientists thought wise. It stressed that the plutonium alternative could only be tested "once we have a functioning atomic pile"; at present they knew neither the concentration in which plutonium would be produced nor its properties in sufficient detail to make any definite predictions. On the actual mechanics of an atomic bomb, the report said: "The point is that since there are some free neutrons in every substance, it would suffice to bring together two lumps of this explosive, weighing a total of ten to a hundred kilograms, for it to detonate."*

There was a strong and coherent Nuclear Physics Research Group in existence, and industrial concerns had been geared to meet the demands for uranium and heavy water. "The interim results from the experiments performed in Leipzig (although not yet complete) indicate that it is probable that the difficulty still being encountered with the supporting material will be overcome." Uranium power sources would be ideal for land-based army installations and for ships and submarines. A major experimental pile, using over a ton of heavy water, was being planned and, if all went well, manpower and machinery would have to be injected into the project on the largest scale. "The

* The limits were set even wider in America: "The mass of uranium-235 required to produce explosive fission under appropriate conditions can hardly be less than 2 kg., nor greater than 100 kg.," was the reported verdict of the U.S. National Academy of Sciences committee on November 6, 1941. The wide limits reflected the experimental uncertainty of uranium-235's "capture cross-section" for fast neutrons. As for plutonium, the Americans had been able to produce a minute quantity with their great cyclotron in California several months before, and they could predict its behavior reasonably well.

enormous importance which attaches to the project both for the power economy in general, and for the armed forces in particular, justifies such measures, especially since the enemy countries and particularly America are working intensively on the problem."

The immediate results of the two Berlin conferences were good. Otto Hahn noted that "our speeches at the Reich Research Council" had made a "good impression"; and Heisenberg afterward said "one can say that the first time large funds were available in Germany was in the spring of 1942, after that meeting with Rust, when we convinced him that we had absolutely definite proof that it could be done." They had convinced their new Minister, but the Commanders-in-Chief of the armed forces were not swayed; one can only speculate on whether the course of history would have run differently had a secretarial error not discouraged them from attending a conference in Berlin.

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THE PRODUCTION of pure heavy water was the bottleneck in the project now. There was no way round it: the Germans believed this to be the only workable moderator for a uranium pile, and until they had a working pile none of the scientists was prepared to ask for the exalted priorities that other research projects were enjoying.

Norwegian-Hydro was still struggling with the German War Office's contract for 1,500 kilograms of heavy water. By the end of 1941 production had increased more than tenfold to about 140 kilograms a month, but the Germans were still unsatisfied; immediate steps were being taken to increase Vemork's production by expanding the high concentration plant and redimensioning some of the electrolytic stages preceding it. In the first two months of 1942, however, the trickle of heavy water had slackened to 100 and 91 kilograms respectively. On January 15, Consul Schoepke, head of the military economic liaison office in Oslo, wrote to Norwegian-Hydro ordering their chief heavy-water engineer, Dr. Jomar Brun, to report to Dr. Diebner's office at 10 Hardenberg Strasse in Berlin. At the same time, Norwegian-Hydro was awarded a new contract for the production of five tons of heavy water. Wirtz, Harteck, Jensen and Diebner sat in on the conferences with Brun. After the main decisions had been reached, including a decision to exploit the heavy-water production in two other Norwegian-Hydro electrolytic plants, Brun visited several German firms to arrange for the equipment necessary for the expansion. He was subsequently invited by Wirtz to look over the Kaiser-Wilhelm Institute, although the Virus House was not shown to him. Brun was perturbed to see two glass carboys standing in a corner of Wirtz's laboratory, containing about 130 kilograms of heavy water, worth a very large sum indeed; he advised the German physicist to handle the liquid with greater respect, as glass vessels seemed excessively prone to disaster. Brun was unable to learn from the Germans the reason for their interest in heavy water, but he did establish that it was considered to be of the greatest importance.

In these early years of the war, there was no reason for the Germans not to rely on Norway: the country was safe from air attack, and sabotage seemed highly improbable. In the production of heavy water, the first stage of the concentration, to 5 or 10 per cent, was always the most difficult, as very large quantities of water or hydrogen had to be handled. For economic reasons it was impossible to set up a full-scale electrolytic heavy-water plant in Germany, and each of the alternative processes had its disadvantages. The most promising method seemed to be that developed by Professor Clusius with a Munich firm of low-temperature specialists, Linde's Ice Machinery Factory. In the Clusius–Linde process, hydrogen would be liquefied and then fractionally distilled. About 5 per cent enriched heavy hydrogen would be produced in this way, which could then be economically concentrated to full strength by normal electrolytic means. At a conference* in the Army Ordnance Department on November 22, 1941, it was unanimously agreed that a 70,000 Reichsmark contract should be issued to the firm for a pilot plant, one-tenth the size of the projected full-scale plant.

Even this process had its disadvantages, however, as Professor Harteck soon pointed out. While the process was cheap the plant would have to be fed with pure hydrogen, already slightly enriched if possible; and the commercially available hydrogen was always contaminated with traces of argon and nitrogen.

The most attractive process seemed to be the simple fractional distillation of ordinary water, which could operate very cheaply with the warm waste-waters available in plenty at numerous large industrial works. But the capital outlay would be large — a fifty-foot distillation column would yield only a few grams of heavy water a day; and even though such a plant would have increased Vemork's annual production by five tons, "it was not desired to reveal a process which could be easily copied abroad," as Harteck explained in 1944. This was a decision rivaling Göring's 1943 veto on anti-*Window* research in the radar war, for fear this might suggest the idea of *Window* to the enemy.

* Attended by Bonhoeffer, Clusius, Harteck, Korsching, Pose, Suess and Wirtz; and the Ordnance Department's Basche and Diebner.

As it was, the Germans arranged for the introduction of the Harteck–Suess dual-temperature exchange process to the Vemork plant to recover much of the heavy hydrogen that would otherwise have been lost, and production would probably soon rise to four tons a year. Professor Harteck strongly recommended that the firm's second electrolytic plant, at Såheim, should also be exploited as an additional source of heavy water, at the rate of one ton a year.

The possibility of erecting a large heavy-water plant on the Harteck–Suess principle in Germany was also examined. After the big Berlin conference at the end of February, Harteck and his colleagues had been approached by Dr. Herold, of I. G. Farben's ammonia works at Leuna, who proposed that his firm should build a pilot plant there. Herold took the matter up with thermodynamics experts and between them arrived at a cost per gram of only 30 pfennigs for heavy water. This was "quite tolerable." In the middle of April, Harteck and the eminent Professor Bonhoeffer began negotiations with Herold for the erection of a 150,000-Reichsmark pilot installation at Leuna. For economy reasons it would comprise only eight stages, aiming at an enrichment of 1 per cent. I. G. Farben undertook to meet the whole cost of the experimental plant, but this was not altruism: the company's director, H. Bütefisch, laid down that "the Army Ordnance Department must afford my closest colleagues working on the project, and myself, the most detailed picture of the problems involved in this method of generating energy." If the project succeeded, there would obviously be a commercial future in it which his company could not ignore.

This request was discussed by Professor Esau, appointed by the Education Ministry as the new titular head of the German atomic energy project, on the last day of April in Berlin.

Bütefisch again insisted that before I. G. Farben would cooperate "an exact knowledge of the overall problems" was required. The point was conceded and it was arranged that the company would be briefed in full on the project's objectives during May. "It was agreed that the pilot plant should be erected at Leuna as quickly as possible."

This was the beginning of I. G. Farben's fatal stranglehold on the uranium project in Germany: for when the heavy-water crisis developed in 1944, the firm was to refuse to meet its obligations, in a way that will be seen in due course.

At present, however, the exploitation of the heavy-water sources lay firmly in the hands of the military economic liaison office in Oslo, and in particular in the hands of Consul Schoepke, a Norwegian of German extraction serving on that staff. At Vemork, heavy-water production had risen to 103 kilograms during March 1942, but during April none was produced at all; the firm seized the excuse of the low water level to shut the whole plant down and overhaul the inside of one of the hydrogen gasometers. Not until May 6 did the turbines begin to whir again. In the meantime, the necessary modifications to give the Såheim plant a daily capacity of four kilograms of heavy water had been begun, and an investigation of the heavy-water content of the electrolyzers at Norwegian-Hydro's Notodden plant was in hand. By the middle of June, the company was tapping heavy water from the second high-concentration plant installed at Vemork on German orders, parallel to the existing high-concentration plant, in February. But general progress was slow, and Schoepke put this down to a "certain passive resistance" from the Norwegians themselves.

While these measures for increasing heavy-water production were being pursued, several teams of scientists in Germany were wrestling with the problem of enriching the uranium-235 isotope.

At the Kaiser-Wilhelm Institute in Berlin, Dr. Erich Bagge had begun the methodical construction of his "isotope-sluice" machine in the first days of 1942, when the first large components had reached him from Bamag. During the next two months he had built and tested various furnaces for vaporizing silver, the metal with which he proposed to prove the machine's practicability. Finally, on February 13, he had filled the furnace with uranium for the first time.

Three separate teams were working on electromagnetic methods of separating uranium-235. In Kiel, W. Walcher had built a mass spectroscope capable of separating minute quantities of silver isotopes, which theoretically should work with uranium too. Similar work was being carried out at Berlin-Dahlem by H. Ewald, in Otto Hahn's institute, although Ewald's design was unusual in some respects. Both these processes had the serious disadvantage that they would separate only minute quantities of the isotopes, literally one ion at a time. That this difficulty could be successfully overcome was shown by Baron Manfred von Ardenne, in a paper "on a new magnetic isotope separator with high mass transport" circulated by his laboratory in April. Von Ardenne actually built such a magnetic separator in his Berlin-Lichterfelde laboratory. It was not until after the war, when details of the magnetic process used by the Americans at Oak Ridge were published, that the similarity of von Ardenne's development could be seen.

By April, Dr. Groth's first prototype centrifuge was ready; the light alloy drum was rotated at increasing speed during its first tests until it had reached 50,000 revolutions per minute — still some way below its designed operating speed. Then it exploded. The alloy just was not strong enough. A month later, another, smaller drum was ready for testing in Kiel; this too exploded. These were only teething troubles, however, and it was obvious that within a very short time they would be getting a real enrichment. As Harteck now stressed, they had failed with the Clusius–Dickel process because they were dealing with imponderables. But with the ultracentrifuge there were no imponderables: the device depended on known physical processes which even uranium hexafluoride must obey.

[III]

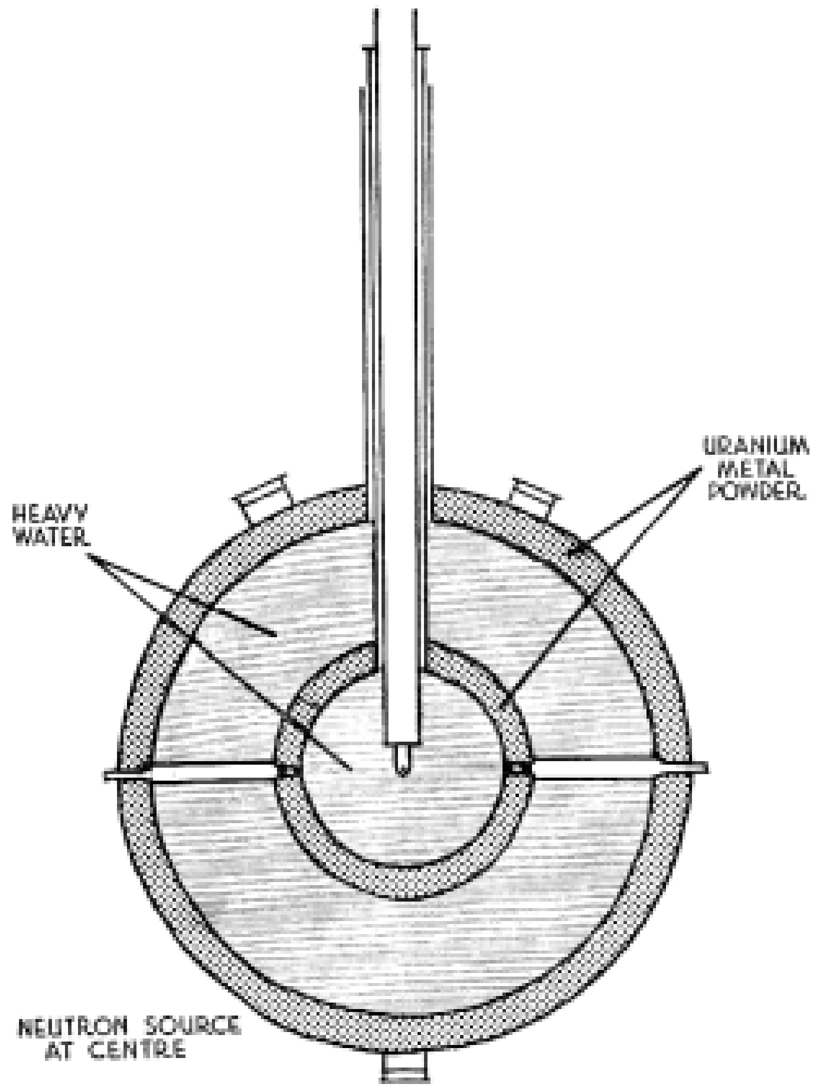
BY MAY 1, 1942, *Degussa* had manufactured almost three and a half tons of pure uranium metal in powdered form, of which the largest quantities had been delivered to the Auer company, to the War Office and to Professor Heisenberg, whose Leipzig institute was on the point of mounting its most important atomic pile experiment so far.

The previous experiment, *L-III*, had proved so successful that he planned to surround the pile used on that occasion with a further layer of uranium metal to see what happened. In the meanwhile, in December 1941, he and Professor Döpel had performed a fast-neutron experiment which had taught both of them a lesson on the unpleasant properties of uranium powder. Uranium is a highly pyrophorous powder — it has a tendency to catch fire upon coming into contact with the air. One of Heisenberg's technicians had been spooning the powder cautiously down into the aluminium sphere when there was a dull thud and a jet of flame about twelve feet high shot out of the funnel, burning his hand severely and igniting the nearby drum of uranium. Döpel and the technician had smothered the drum with sand, but when they cleared the sand away next morning they had found the uranium still burning fiercely. In some distraction, they had dropped the glowing embers into water, and established by this crude means that burning uranium could apparently be doused by an excess of water.

When Döpel and Heisenberg now prepared their crucial experiment *L-IV* — the *Degussa* firm had furnished Heisenberg with 572 kilograms of uranium powder on February 3 — they were obliged to conduct all the filling operations under carbon dioxide gas to prevent a recurrence of the incident. The total weight of uranium metal in the pile was over three quarters of a ton. The pile was encased in two aluminum hemispheres, securely bolted together. Together with the 140 kilograms of heavy water, its weight was not far short of a ton. The radium-beryllium neutron source was introduced into the pile's center through a sealed shaft, and the measurements began.

This time there could be no doubt; there were unquestionably more neutrons escaping the pile's surface than were being injected by the neutron source at its center, even after all other factors had been taken into account. The two Leipzig physicists put the total neutron increase at about 13 per cent. "So we have at last succeeded in building a pile configuration that generates more neutrons than it absorbs," the Döpels and Heisenberg reported to the War Office. "The result attained here is considerably better than could be expected on the basis of the experiments performed with uranium oxide. . . . A simple expansion of the pile configuration described would lead to a uranium reactor from which energy approximating to the energies within the atomic nucleus can be extracted."

Their calculations were still very approximate, but if their pile could be expanded to include about five tons of heavy water and ten tons of solid uranium metal, they would be able to build the first chain-reacting pile in the world. On May 28, *Degussa* transferred the first ton of uranium to its Number 1 Works in Frankfurt to be cut into slabs.



The Leipzig Pile *L-IV*. In May 1942, Professors Döpel and Heisenberg performed the decisive uranium pile experiment in Germany using the spherical apparatus pictured above. They were the first experimenters in the world to obtain a positive neutron production from a pile. No photographs of the pile exist, as it was destroyed in an accident soon after. The diameter of the sphere was roughly 80 cm.

The pile *L-IV* was still immersed in its water tank in Leipzig as Heisenberg traveled to Berlin on June 4 for the most crucial secret conference of the project; the uranium-project scientists were to meet Reichsminister Speer and his senior Munitions Ministry officials to decide on the future of nuclear research in Germany. Two months before, Göring had signed a decree expressly forbidding any development programs that were of purely postwar interest, and Speer alone could decide whether any program could be made an exception to this rule.

The conference was held in the Helmholtz lecture room of the Harnack building, the headquarters of the Kaiser-Wilhelm Institute in Berlin-Dahlem. Albert Speer was assisted by his technical chief, Karl-Otto Saur, and by Professor Porsche, the Volkswagen designer. Among the scientists who accompanied Heisenberg were Otto Hahn, Dr. Diebner, Professor Harteck, Dr. Wirtz and Professor Thiessen, who had written to Göring independently about the importance of atomic fission three months before. Dr. Albert Vögler, the president of the Kaiser-Wilhelm Foundation and of United Steel, was also there. From Otto Hahn's private diary we know that General Leeb (head of Army Ordnance) and his superior, General Fromm, were present, with Field-Marshal Milch* and Admiral Witzell, Leeb's counterparts in the other two services. After another scientist had addressed the meeting with a paper on a new mine-detector, Heisenberg moved up to the lectern. The previous two months, it must be remembered, had seen the beginning of the RAF's real area offensive against German cities, and Lübeck, Rostock and Cologne already lay in ruins, the latter city having suffered the first thousand-bomber raid. Heisenberg accord-

* The military interest in new explosives at this time can be gauged from a remark by Milch some days later: "Give our explosives experts a research contract — tell them to develop an explosive that is shrapnel-proof in the air, but that has a greater effect on the ground than any other such explosive! We must find some way of taking revenge for Rostock and Cologne and when we attack, we must start from the knowledge that it is only fires that destroy cities." See also Chapter 12, section 1.

ingly dealt with the military applications of nuclear fission straight away, and explained how an atomic bomb could be made. This was news even to the Kaiser-Wilhelm Foundation's officers, who until then had linked Heisenberg's research only with the so-called uranium furnace. The Foundation's secretary, Dr. Telschow, later said: "The word 'bomb' which was used at this conference was news not only to me but for many others present, as I could see from their reaction." Theoretically, said Heisenberg, two nuclear explosives existed, uranium-235 and element 94 (i.e., plutonium). From calculations by Bothe, they knew that the element protactinium should also be fissionable by fast neutrons, and that supercritical masses of protactinium should also detonate spontaneously, in the same way as plutonium or uranium-235. Protactinium could never be produced in sufficient quantity, however.

The question-and-answer exchange which remained rooted most deeply in the memories of all those present came at the end of Heisenberg's speech. Field-Marshal Milch asked how large a nuclear bomb would have to be to destroy a large city. Heisenberg replied that the explosive charge would be about "as large as a pineapple," and he emphasized the point with a gesture of his hands. This caused an uneasy excitement among the non-physicists present. Heisenberg, by his own account, hastened to moderate their enthusiasm with a warning that while the Americans, if they were working flat-out to that end, might have a uranium pile very soon and a uranium bomb in two years at the very least; for Germany to produce such a bomb was an economic impossibility at present. Nor could one be produced within a matter of months. "I was pleased," Heisenberg recalled six years later, "to be spared the responsibility of making a decision. The Führer's orders in force at the time ruled out altogether the enormous effort necessary to make an atomic bomb."

Heisenberg did stress however the importance of the uranium reactor, both for Germany's military plans and for her postwar development. Otto Hahn's diary shows that Speer approved the "construction projects," which included a large air-raid shelter specially equipped to house Germany's first large uranium reactor, in the grounds of the Kaiser-Wilhelm Institute of Physics at Berlin-Dahlem. While no decision was taken to inject full-scale governmental support into the nuclear program, it had on the other hand avoided extinction. Milch left the meeting unimpressed, and two weeks later formally authorized the mass production of a simple, unsophisticated weapon to become notorious as V-1, the flying bomb.

Field Marshal Milch (standing at far left): "How big would a bomb big enough to destroy a whole city be?"
Heisenberg: ". . . about as big as a pineapple."

On the evening of the conference, the scientists and politicians dined together in the Harnack building. Heisenberg found himself sitting next to Milch, and in a moment of abandon asked him outright how he thought the war would end for them. Milch retorted that if they lost they might as well all take strychnine; Heisenberg thanked him for the advice. Heisenberg says that from that moment he knew that the war was lost for Germany.

After dinner, he walked with Albert Speer the few hundred yards to the Institute of Physics, which the Minister had expressed a desire to see. The two men stood alone in front of the towering high-voltage particle accelerator, with nobody else in earshot. Heisenberg put to Speer the same question as he had put to Milch. The Minister turned and looked blankly at Heisenberg without uttering a word. The professor found it an eloquent silence. On June 23, Albert Speer discussed the uranium project with Adolf Hitler in Berlin, as item 16 on a long agenda. Afterward Speer noted only: "Reported briefly to the Führer on the meeting concerning atomic fission, and on the assistance we have rendered."

This is the only documentary evidence to show that Hitler ever learned of the uranium project in Germany, although he did touch upon the matter once vaguely two years later. It is tempting to regard the June 4 conference as final for the German project; of course, it was not. Heisenberg had been reluctant to commit himself to a huge atomic project on the state of his knowledge then, before he had even achieved a controlled chain reaction. When he saw subsequently the effort being invested in the V-1 and V-2 secret-weapon projects, he regretted the comparatively lowly status of uranium research, but he realized that this was his own fault: "We would not have had the moral courage to recommend to the government in the spring of 1942 that they should employ 120,000 people" on such a project, he said in 1945. It must be realized, however, that had he and his co-workers once successfully established a chain reaction there was nothing to prevent them from proceeding out of sheer curiosity to the next logical step, whether it was the extraction of plutonium or the separation of uranium-235. The successful chain reaction would give them the confidence — and hence the priorities — that they still lacked in June 1942.

On the same day as Speer was reporting to Hitler in Berlin, June 23, 1942, something strange began to happen in Leipzig, in the institute of Heisenberg and Döpel; the spherical atomic pile *L-IV*, which had been immersed in its water tank for twenty days now, began to emit a stream of bubbles. Döpel tested the bubbles and found they were largely hydrogen; he attributed this to a chemical reaction between the uranium metal and the water — there must be a leak in the sphere somewhere. After a time the bubbles stopped, which seemed to confirm his suspicions.

All the same, Döpel decided that the pile should be hoisted out of the water tank, and one of the inlets unscrewed to see how much water had got in. At 3:15 P.M. on the twenty-third, the same luckless technician as before loosened one of the inlet caps. Almost at once there was the sound of air rushing in, so there had been a partial vacuum inside. About three seconds later, the flow of air reversed, and a stream of hot gas escaped from the fissure, glowing with particles of burning uranium powder. Within seconds, a jet of flame a foot long was escaping from the sphere, melting the aluminum all around and setting still more uranium on fire. Döpel poured water on the blaze, to no avail, at first; the flames gradually subsided, although smoke continued to pour out of the pile's innards. He had the heavy water in the innermost sphere pumped out, so that that at least would be spared. Then, with two technicians, he winched the assembly down into the water tank again, in the hope that it would cool off. Heisenberg called in briefly, saw that all was well, and departed to hold a tutorial.

All was not well, however. The pile's temperature continued to rise. At 6:00 P.M. Heisenberg was summoned from his tutorial, as the pile was getting hotter and hotter. He and Döpel went over to the tank, and stood contemplating the shape of the aluminum sphere, refracted through the steaming water. They had just decided to open it up with a cold chisel at several points to avert disaster, when they saw the object almost imperceptibly shudder, and then quite definitely begin to swell.

Neither physicist needed any further encouragement. They leaped for the door, and reached the open air seconds before the explosion shattered the laboratory. A shower of burning uranium swept up to the ceiling, twenty feet above the ground, and large quantities of burning uranium dispersed throughout the building, which caught fire. "Thereupon," Döpel reported to the War Office, "we alarmed the fire brigade."

The Leipzig fire brigade arrived eight minutes later, and put out the worst of the fires with foam and water. They covered the pit with blankets of foam, but bursts of flame continued to belch out of the water for the next two days and nights, until finally all that remained of *L-IV* was a "gurgling swamp" of burned-out uranium, water, and fragments of aluminum casing. One of the more violent explosions had torn the upper hemisphere bodily away from the lower one, although the two had been bolted together by a hundred bolts.

That Professor Heisenberg and Professor Döpel should have escaped serious injury in the explosion was pure chance; but they had lost much of their laboratory, their uranium metal and the heavy water. The ordeal to their injured prides was equally severe. Heisenberg in particular must have squirmed when the brave fire-brigade commander assured him in broad

Saxon dialect of his brigade's congratulations for such an amazing display of "atomic fission."*

There had, of course, been no atomic reaction inside L-IV. Water had leaked into the outer shell of uranium metal and reacted with it to produce the highly explosive hydrogen gas. If this was unexpected by the physicists, it was thoroughly familiar to the chemists like the Auer company's Dr. Riehl, who had supplied the metal. A year before, *Degussa* had circulated through the Ordnance Department an explicit warning about uranium's unexpected properties: in a similar accident in Frankfurt, a large consignment of powdered uranium had suddenly caught fire and burned out. Professor Döpel wrote his own report on the two Leipzig accidents, specifically recommending that all future piles should be built with solid uranium metal to avoid disaster in this way.

Döpel was a strange man who managed during the course of the war to fall out with virtually everybody he worked with except Heisenberg. On this occasion, he wrote a sour letter to Dr. Riehl, upbraiding him for having sent them such a wicked substance for their experiments. Riehl replied politely, but no doubt drew attention to the warning leaflet circulated the year before. Döpel wrote him a further embittered letter, and the Auer chemist thought it more diplomatic not to reply.

It was June 1945 before he next saw Professor Döpel; both were in Moscow, in the outer office of Beria, head of the Soviet secret police and executive head of the Soviet atomic project to which they had been conscripted. Beria had called in these two

* Robert Jungk has described how Döpel prophesied after this Leipzig incident, "hundreds more will fall for the supreme goal — the atomic bomb." *Brighter Than a Thousand Suns.*

men with Gustav Hertz and Professor Vollmer to discuss the roles they were to play. Just before they went in to see Beria, Döpel crossed the room to Riehl, and apologized profusely for the two letters he had written him in 1942; he hoped Riehl would not hold them against him. This moving episode characterizes the tiny worlds in which each scientist had lived. Their whole world had collapsed around them, their fatherland had been vanquished and they had been transported to the capital of their enemy; they were in the anteroom of one of the most feared men in Europe and Asia. Yet it was the minor entanglements of their past careers that they wanted to straighten out. But we have trespassed on chronology; the narrative must return to the summer of 1942.

CHAPTER SIX

Freshman

"THIS ATOMIC FISSION PROJECT of such burning interest to us all," as Reichsmarschall Göring described it, had now entered its most difficult phase; a month had passed since Albert Speer had heard the German nuclear scientists put their case to him — a month in which the whole organism of scientific research had undergone upheaval. The Reich had resolved to mobilize German science for final victory, and the old Reich Research Council, presided over by Rust, had been replaced by a new independent body of the same name, directed by Reichsmarschall Göring himself. Adolf Hitler signed the decree on June 9; while the structure of the new council was gradually evolved, all its many projects stood still.

The new Reich Research Council would be controlled by Göring's "presidential council," twenty-one cabinet ministers, high-ranking military officers and party leaders, including Heinrich Himmler, but without a single scientist among them.

In actual fact, the council's activities would be directed by a managing subcommittee. It was a brave but belated attempt to put German research in order.

What no kind of internal reshuffle could repair, however, was the damage that the political persecution of academics had done. By 1937 nearly 40 per cent of the university professors had been dismissed and the increasing anti-Semitic trend had forced many more to flee Germany, including some of their best physicists. Now at last the Reich was realizing its mistake; in a remarkable secret speech at a Berlin conference on the Reich Research Council's future, attended by most of its presidential council,* Göring described the pain which the harassing of Jewish scientists was causing the Führer and himself:

> What the Führer abhors is any strict regimentation of science, with results like this: "This invention may indeed be vital — extremely vital to us, and would bring things a long way for us; but we can't touch it because the fellow's got a Jewish wife, or because he's half-Jewish himself. . . ."
>
> I have discussed this with the Führer himself now; we have been able to use one Jew two years longer in Vienna, and another in photographic research, because they have certain things which we need and which can be of the utmost benefit to us at the present. It would be utter madness for us to say now: "He'll have to go. He was a magnificent researcher, a fantastic brain, but his wife is Jewish, and he can't be allowed to stay at the

* The conference was at the Air Ministry on July 6, 1942, and a verbatim note was taken of the proceedings. The conference was attended *inter alia* by Göring, Milch, Speer, Funk, Ohnesorge, Fromm, Witzell, Mentzel, Brandt, Baeumker, Vögler and Rosenberg.

> University, etc." The Führer has made similar exceptions in the arts all the way down to operetta level; he is all the more likely to make exceptions where really great projects or researchers are concerned.

At the end of the conference, Göring returned to the subject of Germany's uranium project — a project "requiring the greatest secrecy," by which even the scientists concerned would have to abide. "Scientists have been prima donnas too long in this particular," he continued; and, referring to the last months before the outbreak of war, he added:

> It makes you sick to read of this or that physical or chemical congress being held in London or New York, and see the enthusiasm with which each scientist trumpets his discoveries to the world, as though they are too much to hold in his bladder one moment longer. How wonderful! Everybody hears about it! Only those of us with any real interest in exploiting the discoveries are the last to learn! In the first place we can't read the papers that these scientists publish — or at any rate I'm too feeble to. And the result is that we, who have the most use for the things, usually don't hear of them, while our scientists' colleagues in Britain, France and America know in detail just what kind of egg their German colleagues have hatched out.

There seems little doubt that Göring's wit was directed against Otto Hahn's publication of the discovery of nuclear fission in 1939.*

* *Hahn* is the German for "cockerel."

Some weeks later, Göring somewhat surprisingly appointed Ministerial-Director Rudolf Mentzel, a civil servant with a high honorary SS rank, to manage the council's affairs for him. As before, Mentzel would delegate the administrative burden to eleven general "faculty directors" — all of them eminent scientists, some with marked Party affiliations. In particular, there would be a number of "special plenipotentiaries" for the most important research projects, but at present nuclear physics was to be part of the domain of the existing physics section's head, Professor Abraham Esau. He would have a "business office"* to control the administration of the project, and Dr. Diebner was brought in from Gottow, together with Dr. Berkei, and put in charge. Their chief now was the same Professor Esau whose fingers had been burnt during the earliest days of the uranium project; his feelings toward its most prominent participants cannot now have been excessively warm.

In fact, it was not the physicists who had made the running in the uranium project so far: while the teams in Leipzig, Berlin and Heidelberg had pursued their theoretical investigations at leisurely pace, it was the group of physical chemists under Professor Paul Harteck in Hamburg who had adapted themselves to the urgency of the problem. It was Harteck — with his intuitive grasp of experimental technique — who had from the outset suggested that the uranium and moderator should be separated in the atomic reactor; it was Harteck again who had set up the first rough uranium pile, using carbon dioxide, in the first months of 1940, two and a half years before Fermi built the first successful pile in Chicago; it was Harteck and Suess who had devised a means of increasing tenfold Norwegian-Hydro's heavy-

* *Geschäftsstelle.*

water output. Again it was Dr. Groth who had toiled for a year with Harteck to make the Clusius–Dickel diffusion process work with the separation of the uranium isotopes, and it was Groth who had pushed through the revolutionary ultracentrifuge as a means of enriching uranium-235 — much to the surprise of Harteck, who had not thought that Groth had it in him.

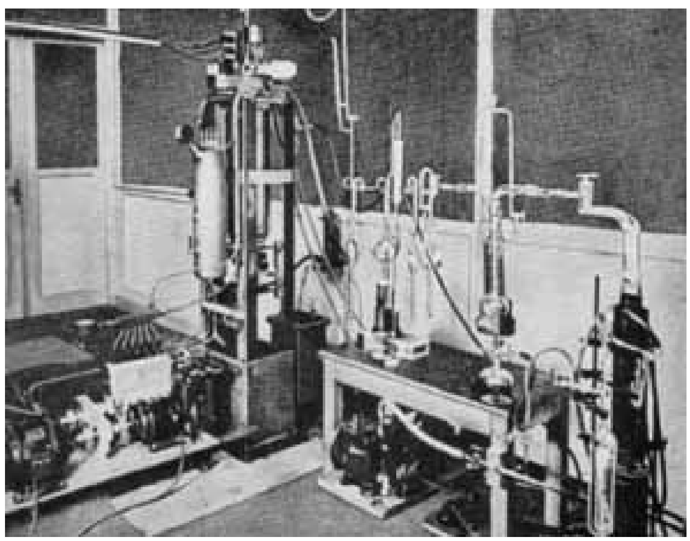
To Harteck, the outcome of the meeting with Speer had seemed a disaster. It was all very well to build the bunker to house the first reactor in Berlin, but now that his ultracentrifuge development was on the brink of success it seemed that they might lose all priority to continue. On June 1, pilot experiments to separate the isotopes of the heavy gas xenon had come to a triumphant conclusion, using the ultracentrifuge of which Anschütz & Co. had begun the construction only six months before. The separation factor of the new process agreed virtually exactly with their theory, and they were on the point of using the machine with uranium hexafluoride for the first time.

On June 26, after Dr. Diebner had traveled specially to Kiel and Hamburg to discuss this new development with him, Professor Harteck wrote to the War Office a plea for continued support:

> As is well known, two methods can be adopted for building a uranium reactor:
>
> *Reactor Type I* consists of natural uranium and about five tons of heavy water;
>
> *Reactor Type II* consists of uranium metal enriched in uranium-235 and consequently smaller in quantity, together with smaller quantities of heavy water or even ordinary water.
>
> The German research group has been following the first method, while the Americans will probably have adopted the second. Only experience will show which of the two is the more prac-

> tical in the long run. In any event, the second method will result in significantly smaller reactor units, which might possibly be usable for driving Army vehicles.
>
> This latter method is, furthermore, more akin to the manufacture of explosives.

As he explained, the enriched uranium pile had not at first been adopted by Germany because of the apparently insoluble problem of enriching the uranium-235 isotope. The results of Groth's ultracentrifuge experiments had been so encouraging, he concluded, that "we must concentrate our energy more and more on this second method."



The first ultracentrifuge, built by Harteck and Groth to enrich uranium-235

Early in August, the machine was run for the first time with uranium hexafluoride in its rotor. In the first series of runs, the average enrichment of uranium-235 was about 2.7 per cent, and when the runs were repeated at higher speeds four days later it increased to 3.9 per cent. These values were less than had been hoped for — probably because of contamination as the samples were drawn off — but there still was an enrichment. Heisenberg and his team in Berlin had shown that a total enrichment of 11 per cent would suffice for a reactor to be built using ordinary water, so in theory all that would be necessary would be a battery of such ultracentrifuges to enrich the uranium-235 stage by stage.

Harteck had already conceived two important modifications to the design, while sitting exhausted in a train from Kiel to Hamburg. Why not subdivide the length of the rotor into a number of chambers, each one's periphery connected to the axis of the next? And why not run two such centrifuges, linked to each other by two pipes, and running at different speeds, in such a way that the pressure difference between them constantly varied? The gas flow would oscillate from one rotor to the other, multiplying the effect several times in just the one double-centrifuge.

Reporting on the importance of the ultracentrifuge to Reichsmarschall Göring, Professor Esau predicted that as soon as its development was complete such machines would have to be manufactured in large numbers to meet Germany's requirements of uranium-235. Late in October, the machine's builders agreed to alter the prototype along the lines suggested by Harteck; the professor advised them that now that they had proven the possibility of enriching uranium-235, the government was certain to place a very large order with them indeed.

Professor Esau, however, had little inclination to pursue the development to its logical conclusion — the uranium-235 bomb. He advised Professor Haxel, who at about this time was detached by the German Admiralty's research establishment to act as liaison officer with him, that if word of the possibilities of a "uranium bomb" once reached the Führer's headquarters then Haxel and all his colleagues might expect to spend the rest of the war behind barbed wire until they had made such a bomb.

Haxel was advised to stress the "uranium engine" as the real *raison d'être* of the project.

[11]

HEISENBERG HAD TALKED of the need for "five tons" of heavy water before they could produce a chain reaction in a uranium pile. By the end of June 1942, the Vemork heavy-water plant had delivered to Germany only 800 kilograms, about one sixth of the required amount. Once again the possibility of manufacturing heavy water in Germany was brought up, this time at a conference between Diebner and Berkei and the heavy-water experts, in Berlin in mid-July; Heisenberg and Bothe also participated. They learned that the full-scale Clusius–Linde process, for which a pilot plant was already being built near Munich, would produce only 200 kilograms of heavy water *a year* if fed with ordinary hydrogen; it would be better if the hydrogen was already slightly deuterium-enriched. Was there a source of slightly enriched heavy hydrogen available to the Germans? Professor Harteck objected that the process would require excessive power and cooling, and hydrogen of the greatest purity as well. His arguments were not heeded. The other scientists recommended dispatching a commission of experts to the big hydroelectric power station at Merano, in the Tyrol, to examine the concentration of heavy water in its electrolytic cells. If there was enough, the Clusius–Linde plant's output could be raised to one and a half tons a year. The conference ended with a general conclusion that "the procurement of heavy water is as urgent as ever," and that consequently the development of other processes was not to wait on the results of the inspection of Merano.

Dr. Hans Suess went to Vemork for ten days and together with the chief engineer Jomar Brun carried out a series of experiments to see how far the use of catalysts would increase the effect of their dual-temperature exchange process being introduced into the earlier stages of the plant. By now the Germans and Norwegians were on the closest of terms. Together with a second Vemork engineer, Alf Larsen, they built a small laboratory-scale apparatus at the plant to test the efficiency of the various catalysts.

At the end of ten days, Dr. Wirtz and Dr. Berkei came up from Germany. Consul Schoepke met them in Oslo and accompanied them to Rjukan, with three Norwegian-Hydro engineers, Voslew, Eide and Johannsen. The humming powerhouse of the Vemork hydroelectric plant provided the inspiring backdrop for their conferences on methods of increasing heavy-water production still further. The local director of Norwegian-Hydro attended as well. They confirmed that work on the modification of Stage 6 of the plant was far advanced. During the next three months Brun and Suess wrote three joint reports to the German War Office on the steps they had taken to increase the efficiency of the process and the various catalysts they had tested for Stage 6.

On July 25, the German scientists inspected the progress being made at the Såheim electrolytic plant: the new Pechkranz electrolyzers were already in service, and two more were being awaited from Bamag in Berlin. "There is agreement that all available electric current must remain switched to *SH.200* [heavy water] production." As some production had been lost at Vemork through various delays, the military authorities in Berlin and Oslo agreed that it was vital for the construction of a high-concentration plant to begin at Såheim as well, and the War Office's research department undertook further to apply for the necessary allocations of scarce materials — V2A steel, rubber and asbestos — for the manufacture of a complete nine-stage heavy-water plant for Germany.

Three days later, Director N. Stephanson of Norwegian-Hydro promised the Germans that "as long as the present head of water can be maintained, the production will be about 125 to 130 kilograms per month." On September 14, the Harteck–Suess exchange-process modification was put into operation for the first time at Vemork. Within a short time, the Germans confidently expected the plant to reach its new maximum of 400 kilograms a month. At the end of November, Professor Esau reported to Göring that as soon as the necessary experiments at I. G. Farben's Leuna works were complete, the large-scale production of heavy water would begin in Germany too.

In the meantime, industry was bent to the task of supplying the several tons of uranium metal plates needed for the full-scale reactor experiment. The contract for casting the metal had been awarded to *Degussa*'s Number I Works, in Frankfurt's Weissfrauen Strasse. The first kilogram of uranium had gone there for experiments late in January, followed by a hundred kilograms in mid-May and a ton at the end of the same month. The smelting was done in electric resistance furnaces under vacuum, but the casting was primitive and unsatisfactory, leaving many cavities and impurities in the slabs.

Production of uranium metal powder had varied during 1941, as the call for the uranium was most irregular. The uranium oxide reduction plant at Gutleut Strasse had a capacity of one ton a month, but during the whole of 1941 — during which time it was totally undisturbed by bombing — it produced only 2,460 kilograms of uranium. It is not easy to ascertain why the output was so low: the plant needed only five or six men to operate it, and there was unlimited raw material; yet the shortage of this metal alone was eventually to cripple the project.* Even though the Frankfurt plant was not operating at capacity, moreover, work began early in 1942 on a second uranium-reduction plant identical with the Frankfurt one at *Degussa*'s chemical works at Grünau, near Berlin. The project started with a very high priority rating indeed. But progress at Frankfurt was slow, and inexperience with the smelting of uranium brought many delays in the casting of the plates demanded by Heisenberg and Döpel. As the uranium project gradually lost priority, *Degussa* experienced mounting difficulties in obtaining spares for the two Frankfurt factories, and at the end of 1942 — with the factory short of vacuum pumps, copper for the transformers and other vital commodities — uranium metal output began to sink.

[III]

BRITISH INTELLIGENCE had been following the German uranium project's development with anxiety since the first warnings of increasing deliveries of heavy water to Germany had come in 1941. The most reliable intelligence continued to come through Scandinavia to Commander Welsh's desk and from him to Michael Perrin at the "Tube Alloys" headquarters in London; some

* Metallic uranium production, in kilograms, in Germany during the war at *Degussa* (Frankfurt):

1940	280.6	(laboratory)
1941	2,459.8	(factory)
1942	5,601.7	"
1943	3,762.1	"
1944	710.8	"

In 1944, the company began production of metallic uranium at Berlin-Grünau: December — 224 kilograms; January (1945) — 376 kilograms; February — 286 kilograms.

of the best information was coming from a leading Berlin scientist whose name we have already encountered in these pages.

At about the same time as Speer was "reporting briefly" to the Führer, the British Cabinet received a most detailed indication that something was indeed stirring inside Germany. Perrin's superior at "Tube Alloys," Wallace Akers, wrote to Mr. Churchill's scientific adviser, Lord Cherwell, that a certain Swedish theoretical physicist had written from Uppsala to a correspondent in Britain, warning that Heisenberg was conducting extensive experiments in German laboratories with the intention of exploiting chain reactions of fission processes and "especially uranium-235." Results, the Swede had warned, must not be excluded.

During the spring of 1942, the British Intelligence services had established an important direct link with the town of Rjukan itself, in southern Norway. In the middle of March the SOE's leading agent in Norway had captured a coastal steamer and with the aid of a small band of volunteers had sailed it to Aberdeen. One of the volunteers was Einar Skinnarland, who not only was willing to work for the Allies, but came from Rjukan as well; if he could return almost at once, his absence would not even be noticed. Skinnarland was hurried through an SOE training course and briefed on his duties by Major Tronstad, the Norwegian physicist now directing his country's espionage organization in London. He was parachuted back into Norway early on the morning of March 29, 1942, just eleven days after his arrival in Britain. His absence had not been noticed.

Skinnarland soon reported to London through Sweden that he had established direct contact with some of the heavy-water factory's technicians and the chief engineer, Jomar Brun, and London obtained a clear picture of the priority attached by the Germans to increasing heavy-water production.

Soon after Suess had visited Vemork, Brun received a request for information from Major Tronstad in London. Brun procured photographs and drawings of the whole high-concentration plant, and details of how the Germans were planning to increase its production. He had these papers microphotographed by Dr. L. D'Arcy Shepherd in Rjukan; the microphotographs were concealed in toothpaste tubes and smuggled through Sweden to Britain by courier. Whether the perspective was distorted in these early reports is open to question. At any rate, Professor Paul Harteck suggested in 1944 that "the security precautions adopted at the plant against sabotage, the military supervision of the project, and the pressure that was exerted from these military quarters for the acceleration of the work resulted in an overestimation by the Norwegians of the importance of *SH.200* [heavy water] for military purposes." Brun's conscience certainly was sorely troubled by the possibility that heavy water might be of military use after all. He had recently learned for the first time of the potential nuclear energy applications from an unguarded reference by Suess to a patent by Professor Joliot. Was this the reason why the Germans were at such pains to increase Vemork's production? Suess's remarks were reported to Tronstad in London: the German physical chemist had tried to reassure him that the Reich's plans were of a peaceful nature, designed to aid Germany's postwar power economy. Suess had suggested that the development might take many years, but Brun was unconvinced.

In Chicago, a group of scientists under Professor Enrico Fermi had by this time completed the basic calculations of effective cross-sections necessary for the completion of a uranium-graphite lattice pile. Indeed, by December 1941, after building several model piles in rapid succession, Fermi had built a pile that was so close to going critical that he believed it required only the employment of purer materials for a chain reaction to begin. In March 1942, Dr. Vannevar Bush had advised President Roosevelt that there were in theory six basic methods of exploiting nuclear energy: four involved the separation of the rare uranium-235 isotope — using either the ultracentrifuge (like Groth), thermal diffusion (like Clusius and Fleischmann), electromagnetic separation (like von Ardenne, Ewald and Walcher) or gaseous diffusion through porous barriers as developed by Gustav Hertz — and two relied on the extraction of plutonium from a uranium pile, moderated by either graphite or heavy water.

While the German scientists had hedged and prevaricated when asked whether their research would result in a weapon in the foreseeable future, the Americans almost simultaneously took a firm positive stand. On June 17, Bush told Roosevelt that under ideal conditions an atomic weapon might be ready in time to influence the outcome of the present war. Within the next month, the decision had been taken to build electromagnetic separation plants for uranium-235 in America; and in Britain the construction of a small pilot gaseous diffusion plant, based on Gustav Hertz's theory, was put in hand. The United States government at last made arrangements to acquire 350 tons of uranium oxide, and contracts were placed for its refinement and reduction to uranium metal powder. Before any uranium pile had even gone critical, work was begun on the construction of a pilot uranium reactor in the Argonne Forest near Chicago; and at the request of the British, contracts were issued for the erection of a heavy-water plant at Trail, in British Columbia, as a precaution should graphite for some reason prove unsuitable as the moderator. By the end of July 1942, an eighty-thousand-acre site at Oak Ridge, in the state of Tennessee, had been selected for the main isotope-separation plant, and its purchase awaited only the outcome of the first experiments with Fermi's Chicago pile.

What lead the Germans had possessed in 1940 and 1941 was being swiftly ground away by the United States, but nobody had yet proven experimentally that a self-sustaining uranium reactor could be built, and the Germans still controlled the only heavy-water factory in the world.

[IV]

SUCH WAS THE CLARITY of the Intelligence picture now forming in London that in July 1942 the War Cabinet urgently requested Combined Operations to prepare a strong ground attack on Vemork to destroy the heavy-water factory. Any idea of bombing the factory had been strongly opposed by Major Tronstad, who warned that if stray bombs were to hit the liquid-ammonia storage tanks the whole population would be in gravest danger. This would be no straightforward operation, and Combined Operations turned to the Special Operations Executive for advice. The latter's Norwegian section informed them that the SOE already had an advance party including an expert wireless operator standing by for a favorable opportunity to parachute into Norway and set up a base camp on the desolate Hardanger plateau, a high plateau some thirty miles northwest of Rjukan.

This advance party was put at the disposal of Combined Operations. It was now planned to land some two score engineer troops of the First Airborne Division, using gliders for the first time, near the Mösvatn lake which fed the Vemork plant's turbines. The troops would form up on the main trunk road winding across the plateau and through Rjukan, and march in full uniform on the Vemork plant. Having blown it up, they would attempt to escape into Sweden.

That *Freshman* — the operation's code name — was ill-conceived and under-planned was at once suggested by SOE's Norwegian section, but the Combined Operations planning officers seemed to exercise the greater influence, for the objections were ignored. The plan still called for the soft landing of two gliders laden with troops and demolition equipment on the Hardanger plateau — an area strewn with man-sized boulders and rugged with fissures and ridges, surrounded by treacherous ranges of snow-capped mountains and canopied by a wild and boiling sky. The operation's protagonists could argue that it had in it the seeds of success: a bold coup, a swift escape, and the war against the German uranium bomb would be over. During September, intelligence reached the Allies that 130 kilograms of heavy water were being delivered to the Germans each month. General Groves, head of the American atomic project, suggested that Vemork should either be bombed or sabotaged, and the wheels of *Freshman* began to turn.

At 11:30 P.M. on October 18, the four Norwegians of the advance party were parachuted into Norway. It took them two days to collect the equipment and supplies parachuted after them, and they had hidden only half these stores when a violent snowstorm broke over them. They tried to establish wireless contact with SOE headquarters, but failed. After a forced march of several days, laboring under the heavy packs of equipment, they reached their operational base at Sandvatn on November 6. Their radio operator again tried to contact London and had just succeeded when his accumulator failed. A fresh accumulator was procured from the keeper of the Vemork dam at Mösvatn, Einar Skinnarland's brother. The four men erected a good wireless mast and again tried to contact London, but this time the wireless set was damp and refused to function. Only on November 9 was contact finally established with SOE headquarters. The relief there at hearing from the advance party was tempered by the somber information contained in its first signal: there was a strong German garrison in the Vemork area, and barricades had been set up around the factory itself and alongside the penstock lines bringing the water down from the Mösvatn lake to the turbines.

In the next few days, the Intelligence attack on German heavy-water production received a strong stimulus. On the day after London received the first signal from the advance party, Jomar Brun, the chief engineer of the Vemork plant, flew into Britain after a long and hazardous escape from Norway. He had set out from Vemork on October 24, seventeen days earlier; two days before that, a secret courier, introducing himself as "Mr. Berg,"* had arrived at his home bringing orders from General Hansteen in London directing him to leave for Britain immediately. Before he and his wife finally left Vemork, Brun took a considerable weight of the factory's documents and blueprints with him; these were microphotographed by the Norwegian underground in Oslo, and the films were duly passed to the Norwegian authorities in London.

Engineer Brun and his wife were installed in the De Vere Hotel in South Kensington as soon as they reached London on the eleventh. That same evening Commander Welsh and Major Tronstad called round on them, and took Brun to a conference with Dr. R. V. Jones. The Norwegian heavy-water engineer was exhaustively questioned about the impressions he had gained during his visit to the Kaiser-Wilhelm Institute of Physics in

* "Berg" was in fact Fredrik Bachke, who now owns a prominent shipping company in Norway.

Berlin eleven months before. Most of the questioning was done by Dr. F. C. Frank, Jones's assistant, who seemed to be very familiar with the institute in Berlin; it turned out that Frank had worked there himself before the war. Brun expressed particular concern for the safety of Dr. Suess in any planned operations; a strong friendship had grown up between them. On the following day, Brun was taken to see Michael Perrin by Tronstad and Welsh.

The planning for *Freshman* was virtually complete before his arrival in London, but he was able to provide the operation's planning staff with final information on the factory's most vulnerable features. Brun — by now assigned the code name "Dr. Hagen" — was given an office next to Major Tronstad's, where he prepared detailed drawings of the heavy-water plant and reports on the Vemork factory's surroundings. His presence in London was kept a closely guarded secret.

By the third week in November, all was ready for the Combined Operations undertaking. The *Freshman* force was made up of thirty-four specially trained sappers, all volunteers, under the command of Lieutenant Methven, GM. They were packed into two Horsa gliders, each towed by a Halifax bomber, late on November 19. That morning, the weather forecast had promised thick cloud over most of the 400-mile route out to the objective, but clear skies and a bright moon over the objective. While it was still light that evening, the two cumbersome pairs of aircraft lifted into the air from Wick airfield in Scotland and set course for Norway.* What exactly happened in the grim hours that followed will never be known with certainty. Neither of the

* The gliders were flown by Sgt. M. F. C. Strathdee and Sgt. P. Doig (Glider Pilot Regiment), and Pilot Officer Davis and Sgt. Fraser (Royal Australian Air Force).

Halifax crews had had much experience of towing gliders and the aircraft seem to have been inadequate for the task set before them.

Soon after take-off, the telephone links between both Halifaxes and their gliders failed. One Halifax approached the Norwegian coast at ten thousand feet, piloted by Squadron Leader A. B. Wilkinson, with the squadron's commanding officer, Group Captain T. B. Cooper, on board. The sky cleared over southern Norway, but despite every attempt to identify their dropping zone, the snow-covered countryside defied all efforts to make out pinpoints on the ground. Finally, with fuel running low, Halifax and glider were forced to turn for home. Forty miles west of Rjukan, they ran into heavy cloud and icing conditions; the tow-rope snapped just as they were crossing the coast. The Halifax radioed back to Britain that the glider had fallen into the sea.

The second Halifax glider combination flew in low across the North Sea to get under the cloud, planning to gain height as soon as the sky cleared over Norway. They crossed the coast of southern Norway at Egersund and crashed into a mountainside ten miles inland. No ground defenses had fired upon them, so the cause of the crash was a mystery. All six men in the towing aircraft and three of the troops in the glider were killed outright, and several others badly injured. When German troops reached the area at ten to six that morning, the wrecks of aircraft and glider were about five miles apart, which suggested that the bomber had slipped the glider at the last moment in a vain attempt to gain height. The fourteen survivors were all still nearby.

The troops were clad in British khaki uniforms with no shoulder flashes or other insignia; some were wearing blue skisuits under their uniforms. The evidence salvaged from inside the wooden glider's wreckage was damning: besides eight rucksacks, tents, skis, radio transmitters, and a number of machine and tommy guns, there was a large quantity of food and explosives. A Counterintelligence officer hurried to the crash sites from Stavanger. As a result of his inspection of the wreckage "considerable quantities of sabotage material and industrial equipment were found; sabotage motive [was] therefore proven beyond doubt."

The fourteen surviving commandos — six of them grievously injured in the crash — had in the meantime been handed over to the German battalion headquarters at Egersund. During a brief interrogation they had "stated just their name, rank and service number." The 280th Infantry Division ordained that the Führer's Commando Order should now run its course, and the fourteen Britons were led out and shot that evening.

The precipitous execution of these Britons was criticized by the Gestapo authorities. Reich Commissioner Terboven and General Rediess, chief of the secret police in Norway, lodged immediate protests about the infantry division's action; and Rediess telegraphed a sour report on the incident to his superiors in Berlin:

> A British towing aircraft and its glider have crashed near Egersund at about 3:00 A.M. on the 20th. Cause of accident not yet known. As far as has been ascertained, towing aircraft's crew is military, including one Negro; all dead. There were seventeen men in glider, probably agents. Three of them were killed, six badly injured. Glider's crew was in possession of large quantities of Norwegian money.
>
> Unfortunately the military authorities executed the survivors, so explanation scarcely possible now.

SS-General Müller, head of the Gestapo in Berlin, forwarded the Oslo telegram to Heinrich Himmler's headquarters. The Military Governor of Norway, General von Falkenhorst, angrily drew his subordinates' attention to the closing sentence of Hitler's order, which made express provision for the execution of individual saboteurs to be stayed long enough for them to be briefly interrogated. Falkenhorst issued an immediate order that all such prisoners were in future to be turned over to the security police for military intelligence and security police questioning before being shot.

Falkenhorst's new order reached the military authorities only just in time, for during the day, November 21, the Germans discovered that a second British glider had crash-landed in southern Norway, also laden with commandos. The German Fifth Air Force had monitored wireless traffic from its towing aircraft as it had returned to Britain, but the first indication that it had reached land came when Norwegian police captured three of the British commandos. The Britons told how after their glider had been released it had crash-landed in mountainous country some thirty miles inland from Stavanger. Of the sixteen men in the glider, several had been killed or injured in the crash, they said. The glider had in fact crash-landed on the north shore of Lyse fjord, over a hundred miles southwest of Rjukan and almost directly opposite the Flöyrli power station supplying Stavanger. The Germans mounted a full-scale search for the wreckage and further survivors, and all suffered the same fate as their comrades.

They had been closely questioned this time on their operational target, before being executed; some weeks later Falkenhorst informed the German High Command that "the interrogation yielded valuable admissions on the enemy's intentions."

There is little point in dwelling upon the exact intelligence derived by the Germans from these unhappy men and their effects. Suffice to say that German police troops cordoned off and searched the areas where the two gliders *should* have landed; many Norwegians were arrested for being in possession of illegal arms or wireless. General Rediess warned Berlin that there were "several indications that the British placed great importance on the execution of the planned destruction of these installations." Through Stockholm London learned that on December 4 a false air-raid alert had been sounded in Rjukan, and while the townsfolk had sheltered indoors two hundred German troops had entered the town and searched every house. "The search lasted for 15 hours," reported *The Times*, "during which a state of siege prevailed." When Reich Commissioner Terboven and General von Falkenhorst drove up to Vemork and inspected the factory in person there could be doubt no longer that the Germans had learned the exact objective of the glider troops. The Rjukan garrison was again strengthened, and work began on a dangerous minefield all round the heavy-water plant.

The first phase of the atomic weapons campaign had thus ended — that in which each side hoped that the other might be unaware of what it was preparing. Now the Germans could only accept that the Allies knew what they were doing; now too they must suspect that the Allies themselves might be working on the same lines.

CHAPTER SEVEN

Vemork Attacked

ON THE MORNING after the disastrous first attempt to destroy the Vemork hydroelectric plant, London wirelessed the unhappy news to the four men of the advance party waiting on the Hardanger plateau in southern Norway. It was a "hard blow," as the party's leader Jens Poulsson wrote that day. It was now November 20, 1942, and they would have to wait several weeks in that icy waste for the next moon period, before another attempt could be made.

In London, Colonel "Jack" Wilson, head of SOE's Norwegian Section, telephoned Combined Operations headquarters and offered his condolences; the SOE was prepared to take over the job of destroying Vemork, he said. Combined Operations expressed unmitigated relief. Wilson went straight down and broke this to Major-General Sir Colin Gubbins, Director of the SOE. Gubbins's first reaction was one of dismay ("You can't do that!"), but he allowed himself to be persuaded. They knew nothing, of course, of the tragic fate of the commandos who had survived the glider crashes.

During the morning, Major Tronstad arrived and briefed the SOE on the detailed intelligence available as a result of Dr. Brun's defection from Vemork; the high-concentration plant's layout did offer some prospect of success for a small, highly trained sabotage party. Brun had in particular described to Tronstad a cable duct providing a secret and unsecured "entrance" to the plant. Within a very short space of time the War Cabinet's blessing had been secured for a small-scale sabotage operation by the Special Operations Executive. Wilson telephoned the SOE's Norwegian "depot" at Aviemore in the Cairngorms and left instructions for one of the most outstanding Norwegians, Lieutenant Joachim Rönneberg, to stand by for a special mission; he was to select five good skiers to accompany him.* Colonel Wilson traveled up on the overnight express, with his operations officer and Tronstad, and briefed Rönneberg on the general nature of the target — an industrial installation — and on the training that would be necessary.

All the Norwegian SOE troops had been through the same courses — basic infantry training, demolition and explosives. At special SOE training establishments, they had been steeped in the handling of dynamite, gun-cotton, TNT and plastic explosive; they had practiced blowing holes in brick walls and armor plate and learned to judge how much material to use; they had been taught the use of fuses and detonators and how to fashion their own devices and booby traps. Finally they were transferred to the depot at Aviemore, waiting for the final call to arms.

* All were volunteers from the Royal Norwegian Army; the five selected were Lieutenants Knut Haukelid and Kasper Idland, and Sergeants Fredrik Kayser, Hans Storhaug and Birger Stromsheim.

All were taken to London and briefed by representatives of General Hansteen's Norwegian defense staff on the importance of their mission. They were warned that the Combined Operations assault sent out shortly before had met with disaster. Lieutenant Knut Haukelid, who was to stay behind in Norway and build up the military organization there, was briefed separately by Major Tronstad as head of the Staff's Sabotage and Intelligence Section IV.

As Tronstad outlined it to the party, the plan — code-named *Gunnerside* — was that they should be dropped into Norway one night, and join up with the four men of the advance party dropped before the ill-fated glider operation, and with Einar Skinnarland, the radio operator dropped in the spring of 1942. They would advance on Rjukan and blow up the vital high-concentration plant at Vemork. Haukelid and three of the advance party would remain in Norway while the others would make good their escape into Sweden under Lieutenant Rönneberg's command.

The six men were transferred to a special training school, Number 17, which was cleared of all other training personnel. As the correct identification of the target machinery was all-important, three dummy stages of the Vemork high-concentration plant were mocked up in a well-guarded hut inside the compound, with the help of Tronstad and Dr. Brun, both of whom had worked on the design of the original plant at Vemork. The six SOE soldiers were unaware of Brun's existence.* They practiced ceaselessly at laying dummy charges in the dark and getting the general feel of the model. They pored

* Cf. Haukelid, *Skis Against the Atom*, p. 63: "Sometimes we raised some special question which he [Tronstad] could not answer and then he took it away and gave us the answer next day. So we guessed that he was in contact with someone who knew the factory even better than he did."

over aerial photographs of the factory and gorge, and fashioned two complete sets of plastic explosives and detonators, each set containing one charge for each of the eighteen high-concentration cells at Vemork. At the turn of the year, they were transported to a final holding school in Cambridgeshire to wait for the next full moon.

[11]

PROFESSOR HEISENBERG had now been "scientific adviser" to the Kaiser-Wilhelm Institute of Physics in Berlin-Dahlem since early 1940. During the summer of 1942, Dr. von Weizsäcker and Dr. Wirtz in Berlin finally persuaded the governors of the Kaiser-Wilhelm Foundation to recognize Heisenberg as the institute's de facto director. This was technically impossible, as Debye — by now in America — had never resigned; so on October 1, Heisenberg was appointed "Director at the Kaiser-Wilhelm Institute of Physics." Now he was finally within the total influence of the two politically conscious physicists who had engineered this "coup." As the big *WHW* signs for the *Winterhilfswerk* — winter relief fund — began to go up over Germany, the other scientists in the institute ironically mocked that the initials stood for "Heisenberg, trapped between Wirtz and von Weizsäcker."

The hapless Dr. Kurt Diebner withdrew from Dahlem to the Army's Gottow research site, where they had already begun the construction of their own atomic pile experiments. The Gottow establishment was primarily an explosives research laboratory, extremely well equipped with workshops and explosives testing pits.

The feud between Heisenberg's followers and the Army's experimentalists remained unhealed. And all were jointly ridiculed by those who wished to capitalize on the disorganization of

German research. If Dr. Diebner was characterized in a memorandum on Göring's file as a man "who never even got out of the technical college rut" and who had been able to save face "only by falling back upon the Official Secrets Act," then Heisenberg was now equally castigated as "the chief theorizer, who even in 1942 still writes his praises of the Danish half-Jew Niels Bohr as a great genius."

It was true that Dr. Kurt Diebner was not a great theoretical physicist, and he was certainly not of Heisenberg's caliber. But he was a good experimenter, and had a good fount of common sense. Dismayed at the slow progress being made by the uranium project, he resolved to perform his own pile experiment, without Heisenberg's knowing, at Gottow. All the theory evolved by the theoretical physicists so far had indicated that alternate layers of uranium and moderator were the best geometry for a reactor. Diebner took this fact, by now amply proven by the Leipzig experiment *L-IV*, and reasoned that projected *into three dimensions* the layer arrangement should be even more effective. In other words, the uranium should be surrounded by layers of moderator in all three dimensions — and this meant using uranium *cubes*, not plates. This was the most important single decision of the whole German research effort.

During the summer of 1941, large quantities of uranium oxide had become available to the Army Ordnance Department, and as he lacked any uranium metal, Diebner set up his first atomic pile in the summer of 1942 using this oxide, with paraffin wax as moderator. A special concrete laboratory was built at Gottow to house the pile, for which Bamag-Meguin manufactured a special aluminum vessel, a cylinder broad enough for several men to work comfortably inside. Diebner's team of technicians and engineers worked in the same kind of special clothing as had been developed for the Virus House, and repeated blood tests were taken as a check against radiation overdoses. Using an ingenious method, they rapidly built up an elaborate honeycomb of paraffin wax, layer by layer, in the aluminum tank, filling each cubic "cell" with powdered uranium oxide (the Auer company had been unable to mass-produce the oxide in briquettes) as they went. Each of the nineteen layers in the pile took one day to build. When they had finished the honeycomb, it contained 6,802 cubes of uranium-oxide — about 25 tons — embedded in 4.4 tons of paraffin. Each cube was separated from the next by a two-centimeter layer of paraffin as moderator. The aluminum vessel stood in turn in the concrete reactor pit, which was filled with water as reflector and shield. Funnels and shafts were cut through the pile to give access for the neutron source and the various measuring devices.

The result of this first Gottow experiment was negative only inasmuch as there was no neutron increase; with only uranium oxide and paraffin wax that had been expected all along. But the great advantages from using cubes instead of plates had been overwhelmingly demonstrated. The Gottow team's first *Secret Research Report* was distributed by the Army Ordnance Department toward the end of November 1942.

While Diebner's group was performing these important experiments at Gottow, the series of pile experiments in the Berlin Virus House had been extended to include piles of uranium metal powder and paraffin wax. During three different experiments, the number of uranium layers was varied from nineteen to twelve and then to seven, while their thickness was varied accordingly. The results grew progressively worse, and none of them was as successful as the heavy-water pile in Leipzig.

For the big underground bunker laboratory now being built at Dahlem, the Germans planned the largest uranium-reactor experiment yet, involving one and a half tons of heavy water and three tons of uranium metal — still in plate form. Heisenberg thought it important to look once again at the question of the thermal stability of the pile; while according to his calculations a pile of these dimensions would not produce energy, it *would* come very close to the "critical point." He still thought that one effect of a rise in temperature would cause the pile to reach equilibrium at a certain temperature: "The resonance of 38-metal [uranium] will expand." He very rightly continued, in his analysis of the planned reactor for the War Office, that there was reason to fear that the whole mass of uranium would undergo nuclear fission at explosive speed. This raised another nagging problem: a simple calculation showed that if the chain reaction *did* get out of hand, the whole mass of uranium would fission within less than a fifth of a second. If they were to rely on cadmium plates to regulate the chain reaction, could any mechanism operate as fast as that?

The experiment itself would have to wait until the new bunker laboratory was finished, but clearly, for the safety of their institute, there was a number of technical problems to be solved. In the meantime, Professor Bothe and Professor P. Jensen at Heidelberg had put the minimum radius of a uranium/heavy-water reactor at 166 centimeters, provided water or graphite was used as a reflector. The more intricate technical problems of building a workable uranium reactor were now also being assailed. W. Fritz and E. Justi began an investigation of the heat transfer and the actual power that would be generated by a small heavy-water pile. The realization that the corrosion of uranium by water — as so explosively demonstrated to Heisenberg and Döpel in Leipzig — was not easily overcome resulted in several conferences being called to discuss possible solutions. Gold-plating the uranium fuel elements was ruled out as gold would absorb too many neutrons; nickel and chromium might suffice if the plating could be made permanent and deep enough. The alternative possibility, of using something other than heavy water, was raised and dismissed. Heavy paraffin — paraffin in which the hydrogen atoms had been replaced by deuterium — might work initially, but each alpha particle produced during the fission processes would destroy upwards of 100,000 paraffin molecules. "As at present informed," a Berlin conference attended by Bothe, von Weizsäcker, Wirtz, Harteck and others late that summer concluded, "we must reject the use of heavy paraffin; heavy water alone can be considered for use as the deuterium carrier." The possibility of simply "canning" the fuel elements in a low-absorption, non-corrosive metal does not appear to have occurred to the Germans; this was the process subsequently adopted in America.

In any event, it was not with heavy water but with graphite that history was being made in America. On December 2, 1942, General L. R. Groves received the historic message from Chicago, "The Italian navigator [i.e., Fermi] has just landed in the New World. The natives are friendly." An experimental graphite-moderated pile built with 350 tons of the purest graphite, 5.6 tons of uranium and 36.6 tons of uranium oxide, in a squash court under the grandstand of the Chicago University stadium, had gone critical. Twelve days later, the first plans were laid for the erection of a full-scale plutonium-producing factory at Hanford: four water-cooled piles (one a reserve) would probably be needed, spaced about a mile apart; and two chemical plants to extract the plutonium from the irradiated uranium fuel. Each extraction plant would have a four-mile safety zone around it. The uranium piles would operate for three months, and then be shut down for a month for their irradiated uranium slugs to be removed by remote control, and for fresh uranium to be inserted. The highly radioactive slugs removed would be shunted in special railway wagons to a remote storage area and kept constantly immersed in water until they had lost sufficient radioactivity to be processed in the plutonium-extraction plant. Thus far had the Americans progressed without even knowing for certain how much plutonium would be needed for a bomb.

Late in 1942 the construction of the main uranium-235 isotope-separation factories had also begun at Oak Ridge, Tennessee. Two processes were to be used, the electromagnetic and the gaseous diffusion plants being erected in valleys seventeen miles apart; it was the electromagnetic plant that finally produced the uranium-235 used in the Hiroshima bomb. In December 1942, Roosevelt was informed that the whole program was now estimated to cost about $400 million, of which perhaps one quarter represented the cost of the electromagnetic process, which was accorded a higher priority than the diffusion process.

It was at about this time that in Germany the Reich Minister of Posts, Ohnesorge, began urgently to demand another interview with Hitler. Himmler was asked to arrange it: "According to his [Ohnesorge's] observations, America is at this moment collecting all her professors of physics and chemistry together to produce particular results," Himmler was told. According to von Ardenne, one of Ohnesorge's best scientists, the Minister was referring to the American atomic project. How he had learned of it must remain a matter for speculation. Von Ardenne recalls that news reached Germany through Sweden of the American project; but it is known that during the spring of 1942 Ohnesorge's experts had succeeded in unscrambling the transatlantic radiotelephone link and had since then made thousands of recordings of these telephone conversations, including many of Mr. Churchill's conversations. The leak may have been tapped at this source.

The American scientists were equally troubled by rumors of work in Germany. Some weeks before the Chicago pile went critical, rumors had reached the team under A. H. Compton to the effect that Heisenberg had been appointed director of the now notorious Kaiser-Wilhelm Institute of Physics on October 1, and then that Heisenberg was going to visit neutral Switzerland briefly. The American Intelligence authorities seemed uninterested in this, so the Chicago scientists asked Dr. S. A. Goudsmit, a famous Dutch physicist with connections in England, to see that the information reached the British Intelligence agencies. Goudsmit himself knew nothing of the American bomb project, but on Compton's instructions he included certain names and code words in his letter. Goudsmit wrote to England that Heisenberg's whereabouts "may be of special interest to those working on 'Tube Alloys,' the group to which Dr. Peierls is attached. The corresponding group here is especially anxious to know whether this transfer of Heisenberg [to the Kaiser-Wilhelm Institute] indicates that that particular problem is now being taken more seriously in Germany." There was little chance that Heisenberg himself would talk freely, but it might be possible to find out "just who is working with him and how hard they are working." The letter was forwarded to London through the diplomatic bag, and a copy was sent to Air Intelligence.

During a meeting in Compton's office in Chicago, a short while after the Fermi pile success, the question was posed: When might they expect the first German atomic bomb? Dr. Wigner, the most pessimistic of the group, proved on a blackboard that at the latest they could expect a German uranium bomb to be ready by December 1944.

[III]

THROUGHOUT THE SUMMER and autumn of 1942, however, the Reich Research Council in Germany had been preoccupied with its own reorganization. The presidential council's members, and particularly Speer and Rosenberg, were slow to reply to queries from the council, and correspondence was left unanswered for several months. The chaos within the German uranium project had increased accordingly. One consequence of the June 1942 meeting with service chiefs had been a sudden blossoming of interest in the most unlikely quarters. German Admiralty technicians had sat in on a conference to discuss the possible applications of nuclear power units to ships, and research into the unknown physical properties of uranium metal — and in particular its liability to corrosion by high-temperature water — had begun. There was talk of a nuclear reactor capable of giving a U-boat an action radius of 25,000 miles for the consumption of a kilogram of uranium. The Reich Air Ministry and several Kaiser-Wilhelm Institute men were now working on the problem, with the most active efforts being made by Professor Harteck's group in Hamburg.

Again, although the Army Ordnance Department had early in the year credited atomic research with "no immediate military significance," and consequently relinquished the project to the old Reich Research Council, it was continuing to finance the atomic research unit under Dr. Diebner at Gottow. German industry wanted strong neutron sources for nondestructive materials testing; medicine wanted radioactive isotopes and the investigation of the biological and genetic effects of radiation; the Air Force saw in the project a means of obtaining artificial substitutes for radium* — vital for their luminous dial paints — and

* By late 1942 Germany had only 60 grams of radium left, which would be consumed within three years at the then current rate of consumption.

even the Post Office had an eye cautiously cocked on the possibilities, with the laboratory under von Ardenne. In October, the Peenemünde rocket establishment had even awarded a contract to the Post Office laboratory at Berlin-Tempelhof for "the investigation of the possibility of exploiting atomic decay and chain-reaction processes for powering rockets."

Professor Esau wrote to the council's general director, the controversial Professor Rudolf Mentzel, on November 24, to propose the strong centralization of the uranium project now, "because during the last few months the research group has had to accommodate an increasing number of military projects in its research program, and expand the number of workers and establishments accordingly." The project would yield practical results only if the procurement of the manpower and apparatus and the necessary construction work could be accorded special priorities, like the *DE* priority — the highest rating in Germany — which Albert Vögler had somehow obtained for the big reactor bunker being erected at his foundation's Berlin-Dahlem institute. There was a trace of bitterness in Esau's letter when it mentioned Vögler. Mentzel drafted for Reichsmarschall Göring's signature a decree ordaining that a Nuclear Physics Research Group should be formally set up. In a letter to Göring's deputy, Mentzel recalled that since Hahn's discovery of nuclear fission, physicists all over the world — particularly in the United States — had applied themselves to the problem. "Quite apart from the fact that the tempo of a scientific research project can never be gauged exactly in advance, thus making surprises quite possible in nuclear physics, the whole complex seems to me so important that even during the war it should not be neglected for one moment. There are furthermore in nuclear physics related marginal problems of immediate military importance."

Mentzel proposed to Göring that Professor Esau should be designated the Reichsmarschall's "Plenipotentiary for Nuclear Physics." While Esau was not a born atomic physicist, he had a good general knowledge of the subject and was above all a neutral: "This is important," stressed Mentzel, "because it is in this very field of atomic physics that, what with the often highly touchy characters, and the delicacy of some of the physicists' feelings, there would be serious friction if an expert were put in charge."

It was certainly true that Esau was well in with the services and with the Post Office, but he was not a favorite of the establishment in Germany, and nor was Mentzel. Above all, Reichsminister Speer held a low opinion of Esau. A few days after Mentzel had written to Göring's deputy, Görnnert, a note appeared on the latter's file claiming that Mentzel had inflicted much damage on German science while still at the Ministry of Education. "In physics the clique that once stood firm behind Einstein and his Theory of Relativity now reigns supreme. . . . The occupation of the Kaiser-Wilhelm Institute of Physics, the laboratory of Professor Debye, the world's unchallenged master of experimental physics, by Heisenberg, the doyen of the theoreticians . . . is characteristic of his efforts." The anonymous critic continued that long-standing Party members who had been attacking Einstein for over twenty years now, were being thrown out of their institutes by Mentzel for no reason at all. Worst of all was "this huge swindle with the so-called uranium machine" being promoted by Mentzel.

But by then Göring had already put his signature to Mentzel's decree appointing Esau to direct the whole German uranium project. It read:

> I herewith ordain the incorporation into the Reich Research Council of the *Nuclear Physics Research Group* being set up and managed by you. I appoint you as my Plenipotentiary for all nuclear physics problems, and direct you to pay particular attention to the following aspects:
>
> 1. the execution of nuclear-physics research aimed at exploiting the atomic energy of uranium;
>
> 2. the production of luminous paints without the use of radium;
>
> 3. the provision of high-energy neutron sources; and
>
> 4. the investigation of safety precautions for working with neutrons.
>
> Heil Hitler!
> (*signed*) GÖRING

The year that followed was not a happy one for the project, as Esau had many enemies. He came from peasant stock and his speech betrayed his East Prussian origins. Described by a Party weekly as "a thickset man with a tough farmer's skull," he was deceptively intelligent and had made a brilliant career in the pioneer years of wireless telegraphy and television, and had done much to promote the therapeutic uses of ultra-short waves. It soon became evident that while Esau eagerly adopted the new and imposing title that Göring had bestowed upon him, with its impressive if misleading letterheads ("Plenipotentiary of the Reichsmarschall for Nuclear Physics") he had little faith in the reactor project. He once told Harteck that he would provide all the funds and priorities he wanted, but only if Harteck could build a reactor and show him "with a thermometer" that its temperature rose by as much as one tenth of a degree.

During the few days before his appointment Esau had even talked of closing down the whole project altogether, as Dr. Erich Bagge's diary for December 4 shows:

> Conference in the rooms of the president of the National Bureau of Standards, State Councilor Esau. Diebner, Basche, Clusius, Harteck, Bonhoeffer, Wirtz and myself present from the physical side; the chemists Albers, Schmitz-Dumont and a third described their attempts to make volatile uranium compounds [to replace the corrosive uranium hexafluoride in the various isotope-separation processes]. Esau is getting ready to throw in the towel in January or February 1943.
>
> It seems that they now think the solution of a certain problem can have no bearing on the outcome of the war after all.

Esau's appointment met with the immediate disapproval of the stately Kaiser-Wilhelm Foundation, and he did not enjoy Albert Speer's confidence. Late in 1942 Speer had demonstrated his belief in the importance of nuclear physics by giving the coveted *DE* priority rating to the foundation's institutes directed by Heisenberg, Rajewsky, Bothe and Hahn; at this stage of the war, the *DE* rating was not even enjoyed by the V-1 and V-2 "secret weapons" projects. On February 4, 1943, Dr. Albert Vögler summoned Esau and Mentzel to a conference on home ground — the Berlin head office of United Steel. As this huge combine's president, Vögler had in the early days financed much of Hitler's political campaign, but not to have the Kaiser-Wilhelm Institute personnel dictated to by men like the unfortunate Professor Esau. Vögler told Esau he had called the conference to "apportion" the share of research between the Kaiser-Wilhelm Institute and Esau's Nuclear Research Group. So the *subordina-*

tion to Esau of the strong Kaiser-Wilhelm Institute research teams was apparently ruled out from the start. Speer must have been behind this, for he had promised Vögler both material and financial support for the necessary construction work, and there is mention in the German record at this stage of "the special interest expressed in one aspect of the nuclear research by Herr Reichsminister Speer." Within a very few weeks, the Kaiser-Wilhelm Foundation was protesting to Mentzel about "individual difficulties" that had cropped up between their institute and Esau's group — particularly over the sharing of materials — and Vögler was demanding a new meeting between the two factions, to be attended by a representative from Speer's ministry, to smooth things out.

[IV]

WHILE IN GERMANY the rival groups of nuclear scientists were waiting for sufficient heavy water to complete research on their heavy-water reactors, the four Norwegians of the Special Operations Executive's advance party parachuted into Norway two months earlier were waiting at Sandvatn for the next assault on Vemork to be mounted. Their living conditions were appalling, and their stocks of dry wood were at an end. The Hardanger plateau is 3,000 feet above sea level, and the temperature seldom above zero; by the middle of December all the men had been taken seriously ill and were suffering from malnutrition. They began to eat reindeer-moss, and the foul weather made it impossible to hunt any reindeer. With failing wireless they heard London announce repeated postponements of the next operation, "Gunnerside."

It was not until January 23, 1943, that the Allied attack on German heavy-water production was renewed. Professor Tronstad and Colonel Wilson of the SOE traveled from London to the Norwegian holding school to brief the six "Gunnerside" saboteurs for one last time before they took off to parachute into Norway that night. Tronstad told them that they might not fully realize the importance of their mission, but it would live in Norwegian history for hundreds of years. They were informed of the fate of the earlier glider-borne troops, and told they would have no hope of staying alive if caught. Each man was issued with a cyanide suicide pill, a small brown rubber capsule which he could force into his mouth.

The advance party had taken a Eureka radio beacon with them to mark the parachute dropping zone, and they had been ordered to pinpoint the new dropping zone for Lieutenant Rönneberg's party by exposing lights when the aircraft approached. The big four-engined bomber carrying the six intrepid Norwegians circled over the rocky wastes of the Hardanger plateau for two hours, but no lights showed. Lieutenant Haukelid, who knew these mountains well, told the pilot that he thought he could identify the dropping zone visually, but he got short shrift from the RAF officer. The bomber turned west again and headed back to Scotland, with the Norwegians in a ferment of discontent over the abortive sortie. It was already daylight as the bomber, badly flak-battered, landed at a remote Scottish airfield.

The parachute drop was postponed until the next moon period, a delay of some weeks. There was no question of the soldiers' going on leave; they were almost at their peak fitness, and security considerations apart, such a softening-up could undermine the success of the whole operation. In London the other servicemen might relax; at the instance of SOE's planning and operations staff, Rönneberg and his five hand-picked comrades-at-arms withdrew to the icy seclusion of a retreat on the west coast of Scotland, and it was in this monastic solitude that they awaited the next full moon.

The weeks passed in hunting, fishing and living off the land. A vigorous training program was enforced. By February 16, when the men were again transported to the "export" airfield, the details of the operation and the link-up with the advance party had had to be changed at the last moment. Six days before, the advance party had wirelessed to London the exact positions of all the sentries and guards at Vemork, and it was obvious that the Germans were expecting an operation against the factory. It was now essential that the transport aircraft should not pass anywhere near the Rjukan valley or the Mösvatn dam; a new dropping point had accordingly been selected, Lake Skryken, thirty tough miles from the advance party's base at Sandvatn.

It was raining heavily at the export airfield as the six Norwegians again boarded the bomber, laden with their sets of demolition explosives, skis, provisions and white-camouflaged weapons and equipment. At about midnight they were over the dropping zone, and the green signal lamp lit up over the hatch in the fuselage. The stick of parachutes separated from the aircraft, and the six Norwegian soldiers and drums of supplies were drifting down to the smooth, level expanse of the frozen lake in the heart of the Hardanger plateau 1,000 feet below. In London the SOE files held ready the last letters each man had written to his next-of-kin; they were going on a dangerous operation, from which they might never return.

[V]

THE HARDANGER PLATEAU is one of the most Godforsaken areas on earth — the loneliest and largest mountain range in northern Europe. Its only vegetation is the stunted juniper tree, its only population the herds of migrant reindeer roaming shiftless as the Canadian caribou. In winter, blizzards sweep the plateau, the winds suddenly so strong that human beings cannot breathe unless they shield their faces and turn away from the stinging hail of snow and ice. Sudden squalls can lift men from their feet and hurl them bodily across the ice.

If this plateau was now to be the enemy of the men of "Gunnerside," it would also be their succor; no lone German could stand exposure to elements as fierce as these. But then any German who did recklessly venture out into the plateau could always cut and run when he had had enough. For these Norwegians there could be no escape from its desolation and deprivations. To surrender to the surrounding enemy spelled certain execution.

All night long Rönneberg's party labored in a rising gale to round up the parachute containers of supplies and drag them to a deserted hut on the shores of Lake Skryken, where they had landed. In the hut they found firewood and a map with the area round the lake discolored by the jabbing of countless fingers, so they were in no doubt as to where they were. By 4:00 A.M. on February 17 they had finished burying their stores in the snow. A blizzard broke across the plateau and the driving snow obliterated all trace of their landing. But by 5:00 P.M. that evening, when they were rested and ready to proceed, the westerly wind was so fierce that they were forced to seek refuge in a hunting lodge. They were unable to leave for two days.

By the time the snowstorm had subsided all six men were in no small discomfort from the change of climate; their neck glands were badly swollen and two of the men looked like becoming seriously ill. During the next three days the worst of the gales passed, but when they finally reached their original supply dump they could no longer identify it, as snow drifts had covered their marker stakes. It took several hours' exhausting work to find one food container. Forty-eight hours later the storm had blown itself out. "The weather turned fine and I gave the order to prepare for departure at noon," wrote Rönneberg, the assault party's leader, on February 22.

They skied southwestward all night and all day, laboring under their 65-pound packs and the weight of the two sledges laden with two hundredweight of supplies. Near Lake Kallungsjå they saw to their consternation two bearded skiers approaching them from afar. Rönneberg told his men to lie low while one of them was sent on ahead to find out who the strangers were; each man had his gun ready. Suddenly, above the noise of the wind, Rönneberg heard three "wild yells of pleasure"; the two strangers were Sergeants Arne Kjelstrup and Claus Helberg from the SOE's advance party dropped into the Hardanger plateau four months before. So contact had been made.

Together they pressed on to the advance party's base hut at Sandvatn, some twenty miles from Rjukan. Here the ten men — both parties combined — pooled their food and rations, and turned their attention to the main problem: how to attack the high-concentration plant at Vemork. Each set down on paper the questions he considered should be answered — the positions of the guards, the security precautions, the machine-gun nests, the best route of attack. By the time the night was over, they had a list of two score such questions. Sergeant Helberg, a native of Rjukan, was dispatched into the town on skis to obtain immediate answers from his contacts there. Primary among their anxieties was the assault on the factory itself. Would it be possible to scale the precipice on which the massive hydrogen-electrolysis plant was built? Sergeants Haugland and Helberg had both thought this gorge impassable, but Haukelid insisted that he had seen trees growing up the sides of the gorge on the aerial photographs. If trees could take root there, then there would be a way for man to climb the rockface too.

The latest intelligence on the Vemork plant was that there were fifteen Germans in the barrack hut between the turbine hall and the electrolysis building, and two more sentries guarding the narrow suspension bridge across the gorge. The guards were changed every two hours. During alerts there were three patrols inside the factory compound, and the road winding down from Vemork to Vier was floodlit. In addition, there were normally two Norwegian night watchmen inside the compound at night, with two more on the main gate and the penstocks. All doors into the electrolysis building were kept locked, except one giving out into the yard.

On the afternoon of Friday, February 26, eight of the Norwegian soldiers set out on the next stage of the advance on Vemork, leaving the precious radio operator Haugland with another man to guard the wireless station at the Sandvatn hut. Helberg would bring to him the news of the success of the operation, or its failure. It was long dark when they reached their objective, one of two lonely huts in the woods on the hillside to the north of Rjukan, and only about two miles from Vemork. The nine white-camouflaged men broke in and waited for Helberg to return from the town. Sometimes when the wind blew their way they could hear the toneless whine of Vemork, the power station that was to be their target.

Helberg brought grim news: the plant's guards had been reinforced, searchlights and machine guns had been set up on the roof and the approaches to the pipelines and the factory itself had been mined. Throughout that Saturday the men argued over the best way of extricating themselves safely after the blast. The suspension bridge seemed so inviting: why had their assault and withdrawal to be made by descending to the floor of the gorge and scaling the rock face each time? Lieutenant Poulsson feared they would collapse from exhaustion if they attempted the feat twice in one night; they were too high up, there was too much snow, and they had afterward to escape variously to Sweden and the Hardanger plateau as well. But if they were to fight their way out, they would have to kill the two German sentries on the bridge and Poulsson was against this. If it came to a shooting match they might have to leave behind a wounded comrade, and the Germans would certainly exact violent reprisals on the Rjukan townsfolk. This left only the double climb. They decided to begin the attack half an hour after midnight, which would give time for the guards to change and settle down. Rönneberg and Poulsson wrote out a detailed Operation Order in the best staff-college tradition, and each man familiarized himself with its content. It ended with the injunction: "If any man is about to be taken prisoner, he undertakes to end his own life."

At about eight o'clock that Saturday evening, February 27, the soldiers set out on the last stage of the assault, their weapons as yet unloaded so as to avoid an accidental gunshot raising the alarm. In their packs were the sets of plastic explosives they had fashioned weeks before in England.

As they left the hut, there was one of those grotesque confrontations with peace that only war can provide. In the hut next door, they found two young Norwegian couples, obviously very much in love, bent on whiling away the hours of the weekend. These were as taken aback by the sudden sight of the heavily armed soldiers of an army disbanded in 1940 as the soldiers were shaken to see them. The couples were forced at gunpoint back into the hut and ordered not to leave it until noon next day. They were only too willing to comply. The saboteurs slid off on skis toward the softly humming Rjukan valley, with Claus Helberg in the lead.

After about two thousand yards, the woods thickened. They had to carry their skis and proceed on foot until they reached the main road zigzagging through the mountains from Mösvatn to Rjukan. They skied about a mile and a half down this road, the gentle humming of Vemork growing louder and louder until finally the factory itself was in sight. The flat, snow-covered roofs of the two main buildings were bathed in moonlight. The factory looked huge and impregnable, perched on its green and black outcrop of rock far below them on the other side of the gorge. Lights glittered dimly behind the painted windows of the electrolysis building. The saboteurs reached the little cluster of houses near the northern end of the suspension bridge and left the road, which went on in a series of hairpin bends down to Rjukan town.

It was now approaching ten o'clock.

The shifts would be changing at Vemork. As the saboteurs slithered down the steep mountainside from one road-bend to the next, two buses laden with shift-workers rattled past heading for the plant. The Norwegian soldiers followed the road several hundred yards until they reached the place where a wide cutting had been made through the woods for the power line from Vemork. Here they broke off into the dark woods on their right, divested themselves of their white camouflage dress and dumped their skis, rucksacks and food. They were now in British army uniforms. They filled their pockets with ammunition and hand-grenades, took their guns, explosive sets, some rope and a pair of armorers' shears and began the final descent down the rock face.

It had begun to thaw, and every move sent tons of loose snow thundering into the gorge below, but the air was full of the low hum of Vemork's turbines and the splash of snow-water cascading off the walls of the gorge, and nobody seemed to hear them. A high wind was springing up, as was to be expected with a thaw.

They forded the semi-frozen shallow river at the bottom of the gorge and began the difficult ascent of the sheer 500-foot rockface to the shelf on which Vemork had been built. They attempted no conversation against the increasing noise, but silently helped each other to secure foot and handholds until all were standing exhausted on the narrowest part of the shelf, several hundred yards from the factory buildings. Between them and the plant would be the minefield. The shelf was almost entirely occupied by the single-track railway connecting Vemork with Rjukan, and ultimately with the railway ferry traversing the Tinnsjö Lake. To the left of this track was a small transformer station, behind which they hid until the guard changed.

They ate what food they had brought, and Rönneberg checked for the last time that each man knew his part in the operation. They would divide into a covering and a demolition party. The former, led by Lieutenant Haukelid, would cut through the fence into the compound and occupy positions ready to deal with any Germans if the alarm was sounded; they would stay there until they heard the explosion, by which time the demolition party would have escaped. The demolition party, led by Lieutenant Rönneberg, would first attempt to force the door to the basement housing the actual high-concentration plant for heavy water; failing that, they would tackle the door on the ground floor. As a last resort they would use the cable-tunnel Dr. Brun had described. The men fixing the demolition charges would be covered by one man with a tommy gun and another with a .45 pistol, while a third man trained a tommy gun on the main door. There was much that could go wrong; if the worst came to the worst, each man would have to act on his own initiative to see that somehow the charges were laid.

By now it was after 12:30 A.M. and they had recovered somewhat from the exertions of the climb. They had seen the two old bridge sentries — who were in fact Norwegians — return to the guard hut. It was time for the attack to begin.

Sergeant Kjelstrup took the lead, walking along the railway line some yards ahead of the rest of the covering party; the demolition party brought up the rear. Somebody had made footsteps in the snow, and they carefully followed these right up to the gate in the perimeter fence. Kjelstrup severed the chain on the gate with the shears and waved the others into the factory compound, shutting the gate behind them. While Poulsson and Haukelid covered the German guard hut, one man swiftly ran down to cover the two new sentries on the bridge and another turned left to watch for the sentry on top of the penstocks. The demolition party had by now also forced a gate in the fence a short way away from the railway gate; this would provide them with an escape route.

So far they had not been detected.

Rönneberg took his demolition party across to the electrolysis building. All the doors were locked. in the ensuing search for the cable-tunnel, Rönneberg and Sergeant Kayser became separated from the other two. They crawled into the building over a web of tangled pipes and cables. Through a vent in the tunnel they caught a glimpse of the high-concentration room, with one man working in it. Rönneberg and Kayser dropped into the room next door. The connecting door was unlocked, and they took the Norwegian workman completely by surprise. Kayser covered him with his pistol while Rönneberg locked the door and began to lay the charges. The models of the cells constructed by the SOE in England were exact duplicates.

He had only finished about half of them when there was a crash of broken glass behind him; one of the missing saboteurs had smashed the basement window from outside. Rönneberg helped him to climb in, cutting his hand badly as he did so. Together they completed laying plastic charges round each of the eighteen cells, which were made of quite heavy-gauge stainless steel. Each charge was connected with a high-speed fuse, to the end of which was attached a slow time fuse.

By some minutes after 1:00 A.M., all was set. They shouted to the workman to run to safety on the upper floor, and unlocked the basement door. Several British parachute badges were scattered round the room, as "visiting cards." As they were lighting the fuses, the workman pleaded that he had lost his spectacles in the room and would never get another pair during the war. A frantic search brought the spectacles to light.

The demolition party had run barely twenty paces from the building when the explosion shattered the night. Then they had melted into the shadows and vanished from the scene: "For a moment I looked back down the line and listened," Rönneberg wrote in his report to London. "But except for the faint hum of machinery that we had heard when we arrived, everything in the factory was quiet." Poulsson and Haukelid both heard the explosion as they covered the guard hut; so did the Germans, for a bareheaded soldier came out, looked round and went inside again, to reappear at once carrying a rifle and wearing a helmet. He played a flashlight round the compound, but did not see the Norwegians in the shadows barely four paces away. Poulsson wanted to shoot him, but Haukelid forced his tommy gun down. The German tried to get into the electrolytic building, but the door was locked. He vanished round the building.

Covering and demolition parties went into retreat, withdrawing along the railway line. With frightening suddenness an air-raid siren on the factory's roof burst into full cry, joined by several others, their deafening wail echoing across the gorge and drowning every other sound. The Norwegians broke into a run, and began a hurried descent of the rockface to the bottom of the gorge. The river was now considerably swollen by the thaw.

Chief Engineer Alf Larsen, who had succeeded Brun at the heavy-water plant, was just about to leave a bridge party at a neighbor's house just outside Vemork's main gate when he heard the explosion and the sirens begin to sound. Larsen telephoned the works to find out what had happened. The foreman, exhausted by his ordeal at gunpoint in the high-concentration room, managed to stammer out that the heavy-water plant had been blown up. Larsen at once telephoned this intelligence through to Bjarne Nilssen, the Norwegian-Hydro director responsible for Rjukan; Nilssen alarmed the German garrison headquarters. It took him some time to start his wood-burning motorcar and when he did eventually drive up the precipitous road to Vemork he paid no attention to the weary men trudging across the road from the gorge and climbing further up the mountain. In Vemork's high-concentration room, Larsen had in the meantime surveyed the wreckage. It was a perfect piece of sabotage. The bottom had been knocked off every cell and the priceless fluid had flooded down the drains; to compound the damage, the flying shrapnel had punctured the tubes of the plant's cooling system, and the room was full of spraying jets of water. This *ordinary* water had effectively swirled the remains of the heavy water away.

All eighteen cells had been completely drained of their contents — almost half a ton of heavy water. Even after the torn and blasted installation had been replaced it would still take weeks of full-power working before each cell's contents had been put through nine stages of concentration; months would pass before any heavy water could be tapped from the rebuilt plant. In short, a delay of many months had been inflicted on the German uranium research program — a delay which it could not afford.

As the saboteurs climbed the mountainside they could see searchlights mounted on the factory roof sweeping the gorge, and the flashlights of a search party setting out along the railway line. The Germans had evidently found the trail of blood from Rönneberg's hand. The wind was blowing gale force now. The Norwegians retrieved their equipment from the cache in the woods and began to split up. Helberg was the first to leave them, as he was going to continue working in the Rjukan area. That night the rest reached one of the base huts they had used and stayed there overnight. A tremendous storm confined them to this hut for the next two days, then they continued on their march toward the original base at Lake Skryken. From here the five "Gunnerside" men set out on their 250-mile march to Sweden, and all eventually reached Britain. Poulsson transferred to Oslo, leaving Haukelid and Kjelstrup to contact the radio operators. A week after the sabotage, their coded telegram was transmitted to London, the first hard news of the success of the attack:

> High Concentration Installation at Vemork completely destroyed on night of 27th–28th. "Gunnerside" has gone to Sweden. Greetings.

On the morning after the attack, General von Falkenhorst arrived at Vemork with the local security officer, Muggenthaler. Chief Engineer Larsen and the director of the Vemork factory were directed to attend. All the eyewitnesses were closely questioned, but no clues were found as to the identity of the saboteurs. The Germans quickly realized that the disappearance of Larsen's predecessor, Dr. Brun, was connected with the attack. Some fifty works employees were arrested and interrogated but subsequently released. Falkenhorst was very scathing about the lack of security measures at Vemork and went so far as to dress the German troops down in front of the Norwegian bystanders. He summed the operation up as "the best coup I have ever seen."* Falkenhorst's inspection ended in a farce when it was determined that, impressive though the plant's floodlighting was, the security officers did not know how to switch it on.

General Rediess, head of the security police in Norway, reported on the incident in some detail to Berlin:

> On the night of February 27–28, 1943, toward 1:15 A.M. an installation of importance to the war economy was destroyed at the Vemork factory near Rjukan by the detonation of explosive charges. The attack was executed by three armed men clad in grey-green uniforms.

* A signal reporting Falkenhorst's remark caused some gratification in SOE headquarters in London soon after.

The operation was, Rediess believed, partially the work of the British Intelligence Service and partially the work of the Norwegian Independent Company. His investigations had established that the saboteurs had gained entrance to the factory by cutting a chain on a gate; they had passed undetected both the German sentries and the Norwegian watchmen. "From such effects as the perpetrators left behind, it can be assumed that they came from Britain. Security police investigations are still proceeding into this matter."

As an immediate security precaution, the Rjukan telephone exchange was shut down and the railway station closed to passenger traffic for the rest of the war. A partial state of emergency was proclaimed in the town, with an 11:00 P.M. curfew. Road blocks were set up, the minefield round the factory was strengthened, and the Germans, realizing that they now had to bargain with air attacks as well, emplaced smoke generators round the whole site and camouflaged the conspicuous pipeline leading from the mountain-top to Vemork by means of eight hundred artificial trees. After the successful RAF Bomber Command attack on the Ruhr dams some weeks later they also secured the Mösvatn Dam with a balloon barrage and torpedo nets.

It was not long before firm evidence reached the Germans that saboteurs had been seen on the Hardanger plateau: a Norwegian fisherman reported having seen "six uniformed men" — apparently dropped from a British aircraft — near a certain hut. A vast army of German troops, German and Norwegian police units, "Germanic SS" and Norwegian *Hird* detachments massed for a huge sweep across the plateau to rid it once and for all of the resistance workers who seemed to be infesting it. From March 24 to April 2 the whole plateau was sealed off and combed from one end to the other, possibly as many as 10,000 troops being involved. The German-controlled news agency in Oslo explained: "It has long been rumored that British parachutists have made the mountain area their headquarters for launching sabotage raids against the adjacent industrial establishments." Every hut was forced open and searched and its contents confiscated; all huts found to contain arms and explosives were burned to the ground.

Extraordinary rumors swept southern Norway, despite the German press releases; eight hundred British paratroops had landed there, and a "fierce battle" was raging with German security forces "directed by SS-General Rediess himself." The Germans had suffered a bloody defeat and countless ambulances had actually been "seen" bringing back the injured troops. But there were no armies of the enemy out there; nor even lone skiers.

And when Germans and SOE did finally clash, the scene was as strange and evocative as the whole lonely offensive against an invisible underground army: when the German sweep reached the hut named by the Norwegian fisherman, a lone skier was sighted from afar. He almost managed to evade the hunting patrol. General Rediess related to Berlin some days later: "The hunting group's machine-gunner, equipped as such with only a .30-caliber pistol, was able to keep on his tail and finally confront him from only 100 feet away."

There followed a curious and desperate duel, each man's face clearly visible to the other across that short expanse of snow in the midst of the desolate plateau.

The skier was Claus Helberg. In a report later to SOE headquarters in London, he related how on March 25 he had suddenly been confronted by these three Germans only a hundred yards away. He had turned to escape, but after two hours' hard skiing realized that one of the enemy was certain to outdistance him:

> I therefore turned round, drew my pistol and fired one shot from my Colt .32. I saw to my joy that the German only had a Luger and I realized that the man who emptied his magazine first at that distance would lose, so I did not fire any more but stood there as a target at 150 feet range. The German emptied his magazine at me, turned and started back. I sent a bullet after him. He began to stagger and finally stopped, hanging over his ski-sticks.

As General Rediess told Berlin for his part, the Norwegian quarry was equipped with superior fire-power and able to force the hunter to turn back. The quarry had vanished into the gathering dusk. And that was the last that the Germans saw of the men who had destroyed the heavy-water plant.

In the meantime, the newspapers in London had reported statements from Stockholm about the blowing up of the Vemork plant, described as "one of the most important and successful undertakings the Allied saboteurs have carried out as yet during the war." *The Times* even announced that the saboteurs had succeeded in destroying equipment for producing heavy water, "supposedly for purposes of war industries," but this bald statement was omitted from all but the earliest edition of that newspaper. "Many scientists," another newspaper commented, "have pinned their hopes of producing the 'secret' weapon upon heavy water, namely an explosive of hitherto unheard-of violence."

Compared with the ill-fated Combined Operations assault three months before, this first SOE attack on Vemork had been a conspicuous success. No lives had been lost on either side, and the maximum damage had been inflicted on the heavy-water plant without harming the hydroelectric power station itself, which was of vital importance to Norway's civilian economy. As soon as all the reports had been received, the Special Operations Executive compiled a detailed account of the operation which was forwarded by their Minister, Lord Selborne, to Mr. Winston Churchill. The prime minister read it on April 14, and wrote across its foot: "What rewards are to be given to these heroic men?"

Lieutenants Rönneberg and Poulsson were awarded the DSO, and the other saboteurs either the MM or the MC. Nor was that all, for Dr. Jomar Brun was awarded the singular distinction of a MOST SECRET appointment to the OBE.*

British damage assessment experts put the setback to German heavy-water production at about two years. The Americans accepted this estimate only with reservations. In fact about a ton of heavy water, in concentrations ranging from 10.5 to 99.3 per cent, had been lost from the damaged cells, the equivalent of about 350 kilograms of pure heavy water. It was particularly distressing for the Germans, as the modification and expansion of the plant was almost complete at the time; production had risen to about 150 kilograms a month and would have risen to 200 kilograms in the next month. As it was, the whole of March was taken up in clearing the damage, with Chief Engineer Larsen prevaricating and insisting that a larger room be built to hold the expanded high-concentration plant. Dr. Berkei traveled specially to Vemork from Berlin to insist that the repairs be

* Colonel J. S. Wilson and Major Leif Tronstad were similarly rewarded.

speeded, but it was not until April 17 that the high-concentration plant began to function again, and several months would pass before heavy water could again be drawn off from its final stage.

CHAPTER EIGHT

An Unexpected Result

THE TEMPORARY LOSS of the Vemork high-concentration plant was the first direct setback to the Germans.

By the turn of the year they had made great progress in all the other fields under investigation: they had designed a large intermediate uranium pile experiment; they were mounting a realistic attack on the technical problems likely to be encountered inside a reactor; and adequate industrial capacity had been provided for processing the uranium. No positive work was being done on atomic explosives at this time, but small teams of scientists in Vienna and elsewhere were measuring the general nuclear constants of importance in this field, and in particular the fast-neutron fission cross-section of uranium-235.

Confidence in the whole project depended very much on the progress made with the uranium reactor, however, and now that the heavy-water supply had been temporarily stopped, the Germans realized for the first time the limitations they had placed on themselves by relying on Norway. During their many journeys north, the scientists had been comforted by prospects of constant supplies of heavy water — "four tons a year" — resulting from their expansion project at Vemork. Dr. Wirtz had visited Rjukan in the middle of November 1942, and reported upon his return that the Såheim plant would also be delivering heavy water by mid-October 1943.

At the end of November, Dr. Wirtz had scoured the whole of occupied Europe for further possible sources of the precious fluid. His verdict was that apart from Vemork only two hydrogen-electrolysis plants were worth any attention — the two Montecatini electrolytic plants in Italy, one near Merano and the other at Cotrone. Both employed an electrolytic process less suitable for heavy-water manufacture, and they had a combined power consumption of 68,000 kilowatts — half that of Vemork. Professor Harteck advised the War Office to send two or three of the Nuclear Physics Research Group's members "in plain clothes" to Merano to compare the efficiency of the Fauser process employed there with the Pechkranz electrolyzers in use at Vemork. His proposal was that the Italian plants should be exploited for the concentration of heavy water up to 1 per cent, which would then be shipped to Germany for concentration there to the full 100 per cent — an arrangement more economical than might at first seem. During the spring of 1943, Harteck and Professor Esau personally inspected the Merano plant; but to Harteck it was obvious that Esau had little confidence in the German uranium project's future.

The War Office dropped out of the project altogether at the end of March, refusing even to pay the two million Reichsmarks promised by General Leeb, head of Army Ordnance, for nuclear research during the coming financial year. Dr. Diebner's research unit was turned over to Professor Esau, but Diebner was allowed to remain on War Office property at the unit's Gottow laboratory. He and Berkei moved their offices out of the Ordnance Department building at No. 10 Hardenberg Strasse, and into the headquarters of Professor Esau's National Bureau of Standards. Their new immediate superior was Dr. Beuthe, the mediocre head of the bureau's radiological department.

The Reich Research Council was instructed to find the funds for the whole project itself. The council asked Professor Esau to draw up a two-million-Reichsmark budget for the coming year,* and this sum was approved by Göring soon after.

The most significant item in Esau's budget was the 600,000 Reichsmarks set aside for the construction of a series of ten double ultracentrifuge machines for enriching uranium-235. The first "oscillating-flow" experiment, using xenon, had taken place at Kiel in mid-January, and on March 2 uranium hexafluoride had been fed into the machine; the machine had produced an enrichment of 7 per cent for the first time, so that eight days later the Hamburg group had officially proposed to the War Office the mass production of the machines, and the procuring of the necessary machine tools and materials. Coming as it did

* The two million Reichsmarks were allocated by Professor Esau for the year 1943–1944 as follows:

	RMs
Uranium-reactor experiments, primarily cost of uranium-metal production	40,000
Heavy water, primarily cost of pilot heavy-water plant in Germany	560,000
Uranium-isotope separation, primarily the manufacture of ten double ultracentrifuges	600,000
Luminous paint research for Air Force	40,000
Radiation-protection research	70,000
Overhead costs of high-voltage neutron sources	50,000
The chemistry and corrosion of uranium	80,000
Contingencies and sundries	200,000

just after the SOE's destruction of Vemork, the proposal had met with immediate acceptance.

It was not until April 17 that the damage at Vemork was completely repaired. At a conference a few weeks later, Esau hastened to reassure his hearers that the damage to the high-concentration plant had been made good in a relatively short time, and that there were two smaller plants approaching completion in Norway, at Såheim and Notodden. But he added: "As we have to assume that, in view of the prevailing circumstances in Norway, there may be further sabotage acts despite all our security measures, this important part of the Norwegian plant is being duplicated at I. G. Farben, Leuna, and is nearing completion. Should the plant in Norway be destroyed again, the high concentration of the 'raw product' — low-concentration heavy water — produced in Norway can then be undertaken at Leuna." Taking the most pessimistic view, and assuming that the whole Vemork hydrogen-electrolysis plant was destroyed, the Leuna plant could still draw upon other sources. Negotiations had begun in all secrecy with the only other available source, the Montecatini plant at Merano, for the production of low-concentration heavy water, as Marteck had envisaged. "In any event," Esau promised, "we have here sufficient heavy water for the experiments in hand."

This was a dangerous exaggeration, of course; Esau's belief in this was probably the reason why throughout 1943 no final decision was reached on which of the four German processes for large-scale production of low-concentration heavy water should be adopted; and by 1944, when Esau had gone, it was already too late.

During their Leipzig pile experiment *L-IV*, one year before, Heisenberg and Döpel had been obliged to contain the uranium powder and the heavy water in relatively thick aluminum spheres, and this aluminum must have had some effect on their neutron intensity measurements. It was Dr. Kurt Diebner, working now under the auspices of Professor Esau, who devised a neat way to obviate the use of supporting materials altogether for his first experiment with uranium metal. During 1942, about a ton of uranium had gone to *Degussa*'s Number I Works in Frankfurt for smelting into solid metal. Diebner had wanted some of this metal to be machined into small cubes, but all that was available was the one-centimeter-thick uranium plate produced for the Berlin experiments. Ideally the uranium cubes should have been 6.5 centimeters along the edge (from theoretical considerations); Diebner was, however, obliged to make up cubes of 5 centimeters, in order to cut the uranium plates (19 _ 11 centimeters) to the best advantage.

Dr. Diebner accepted these vicissitudes of working with other scientists' cast-off materials philosophically. What he lacked in influence, he made up in experimental genius: to avoid the use of supporting materials like aluminum, he had conceived the idea of freezing the heavy water solid, and embedding the uranium cubes in it layer by layer to form a lattice throughout this "heavy ice." This unusual but promising experiment was set up in the low-temperature laboratory of the Reich Institution of Technical Chemistry.* The total of 232 kilograms of uranium metal cubes, and 210 kilograms of heavy ice, was arranged in a spherical pattern, which was in turn embedded in a paraffin-wax sphere 75 centimeters in diameter.

It was a difficult experiment, and had they realized the difficulties involved they would probably have attempted some

* *Chemisch-Technische Reichsanstalt*, analogous to the *Physikalisch-Technische Reichsanstalt*, the National Bureau of Standards.

other method. The necessity of lowering the pile's temperature to 12 degrees below zero was a time-wasting factor and, as with paraffin wax, the use of heavy *ice* as moderator prevented them from rearranging the geometry of the uranium lattice as they might have wished, to improve the pile's characteristics. But the effort was worthwhile, for it yielded a much better "neutron-production coefficient" than any pile so far; in particular it was a considerable improvement on the Leipzig pile *L-IV*. Diebner's group themselves were surprised at this "extremely favorable and unexpected result," considering the pile's very modest size. The obvious conclusion was that the use of a lattice of metallic cubes was as good as, if not better than, the use of layers of uranium and moderator.

They began to prepare two further experiments to investigate how far the neutron increase was a factor of reactor size alone, all other factors being constant. The first experiment would be much the same size as this heavy-ice pile, but at normal temperature; and the second would be over twice as large. They could reduce the supporting material to a minimum by suspending the cubes on fine alloy wires inside the reactor vessel. "There could be no further doubt but that the enlargement of this pile must inevitably result in a critical reactor," wrote Diebner afterward. "It was now only a question of increasing the quantities of uranium and heavy water enough."

Professor Heisenberg was not unnaturally reluctant to give Diebner's group the credit it deserved for the clear demonstration of the superiority of cube lattices. At a Berlin conference a few days after the last of the heavy-ice experiments, Heisenberg stressed the significance of the pile which he and Döpel had built in Leipzig a year before, and dismissed the Diebner experiment as a "somewhat improved apparatus of a similar kind" which had "yielded the same result"; he did not mention its important difference from Döpel's design. Heisenberg had no intention of changing the geometry of the large reactor experiment being planned jointly by his Berlin institute and the Heidelberg institute of Professor Bothe, to incorporate the new improvements developed by Diebner's group. For the sake of consistency, the reactor, on which they hoped work would begin during the coming summer, would still use the uranium in plate form, alternating with layers of heavy water.

Heisenberg now expressed no doubts but that when the reactor went critical it would reach thermal equilibrium of its own accord. We now know that if no provision for cadmium regulators had been made, and the reactor *had* gone critical, it would in fact have led to a very nasty accident indeed.

Professor Heisenberg had made his remarks about the heavy-ice experiment at a Berlin conference on nuclear physics called by the German Academy of Aeronautical Research on May 6, 1943. This academy had a high reputation among the scientists, but was tolerated only with reluctance by the government. Only one month before, Carl Ramsauer, the president of the Physical Society, had used it as a platform for an attack on the government's ability to direct German physical research in war.

It was not surprising that when the academy now invited all the leading nuclear physicists to lecture on their progress so far, Professor Esau, their titular head, was most reluctant to attend. The authorities attempted to suppress the meeting, and because Field-Marshal Milch had called a rival conference on the same day in Berlin, there were once again very few military or political leaders available to attend a conference devoted to nuclear physics. Otto Hahn talked in general terms about nuclear fission and its importance for the future; Professor Clusius described the various processes developed to separate uranium-235; and Professor Bothe enumerated the advances being made in the design of cyclotrons and betatrons for German laboratories.

Again, it was Professor Heisenberg who touched upon the possibility of producing atomic explosives, describing in simple terms how a uranium bomb would work. He projected a lantern slide showing what would happen if they could succeed in extracting "pure uranium-235 in a large quantity." In short, the total neutron population would constantly increase, with no absorption at all, and if the lump of uranium-235 metal was so large that the internal neutron increase was greater than the number of neutrons escaping at the lump's surface, the total number of neutrons produced would increase to enormous proportions within a fraction of a second, until a large part of the material was fissioned. A huge amount of energy would be "explosively released" in that fraction of a second. In this connection Professor Heisenberg particularly stressed the importance of Professor Harteck's successful ultracentrifuge experiment the year before, and the more recent experiments which had succeeded in enriching uranium-235.

In the circumstances, it was unfortunate that most of their important guests had been unable to attend. Dr. Adolf Baeumker, the Academy's chancellor, arranged for the distribution of a printed report of the proceedings to give their absent guests an insight into the project. Under a MOST SECRET classification the 80-page report, with excellent photographs and diagrams of the most up-to-date German equipment developed in this field, was printed for distribution — to the horror of both the Reich Research Council and the Munitions Minister, Speer; the latter ordered all copies to be destroyed.

By the spring of 1943 it was clear that German war research had not benefited from the reorganization of the Reich Research Council. The scientists' attitude to the war in general was at best ambivalent: they took care not to become entangled with the Party and were still contributing less to the war effort than the scientists in any other country. It was not in any case easy to be a physicist in National Socialist Germany. The most modern and fundamental theories were largely Jewish and therefore "decadent." Repeated meetings were called in various parts of the Reich to try to find ways of using Albert Einstein's theories while denying his authorship of them. How could the German physicists hope to exploit atomic energy if the Party disapproved of Einstein's special theory of relativity? Some scientists, like von Weizsäcker, the politician's son, sought to placate the Party; others, like the courageous Max von Laue, were more outspoken. Thus when Professor Mentzel sharply rebuked von Laue for mentioning the theory in Sweden without "adding that German scientists expressly dissociated" themselves from it, von Weizsäcker advised the great physicist to reply that the theory had in fact been largely developed by the Aryans Lorentz and Poincaré long before Einstein. Von Laue ignored the friendly advice, and sent an openly defiant article to a scientific periodical about the theory: "That shall be my answer," he wrote to von Weizsäcker.

Caution and an anxiety to avoid provocation had ruled the scientists. There were security-service agents planted in every institute; Professor Harteck was reported to the SS early in 1943 by the head of the Physics Institute at Hamburg on some pretext and had to devote an inordinate length of time to extracting himself from the meshes woven by this unseemly intrigue. Again, when the Jewish parents of Dr. Samuel A. Goudsmit, the famous Dutch-American physicist, were removed to a concentration camp in Holland, it was to Professor von Laue and Professor Heisenberg that friends of the family appealed for help. Goudsmit was the physicist who had discovered the magnetic properties of the electron, and had always been friendly toward the Germans; Heisenberg had even been his guest in the summer of 1939 in America. But what could Heisenberg do now? Although there was an innocent and long-standing family friendship between Heisenberg's and Himmler's parents, dating from long before the war, he hesitated to act. Von Laue replied sympathetically to the mediator in Holland, but forgot to sign the letter. Heisenberg wrote testifying to Dr. Goudsmit's active sympathy for the Germans, and added that he would be very sorry if his parents should suffer any inconvenience in Holland, "for reasons unbeknown to me." It was in any case too late, for five days before Heisenberg finally wrote Dr. Goudsmit's blind mother and father had been put to death, on the father's seventieth birthday.

Dr. Samuel Goudsmit

Scientists with good connections with the Party were outspoken in their condemnation of the existing organization of research. There were repeated complaints to Göring, for example, from the naval research scientist Professor Werner Osenberg, about Mentzel's "unfit leadership" and the "chaotic confusion" reigning in the universities. Osenberg was a poor scientist but a capable administrator, with the requisite close connections with the Party and SS security service. He had a muddled understanding of nuclear physics and had initiated some detective work during April 1943 into the German progress in this field. Thus on April 7, 1943, an SS representative from Gotenhafen had visited Professor Henry Albers in Danzig to ask his opinion of reports on American atomic bomb work. Albers's laboratory was working, as we have seen, on the development of volatile organic uranium compounds as a substitute for gaseous uranium hexafluoride in the various gaseous isotope-separation processes. The result of the visit to Albers is recorded in a memorandum on Osenberg's file, dated two days after the big Berlin conference, May 8, 1943:

> RE: Uranium Bombs.
>
> According to Intelligence reports workers in the U.S. are now occupied with the manufacture of uranium bombs. To investigate the technical possibility of this, the Army Ordnance Department has assembled about 50 scientists (mostly physicists, and a few chemists) in a research group.
>
> Thus Professor Albers has been commissioned to develop a certain amount of a raw material necessary for extracting pure uranium-235.* Professor Albers is working with two Ph.D.s on this: provisional research period, eleven months; from the kind of work and the availability of apparatus and laboratories, it would seem possible to employ twelve or fourteen scientists, cutting the time of development to about two months.
>
> In addition to Albers, several other teams are working on the same project: the personnel position is said to be the same in them.

That Göring was impressed with Osenberg's organizing ability was evident, for at the end of June 1943 he appointed the

* Osenberg explained in a separate memorandum that pure uranium-235 was necessary to make bombs.

professor to set up a planning office within the Reich Research Council to reorganize its chaotic affairs.

[11]

IT WAS EARLY IN 1943 that further news arrived in London, warning of the developments in German uranium research. The British had for some time been very anxious to evacuate Professor Niels Bohr from German-occupied Copenhagen, as he would be able to contribute much to the Allied project. On January 25, 1943, Professor Chadwick had written Bohr a letter offering him asylum in Britain, should he so choose; the letter had been smuggled to Bohr as a microdot hidden in a hollow key. Bohr guessed at once what was afoot, but replied by the same channel during February, saying that he now believed that in spite of everything any future use of the recent discoveries in the field of atomic physics was impracticable. Within a very few weeks, however, Bohr changed his mind. He had heard rumors of the large-scale production of heavy water and uranium metal for the manufacture of atomic bombs, and he hastened to use the same underground channel of communication to inform Professor Chadwick of these developments, while at the same time expressing the belief that, in view of what seemed to him the impossibility of extracting sufficient uranium-235, such developments were not very promising.

This renewed threat of a German atomic bomb program came at an opportune time for the directors of the British "Tube Alloys" project. The relations with the Americans on this subject had deteriorated markedly during the past months, and Mr. Winston Churchill's grasp of arithmetic, let alone the principles of nuclear physics, was weak enough to defy the strongest scientific argument in favor of investing in an Allied atomic bomb. Of the repeated references now made in communications to Mr. Churchill to possible German work on an atomic bomb, Michael Perrin, deputy director of the "Tube Alloys" project, said later that they were "quite reasonably used as an argument to people who might otherwise say: 'Well, why do you want this terrific waste of money, manpower and effort?'"

This pressure campaign can be seen in action during the first weeks of April 1943. At midday on April 7, Perrin had an interview alone with Lord Cherwell, Mr. Churchill's scientific adviser. On the same day, Cherwell wrote to Mr. Churchill summarizing in necessarily simple terms the progress made toward an Allied atomic bomb so far. In five pages, he reiterated the basic principles behind nuclear energy. There were two possible lines of research, both involving the use of light uranium — uranium-235 — a substance invariably mixed with heavy uranium and "excessively difficult" to separate from it. Either this light uranium, some ten to forty pounds of it, would form the explosive, in an atomic bomb measuring up to six inches in diameter and delivering an explosive power equivalent to up to 40,000 tons of TNT; or an element formed from heavy uranium by the action of light uranium on heavy water would form the explosive (now known as plutonium). As Lord Cherwell told the prime minister, "for this purpose the light uranium need not be extracted, but a good many tons of heavy water are required. The feasibility of this method is much more doubtful. . . . The Germans," he added significantly, "probably have one or two tons from Norway but are believed to be interested in home production." He informed Mr. Churchill that large quantities of heavy water could be obtained only from hydroelectric power stations, because of the vast quantities of electricity required. "The Norwegian plant, now out of action, has produced about one and a half tons. A plant in Canada, subsidized by the Americans, is expected to produce about four tons a year. It was originally thought fifteen tons would be required, but some new ideas lead us to think we could manage with about five."

As he confided to the prime minister, British scientists had stumbled across a new process for manufacturing heavy water, still only on a laboratory scale, but promising to be vastly cheaper than the existing methods. Clearly the prime minister was struck by the idea that the same process might have occurred to the Germans, for after he had read Lord Cherwell's outstandingly lucid summary, he arranged for Lord Cherwell, Sir John Anderson and the Foreign Secretary to meet to discuss the subject. On April 11 he told Cherwell:

> Meantime I should like you to talk to CAS [the Chief of Air Staff] and ascertain from him whether there is the slightest chance of the Germans having erected a large scale plant. Their Intelligence staff would surely be able to detect any such very large installation being put up.

Mr. Churchill also asked Lord Cherwell to consult the Intelligence authorities, and added that he would be seeing them and the Chief of Air Staff during the week himself.

Lord Cherwell called in both Perrin and Dr. R. V. Jones, head of the Air Scientific Intelligence branch, to see him next day; Wallace Akers, Perrin's superior, came as well. He told them that the prime minister had asked whether there was any evidence that the Germans had started a large new plant for an atomic bomb project. Perrin was by now convinced from the Intelligence reports that they had not. Jones must have been slightly alarmed, for this was the week during which the vague reports of German "secret weapons" and rockets had suddenly begun to materialize into a real threat, with the beginning of the

V-weapons Intelligence campaign. On the following evening, April 13, Mr. Churchill called the promised meeting between Eden, Cherwell and Anderson in his private office at Number 10 Downing Street, where he heard no doubt that the necessary Intelligence measures were being put in hand.

It may seem strange that there were two Intelligence agencies working on this subject now: the "Tube Alloys" officers, in conjunction with Commander Welsh; and the Scientific Intelligence branch, directed by Jones. "There was," an Intelligence officer described, "no love lost between R. V. Jones and Eric Welsh." Jones had worked for nearly a decade in pure scientific intelligence; the other had some scientific smattering, some intelligence and "an immense cunning." He had taken over atomic Intelligence from the wings, because of the importance of Norway in the investigation.

As the months wore on, and the higher-level streams of international diplomacy obliged Perrin to work more and more closely with his American opposite numbers, Jones's highly developed sense of patriotism strained to a point where there was "virtually open warfare" between him and Commander Welsh. For Jones it was unfortunate that much of the intelligence on what the Germans were doing continued to come through Scandinavia, which was very much Welsh's domain. Major Leif Tronstad was in contact with the Norwegian nuclear scientist Professor H. Wergeland in Oslo, and with a further Norwegian, N. Hole (usually referred to as "my young friend" by Tronstad), living in Stockholm. Through Wergeland, some very good reports were coming out of Germany, and in particular from Dr. Paul Rosbaud, the editor of *Naturwissenschaften*, who was keeping the Allies well briefed on the personalities in German science. Rosbaud continued to enjoy the German scientists' confidence until the end of the war.

While Perrin and Welsh seem to have regarded some of their reports on German atomic bomb developments as an expedient to keep the threat under review, the Americans were alarmed by another possibility: even if the Germans could not produce a bomb, they *could* use a uranium reactor to manufacture radioactive material in sufficient quantities to use as a form of poison gas. During the late spring of 1943, this possibility was closely investigated by General L. R. Groves, and in May he requested Dr. James B. Conant, chairman of America's National Defense Research Committee, to furnish him with a report on this. On July 1, Conant reported: "It now seems extremely probable that it will be possible to produce by means of a self-sustaining pile large quantities of radioactive materials with varying half-lives of the order of magnitude of twenty days." He added that it was quite possible that some time in the next year the Germans, with the aid of heavy water, could produce such materials in quantities corresponding to the equivalent of approximately *one million grams* of radium per week. Handling such material would of course present the enemy with formidable problems, but if one week's output of radioactive materials — equivalent to one ton of radium — were to be distributed over two square miles, the complete evacuation of the area would become necessary, and a considerable proportion of the population would be "incapacitated."

Conant warned that it was "quite conceivable" that a series of circumstances might enable the Germans to produce in a city such as London a concentration of radioactive solids varying in size from half a square mile to several square miles, "sufficient to require the evacuation of the population." For General Groves there was a note of comfort: "If any attack is made by the Germans using radioactive poisons, it seems extremely likely that it will occur not in the United States but in Great Britain."

This was no comfort to the British. Sir John Anderson discussed Conant's warning with the American at the Cosmos Club in Washington a month later. He told Dr. Conant that Britain was vitally involved in the atomic project because of her exposed position, and cited Conant's memorandum on the possible use of radioactive products as a kind of poison spray. All the evidence from Norway was that the Germans had not yet got on to the most efficient method of making heavy water, he said. In Britain, the scientists were interested in three possible processes: the fractional distillation of ordinary water; a catalytic exchange process, using electrolytic hydrogen; and the fractional distillation of liquid hydrogen.

The first (which Harteck had developed in Hamburg anyway) was probably the best, said Anderson, but it involved a great deal of plant; this was an objection which Hartek had also made. The second was, of course, the one the Germans had introduced at Vemork, and this the British knew. The third process (being developed by Professor Clusius) involved a measure of uncertainty. What was troubling the British was that they believed they had discovered a method of increasing output fivefold, and if the Germans were on the same track it could be a serious matter.

Just what consequences the German release of radioactive fission products over Britain might have had can be estimated from a paper written at the time by an officer of the Medical Research Council, in which he drew specific attention to the genetic effect of such radiation. He concluded that the mutation rate in human beings exposed to such radioactive poisons would be a function of the *total* dose absorbed, even if it was received over a long period of time. The effects would probably be a weakening of the race in the second and third generations. According to the Official Historian,* this was apparently the only mention of the possible genetic effects of radiation in all the documentation on the subject. And it was concerned not with the effects of the Allied bomb upon the enemy's citizens, but with the possible effects of enemy radioactive attack upon Britain.

The Germans had made a much more rigorous investigation of the genetic effects of neutron and other radiation, and between 1943 and the end of the war several research contracts were issued by both the Plenipotentiary for Nuclear Physics and the War Office on this subject, mainly to the Genetics Department of the Kaiser-Wilhelm Institute at Berlin-Buch. About a year later we find in the German record a letter from the Kaiser-Wilhelm Institute of Biophysics' Professor B. Rajewsky telling the Plenipotentiary for Nuclear Physics that his group was concentrating *inter alia* on "the biological effects of corpuscular radiation, including neutrons, with respect to the possibility of their being used as weapons [*Kampfmittel*]." This seems however to have been a purely precautionary research contract, in the event that the Allies should use such weapons. There is no reason to suppose that the Germans would not have abhorred the use of radioactive poisons as much as they did conventional poison gases.

The American "Manhattan Project" had made enormous strides by this time, since its transfer to U.S. Army control. The construction of the gaseous diffusion and electromagnetic plants for separating pure uranium-235 was well in hand; the first experimental graphite pile was on the point of beginning operation; and the full-scale plutonium-producing piles at Hanford

* Margaret Gowing, *Britain and Atomic Energy 1939–45*, p. 384.

were under construction. Some research effort had been expended on the theory of heavy-water piles, but none had yet been built; even so, four heavy-water plants were nearing completion, including three in the United States. A formidable team of scientists under Dr. J. Robert Oppenheimer had assembled at a laboratory in New Mexico to work on the design and delivery of the American atomic bomb itself.

When the British learned of the great progress that the Americans had made, and considered the apparent threat from Germany, they reached the decision to close down virtually all the remaining work in Britain on atomic explosives, to feed their scientists and engineers into the American project at every level, and to do everything possible to speed the production of the first bomb. This decisive step was not entirely altruistic: so far advanced were the Americans now that the British could only benefit from having a strong team of experts placed throughout the American project. By the end of 1943, work in Britain was at a virtual standstill.

[I I I]

THROUGHOUT THE SUMMER, rumors continued to multiply in Germany about the wonder weapons on which the country's scientists were supposed to be working. The morale reports drawn up by the security police catalogued a long list of "giant guns," "stratosphere guns," projectiles powered by compressed air, rockets and huge bombers. "There are furthermore," reported the security service in Germany on July 1, "rumors rife about a 'new kind of bomb,' so large that only one can be carried by any aircraft at one time. Twelve such bombs — which are built on the atomic physics principle — would suffice to destroy a city of a million people. . . ." During July, these rumors began to figure in the Intelligence reports placed before the Chiefs of Staff in London. One fairly circumstantial report described a rocket with a range of 800 kilometers in theory and about 500 kilometers hoped for in practice, weighing forty tons; the rocket had already achieved a range of 270 kilometers. The first third of its 20-meter length was said to contain explosives of "atom-splitting type." Rockets had already been seen on aerial photographs of Peenemünde on Usedom Island; and "Usedom" was given in the report as one of the places where such rockets were under manufacture.

The Germans also seem to have formed a hazy and possibly speculative picture of enemy work on nuclear physics. Professor Heisenberg referred at the May 1943 Berlin conference to the "major resources" which other countries, particularly the United States, were known to be devoting to the problem. When Professor Esau, the current Plenipotentiary of Nuclear Physics, wrote a report on his first half year in office, Professor Mentzel forwarded it on July 8 to Göring's office with the comment: "Even if this research does not result in the development of practicable sources of power or explosives, we can on the other hand rest content that the enemy powers cannot spring any surprises upon us in this field."

Although the Vemork high-concentration plant had been repaired by mid-April, as Esau had reported, it was not until late in June that heavy water had been drawn off in minute quantities from its final stages. The total output for June was 199 kilograms, with the "exchange-process" attachment to one of the stages now working well. In July, however, only 141 kilograms were produced, for on the twenty-fourth of that month American bombers attacked Norwegian-Hydro's associated fertilizer factory at Heröya and, as the Heröya factory was the main outlet for Rjukan's synthetic-ammonia production and Rjukan drew its hydrogen by pipeline direct from the nearby Vemork hydrogen-electrolysis plant, Vemork had to reduce production too.

To the Reich Commissioner's office in Norway this chain of events was quite intolerable. They demanded that the surplus hydrogen be allowed to escape into the air; the repaired heavy-water plant had to be kept running at all costs. During August 1943, a further exchange-process stage was incorporated into the plant, which would bring total annual output up to three tons by December. With no small courage, Norwegian-Hydro's Director General, Bjarne Eriksen, rescinded the costly order to allow the hydrogen gas to go to waste, and he announced from Oslo that he would recommend to his Board that the firm cease heavy-water production altogether, as it provided too tempting a target for Allied air attack. In face of the strongest threats from the German authorities, Eriksen forced this decision upon his Board of Directors, threatening to resign if they did not agree. But before a vote could be taken, Eriksen was arrested and removed to Germany, where he spent the rest of the war in a prison camp. At the time his arrest was connected with his obstructionism, but perhaps it was merely coincidence, for this was the occasion of a general rounding-up of former Norwegian army officers by the Germans.

The reason for the uneasiness among the Norwegians was not hard to find: they had observed the intensified military precautions that had followed the sabotage in February and drawn their own conclusions. They had seen "barbed-wire entanglements, minefields and machine-gun nests" spring up around Vemork and had reacted accordingly. Visibly cowed by the Norwegian protest, the Germans agreed that in future they would not therefore insist upon extracting more heavy water from Vemork than was the normal by-product of ammonia production.

As the Allied air offensive against Germany increased in momentum, the difficulties besetting the project multiplied. No sooner had one group settled down to definitive experiments than its laboratories were destroyed, or its work caught up in the general move to disperse important projects out of the bigger cities in the western territories. During the summer, the ultracentrifuge project had encountered difficulties anyway; they had troubles with leaking joints, and the rotor drum of the prototype twice exploded under trial. But during July 1943, the whole laboratory had to be uprooted and transferred to Freiburg in southern Germany, after Kiel was heavily damaged in a series of air raids associated with the RAF's Battle of Hamburg, and many weeks were lost.

The same fate befell the second method proposed for separating the uranium-235 isotope, the "isotope sluice" developed by the young Berlin physicist Dr. Bagge. He had worked the prototype with silver, instead of uranium, because the final machine would almost certainly run on gaseous uranium hexafluoride, in the handling of which there were still technical difficulties to be overcome. On June 28, Bagge had finally heard from a Göttingen analyst that the minute sample of silver his machine had produced was indeed enriched — by between 3 and 5 per cent — in the light isotope. The results were in fact unaccountably better than theory had predicted.

The Bamag-Meguin firm was asked to construct a second prototype of the machine; but whereas the first had produced a "molecular beam" by heating and vaporizing the working metal, silver, Bagge's new design would work with gaseous compounds. The construction of this new machine began on August 5, with Bagge now aided by a trained engineer and Dr. Siebert of Bamag-Meguin. Then things began to go wrong. The end of

August 1943 saw the commencement of a series of heavy air raids on Berlin, and in anticipation of a Hamburg-scale catastrophe the authorities ordered the evacuation from the Reich capital of a large number of the more important organizations. During August and September, Bagge was preoccupied with organizing the evacuation of about one third of the Kaiser-Wilhelm Institute of Physics from Berlin-Dahlem to a town called Hechingen in southern Germany.

As Berlin began to shake to the detonations of the winter bombing, the Dahlem Institute was strangely empty. Heisenberg had stayed because he needed to use the high-voltage particle-accelerator equipment there; besides, he and Professor Bothe were setting up the large reactor experiment in the bunker in the institute's grounds. Bagge and Wirtz had also stayed. But this uprooting of their laboratories, and the necessity now to make frequent and tedious journeys from one end of Germany to another, must inevitably have had a detrimental effect.

There were other factors hampering the German project, however, most notable of which was an element of obstinacy among some of the most eminent scientists. By the middle of October, they were clearly brought to light at a three-day secret conference summoned by Professor Esau at his National Bureau of Standards building in Berlin. It was significant that of the forty-four leading project scientists who read papers at this convention, none was from the group immediately surrounding Professor Heisenberg, although Hahn, Bothe and Rajewsky (the other Kaiser-Wilhelm Institute directors involved) all read papers. Dr. Erich Bagge wrote:

> Read a paper to invited members of the larger Uranium club, about the enrichment of the light silver isotope by means of the isotope sluice.

(Esau, Witzell, a Speer representative and others present.) At the headquarters of the Bureau of Standards.

The most important papers were probably the first two to be read: Fünfer and Bothe described small heavy-water and uranium-pile experiments they had made, systematically varying the separation between the layers; and Professor Pose and Professor Rexer, of the former War Office team, read a paper on "experiments with various geometrical arrangements of uranium oxide and paraffin."

The former experiments, conducted in Heidelberg, had yielded the basic rule of thumb that approximately equal weights of uranium and heavy water would be needed in the final reactor, and that with one-centimeter-thick uranium plates, the best thickness of heavy water between them was about twenty centimeters. The latter experiments, although performed by Pose and Rexer only with the less satisfactory uranium oxide and paraffin discarded by the War Office, examined once again the whole question of whether *plates* were the most suitable shape for the uranium elements. In a series of modest experiments in Professor Esau's laboratories the two physicists had proved beyond all doubt that of all possible shapes, plates were in fact the *least* favorable: "Arrangements of cubes are superior to those of rods, and those of rods to those of plates," they reported.

Because heat-transfer problems would obviously be more formidable in an intricate lattice of cubes, there were technical arguments in favor of using the uranium in the form of rods; but there seemed to be no arguments in favor of plates at all, particularly as their manufacture and protection against corrosion were already presenting great technical difficulties. The only argument in their favor was developed by Professor Heisenberg during a conversation with Professor Harteck, who was evidently deeply disturbed by it. The Nobel Prize winner told him that he was insisting on plates for the big reactor experiment in the Berlin bunker because the *theory* was so much easier with simple layers of plates than with complex lattices of cubes.

The whole project would have to wait upon the provision of adequate casting facilities for the heavy plates. A new casting furnace would have to be constructed with sufficient capacity, and the anti-corrosion surfacing of the plates would have to be thoroughly investigated by the Auer company and other laboratories. Esau's laboratories developed an aluminum or tin plating technique, but this had to be dropped as it required uranium of a purity higher than that used at present. In November, the Auer company succeeded in protecting the uranium plates with a phosphate enamel, proof even against steam at 150 degrees and 5 atmospheres pressure. Late in 1943, the Auer company began the casting and rolling of the uranium plates needed for the big Heisenberg reactor experiment in Berlin.

At the end of their October 1943 paper, firmly establishing the superiority of cube lattices over plates, Pose and Rexer had recommended the manufacture of uranium metal cubes on a large scale. At a conference at the Auer company's Berlin offices during November, Esau and Diebner privately arranged for the early manufacture of a number of uranium metal *cubes* to be fitted in by the firm in such a way that their uranium-plate production was not disturbed. A separate casting furnace was constructed by Auer to manufacture the uranium cubes for Diebner and his research group at Gottow.

In his previous reactor experiment, Diebner had embedded 108 makeshift uranium cubes in "heavy ice" to avoid the use of aluminum supporting material, which would affect the calculations. He now planned two further experiments, one using over twice as many cubes as the other. The cubes would be suspended this time in heavy water by means of very fine alloy wires. The cylindrical aluminum tank which had accommodated the heavy-ice pile was transported to Gottow and sunk into the ground within the same special laboratory as had been used for the first experiment there. To economize on paraffin wax, Diebner had the tank lined with wooden sleepers, and filled to a depth of 160 centimeters with paraffin wax. Near the bottom of the wax was a 102-centimeter spherical cavity. The vertical cylinder of wax surmounting this cavity was suspended from a steel plate, by means of which the whole cylinder could be raised to give access to the cavity. It was in this cavity that the two uranium piles would be built.

The first pile was expressly made the same size as the heavy-ice pile some months before, as a kind of "control"; for reasons of geometrical symmetry, 108 cubes could not be used so 106 were used instead. They were strung in chains of eight and nine cubes to each wire, fastened through the paraffin lid to the steel plate. Each cube was lacquered with a new polystyrol emulsion developed by Auer's laboratories; Professor Haxel had tested this emulsion and found its neutron absorption to be virtually nil. The cubes were arranged not in spherical symmetry round the center of the pile but in such a way that each cube was exactly the same distance — 14.5 centimeters — from its twelve nearest neighbors. The design of this complex uranium cube lattice was so elegant that it took just one day to install.

The "control" pile would finally contain 254 kilograms of uranium metal and 4.3 tons of paraffin wax as a reflector and shield. The radium-beryllium neutron source was first introduced into the empty *cavity*, held on to the end of a rod by means of a small magnet, and the neutron intensity at the surface of the empty pile was measured. Then the uranium was lowered into place, and 610 kilograms of heavy water poured in. Fresh measurements were made, and the uranium and lid were winched out of the pit again. Small samples of the heavy water were taken and tested for concentration, while the second, larger experiment was mounted. Hard though they had worked, Auer had unfortunately been able to manufacture only 180 proper five-centimeter cubes by then, because of the priority behind the uranium plate production for Heisenberg; but Diebner made up the rest of the 240 cubes necessary by drawing upon his stock of improvised cubes remaining from his previous experiments. These latter cubes, which were made of sandwiches of uranium plates, were slightly lighter (2.2 kilograms) than the solid cubes (2.4 kilograms) but this could not be helped.

This time, after the initial dry run, no less than 564 kilograms of uranium were in the pile, and the remaining space was filled with 592 kilograms of heavy water.

After all the sources of error had been taken into account, Dr. Diebner's group was surprised to find a net increase of 6 per cent in the number of neutrons leaving the surface of the pile, over the number that the neutron source had injected. This was still not the infinite neutron increase that a self-sustaining pile would show, but it was very promising indeed. The values of both these experiments were "extremely high," and Diebner reported that "they lie far above the values predicted by theory." He began to plan immediately for a still larger pile using proper cubes of six centimeters, not five, to provide him with a real basis for determining how large the final heavy-water pile would have to be.

[IV]

EARLY IN THE AUTUMN of 1943, the Germans planned an operation to eliminate the Jews from Denmark. Late in September, the Führer gave his agreement in principle to the seizure of about 6,000 Danes in this operation, and their deportation. The German Governor of Denmark informed Ribbentrop that he planned to leave untouched the property of the Jews being deported "in order that the confiscation of their valuables cannot be said to have been the whole or partial object of the operation." The mass arrests would take place on the night of October 1, 1943. Some days before this, a German embassy official in Copenhagen learned of the plan and put into action a cautious rescue operation. In particular, this official, Herr Duckwitz, saw that Professor Niels Bohr was informed of the great danger he was now in. During the next few nights a small flotilla of boats carried numbers of the endangered Danes across the waters to neutral Sweden, while Duckwitz ensured that the patrol boats were occupied elsewhere. Among the escapers was Niels Bohr, who fled to Sweden with his family in a very overcrowded fishing boat. On October 6 he was flown out of Sweden, making the hazardous journey in the empty bomb-bay of a Mosquito bomber.

Upon his arrival in London, Niels Bohr learned many details of what had transpired since he and Dr. Wheeler had elucidated the theory of uranium fission at Princeton in 1939. He met Michael Perrin and Commander Welsh, and on October 12 had the first of many wartime meetings with Lord Cherwell. In return for what he learned, Bohr was able to tell the British something that they did not know: during 1941, a number of eminent German scientists, including Professors Heisenberg and Jensen, had visited him in Copenhagen, and from the nature of their business he believed that the Germans were very seriously considering the military exploitation of atomic energy.

The British had hitherto estimated that the successful SOE attack on Vemork had cost the Germans about two years' heavy-water output, but by now reliable information had arrived that partial production had been resumed in April. Under "gentle prodding" from General Groves's office, the British representative in Washington, Sir John Dill, advised the American General Marshall that a more realistic estimate now suggested that the damaged plant could be repaired completely in twelve months. This time, the recommendation that another big commando operation should be mounted was not approved, and Groves persuaded Marshall to press for a high-priority bombing attack to be directed against the hydroelectric plant. As it would be a precision target, the Combined Chiefs of Staff called upon the American Eighth Air Force in Britain to execute the operation.

The attack was delivered by the Third Air Division's Flying Fortresses. They climbed into the cold pre-dawn air over England on November 16, each aircraft heavily overloaded with the extra fuel needed for the long return trip. They were to attack the factory precisely between 11:30 A.M. and noon, when most of the workers would be at lunch.

Major John M. Bennett commanded the 100th Bomb Group as it headed in company with several other groups out over the North Sea at 14,000 feet. No German fighters were encountered; in fact, the operation went so smoothly that as the group approached the Norwegian coast, they were actually eighteen minutes early. Bennett ordered the whole formation to turn back and circle over the sea for fifteen minutes. By the time the bombers headed back in to the coast, the enemy defenses were alerted, and heavy and accurate anti-aircraft fire was directed at the bomber formations. One aircraft began to burn, and another yawed out of formation, one engine on fire. Ten men parachuted out toward the sea. As the 100th Group began its bombing run, it encountered the propeller-wash of the 95th Bomb Group which had gone in ahead of them; the 95th had been early, but because the target had been cloud-obscured it had not bombed. The 100th Group's bombardier clearly saw the target aiming point, and just before 11:30 A.M. the first pattern of bombs was hurtling down toward Vemork.

During the next thirty-three minutes, 140 Flying Fortresses attacked; at noon 15 more bombers attacked the town of Rjukan itself.

Over seven hundred 500-pound bombs were aimed at the Vemork plant, and over one hundred 250-pounders at Rjukan. The smoke generators emplaced during the security review after the February SOE operation had been operated to good effect: the bombing was diffuse, and there were few hits on vital installations. Twenty-two Norwegians were killed, including one man killed by a stray bomb several miles away in the forests. Three bombs had hit the hydroelectric plant's pipelines, and two the penstock at the top, but automatic sluices had slammed shut and prevented a flood disaster. Only four bombs hit the power station, and two the adjacent hydrogen-electrolysis plant. A direct hit collapsed the suspension bridge over the gorge, but the heavy-water high-concentration plant in the factory's basement was undamaged. But even so, the raid achieved its object.

The Germans soon realized the reason for the attack on Vemork. Professor Esau informed Göring's office that it was certain that the attack was directed at Vemork's heavy-water production alone. Without electric power, the undamaged high-concentration plant had to shut down, its cells still full of a quantity of dilute heavy water. Dr. Berkei inspected the damage and told Berlin that all prospect of resuming heavy-water production was gone. The time had come, as Esau had foreshadowed in his speech in May, for heavy-water production to be evacuated to the relative safety of the Reich.

An added bonus of the American attack was that Norwegian-Hydro's second plant, at Såheim, was also shut down. The plant was less than a year old, and as its most concentrated heavy water was still little over 70 per cent pure, none had been drawn off. It would have produced about 50 kilograms a month from the end of 1943. Three days after the bombing attack, Esau informed the Reich Research Council that he had set aside 800,000 Reichsmarks for the erection of a heavy-water plant in Germany to replace that in Norway destroyed by "enemy action."

On the last day of November, Einar Skinnarland, the SOE's wireless operator in Telemark, was able to wireless to London the news that all the heavy-water equipment was to be dismantled and removed from Vemork to Germany. This intelligence was considered by Sir John Anderson and the "Tube Alloys" directorate at once: they decided that as Germany's available hydroelectric power was so limited and costly, the shipment to Germany of the special plant itself represented no danger. On the other hand, the disposal of the remaining stocks of heavy water was a matter which *did* cause concern, and a wireless message was sent by SOE headquarters to Skinnarland directing him to report any new developments at once.

In London, the Norwegian government-in-exile had been shocked by the USAAF raids on Rjukan; there had been no advance consultation with them at all. Nor, for that matter, had SOE been informed. On December 1, the Norwegians lodged a formal protest note with the British and American governments, recalling their readiness to provide intelligence on Norwegian industrial installations and to initiate themselves the sabotage of vital war factories with the minimum loss of life and property in Norway. The damage caused by the bombing of Norwegian-Hydro's factories, first at Heröya, and now Rjukan and Vemork, seemed "out of all proportion to the desired effect." After the July bombing of Heröya steps to improve cooperation between the Allied governments had been promised as the Norwegians protested that they had already evolved plans for sabotaging their country's light-alloy production without crippling the associated fertilizer industry. Despite the promise of closer cooperation, however, "the attacks on Vemork and Rjukan were executed without the Norwegians' prior consent, and without their even being informed. If," the note continued, "the reason for the attack was the necessity of stopping other production than that of fertilizers — for example heavy water — specialized methods of attack would have been more suitable than bombing." The attack on the Telemark hydroelectric factories left a sour taste in many Norwegian mouths, and a deep-rooted suspicion that the raids were a product of American postwar commercial planning rather than of military necessity.

It was a month before the British government replied. They rejected both the protest and the Norwegian suggestion that they were best suited to decide upon the fitness of targets for bombing or sabotage. Vemork had been bombed, the British note added, because accurate information had shown that the Germans had increased security precautions to the extent where sabotage could no longer meet with success. Three weeks later, the Norwegian embassy in Washington was officially informed that the Secretary of Defense had assured the State Department that the most thorough investigation had preceded the bombings. The Norwegians' darkest suspicions seemed to be confirmed when the Americans refused to underwrite Swedish deliveries of the electrical equipment necessary for rebuilding the nonmilitary factories that had been bombed. Sweden sent the material nevertheless, and within a few months the fertilizer and alloy factories were functioning as before.* Not so the heavy-water plant: during November, Professor Esau and Dr. Diebner had already decided that in future I. G. Farben should administer heavy-water production and not the military authorities in Norway. For a time there had been some discussion as to whether production should somehow be maintained at Vemork, or whether the plant should be used only to produce low-concentration heavy water for shipping to Germany; but now, on December 13, the Reich Commissioner's office finally confirmed to Norwegian-Hydro that heavy-water production at Vemork was not to be resumed. At the end of the year, Esau told Göring's office that what semi-concentrated heavy water was left in the damaged Vemork plant was to be shipped to Germany for final high concentration.

A small pilot plant — code-named *Stalin–Organ* — had already been built by I. G. Farben at Leuna, operating on the Harteck–Suess dual-temperature exchange principle. But the cost of a full-size heavy-water plant to use this process was formidable: a Leuna works engineer had estimated that it would cost 24.8 million Reichsmarks, require 10,800 tons of iron and 600 tons of steel alloys, and several hundred tons of nickel; it would moreover consume 50 tons of brown coal an hour. Esau hesitated to recommend such a costly project.

* Dr. Friedrich Berkei writes: "In consequence of the loss of the Vemork plant, the production of fertilizers for all the Nordic states was in jeopardy. I went to Oslo once again, and confirmed that we would refrain from producing any more heavy water. This decision was taken to enable Norwegian-Hydro to carry out the reconstruction of the damaged plant with Swedish credits."

Besides, there seemed to be other viable alternatives. Firstly, one of Harteck's most promising students, Dr. K. Geib, had evolved at Leuna an entirely new process for manufacturing heavy water — the dual-temperature exchange process using hydrogen sulphide (a process now widely used in America). The plant installation and energy requirements would be cheaper than those of the Harteck–Suess process; on paper, it looked ideal, because the separation factor of hydrogen sulphide would be so high. Harteck discussed it in detail with Geib, but both agreed that it was now too late to transfer to the new process, because of the corrosive nature of hydrogen sulphide and the consequently extensive design problems.

The second alternative confronting the irresolute Professor Esau was that they might soon be able to dispense with the use of heavy water altogether, if one or other of the uranium-235 enrichment processes should prove successful. How would it look, then, if he had recommended that millions of Reichsmarks should be spent on a heavy-water plant?

He had gone so far as to approve that a contract should be issued to I. G. Farben for the erection of a high-concentration plant at Leuna to replace the one they had lost in Norway; this plant should process to over 99.5 per cent such semi-concentrates as arrived in Germany, with an initial capacity of 1.5 tons per year. "The construction of this plant was to be pressed with the utmost priority," he later recorded, "so that the heavy water necessary for the large-scale experiment would become available as soon as possible." Apart from the surviving heavy water in Norway, they could at present hope for only about one ton per year of very low-grade — about 1 per cent — heavy water from the Montecatini plant at Merano.

Returning to the progress that had been made with processes for enriching uranium-235, in his last report, in 1943, Esau mentioned only two — Dr. Bagge's "isotope sluice" and the Freiburg group's ultracentrifuge — as having any prospect of success. But disaster had already struck Dr. Bagge's project. During a British air raid on Berlin, the new gas-driven prototype and all the blueprints had been destroyed when a bomb hit the Bamag-Meguin works; and they had to begin all over again.

Dr. Diebner's group at Gottow was the first affected by the air raid on Vemork. When we last saw them, they had performed two uranium pile experiments using uranium cubes suspended in heavy water, and were preparing for a third that would tell them all they needed to know about the final size of a critical heavy-water reactor. Now Esau explained to Göring: "They had planned an analogous expansion of their pile, but it could not be carried out because of the loss of heavy-water production." In the meantime, such heavy water as Dr. Diebner had controlled had been transferred to Professor Heisenberg, who was preparing a series of pile experiments using uranium plates in the reactor bunker of the Kaiser-Wilhelm Institute in Berlin.

The uranium plates had still not arrived in any quantity; perhaps this was because of the technical difficulties involved in manufacturing them. There also seems to have been a lack of emphasis on uranium production during 1943. During the year, *Degussa* had manufactured less than four tons of uranium metal, but three tons of thorium, using the same reduction plant; four and a half tons of the uranium metal had been shipped to the company's Number I Works for smelting into slabs during the year. Problems were still arising in the casting and rolling of the plates, and general dislocation and shortages of spares resulting from the RAF bombardment of other towns were given as the reasons for prolonged delays.

Very soon after *Degussa* had finally begun the mass production of uranium cubes, in view of the success of Diebner's pile experiments, the folly of the delay was underlined. A single RAF Bomber Command night attack on Frankfurt left *Degussa*'s factories gutted, and all uranium metal production came to a halt after only a few hundred cubes had been produced.

How far the slackening in the progress made by the uranium project toward the end of 1943 can be blamed on Professor Esau, and how far on the scientists themselves, is open to dispute. Professor Esau had made himself unpopular with most of the project workers, and he had incurred the enmity of Dr. Vögler, president of the Kaiser-Wilhelm Foundation as well. Now, above all, he was *persona non grata* to Reichsminister Albert Speer. Professor Esau was 61 when he was finally dismissed from his position as Göring's Plenipotentiary for Nuclear Physics.

The wheels of intrigue against him had already begun to turn many weeks before. On October 23, Abraham Esau's chief, Professor Rudolf Mentzel, had called in a Munich physics professor, Walther Gerlach, for an interview. After wasting a good half hour consuming his customary libation of schnapps, Mentzel suddenly asked Gerlach whether he would take over the physics section of the Reich Research Council — Esau's post. Why Gerlach, a lanky, bird-faced Rhinelander, had been singled out for this, and for its associated office as Göring's Plenipotentiary for Nuclear Physics, was something of a mystery. The reader will realize that he had not hitherto had any contact with the German uranium research program, his contribution to the war having been the design of large degaussing installations for the German Navy and work on torpedoes. In 1940, he had been director of all German research into torpedo fuses, with particular emphasis on the magnetic proximity fuse. He currently held a chair at the Institute of Physics at Munich University. A quiet, academic scientist with a passion for flower-arranging, he was on excellent terms with most of Germany's leading physicists, and despite an awkward frankness he had managed to steer a diplomatic course through the shoals of political intrigue in an authoritarian state; he knew how to handle the SS.

Professor Gerlach discussed Mentzel's proposal with Heisenberg and Hahn; both urged him to accept. He insisted that he be given absolute authority and discretion in the distribution of the funds at his disposal, and that he alone should decide how much money each institute — "including Heisenberg's" — should get. (He is said to have viewed the ambitious Heisenberg with some suspicion.) In particular Gerlach demanded the right to annul call-up papers issued to any of his scientists. All these powers were promised him.

Five days later, on October 8, Mentzel summoned Professor Esau and informed him that he and Reichsminister Speer were dissatisfied with his record as head of the physics section of the Reich Research Council. Esau composed a letter of resignation from both his offices and sent it to Göring. Mentzel, in the meantime, wrote to Speer's office to ask formally what notions the Minister entertained about Esau's successor; in fact he and Speer had already discussed this privately weeks before. "We were last thinking of Professor Gerlach, of Munich, and he has verbally agreed with me to accept both offices."

Esau angrily discussed his dismissal with several of Göring's senior officers, including General Bodenschatz, claiming, not without substance, that Speer had interfered with the Reich Research Council's running, which was Göring's own province. Esau found little support among his peers. Few of the other plenipotentiaries wanted him to stay. Professor Ramsauer had expressed strong animosity toward him, and Dr. Vögler was privately "delighted" at the imminent change. Above all, Speer himself urged Göring to make the change. The appointment of Gerlach to direct the nuclear project was ideal, as the professor was much closer to these subjects than his predecessor had been.

In a way it was a real turning point in the German project. Gerlach was a cynic and an idealist; he believed at this stage that the whole fabric of priorities in war research was a "*Schwindel*" in which pure, academic science was being pushed to the wall. He saw it now as his one-man mission to save pure research in Germany, and the tottering uranium project would be the ideal vehicle for this.

Prof. Walther Gerlach

On December 2, 1943, the deed was done. Hermann Göring signed the decree appointing Walther Gerlach supreme head of all German physics research, and turned Esau's Nuclear Research Group over to him, with effect from the first day of 1944. To soothe his ruffled feelings, Esau was offered another command, that of high-frequency research; he agreed to accept provided that Speer was in accord, as he "had no inclination to be shot at from that quarter again." During the first few days of December, Speer approved the reshuffle, and the Reich Research Council circulated the necessary notices to all concerned. On January 1, 1944, Professor Walther Gerlach, the cynic, was in command.

[v]

BY THE END of January 1944, the final heavy-water consignment was ready for its last journey from Norway to the Reich. Fourteen tons of fluid had been drawn off from the last stages of the high-concentration and electrolysis plants at Vemork and Såheim, and stored in thirty-nine drums marked "potash lye"; the actual content of heavy water in these fourteen tons was only 613.68 kilograms, and the concentration varied from 97.6 per cent to only 1.1 per cent over the whole consignment of thirty-nine drums. Even so, the German authorities were taking no chances; much depended on the safe arrival of this weak heavy water in Germany. A special Army unit was sent to Rjukan to guard the transport, and in Berlin Dr. Diebner called his deputy Dr. Werner Czulius to his new office in the Harnack building, and told him to go to Norway as his personal representative and accompany the heavy water on the whole of its journey from Vemork to Germany. In Norway negotiations began for the provision of vehicles to carry the load by road to the port of embarkation.

These preparations did not escape the attention of the Intelligence authorities in London. In the last days of January, they wirelessed the SOE operator in Rjukan, Einar Skinnarland, that there were reports that the heavy-water plant was to be dismantled and evacuated to Germany; if this was true, what prospects were there of preventing the shipment? At the end of the first week in February, Skinnarland wirelessed to SOE headquarters the news that the transport of the remaining heavy-water stocks to Germany was about to be carried out, possibly within the next seven days, so if anything was to be done the military organization would have to be briefed at once.

This time, the British authorities moved with a speed born of fear. The War Cabinet instructed SOE headquarters to do everything possible to destroy this last heavy-water shipment; orders were wirelessed to SOE's Lieutenant Knut Haukelid — about fifty miles west of Rjukan — and Skinnarland, that they were to destroy the last heavy-water consignment. These were the only two men SOE had in the area, so an attack on Vemork itself was out of the question. Besides, the guards had been strengthened, the minefields had been completed, and all the entrances to the plant except one heavily guarded steel door had been walled up.

Since participating in the earlier sabotage attack on Vemork, Haukelid had lived for a year in the open wastes of the Hardanger plateau, as he directed the establishment of the Norwegian Military Organization in Telemark. Far to the west, Skinnarland had set up a semi-permanent radio station, powered by a makeshift waterwheel, and it was with this that he had remained in communication with SOE's wireless station in Buckinghamshire. The food they had brought with them was long exhausted, and they had fought a desperate battle against the elements as winter approached.

It was only late that autumn that the RAF had alleviated their immediate sufferings. In two air drops, they had been supplied with food, weapons, clothes, radio sets and explosives. It was the explosives that formed the basis for the operation that was to follow.

On Wednesday, February 9, Skinnarland wirelessed London that an attack on the consignment while inside the factory was impossible. They would have to sabotage the transport itself, and this would involve reprisals. Lieutenant Haukelid asked London for immediate authority to proceed along these lines. Colonel Wilson, head of SOE's Norwegian section, received the signal next day and saw the Norwegian Defense Minister at once. The Minister gave permission for the attack on his own authority, and Haukelid was wirelessed to this effect. Haukelid realized that the operation's success would depend on detailed inside information on the Germans' intentions. One night, he was taken down into Rjukan by one of Hydro's engineers and introduced to the Norwegian-Hydro official best placed to assist them — the Vemork plant's new chief engineer, Alf Larsen. The engineer had lost his home during the American bombing raid and had moved into the firm's elegant guest house on the opposite side of the valley from the plant itself. Haukelid told him of his mission, and together they analyzed the various possibilities open to them. It seemed that destroying the transport was the only way, even though it would possibly cost German lives and thus involve heavy reprisals.

On Haukelid's instructions, Skinnarland again radioed London, asking for a decision on the urgency of the attack. All the evidence was that the German heavy-water process was inferior to the Vemork process: was the operation considered worth the reprisals? The reply from London came the same day: it was still thought "very urgent" that the heavy water be destroyed. At a further clandestine meeting with Larsen, attended this time by Gunnar Syverstad — Skinnarland's brother-in-law and an employee of the firm — and Kjell Nielsen, the firm's transport engineer, four plans were discussed.

Firstly, there was a dynamite store next to the railway line leading from the Vemork plant to Rjukan; they could try to blow this up just as the heavy-water train was passing. The plan presented immediate disadvantages, however; the suspension bridge carrying the road across the gorge had been destroyed, so the Norwegian workers were also transported along that railway line to the factory. The Germans would obviously load the heavy-water drums onto one of these "passenger" trains. There would be heavy loss of life, and the greater part of the drums would probably be intact.

Because of "unforeseen circumstances," the Germans had been unable to procure road transport for the rest of the journey across Norway, so the heavy-water drums would continue in railway wagons onto the rail-ferry traversing the length of Lake Tinnsjö to Tinnoset at the far end; from there they would proceed by rail to Notodden and eventually to Heröya, where they would be embarked for Germany. The second plan, to attack the railway wagons somewhere along this latter part of the route, offered similar disadvantages. Again, they might recommend that the ship carrying the heavy water to Germany should be sunk. This opened up at once the fourth possibility as their eyes reverted to that brief stretch of the journey where the rail-ferry would traverse Lake Tinnsjö. The lake was so deep that it was virtually bottomless. If the *ferry* were to be sunk there, its cargo could never be salvaged. Chief Engineer Larsen agreed to assist, but said he would have to flee Norway for the rest of the war; Haukelid promised to "export" him on the night the deed was done. It was a plan that had the attribute of finality about it.

[VI]

SO IT HAD TO BE the Tinnsjö ferry. There would always be some of their compatriots aboard, but the Sunday morning ferry, on February 20, would probably be least crowded. Larsen undertook to arrange for this to be the ferry to which the heavy-water consignment was allocated.

In the middle of the week, Haukelid set out to reconnoiter the target. The three ferries that plied the Tinnsjö lake were similar in construction, but not identical. By studying the timetables he deduced that the ferry leaving Rjukan early on Sunday would be Captain Sörensen's *Hydro* — an elderly screw-driven ferry distinguished by the twin funnels gracing the superstructure on either side of the broad main deck. The railway wagons would be shunted aboard on railway lines, and shunted off the ferry at the dock at the other end of the lake. It was not a singularly attractive vessel.

The ferry *Hydro* on Lake Tinnsjö

As he boarded the *Hydro*, carrying a Sten gun concealed in a violin case, Lieutenant Haukelid recalled that this was his first trip since before the war, when he had visited Rjukan to buy some fingerling trout to take to his family's mountains in the west. The circumstances were different now. Against his wristwatch, Haukelid — now an ordinary Norwegian workman clad in overalls — noted that the *Hydro* entered the really deep water about half an hour after sailing, and for twenty minutes would then churn across a part where the lake was 1,300 feet deep. So if the ferry's bottom could be holed exactly forty-five minutes after the scheduled sailing time, this would still allow for a little unpunctuality in the ferry's sailing.

To be sure of sinking the ferry, they had to obtain electric detonators. Haukelid paid a nocturnal visit to a Rjukan ironmonger's home but the man was suspicious and refused to supply the detonators. Through an intermediary, Haukelid did procure about two dozen of the detonators from the ironmonger, who was advised for his own good to vanish until the hue and cry had subsided. For extra reliability, Haukelid wanted a timing mechanism, rather than a time fuse. Back at Rjukan on the night after his ferry trip, he roused a local handyman who had been recommended to him, a Mr. Diseth, and frankly explained to him what was afoot. Diseth, an elderly former employee of Norwegian-Hydro, kept a handicraft shop with a little workshop on the first floor. He donated one of his own alarm clocks to the cause; Vemork's chief engineer donated the second. It was fitting for a town with Rjukan's history of prolonged resistance during the German invasion in 1940 that this was an enterprise in which plant and townspeople were thus symbolically linked.

Haukelid already had the necessary explosives — short, stubby sticks of plastic from the big SOE supply drop to him the previous autumn. To prevent the ferry's being maneuvered to the shallower reaches after the charge went off, he wanted the ferry to sink by the bows; the screws and rudders would then clear the water and leave her helpless. Should this not happen, he guessed it would take five minutes for the sinking ferry to reach the banks of the long, narrow fjord, so the hole had to be big enough to sink the ferry before then; but not too big, for this would cause unnecessary casualties. He calculated the necessary size of hole as being about eleven square feet. Using Diseth's workshop as a base, Haukelid and an assistant, Rolf Sörlie, kneaded eighteen pounds of the plastic into a sausage twelve feet long — just enough to circumscribe a circle of the required area. This explosive was sewn up in a sacking cover.

They then turned their attention to the timing mechanisms. The bells were removed from the two alarm clocks, and in their place Diseth fixed a Bakelite insulating plate holding a brass contact; when the "alarm" began to ring, the clapper would close the detonating circuit. The whole contrivance was powered by four flat torch-batteries, whose terminals Diseth soldered together for added reliability.

As dawn came, Haukelid and Sörlie retired to their mountain hideout. They knew there could be no second chance. To test their improvised timing devices, they wired each to an electric detonator and set the clocks to ring that evening. They retired to bed and slept all day. As dusk fell, they were violently awakened by the rifle-like cracks of the detonators, in rapid succession. Sörlie was behind the door with his nervous Sten gun cocked almost before the sound had finished echoing round the empty valley. There was no doubt: the timing mechanisms functioned admirably.

In London, extraordinary measures were being taken to insure that this last heavy-water consignment should not reach Germany. SOE headquarters wirelessed orders to a second Norwegian underground group, code-named *Chaffinch*, at Vestfold, to dispatch sufficient men to Skien, near Heröya, to sabotage the heavy water should it get that far. Michael Perrin and Dr. Jones called on a senior officer at RAF Bomber Command and asked him to prepare to bomb the cargo ship which would carry the heavy water to Germany, explaining that heavy water was a chemical which could be used in the production of a very powerful explosive. The RAF officer expressed a natural curiosity about this explosive: was it as powerful as RDX? twice as powerful? three times? Perrin and Jones cut him short, saying that there was no point in holding a Dutch auction over it. Suffice to say that the explosive would be Extremely Powerful. The RAF agreed to prepare to sink the ship, and it is believed that the Admiralty was also invited to detach a force for that purpose.

The Germans had taken security measures commensurate to the importance of the consignment. The first company of the 7th SS Police Regiment had been moved into Rjukan, and Himmler had sent the sixth squadron of his 7th Special Air Group to operate its Fieseler Storchs from a landing strip not far from the heavy-water factory. In addition to this, a special army detachment is understood to have been sent to Rjukan to guard the heavy water, and Dr. Diebner of the Army Ordnance Department had sent a lieutenant to Norway to keep an eye on things for himself. The lieutenant, Dr. Werner Czulius, flew into Oslo's Fornebu Airport on about February 18. He told the security police who questioned him there that his mission was connected with the "heavy water" at Rjukan. The police arrested him and held him in custody as a suspected enemy agent. Czulius pointed out that they had only to telephone the War Office in Berlin for his story to be substantiated, but in vain. The Germans had evidently heard somehow of the plans to sabotage the consignment, for Chief Engineer Larsen learned that a telephone conversation from Oslo had been intercepted by the underground organization, and that the Germans were now planning to split up the consignment at the far end of Lake Tinnsjö: half would proceed by rail, and the rest by road. A heavy German guard was mounted on the railway line leading from the blitzed Vemork plant to the railhead on the lake.

That night, as the unhappy Czulius languished in his Oslo cell, there was the usual Friday evening concert at the Norwegian-Hydro works in Rjukan. The ferry brought the famous musician Arvid Fladmoe — a more orthodox instrument in his violin case than in Haukelid's a few days before. Haukelid was down in Rjukan too, arranging transport for the following night; without a car, they could not confirm for themselves that the heavy water had been entrained and then travel the nine miles to the ferry-dock at Mael to lay the charges. He contacted two doctors, but their cars were out of order. After a long search, he found a car and warned its owner in the name of the King that it would be stolen briefly during the following night and returned on Sunday morning. Sörlie mustered two reliable men, one to drive the car and one to cover the demolition party as it went to work.

By Saturday morning, there were thus eight men aware of what was to befall the *Hydro*. Of these, the most seriously implicated would have to have alibis. Kjell Nielsen, the firm's transport engineer, was an obvious suspect. On Haukelid's instructions, he was taken to a local hospital where an appendectomy was duly performed. When the police checked up on Nielsen next day, they found his alibi watertight: not so the ferry.

That evening, February 19, Haukelid returned to the town. The station had been closed to passenger traffic since the sabotage of Vemork as a security measure. From a bridge, he saw two covered railway wagons standing in floodlit splendor on the line leading down from Vemork. There was an armed guard on them, so the heavy water had obviously begun its last journey.*

* The actual consignment aboard the *Hydro* was as follows:

Drum no.	Contents (liters)	Concentration (percent)	Equivalent heavy-water content
1	46.94	97.6	45.75
2	46.78	95.4	44.65
3	48.07	87.0	41.80
4	46.70	75.6	35.30
5	46.29	65.4	30.30
6	90.78	46.0	41.80
7	139.98	29.0	40.60
8	199.50	19.0	37.90
9	248.80	13.0	32.35
10	144.65	10.6	15.35
11	95.7	9.4	9.00
12		6.0	
13	1,046.0	6.0	61.78
14		5.6	
15		3.8	
16	1,000.0	4.2	38.00
17		3.6	
18–23	2,365.0	2.54	60.10
24–29	2,290.0	1.64	37.60
30–39	3,750.0	1.105	41.40
		Equivalent total 100% heavy water =	613.68

At Norwegian-Hydro's guest-house, Chief Engineer Larsen was holding a dinner party. The violinist who had performed the night before was among the guests. Fladmoe mentioned in passing that he would be leaving Rjukan by the first ferry next morning. Larsen enjoined his guest to stay one more night in the valley: nobody should miss such an opportunity of sampling their famous ski slopes. Fladmoe was adamant. He had to be in Oslo for a concert next evening: there was no other way.

At about eleven o'clock, the conspirators met outside the garage of the car they were to appropriate for the operation. Soon they were joined by Larsen, carrying all his most precious possessions in a suitcase, and by the two local men selected to drive the car and cover the sabotage party. For over two hours they wrestled with the obstinate engine. The car was modified to run on producer gas, but it refused to start. It was well into the small hours before the raiding party finally set off for the ferry-dock at Mael. The night was icy, and the dockside covered in a crisp fall of snow. The car halted some distance from the blacked-out shape of the silent *Hydro*, and Haukelid and two men got out. Haukelid ordered the driver and Larsen to wait by the car. He handed Larsen a pistol, and told them that if the raiding party was not back in two hours, or if they heard shooting, they were to drive off at once. Larsen would have to find his own way to Sweden.

To SOE headquarters, Haukelid later reported:

> Almost the entire ship's crew was gathered together below round a long table, playing poker rather noisily. Only the engineer and stoker were working in the engine room, so there was no question of going in there. We therefore went down to the passenger cabin, but were discovered by a Norwegian guard. Thank God he was a good

> Norwegian. We told him that we were on the run from the Gestapo, and he let us stay.

Evidently satisfied by their explanation, the watchman showed them the hatch giving access to the bilges. Haukelid and another man climbed down through it, leaving one armed man in the cabin to cover them. They shut the hatch behind them, and crawled along inside the ferry's flat bottom toward the bows. Haukelid, forced to crouch up to his waist in foul and brackish water, laid the circle of plastic explosive on the bottom plates, and tied two long, high-speed detonating fuses to each end of this explosive ring: "I reckoned that the charge was enough to sink the ferry in about four or five minutes." The four long fuses he taped together, and their loose ends he brought out of the water and tied to the stringers — the ferry's steel ribs — to which he had already taped the two sets of timing clocks and batteries.

The most dangerous operation would be linking the timing mechanisms to the fused plastic charge.

Haukelid sent the other man aloft. He set each clock to "ring" at 10:45 A.M. and wired four loose electric detonators into the two clock circuits; holding them well away from the high-speed fuse, he connected up the batteries. Nothing happened, so the timing circuits were still open. Exercising extreme care to avoid jarring the clocks, he taped the four detonators to the four long fuses trailing out of the water: "At 4:00 A.M. the job was finished."

They drove in silence along the deserted pre-dawn highway for about ten minutes, when Sörlie left them on the first stage of a long trek to Skinnarland, the radio operator who would report the attack to London. At Jondalen, about ten miles west of Kongsberg, Larsen and Haukelid also left the car, which the driver was ordered to return to its garage before dawn. The two men continued on skis toward Kongsberg, where they bought rail tickets for the first stage of their journey to Sweden.

As Lieutenant Haukelid and Chief Engineer Larsen waited on the platform at Kongsberg for the eastbound train to Oslo, a westbound train pulled in. Among its passengers, Larsen was dismayed to see Muggenthaler, the Rjukan secret police chief, who was the last person who should see him here. The Vemork engineer locked himself into the station lavatory and stayed there until the westbound train had left, hastening to make its connection with a ferry that would never arrive.

[VII]

AT EIGHT O'CLOCK that morning, Sunday, February 20, 1944, the short ferry train left the Rjukan freight yards, pulling the two railway wagons laden with heavy-water drums. Guards were posted in strength all along the line to the ferry dock. By ten o'clock, the train was safely on the *Hydro*'s deck, and the ferry began ploughing southwards across the icy waters of Lake Tinnsjö with fifty-three people aboard. Her skipper, Captain Sörensen, had a brother who had twice been torpedoed in the North Atlantic, and he was glad he had won the job of captaining a ferry in this landlocked lake far from the thrash of the U-boats' screws.

At 10:45 A.M., as the ferry was plunging steadily across the bottomless depths of the Tinnsjö gorge, the captain felt — rather than heard — a violent knock, which suggested at first to him that his ship had been torpedoed. The ferry began to settle by the bows, and passengers and crew abandoned ship as best they could. As the bows sank, the railway vans broke loose and trundled over into the lake. Within three to four minutes the ferry had completely vanished, dragging twenty-six passengers and crew down with her.* The surface of the lake was bare save for the lifeboats, some scattered débris, a few floating spars and a violin in its case. After some time, four of the heavy-water containers bobbed up onto the surface, but that was all. At the entreaty of the violin's owner, who had somehow escaped even the least immersion in the disaster, the instrument was saved; but the remaining heavy-water drums were beyond salvation.

The second SOE unit waiting at Heröya had identified the cargo vessel which was to transport the heavy water to Hamburg and the Reich; but the cargo never came, so their plans to destroy the vessel were not put into effect.

In Oslo that Monday Haukelid bought the evening newspapers and found a small paragraph reporting the sinking of the ferry. Sabotage of ships was a frequent occurrence in Norway, and rated little attention in the press; in Rjukan, of course, the incident made headlines.† Skinnarland signaled the news to London, and reported next day that the whole consignment had been lost.

This was Lieutenant Haukelid's last contact with heavy water. After "exporting" Chief Engineer Larsen safely to Sweden, he returned to Norway to resume the fight against the Germans. For his gallant attack on the ferry, he was later awarded the

* The casualties have been previously open to doubt, but an Intelligence report in the file of the Military Governor of Norway stated two days later: "On 20 February 1944, the railway ferry over the Tinnsjö, to the east of Rjukan, sank after an explosion in the bows. Of 53 people on board, 27 (including 4 German servicemen) were rescued. Investigations are in hand, but cause not yet established." The *Alsos* mission subsequently captured a detailed German report on the incident.

† Thus at a secret police conference early in 1945, SS-General Rediess, head of the police organization in Norway, reported "there have been all together twenty-three cases of ship sabotage during 1944"; the Tinnsjö incident was not among those he described in detail.

DSO. Larsen himself was flown out of Stockholm airport to Leuchars in Scotland. At Kings Cross station in London, Major Tronstad was waiting on the platform to meet him. Larsen was taken to see Commander Welsh, who interviewed him closely on the Vemork plant's layout; then the engineer also passed out of the story and into obscurity. In Oslo, Dr. Czulius was released by the police authorities, profusely apologetic for their mistake. There was now no point, they said, in his continuing his journey to Rjukan, so he flew back to Berlin.

The attacks on Norwegian heavy-water production, culminating in the sinking of the *Hydro* in February 1944, can be seen in retrospect to have played the largest part in destroying any hopes the Germans still entertained of constructing an atomic reactor, let alone an atomic bomb. One can do no better than quote the views expressed after the war by Dr. Kurt Diebner, Professor Gerlach's deputy: "When one considers that right up to the end of the war, in 1945, there was virtually no increase in our heavy-water stocks in Germany, and that for the last experiments early in 1945 there were in fact only two and a half tons of heavy water available, it will be seen that it was the elimination of German heavy-water production in Norway that was the main factor in our failure to achieve a self-sustaining atomic reactor before the war ended." From early 1944, the lack of sufficient heavy water dogged the German researches at every stage.

CHAPTER NINE

The Cynic in Command

SOME WEEKS AFTER the Tinnsjö ferry, laden with heavy-water drums, had plunged to the bottom of the fjord, Dr. Karl Wirtz was informed that a consignment had arrived from Norway from Rjukan. Wirtz found the consignment consisted of a number of large drums of assorted sizes; they contained heavy water of various degrees of concentration, one large drum's contents being about 50 per cent, and the others varying above and below this. Wirtz asked Diebner what was the object of providing such low-concentration heavy water. Diebner explained that the whole heavy-water plant at Vemork had been drained, as it was to be dismantled and shipped to Germany. He hinted that they had got wind of a planned sabotage attempt on the heavy-water consignment, and had secretly switched ordinary water for the heavy water in the drums. It was just as well, he continued, for the ferry carrying the "dummy" consignment had been sabotaged and sunk. The containers now standing in

Berlin had come by road. Wirtz had no cause to doubt this story: the relatively low concentration of the material certainly bore it out.

Had Haukelid's brave effort been in vain? In fact there was a simple explanation. Four drums — numbers 6, 8, 9 and 11 — had floated out of the wreckage of the ferry and been salvaged; they contained the equivalent of 121 liters of heavy water. On March 3, 1944, twenty more drums, containing the equivalent of 37.1 liters from Såheim and 32.4 liters from Vemork, had been dispatched to Germany by road, and a further 50.7 liters had followed six days later. But these 120 liters of heavy water were diluted in a hundred times their weight of ordinary water and potash-lye, and of no use to the project unless they could be further concentrated. The surviving drums of heavy water were transported safely by road to Myrow, in Silesia, where it was planned that I. G. Farben would process the heavy water to full strength; but the military developments on the Eastern Front eventually made this impossible.

The situation now was that there were about two and a half tons of pure heavy water in Germany, and the last immediate source was gone.* It remained to establish whether this was enough for the construction of what the Germans were still sure

* By the time the November 1943 air attack brought heavy-water production at Vemork to a standstill, the plant had manufactured 2,840 kg. of heavy water of over 99.5% concentration, as follows: 1939–40, 20.35 kg.; 1940–41, 28.25 kg.; 1941–42, 871 kg.; 1942–43, 1,179 kg.; 1943–44, 487 kg.; 1944–45, nil. Output of heavy water of over 99.5% concentration during 1942 and 1943 was:

	1942	*1943*		*1942*	*1943*	
January	100	141	July	128	141	
February	91	107	August	121	100	
March	103	0	September	96	100	
April	0	0	October	93	105	
May	51	3	November	117	41	(16 days)
June	94	199	December	147	0	

As the Allies were able to secure 185 kg. of heavy water from Vemork in 1940, the Germans probably received a total of 2,655 kg.

would be the first chain-reacting uranium pile in the world; their calculations indicated that it might not be enough.

At the German Army's explosives research establishment in Kummersdorf, a remarkable series of nuclear experiments of an entirely different nature had begun, again under the energetic direction of Dr. Diebner. At the end of May, Gerlach was to mention briefly: "The question of unleashing nuclear energy by means other than uranium fission has been taken up on a broad front." In short, a small team of explosives experts was working on thermonuclear fusion. In retrospect it is obvious that their attempts were doomed to failure, but as the details have never been published before it is worth examining the two series of experiments in detail. The only vestige that remains of these experiments at Gottow — which was captured by the Russians at the end of the war — is a six-page report among the *Alsos* collection of German documents housed at Oak Ridge, Tennessee, entitled "Experiments on the Initiation of Nuclear Reactions by Means of Exploding Substances." Diebner himself wrote a brief account of the later experiments shortly before his death in 1964.

By 1944, ten years had passed since physicists had first recognized that the fusion of two heavy-hydrogen atoms to produce helium was accompanied by the liberation of large pulses of energy. Paul Harteck, the German physical chemist, and Lord Rutherford and Mark Oliphant had used a high-voltage particle accelerator to hurl single deuterons (they called them "diplons" in 1934) against a target also containing heavy hydrogen, and they had measured the abnormal pulses of energy on an oscillograph. Several physicists had thereafter declared that if a quantity of heavy hydrogen could be heated to a sufficient temperature — of the order of millions of degrees — the deuterons would collide with each other so violently that numerous "thermonuclear" fusions would occur, liberating energy on a colossal scale. In 1939 Professor Hans Bethe had published some calculations on this in a *Physical Review* paper entitled "Energy Production in Stars." Could such temperatures be reproduced on Earth?

> It has often been suggested [the 1944 German experimental report began] that the gas velocities created by the detonation of explosives should be used to bring about nuclear chain reactions. . . . Although this path seems impracticable from superficial considerations, a number of initial experiments has been performed at the Army's Kummersdorf research establishment, on Professor Gerlach's initiative, in order to provide an experimental basis for a final verdict on this.

The first trials were conducted by three of Diebner's group and Dr. Trinks from the War Office, using cylindrical TNT charges of varying diameters and eight or ten centimeters high. A small conical pit was scooped out of the bottom of each cylinder, and a cone of heavy paraffin inserted as the deuterium carrier. A silver foil was laid under the whole assembly, to show any radioactivity resulting. Two explosions were set off, but the resulting damage to the test beds was so great that "no significant traces of the silver foils were found." In the next experiment, the silver foils were better protected, and large fragments were found; but they showed no radioactivity.

A new approach was adopted. Late in 1942, G. Guderley had published an academic paper on the subject of the intense temperatures created by strong spherical or cylindrical shock waves in a gas. Guderley's paper referred to an "ideal gas," and

Trinks suspected that the theory would break down long before the convergent shock waves had reached the center of a volume of heavy hydrogen. Shock waves alone were not enough. He proposed a modification of the earlier experiment to circumvent this. In 1936, F. Hund had written a paper on the behavior of matter under extreme pressure, and Trinks calculated on the basis of this and Bethe's theory about the energy-production processes in the stars, that if he could generate a temperature of about four million degrees at a pressure of 250 million atmospheres, there would be a considerable number of fusion processes; and this he thought he could do with a bomb about three to five feet in diameter. He and an assistant, Dr. Sachsse — Diebner's brother-in-law — prepared a simple experiment to try the theory out. Sachsse made a hollow silver sphere about two inches in diameter, and this was filled with heavy hydrogen; silver was again used in the expectation that this would show the traces of radioactivity caused by a few fusions. Round the sphere was packed a quantity of ordinary explosive.

The theory of what happened next was this. The explosive was detonated at several points on its outer surface simultaneously. The silver liquefied under the intense pressure, and began to converge on the center at a fantastic velocity — about 2,500 meters per second. Since the layer of liquid silver grew thicker and thicker as its radius decreased, the *inner* surface was actually accelerating faster than the outer, until it was finally traveling at an incredible velocity, converging on a minute ball of compressed heavy hydrogen, by now at very high density and temperature. One could regard this system as "focusing" nearly all the energy contained in a large amount of conventional explosives on the minute mass of heavy hydrogen at its center. For a brief space of time, the heavy hydrogen was trapped under conditions approximating those at the center of the sun, unable to escape because of the inertia of the molten silver.

Several such experiments were carried out, and the surviving traces of silver tested for radioactivity, but none was found. It seems now that the experiment was on too small a scale. Similar experiments were conducted by *CPVA*, the German Admiralty's explosives research establishment at Dänisch-Nienhof, near Kiel. Professor Otto Haxel, who was working on the larger uranium project, was called in to advise on neutron indicators for the experiments, but he was unable to recommend the Admiralty to invest further effort in them.

Although the experimental and measurement procedures were admitted to be open to error, it seemed unlikely that much good would come out of them, and no more were carried out before the war ended; but it is believed that such experiments have been resumed in some European countries since then. For the Germans, the mystery remained as to why the Allies should have concentrated so much on destroying their heavy-hydrogen sources, if it was impossible to produce bombs with heavy hydrogen.

[11]

ADMIRABLE THOUGH Professor Walther Gerlach's personal qualities were, he did not abound in energy and drive. Those who knew him then, and those who visit him now, retain an impression of an outstanding scientist imprisoned behind a desk heaped with reports, papers and documents through which he laboriously and methodically works, while never quite getting to the bottom. The calendars on his wall are over eight years old. The surface of his desk is seldom seen.

Very soon, the Reich Research Council was sending Professor Gerlach exasperated letters asking for the long-overdue bimonthly reports on nuclear physics to submit to Göring. They were met with a wall of silence from Gerlach's flower- and plant-bedecked Munich institute. In the German record that has survived, there are only two progress reports by the professor on nuclear research: on one the date "March 1944" has been altered in Gerlach's hand to read "May"; and the other, written late in 1944, was still in pencil draft when the Allies captured Gerlach in the last days of the war. If there were delays now in the circulation of the individual research reports by Gerlach, the reason was not so much indolence as an inability to cope with the huge task of running the whole of German physics and the uranium project at the same time.*

Professor Gerlach's diary reflects the strain of the first few weeks of his command. We see him shuttling backward and forward in privileged sleeping cars between bomb-torn Berlin and Munich, four hundred miles away in southern Germany, calling hurried conferences with Esau, Mentzel, Schumann and Harteck, journeying with I. G. Farben's eminent Dr. Bütefisch to Leuna, scribbling notes for appointments on "heavy water, then Dr. Diebner." And always we see the kindly Dr. Paul Ros-

* It is permissible to regard the volume of research papers as an index of research activity. Carl Ramsauer made delightful use of this device in his April 1943 speech on the backwardness of German physics. An analysis of the German documents on atomic energy listed in Oak Ridge report TID-3030 gives the annual totals of *dated* nuclear research reports as follows:

1939..............4	1943..............51
1940..............54	1944..............55
1941..............61	1945..............17
1942..............84	

Thus the "brain output" of the German nuclear scientists was greatest in 1942, as was the uranium and heavy-water output. Gerlach's performance during 1944 and 1945 is only moderate, as many 1944 papers would have been initiated in 1943.

baud hovering in the background, lunching with him sometimes two or three times a week, and sympathetically discussing the problems of the German uranium project. "He regarded me as a personal friend," Rosbaud told American investigators later.

The weather worsened. During February, Gerlach fell ill after a bleak visit to the huge I. G. Farben plant at Leuna, where the full-scale heavy-water plant would probably be built. He struggled on, his nights in the capital rent by the air-raid warnings of the Battle of Berlin, and his life in Munich harsh and uncomfortable in a flat with its windows blown out and no central heating. The diary reflects the different milieus in which the professor was now obliged to move: the names of Fischer and Spengler, the two SS officials watching over German science, begin to appear.

One night Gerlach received a long-distance telephone call at the Harnack building in Berlin where he had established his main office. He was ordered to stay awake and leave the main door unlocked, because that night a number of high SS officers would be calling on him. In the middle of the night, an SS general arrived. Gerlach was asked whether he knew Professor Niels Bohr by sight, and was he a dangerous man? Gerlach replied that he had met Bohr on occasion. The general said that Bohr was to be found and liquidated. The professor asked whether the SS knew where he was, then. Was he still in Stockholm? With due deference he suggested that the assassination of a world figure like Bohr would greatly harm Germany's cause abroad, while contributing nothing to her war effort. Visibly impatient, the SS officer said that Gerlach apparently believed that a human life was worth something; he would soon learn differently. Professor Gerlach now stated that he believed that Niels Bohr was in London anyway. At this, the general brightened visibly: that was *Prima!* In London their security service had very reliable people, and an assassination would cause fewer complications than in a neutral country.

The SS officers returned several times to discuss the matter further with Gerlach. The latter was able to use an SS contact in the Foreign Office to prevent reprisals being exacted against Bohr's remaining staff in Copenhagen. But Bohr himself was already out of reach of the SS assassins: as "Mr. Nicholas Baker," he was at Los Alamos in the United States, where the design of the American atomic bomb was in hand.

[III]

THE AMERICANS were still afraid that the Germans might be working on the atomic bomb. During the autumn of 1943, the German leaders had begun to boast of the existence of new and terrible secret weapons they were preparing, and the Americans were all too conscious of the one their own science was hatching. The office of the Secretary of War proposed, on the recommendation of the head of Military Intelligence, General Strong, that a special Intelligence mission should be established to uncover the secrets of German uranium research.

General Groves had realized that there was a possibility of gathering information as the American Fifth Army advanced up Italy, and especially once Rome could be captured. This was the birth of the controversial *Alsos* (Greek: "grove") mission, a co-operative effort by the Army's G-2 (Intelligence) department, General Groves's Manhattan District, the U.S. Navy* and Dr. Vannevar Bush's Office of Scientific Research and Development. General Marshall was advised that the *Alsos* mission would form

* Some months later, the U.S. Navy left the mission, having established its own Intelligence mission in Europe.

"the nucleus for similar activity in other enemy and enemy-occupied countries when circumstances permit."

Lieutenant-Colonel Boris T. Pash, an officer in the U.S. Military Intelligence Service who had distinguished himself by his forceful interrogations of Robert Oppenheimer a few months before, was appointed to command the *Alsos* mission. Pash had enraged so many senior officers by his unorthodox security methods on the West Coast — lifting classified files from their offices being his usual ploy — that his posting to this overseas mission was greeted with audible relief. He was not a scientist, however, and the *Alsos* mission to Italy was not an outstanding success.

The mission left for Naples on December 16, 1943; Pash and his technical staff proceeded to Taranto to meet Italian naval officers familiar with German research. During the following two weeks, the mission had a series of interviews with Lieutenant-General Matteini, Chief of Naval Ordnance, and with a small number of Neapolitan and Genoan university professors. They established with little difficulty that the Italians themselves had done no work on "explosives based on nuclear energy"; but it was obvious that they could hope for little positive detail on work in Germany, as the Germans had kept their Allies ignorant of the status of the various research projects, and the Italians had made little effort to find out what the Germans were up to.

The most reliable report came from an Italian officer who had been air attaché in Berlin for six years, and had escaped two days before the Italian armistice. This officer, Major Mario Gasperi, was housed in the *Alsos* mission's apartment in Naples for three days toward the end of January, and questioned at great length. Classed an "excellent source," he had been a close personal friend of General Marquardt, the German air-force officer in charge of bomb ordnance. Marquardt had stated that Germany had developed "no new, very violent explosive." (In fact the German air force had had no contact with uranium research, as we have seen.) An OSS — the American Office of Strategic Services, similar to SOE — agent, a chemical company executive in business contact with explosives manufacturers in Germany, had stated much the same.

Gasperi "knew from casual conversation" of German heavy-water activity in Norway, and had a vague recollection that I. G. Farben was involved. But when asked outright about the Joachimsthal uranium mines, or the existence of any large group of physicists working on this problem, he knew nothing. Where were Bothe and Gentner? He could not help. Were there in Germany any heavy-water plants? Had there been any "epidemics," or cases of radium poisoning? The ex-attaché's knowledge was already exhausted. The investigation of the academic physicists was even less rewarding.

There was no evidence that the Germans were conserving radioactive ores, or that they were developing new or unusual power demands not connected with known industrial activities. In its general conclusions, the mission recalled that long-term weapons research had been forbidden in Germany at the outset of the war by high-level decree, and this made it "doubtful" that the Reich would have embarked on nuclear explosives research: "this decision may not have been altered even after the reorganization of German research in 1942." In short, when Colonel Pash and his officers left for Washington on February 22 they had very little hard information to show at all, and only a few copies of their report, couched in guarded language, were circulated.

Until the *Alsos* mission was formed, the British Intelligence authorities had led the investigation of the German uranium project. In particular, Michael Perrin of "Tube Alloys" and Commander Welsh had together built up a brilliant picture of the progress the Germans had made. For Perrin and Welsh, the establishment of the *Alsos* mission spelled a new era, for the resources of the Americans were greater than theirs. Was this the end of the British monopoly of nuclear intelligence?

At first the danger had seemed slight. In December 1943, Groves had sent to London one of his officers, Major Robert Furman, to discuss the possibility of establishing a Manhattan Project liaison office there, and establishing a joint Anglo–American intelligence attack. Furman was educated and erudite, a close personal friend of Groves and a good tennis player. He was introduced to Welsh and Perrin at the latter's office in the "Tube Alloys" office in Old Queen Street. A witness of the scene has described their exaggerated delight after Furman had left the room: the impression was that as long as they sent people like that, we would be able to outsmart them every time.

Very soon, however, the position changed in London. The British had received the idea of a joint effort well, but it was not Furman who arrived to head the American liaison office; it was Major Horace K. Calvert, a tough, legal-minded Intelligence expert with an extensive background in the American nuclear project. Calvert, given the rank of assistant military attaché in London, soon had a desk in the "Tube Alloys" building and a high-powered staff of six officers and agents working under him in London.

He began by investigating how far the Germans had control over the necessary materials for a bomb — uranium and possibly thorium. The Americans were in no doubt of Germany's scientific and industrial ability to make a bomb, if they had applied themselves to it. Thorium seemed out of the question, as Germany had been unable to import any since the war began. In view of the enormous effort necessary for extracting uranium-

235, it seemed most likely that the Germans would go for the plutonium alternative, and they certainly had enough uranium for that. Calvert listed about fifty of the leading German nuclear scientists, and began to search for them.

Even if the Germans were not using the uranium and heavy water to manufacture plutonium, there was another unpleasant possibility: they might produce considerable quantities of radioactive poisons in a heavy-water reactor. During January, General J. L. Devers had spoken to Mr. Churchill about the possibilities of a German bomb capable of causing radioactivity over an area up to two miles square, causing nausea and death, and making the area unapproachable. Devers had added that the Americans had made many experiments in this direction; perhaps the Germans had now achieved success? "All this seems very fruity" was Mr. Churchill's uneasy comment. "I do not know whether he is mixing up the possible after-effects of an explosion on the lines of Anderson's affair (I have forgotten the code name)." Lord Cherwell recalled that during the previous summer the Americans had advised that Germany might have obtained highly radioactive elements which could be spread as a sort of super poison gas. "I imagine General Devers's anxieties refer to this," Cherwell said. He hastened to reassure Mr. Churchill that it was "most improbable" that the Germans were working along these lines, and Field-Marshal Dill was asked to explain this to the Americans. British Intelligence was prepared to stake its reputation that no large-scale German uranium project was in hand, and that consequently neither atomic bombs nor radioactive poisons need be feared from that quarter.*

* The only German reference to the possible use of radioactive products as "weapons" has already been noted (see Chapter 8). The German scientist E. Schiebold did, however, deliver a lecture in May of 1944 on the possibility of using X-rays and gamma rays in radiological warfare over long distances.

During the spring of 1944, however, the Americans were less inclined to accept general assurances from British Intelligence than hitherto. This was a consequence, in General Groves's belief, of their shock at learning very belatedly from London of the effort the Germans were making with their other secret weapons.* As for the British belief that there was little to fear from Germany, Groves wrote: "I could not help but believe that the Germans, with their scientific capacity and with their extremely competent group of first-class scientists, would have progressed at a rapid rate and could be expected to be well ahead of us." He was "reasonably sure" that the Germans' most probable approach would be to develop a bomb with no regard for the safety of the project workers. It was even more probable that by these means they could produce large quantities of radioactive materials, and use them in ordinary bombs. The unchallenged use of such weapons might cause a panic in Allied countries.

On March 23 Groves advised General Marshall to send an officer to General Eisenhower, by now in England, to warn him that his invasion troops might encounter a "radioactive barrage" on the beaches. "Radioactive materials are extremely effective contaminating agents; are known to the Germans; can be produced by them and could be employed as a military weapon. These materials could be used without prior warning in combating an Allied invasion of the western European coast." General Marshall authorized the dispatch of the officer to warn Eisenhower of this unusual danger, and some weeks later the U.S. Army's chief surgeon issued orders designed to insure that

* The first exchange of intelligence on this had begun early in January 1944, nine months after the threat had first been recognized in London (cf. David Irving, *The Mare's Nest*, pp. 196–98).

any inexplicable fogging of photographic materials or multiple cases of certain diseases were to be reported to him.

In the meantime, Calvert's intensive Intelligence search for the fifty German scientists was gathering momentum. The lists of scientists were passed to the agencies monitoring the German newspapers and gradually a virtually complete directory of addresses was compiled, with individual dossiers on each scientist. His first solid information came from the OSS in Berne: the Swiss physicist Professor Scherrer had learned from Heisenberg that he was living near Hechingen, in the Black Forest. Almost simultaneously one of Britain's most reliable agents in Berlin reported that other top-ranking German nuclear scientists had been seen near Hechingen. American postal censorship had already intercepted a letter from an American prisoner of war in which he mentioned a research laboratory in which he was working; the letter was postmarked "Hechingen." So the new site of German uranium research seemed to have been established beyond doubt. None of the scientists listed by Calvert seemed to have been to Peenemünde, the Army establishment where — according to the Italian Major Gasperi — most explosives research was carried out.

Britain did not now take the threat so seriously. On March 21, 1944, Sir John Anderson reassured Mr. Churchill that while it seemed certain that the Americans would now get their first atomic bomb ready for use — presumably against Germany — as early as the autumn of 1944, "fortunately all the evidence we have goes to show that the Germans are not working seriously on the project."

[IV]

AS THE BATTLE of Berlin drew to a close, the German scientists — Gerlach, Bothe and Heisenberg in particular — began to worry seriously about the progress the Allies might be making toward atomic bombs. Night after night, as the city was pounded by RAF bombers, they continued their atomic pile experiments in the air-raid shelter at Berlin-Dahlem, hampered by continual power cuts and material shortages. Heisenberg and his team were now working hard on the construction of a big sub-critical pile using 1.6 tons of heavy water and uranium plates in the bunker, as Professor Esau had already been able to report in his last report of 1943. The purpose of the experiment was to investigate the characteristics of piles built of uranium plates and the stabilization of their neutron production. On the night of February 15, there was what Gerlach recorded in his diary as "a catastrophic air raid" on Berlin. The Kaiser-Wilhelm Institute of Chemistry in Berlin-Dahlem, where Hahn and his co-workers were carrying out extensive research into the fission products of uranium, received a direct hit. Mattauch's costly Van de Graaff machine was fortunately undamaged, but the Institute had to be evacuated to Tailfingen about ten miles south of Hechingen, to which the bulk of the Kaiser-Wilhelm Institute of Physics had been evacuated. As the Battle of Berlin ended, the Physics Institute's building in Dahlem was still standing, undamaged. On February 20, Dr. Bagge commented in his diary: "The decision to evacuate to Hechingen was somewhat prematurely taken." He himself stayed in Berlin until the last days of March — just long enough to see the second, reconstructed prototype of his gas-driven "isotope sluice" meet the same fate as the first, as it was destroyed in an air attack on Bamag-Meguin's works. On April 1, Bagge emptied the contents of his Berlin flat into a furniture van and sent his young wife to Neustadt. Within two weeks he himself had moved to Butzbach, near Frankfurt, commencing the construction — all over again — of the isotope sluice, aided now by a camp of Russian internees employed by Bamag's Butzbach works.

The devastation caused by the bombing in Berlin turned the German scientists' minds back once again to the possibilities of building thermonuclear-fusion bombs. They had already conducted experiments on these lines themselves, and to both Professor Gerlach and Professor Bothe there seemed some chance that by using hollow-charge bombs containing a small amount of heavy hydrogen the Allies might have succeeded where their own research group at Gottow had failed. Some of the bomb craters in the Berlin-Dahlem area were larger than any they had seen before, and one single bomb had stripped the roofs off whole blocks of houses. If the British bombs had gained this unusual extra efficiency by means of thermonuclear-fusion reactions, then a very large number of neutrons would have been released in each blast, and these would certainly have left the craters radioactive.

Nor was all this just idle speculation. At the end of May, Gerlach wrote in a report to Göring:

> Reports from America about alleged large-scale production of heavy paraffin and its use for explosives, and the particular interest which the destruction of the Norwegian heavy-water plant shows the Americans to have in heavy-water production, have made it clearly necessary for us to devote closer attention to the application of nuclear reactions to explosives.

In particular, he added, the Army Ordnance Department had been asked to investigate bomb craters and unexploded bombs for evidence of nuclear reactions and heavy water. At Gerlach's request, Dr. Kurt Diebner's office provided a number of Geiger–Müller counters and, armed with these, technicians closely investigated the bomb craters in Dahlem, while Gerlach personally looked on. The conclusion was that there was no evidence that Berlin had been attacked with thermonuclear-fusion bombs.*

Professor Bothe now said that he had believed so all along. After the war, however, Gerlach heard from Allied scientists that at one time the Allies had entertained similar fears about German bombs, and these too had been proved groundless.

The Allied interest in their heavy-water production finally made the Germans uncomfortably aware of what Gerlach called the "critical heavy-water supply situation." Hitherto they had based all their planning on Norway, but as he finally reported to Göring and the Reich Research Council now, "the Norwegian plant and the major part of the supplies still kept there have been destroyed. Further production from Norway can now be counted out." The contract which had been issued to I. G. Far-

* The reader who is skeptical about this remarkable episode will have his doubts dispelled by a report on a September 1945 U.S. Army interrogation of Colonel Friedrich Geist, chief of technical research in the Munitions Ministry. Discussing German knowledge of Allied atomic research, Geist wrote: "Intelligence that the Allies were about to complete the development of an atomic bomb did not reach me as far as I recall. Nevertheless, I approved the suggestion that after bombing raids the bomb craters should be investigated for radioactive effects. How far this in fact happened is unknown to me. No positive results were reported to me. We did not totally exclude the possibility that the Allies *might* find some way of exploiting a part-process of the atomic-fission reaction. It is possible that the officers directly concerned (e.g., Ministerial Director Schumann or Professor Gerlach) received intelligence on Allied developments which I did not."

ben for the erection of a high-concentration plant like that at Vemork was withdrawn; there was little point in erecting this if sufficient low-concentration heavy water could not be provided to feed into it. The Italian Montecatini plant at Merano and the other electrolysis plants in the Reich would between them produce only enough for a few hundred kilograms of heavy water a year — a totally inadequate quantity.

Professor Harteck, the heavy-water expert, urged that sad though the loss of the Norwegian production was, it need not spell the end of the program. In mid-April 1944, he reviewed the four alternative heavy-water processes for manufacturing low-concentration heavy water to feed into a high-concentration plant. The four processes, he reminded the authorities, were:

> 1. His own simple process for distillation of water at low pressure.
> 2. The Clusius–Linde process for distilling liquid hydrogen.
> 3. The Harteck–Suess dual-temperature exchange process.
> 4. Dr. Geib's revolutionary dual-temperature hydrogen sulphide exchange process.

He stressed that the second and third processes could be used as the basis of full-scale plants immediately, either in conjunction with each other or using just the third process alone. The second process was, however, dependent on electric power and a very pure hydrogen supply.

The most important requirement was that the process adopted should not be tied to any one large plant; otherwise Harteck feared that "air attacks directed against the *SH.200* [heavy water] production would jeopardize the whole plant." So alarming was the prospect of air attacks that when Harteck added that there was the possibility of producing very low-grade heavy water from the by-products of certain existing industrial plants, he undertook not even to mention their names in his reports to the Research Council, for fear that foreign agents would get hold of them.

In short, Harteck was pressing urgently for the construction within two years of a medium-scale (two tons a year) heavy-water plant. He appended a concise historical argument in favor of this:

> During 1940 and 1941 it was still not clear how much *SH.200* would be necessary for a reactor. There were even estimates of up to five tons per reactor. Considering that in those years only "Immediate Projects" could be sanctioned, we must be grateful to the people responsible for the running of this that the project made any headway at all.
>
> By the co-option of Norwegian-Hydro into our project, the early *SH.200* requirements could be met without great investment, allowing us to construct the first geometrical pile configurations and make the appropriate measurements.
>
> The loss of Norwegian-Hydro, and the favorable experimental results from the model piles, have brought about a completely new situation. It is accordingly very satisfactory that the problem of producing *SH.200* has already been investigated from so many angles. With the state of affairs as it was in 1941 and 1942, one could not have authorized an investment of several millions of Reichsmarks just for *SH.200* production.

Professor Gerlach seems to have hesitated even so to recommend such a large and immediate investment. He authorized a start to be made with the planning of a 1,300,000-Reichsmark plant, to use the Clusius–Linde liquid-hydrogen process to produce one and a half tons of pure heavy water a year; and he authorized the planning of a big distillation column at the Leuna works of I. G. Farben as well, for which he budgeted 1,200,000 Reichsmarks under the heading "production of *SH.200* and erection of a production plant." Both these processes were more economic than had seemed possible earlier.

None of these sources would produce heavy water inside the next two years, given the present priorities. For two years, German uranium research would have to content itself with the 2,600 kilograms already delivered to it.

The lack of priorities behind heavy-water plant construction stemmed from a lack of resolution; and the Germans' lack of resolution stemmed from an unspoken belief that, before any heavy-water plant could be built, their isotope-separation experts might have found a way to enrich the rare isotope uranium-235. Harteck himself had ingenuously advised the authorities that, "In all probability quantities of enriched 38-preparation [uranium] can be produced, which will effect a significant reduction in the *SH.200* requirement. Whether enough enriched 38-preparation can be produced to dispense with *SH.200* altogether remains to be seen." In America they had solved this dilemma by deciding to accord *both* projects high priority; in Germany they had so far given priority to neither.

Uranium-isotope separation was the stepchild of the nuclear research project in Germany. Five separate methods were being investigated, of which the ultracentrifuge and Dr. Bagge's "isotope sluice" seemed furthest advanced. Ultracentrifuge Mark

I already had a long endurance test behind it, and the Mark III double-rotor version had already been satisfactorily tested in the Freiburg factory where it was being built; it yielded about 70 per cent of the enrichment predicted by theory, as Groth informed Gerlach during May. A series of ten double-rotor ultracentrifuges was under construction. At the Hellige factory just outside Freiburg, Harteck and Groth had set up a pilot installation, as a guide for the full-scale isotope-enrichment factory being built at Kandern twenty miles to the south. Harteck had chosen Kandern because it was so close to the Swiss frontier that he guaranteed that the Allies would never dare to bomb it. The Kandern factory would be capable of producing several kilograms of uranium, enriched to about 0.9 per cent in uranium-235, each day. It was Harteck's private intention to use this enriched uranium to carry out his own small-scale pile experiments.

Gerlach had also applied adequate resources to the other isotope-enrichment processes, including a photochemical technique which involved beaming light of a certain specified wavelength into a liquid uranium compound; one of the isotopes in solution would be preferentially affected in such a way as to enable it to be drawn off.

Reporting on the uranium pile experiments that had been made or were in hand, Gerlach informed the authorities at the end of May that preparations were being made for the "large-scale experiment" in the bunker at Berlin-Dahlem. He himself did not expect much time to pass before the first reactor went critical, and methods of shutting it down and controlling its energy output were already being developed. The Auer company, moreover, seemed at last to have found a process capable of protecting the uranium fuel elements against corrosion, after several unexpected failures. In the new process the uranium was dipped in an alkaline or alkaline-earth cyanide compound, and the behavior of the resulting coating seemed promising. Only the heavy air raids were hampering the production of the uranium plates, but a new vacuum casting furnace and casting equipment had been set up at a site "relatively safe from air attacks" at Grünau, outside Berlin. Finally, a number of professors of geology were investigating the yield of various uranium deposits in German-occupied territories, in case the Reich should run short of this material.

If one reviews the contracts issued by Esau and Gerlach during the year prior to April 1944, a picture emerges of a project in which many theoretical research problems, some of only academic interest, were being only moderately forced (*SS* priority), while one or two special problems were being attacked with all the priority that could be applied. In the whole uranium research field, only two research contracts were *DE* (top priority) during the year in question — the manufacture of Dr. Bagge's isotope-sluice prototype at Bamag-Meguin and the manufacture of three corrosion-proof sample plates by the Auer company. Some of Harteck's, Martin's and Esau's research was partially covered by *DE*, but none of Heisenberg's or Bothe's was so privileged. The sums of money involved in these contracts were often very large: Harteck's contracts were worth 265,000 Reichsmarks, Hahn's were worth 243,000 Reichsmarks, and Esau's was worth 150,000 Reichsmarks. But the imbalance was marked: Dr. Diebner was allocated 25,000 Reichsmarks, but Heisenberg only 8,500, and Dr. Groth, the ultracentrifuge scientist, only 4,200. Most of the large sums of money provided for uranium research went to German industry — the Auer company and *Degussa* for uranium, I. G. Farben for a heavy-water plant, and Hellige and Anschütz for the ultracentrifuge prototypes. When Gerlach reissued the research contracts during

April and May, only Harteck's isotope separation had any partial priority at all, the others having been reduced to the by now worthless *SS* rating.

What was the most remarkable aspect of the new régime under Gerlach was the concentration in time of war on scientific investigations with no possible application to the war effort. He took care to provide equipment for the teams working in Berlin-Dahlem and Göttingen on the more abstruse problems of nuclear physics — the determination of nuclear moments and spectra, the specific heat and thermal expansion coefficient of uranium metal, and similar problems. If Germany's original lack of cyclotrons had been removed first by the completion of Joliot's cyclotron in Paris, and then by the Heidelberg cyclotron — currently being worked up to full power — Gerlach had no intention of using them for military research, as had the Americans with such important results. The new radioactive isotopes these machines produced would be used for medical and biological investigations.*

Some years before, the German government had propagated a new slogan: "German science in the cause of war." But although the funds and special privileges were being provided for the whole uranium project only in the expectation that some military benefit would accrue, Gerlach had no hesitation in applying the funds for the general furthering of German science. For him the new slogan might have read, "The war in the cause of German science."

* Such research was centered on the Kaiser-Wilhelm Institute at Berlin-Buch and Professor Heubner, the Kaiser-Wilhelm Institute of Psychiatry in Munich, and the French hospital at Gare du Nord in Paris. A third and more sophisticated cyclotron was under construction at Siemens and Halske, but this had been delayed by about one year by air raids on Berlin.

When Gerlach came — two months late — to set up Germany's nuclear research budget for the following financial year, late in May 1944, the contracts to the institutes were considerably smaller than in the previous year: none was over RM. 65,000, the sum allocated for Professor Bothe's laboratory at Heidelberg; RM. 20,000 was earmarked for Professor Stetter's fast-neutron work in Vienna; RM. 24,000 for both Rajewsky and Starke, and RM. 25,000 for Riezler, all of whom were working on biological applications of nuclear research; he set aside RM. 50,000 for Diebner at Gottow, and no less than RM. 46,000 to Professor Hahn for his work on the chemistry of uranium. Professor Gerlach estimated that the total nuclear research appropriation for the coming year would be about 3.6 million Reichsmarks.* Of the 3 million† Reichsmarks which had been appropriated for the previous year, about half a million remained unallocated; Hermann Göring signed the necessary authorization for Professor Gerlach to draw the balance, about 3.25 million Reichsmarks, toward the end of May.

* The estimate for nuclear research expenditure likely from April 1944 to March 1945 was arrived at as follows:

	RMs
Twenty-two research contracts to institutes	447,900
Ultracentrifuge manufacture at Anschütz and Hellige	200,000
Processing and casting of uranium at Auer company	300,000
Production of heavy water, and erection of heavy-water plant by I. G. Farben at Leuna works, Merseburg	1,200,000
Construction of heavy-water plant by Linde's Ice Machinery Factory	1,300,000
Various orders placed with other firms	200,000
Total:	3,647,900

† In April 1943, Professor Esau had been allocated two million Reichsmarks, but he had had to ask for a further million in November 1943, after the American attack on Vemork.

[V]

AT A TIME when the project had still rated a high priority in Germany, and Professor Pose and Dr. Diebner had still reigned at the Kaiser-Wilhelm Institute of Physics in Berlin-Dahlem, work had begun there on the construction of the underground uranium-reactor bunker, large enough to hold Germany's first pilot ("zero energy") reactor when the time came. The experience gained from the experiments in the "Virus House" had been fully exploited: six-foot-thick reinforced-concrete walls, floors and ceilings — provided as a shield against the radiation the pile would generate when once it went critical — meant that the large subterranean laboratory could withstand the heaviest conventional bombing.

Until the early spring of 1944, we find only scattered references to the burrowing in the grounds of the Dahlem Institute. We have noted from Professor Hahn's diary that Speer approved the "construction work" in June 1942, and in November of that year we find Professor Esau writing to his superiors that Privy Councilor Albert Vögler, of the Kaiser-Wilhelm Foundation, has managed to obtain the *DE* priority rating for the building work, "which is not possible for us mere mortals." Throughout 1943 Esau had looked forward in his reports to the time when the first pile experiments could be run in the bunker; now at last it was ready.

It was an impressive sight. When the head of the American scientific Intelligence mission inspected it in July 1945, empty and deserted by then, much of its equipment had already been removed. But it made him shudder nonetheless: "It looked as if it had once been excellently equipped," he wrote. "I remembered the primitive setup with which Enrico Fermi had started in a basement room at Columbia University. By contrast this

Berlin laboratory, even empty, gave an impression of high-grade achievement." The shelter was dominated by a circular pit in the floor, like a small swimming pool, with an electric winch running on a rail overhead. The shelter contained special pumping gear, ventilation equipment and a magazine for the glazed-steel heavy-water tanks. A special room housed the heavy-water decontamination plant, still under construction. An air-conditioning plant would extract radioactive gases; there was a remote-controlled uranium-handling system, and water-jacketed double portholes for viewing the pile with minimum danger from radiation. Double steel airtight doors gave access to this laboratory from the surrounding rooms, which were equipped for processing the uranium and examining the heavy water.

It was in this bunker that the Kaiser-Wilhelm Institutes of Physics of Berlin and Heidelberg now collaborated on the construction of the first large heavy-water pile. Four whole years had passed since the War Office's Dr. Basche had urged that all nuclear physics research should be concentrated under the one roof at Berlin-Dahlem; now it was beginning to happen.

This winter, however, the RAF had turned its attention to the Reich capital, and every night the air-raid sirens were sounding. Those scientists who had no family in Berlin, like Heisenberg, closeted themselves in their underground bunker laboratory and worked night after night on the uranium pile. But no scientist could concentrate in circumstances like these. The Berlin reactor experiments dragged on far into the summer, and progress was very slow.

Under the direction of Dr. Karl Wirtz and his team, a new large pile was assembled in the bunker. By now the experiments at Gottow had clearly demonstrated the superiority of uranium cubes over plates, but "for the sake of method" this first Berlin pile was again built of alternate layers of uranium *plates* and heavy water. A cylindrical reactor vessel was obtained from the same firm, Bamag-Meguin, as had provided all the others; it was made of a very light magnesium alloy with particularly low neutron-absorption characteristics, 124 centimeters tall and 124 centimeters in diameter. Four different arrangements of the one-centimeter-thick uranium plates, totaling from 900 to 2,100 kilograms, were tried out; they were inserted horizontally in the upright vessel, and held apart by suitable magnesium spacers. The vessel was then winched down into the water-filled pit and filled with about one and a half tons of heavy water.

During the long months that followed the number and spacing of the uranium plates inside the vessel were varied four times. Finally a separation of eighteen centimeters between the plates was found to yield the biggest neutron increase. This was what Bothe and Fünfer had already established during their experiments at Heidelberg in November 1943. So after several months' labor they were not much further on than they had been at the end of the previous year. When Dr. Vögler, president of the Kaiser-Wilhelm Foundation, heard from Heisenberg of the results of these experiments, it was clear that he did not consider them satisfactory, and in May 1944 he wrote to Professor Gerlach to this effect.

At the beginning of June, Dr. Bagge's third "isotope-sluice" prototype — the previous two having been destroyed by enemy action — was ready at Butzbach. Dr. Bagge switched the machine on for an empty trial run, but within two hours the bearings had seized up, and all work stopped again. A new, modified prototype was ready by the end of July for endurance trials. Dr. Diebner came down in person, with Dr. Berkei, Anschütz's Dr. Beyerle (a centrifuge expert) and Bamag's Siebert to witness the trials. They agreed that the endurance trial should now be carried out, and on July 10 the machine was started and left running for six days and six nights. The result was the production of about 2.5 grams of much-enriched uranium hexafluoride. At last the Germans had an isotope separation system that worked, without the technical difficulties confronting the ultracentrifuge even now. Toward the end of the following month, Bagge went on leave and arranged for his whole family to move to Hechingen. He dismantled the isotope-sluice machine at Butzbach and had it transferred to Hechingen too. "Reason: the transportation situation resulting from the developments in the war, and particularly in aerial warfare, makes the regular procurement of liquid air impossible. Uranium hexafluoride is short as well." All the equipment was stacked onto a furniture van, and moved to Hechingen.

The most far-reaching work on isotope separation was being done at this time by Baron Manfred von Ardenne at his Berlin-Lichterfelde laboratory. Von Ardenne was privately building an electromagnetic uranium-isotope separating machine, on the same general principle as the mass spectroscope — that electrically charged particles of different mass will follow different curved tracks across a magnetic field. Von Ardenne was planning to use a plasma ion source affording a high ion-beam density and low energy-scatter. The von Ardenne design can be seen to have had clear similarities to the American equipment actually being used at Oak Ridge to separate the fissile uranium-235 for atomic bombs. The ion source used by von Ardenne was in fact better, and is now universally described as a "von Ardenne source" in modern plasma physics. Von Ardenne's effort was not appreciated by the Germans, but his work on magnetic isotope separation and improved mass spectroscopes was recognized by the Soviet Union, and given full support, with the results familiar today.

During July, the American air force began a series of systematic attacks on Munich. Professor Walther Gerlach's home was set on fire, the city's water and electricity supplies were cut off, and on the fourteenth Göring himself inspected the blitzed streets of the Bavarian capital. Gerlach wrote in his diary, "Munich is destroyed. The fires burn all night long." The raids continued for a whole week more, until a summer thunderstorm extinguished the last fires on the night of July 21. Gerlach woke to the noise of buildings collapsing in the wind, and to find rain pouring down on his bed.

As the air war intensified, Hitler swore vengeance on the Allies for what they were inflicting on his people. Plans were reexamined for bombing New York*; and Hitler told Mussolini on July 20 that with his new V-weapons he was determined to raze London to the ground (*dem Erdboden völlig gleichmachen*). On the following day he promised a visiting foreign statesman that

* The plan was for a large aircraft to carry a smaller bomber most of the way across the Atlantic and then turn back, while the bomber would carry on, bomb New York, and ditch in the Atlantic. The crew would be picked up by German U-boat. The plan was dropped finally on August 21. There is a note in the diary of General Kreipe, Chief of Air Staff, that day: "Morning conference. Short briefing on long-range bomber operation against New York. The Navy cannot now supply submarine for refueling and pick-up. I drop the operation. . . . Final discussion with Admiral Fricke (German Admiralty) on New York operation, until 5 P.M. . . . During the night telephone conversation with Meisel (Chief Operations Officer, Naval Staff) about the USA operation." The first references to such an operation can be found in Volume 14 on Field-Marshal Milch's verbatim conference reports; at several conferences in May and June 1942 he mooted the possibility of bombing New York and San Francisco. The difficulty was that the largest bomb possible was only one ton. This was shortly before the Harnack building meeting on June 4, 1942, when Milch asked Heisenberg how large an atomic bomb capable of destroying a city would be.

V-1 was to be "followed by V-2, V-3 and V-4." London was to be reduced to a heap of rubble and would "certainly have to be evacuated."

On the twenty-fifth, Professor Gerlach left the ruins of Munich and moved briefly into the Kaiser-Wilhelm Institute in Berlin-Dahlem. He was convinced that it was pointless to expect the uranium-pile physicists to make any real progress with Berlin under repeated bombing attack, even though their laboratory itself was in the bunker. For some weeks he had been looking for a narrow, cramped valley, inaccessible to Allied bombers, to which he could have the Berlin pile experiments eventually evacuated. He had recalled the romantic Swabian village of Haigerloch, astride two precipitous heights above a river; he had often seen Haigerloch in lilac time.

Like the setting of some extravagant Wagner or Weber opera, a cliff reared sheer out of the medieval village, topped by a château, a prison and a church. Haigerloch was only about ten miles west of Hechingen, the other main research center now. Gerlach had been prepared to have a new bunker blasted out of the foot of the cliff, but he learned that there was already an old wine-cellar hewn out of the rock. At conferences with Schumann and Diebner on July 29 he was told that this cave had now been requisitioned for him, together with the adjacent Swan Inn. Contracts were issued to local building firms for the enlargement and adaptation of the cave to hold the Berlin pile; this work would last several months. The Haigerloch laboratory would in the mean-

The last German atomic pile was built in a cave at Haigerloch, in southern Germany time be referred to by the code name "Speleological Research Unit."

The rest of the nuclear-research project would also be gradually moved to this southern German area round Stuttgart. Otto Hahn had already moved to Tailfingen; Professor Philipp could be evacuated to Haigerloch from Freiburg as soon as the war situation worsened. The dispersal of ultracentrifuge research to Kandern, on the German-Swiss border, was also complete by August. The Mark I ultracentrifuge was installed in a building code-named "Vollmer's Furniture Factory." After the recent bombing-out of Anschütz & Co. in Kiel, the company's research director, Dr. Beyerle, had suggested moving into a wooden building near the Mark III-A ultracentrifuge laboratory at Hellige & Co.'s works in Freiburg's Adolf-Hitler Strasse, but the suggestion had been overruled by Professor Harteck because of the danger of air attack, so the Kiel firm's work on the advanced prototype, the Mark III-B version, would also be moved into a building at Kandern, half-occupied at present by a linen factory. This building was known as the "Angora Farm." Here Anschütz & Co. would establish first a general workshop, then a mass-production line for Mark III-B centrifuges. Gerlach had obtained assurances from both Göring and Vögler that the necessary machine tools would be forthcoming.

By the end of the first week in August, the power and water supplies had still not been reconnected in stricken Munich. Professor Gerlach traveled to Berlin and confided to Vögler details of the progress at Kandern and elsewhere. His biggest headache now was the provision of heavy water: "Heisenberg is asking for two and a half tons," he wrote in his notebook. On August 11, the eighteen electrolytic cells of the high-concentration plant at Vemork were finally dismantled for transportation to Germany: nine would go to the bunker at Berlin-Dahlem for incorporation in the heavy-water decontamination and reconcentration plant being constructed there; the remainder would go to Haigerloch, where a similar plant would be erected one day.

The outlook at Leuna looked very black indeed. On July 28, the I. G. Farben hydrogenation works had been totally destroyed in a raid so heavy that Speer reported to Hitler the same day that it would have the "direst consequences." On the same day, his personal assistant Dr. Goerner had told Professor Gerlach that to all intents and purposes Leuna was finished as far as heavy water was concerned. Together with Professor Harteck and Dr. Diebner, Gerlach spent the whole of August 11 at the Leuna works, while all around them armies of engineers struggled to rebuild the shattered plant. The three of them discussed for the last time with Bütefisch and Herold, I. G. Farben's research directors at Leuna, and with Bonhoeffer and Geib, the idea of a full-scale heavy-water plant; but the attitude of I. G. Farben was hardening. There was an unseemly wrangle behind the scenes over patent rights for the Harteck-Suess process, and Bütefisch was beginning to entertain wild notions about the real reason why the Allies had bombed his plant.

In the bombing, the *Stalin-Organ* pilot plant using the Harteck-Suess process had been totally destroyed. Obviously, pure heavy water could not be produced by one process alone in Germany; but could they not use the economic low-pressure distillation column at Leuna for the range up to 1 per cent, and then electrolysis, using catalytic exchange in two of the stages, as at Vemork, for the rest of the range up to 100 per cent? Alternatively, might they not divide the whole range into three — 0 to 1, 1 to 10, and 10 to 100 per cent? Harteck afterward said that if only they had a method for producing just 1 per cent heavy water in quantity, they would be "in business." During the conference, Gerlach wrote in shorthand: "From 0 to 1 per cent, the column is far more economical than electrolysis; but why is that not so from 1 to 10 per cent?"

I. G. Farben was just not interested in discussing a full-scale plant any further. Leuna had been bombed before, but had survived; this bombing had been different. Professor Harteck heard with disbelief Bütefisch talk of a "gentleman's agreement" between heavy industry in Germany and heavy industry abroad, insuring that the hydrogenation works — in which Allied countries had invested so heavily — were not destroyed. That this "agreement" had now been so openly violated the indignant Bütefisch could attribute to only one thing — the Allies must have heard of the plans for a heavy-water plant at Leuna. This was a warning which he could not ignore. The plans must be abandoned.

The I. G. Farben directors seem to have heard vague rumors of the possible uses to which atomic fission could be put. Such rumors had circulated even at the highest levels in Germany. Late in 1943, Hans Frank, Governor of Poland, had invited Heisenberg to lecture on nuclear physics in Cracow, and after the lecture he had drawn Heisenberg aside and said that he had heard rumors that the secret weapons Germany was working on were atomic bombs. Heisenberg told Frank that he did not see any possibility of producing atomic bombs in Germany, but that such a thing might not be impossible for the Americans. During July 1944, Heisenberg had been visited in Berlin by Major Bernd von Brauchitsch, Göring's adjutant, with a report that the German legation in Lisbon had learned of an American threat to drop an atomic bomb on Dresden during the next six weeks if Germany did not sue for peace in some way before then. Göring's adjutant asked the nuclear physicist whether he thought it possible that the Americans already had the atomic bomb. Professor Heisenberg answered that the effort involved was so enormous that he could not believe the Americans had managed it already.

From Stockholm came further news of the American bomb project. Germany's Transozean agency reported confidentially during August that a dispatch had come from London:

> Scientific experiments are being conducted in the United States with a new bomb. The material used is uranium, and when the binding forces in this element are liberated explosive forces of hitherto undreamed-of violence are generated.

The agency report, which talked of a "five-kilogram" bomb, somehow — perhaps through the hands of Professor Ramsauer — found its way into a little physical periodical; fortunately for Professor Schumann and the other military research leaders, this does not seem to have attracted much attention. Like Professor Esau, Schumann's greatest fear had been that his superiors would tell Hitler about the atomic bomb, and the order would then come that a bomb was to be produced within, say, six months. It was easier to lie low and say nothing.

Hitler would certainly have approved the construction of a German atomic bomb. He eagerly promoted the development of the most advanced conventional explosives in the world, and privately boasted that in the V-1 flying bomb he had been able to use an explosive "2.8 times as powerful as normal bomb explosives," because there was no crew to be endangered. During a private talk with Keitel, Ribbentrop and the Rumanian Marshal Antonescu, on August 5, 1944, Adolf Hitler began to talk vaguely of atomic bombs. He described Germany's latest work on "new explosives, whose development has been advanced to the experimental stage," and added that in his view the jump from modern explosives to this one was the biggest since gunpowder. The record of their conference continued:

> When the Marshal rejoined that he hoped that he would never live to see the employment of these new explosives, which might bring about the end of the world, the Führer mentioned the next stages in this development, as envisaged by a German writer, leading to a point where matter as such would disintegrate, bringing about, it must be said, catastrophes of undreamed-of magnitude.

The difficulty with all new weapons was the same, Hitler explained: he had ruled that no new weapon was to be employed until Germany had herself developed measures counter to it; for this reason a new type of mine they had developed could still not be employed.

Altogether, Germany had four secret weapons, Hitler confided to Marshal Antonescu. Of these, the V-1 flying bomb and the V-2 rocket were only two. He said: "Another of these weapons, for example, has such colossal force that all human life is destroyed within three or four kilometers of its point of impact. . . ." This was the last time Hitler saw Antonescu. We shall never know for certain what the fourth weapon was — probably it was an empty boast designed to hold his vacillating ally at his side. Ironically, Antonescu lived just long enough to see the first atomic bombs employed; Adolf Hitler did not.

CHAPTER TEN

The *Alsos* Mission Strikes

AMONG THE BODY-SNATCHERS and document-sifters of the Second World War, the second *Alsos* mission reigned supreme. Within a few months of their landing in France on August 9, 1944, their headquarters at Neuilly was piled high with documents removed from every Intelligence target of scientific importance. They had unlimited transport resources and an audacity to match. Above all, their military head, the same Colonel Boris T. Pash as had led the abortive mission to Italy at the end of 1943, carried in his pocket a personal authority signed by Henry Stimson, the U.S. Secretary of War, ordering everybody to accord the Colonel "every facility and assistance" to help his mission. The British had nothing like it.

The failure of the mission to Italy had been attributed to the lack of sufficient qualified scientists and an imprecise division of responsibility. At the end of March, the new head of Military Intelligence, Major General Bissell, had recommended the reconstitution of the dormant *Alsos* mission with the assistance of General Groves and Dr. Vannevar Bush, of the OSRD; General Marshall's office had approved this some days later. This time a team of scientists was to be attached to the mission, to see that no apparently meaningless clues would be overlooked.

While Pash would be military head, the mission's scientific chief would be Dr. Samuel A. Goudsmit, a physicist whose name we have already encountered in these pages.*

The official view of Goudsmit was that he had "some valuable assets, some liabilities." He was an outstanding nuclear physicist who had remained outside Groves's atomic bomb project; indeed, he was virtually unaware of its existence, so he was not a security risk should he be captured by the enemy. He had a flair for criminology, having studied years before in the police laboratory at Amsterdam, and he had just returned to the United States from five months' work in England for the Radiation Laboratory. For this reason he originally believed that his brief would be to look into German radar development. A warm, human scientist, he spoke several European languages; but his particular attribute was his close contact with many of the physicists in Europe. "I think," he had written some months before, "there are even some German physicists who still believe I am their friend." All in all, it seemed probable that a man like Goudsmit could extract intelligence from the enemy that a total stranger could not.

Goudsmit was called before a screening committee in Washington, and it was here that Major R. R. Furman, Groves's personal assistant, took him aside and quietly briefed him on the real object of the mission. Furman himself was to accompany the

* See Chapter 8, section 1. Samuel Goudsmit wrote an excellent popular account of his exploits in *Alsos* (Henry Schuman, Inc., New York, 1947).

mission as Groves's representative, authorized to deal directly with the highest authorities in Europe, including Mr. Churchill and Lord Cherwell.

Colonel Pash visited London in the middle of May and arranged for the establishment of the mission on the Continent as soon as the invasion began. In America, Goudsmit, appointed with effect from May 25, built up his scientific organization.

The new mission was to collect information over a far wider field than its predecessor in Italy. Whereas the mission to Italy had concentrated primarily on German uranium research, masked by investigations of a few other general activities, Pash and Goudsmit were now to investigate no fewer than ten fields of German research.* Dr. Goudsmit and some of the better scientists were to concentrate on field work on the German uranium project and investigations of the organizations of German science and the Speer Ministry. About forty key scientists were alerted by the authorities to stand by to investigate such targets as fell into Allied hands.

Goudsmit was shown the file on German secret weapons work, and on the strange concrete structures being built along the French coast facing England. The question was, would the Germans really have produced such costly weapons if their warheads were only of conventional explosive? Goudsmit was informed that there was some possibility that the enemy had built the enormous concrete bunkers on the French coast as shelters for atomic warheads.

* The ten subjects were: "The Uranium Problem; Bacteriological Warfare; Organization of Enemy Scientific Research; Aeronautical Research; Proximity Fuses; German Research Facilities for Guided Missiles; the Speer Ministry's Interest in Research; Chemical Research; Shale Oil Development; and Miscellaneous Intelligence."

Before the *Alsos* mission even entered France, both Major Calvert in London and Dr. Walter F. Colby, a former Michigan physicist colleague of Goudsmit's, now at *Alsos* headquarters at the Pentagon, had listed the scientists and institutions in Europe vital to their investigation. Many people personally acquainted with these "targets" were interviewed in America: Francis Perrin, the French nuclear physicist, was questioned about the personalities and whereabouts of Joliot's laboratories; in New York Goudsmit and Colby interviewed M. Blumenfeld, the director of the Paris Société des Terres Rares, a firm specializing in rare earths, about its activities.

No information had reached the mission at all through wartime intelligence channels — they had to rely entirely on prewar information. But slowly a comprehensive target list was built up. All the high-grade metal refiners, manufacturers of certain classes of equipment known to be necessary for nuclear research and isotope separation, physics laboratories, and dealers in uranium and thorium were catalogued in this way.

Samuel Goudsmit flew out to England on June 6. In London, he made contact with both Wallace Akers and Michael Perrin at the headquarters of the "Tube Alloys" Directorate, and began to write a flood of letters to Washington, preparing for the day when he and his scientists would land with Colonel Pash in France — asking for "pictures of J. [Joliot]," the "home address of Houtermans," "details of Swiss relatives of von W. [Weizsäcker]" and countless other items. When the first flying bomb landed on London six nights after his arrival, he and another officer vainly investigated its fragments for signs that it was connected with uranium research. The Allied troops captured the German bunker sites along the French coast soon after, and it was established that they had not been connected with atomic warfare either.*

During July, the attention of the Intelligence authorities reverted to the uranium mines at Joachimsthal, and periodic reconnaissance sorties were laid on over the entire mining area. On Major Calvert's instructions, the photographic interpreters scrutinized the photographs for evidence of new shaft construction or other unusual surface activity; the quantities of materials stockpiled on the surface were measured, and the output assessed. The conclusion was that there were no signs of extraordinary activity there. But this in no way answered the main question: where were the Belgian uranium ores?

[11]

IT WAS NOT UNTIL early August that the first *Alsos* units landed in France. Goudsmit stayed behind in London, while Colonel Pash searched Rennes and the summer homes of Joliot and two of his colleagues. The search yielded nothing but some catalogues of possible future interest.

On August 24, a further address for Joliot was reached, a house on the outskirts of Paris. The servants informed Colonel Pash that the professor was probably at his laboratory in Paris, which still had to be liberated. With typical aplomb, Pash had the laboratory telephoned, and left a message for Joliot to the effect that they would be wanting to see him in the next day or two. Pash entered Paris next day behind the first five French tanks to enter the city, although four times forced back by

* A French commission, consisting of Prof. Joliot, Prof. H. Moureu and Dr. Chovin, inspected the Watten bunker in this connection. A British investigating mission reported that "the suggestion that the factory might be concerned with the production of the atomic bomb could be definitely ruled out."

sniper fire, and reached Professor Joliot's laboratory at the Collège de France that evening. Samuel Goudsmit landed in France the same day, and began making his way toward Paris. Colonel Pash and Major Calvert found Joliot waiting on the steps of the university for them, wearing a French resistance movement armband. The liberation of Paris was celebrated in precious champagne, quaffed from laboratory beakers.

To the Intelligence officers, Joliot expressed the sincere belief that the Germans had made no real advances on the uranium problem. They were nowhere near to making an atomic bomb.

Goudsmit reached Paris on August 27, and arranged to see Joliot immediately. Joliot was flown to London two days later with Major Calvert, and interrogated at length by Michael Perrin and British Intelligence officers. His story now changed somewhat: a number of German scientists had stayed at his laboratory and had put its cyclotron in order. Joliot mentioned the names of Professor Erich Schumann, Dr. Kurt Diebner, Professor Walther Bothe and Professor Esau among others; they had been directed by Professor Wolfgang Gentner, a cyclotron expert, and Dr. Erich Bagge had assisted in the construction of the cyclotron. Professor Joliot consistently maintained that the Germans had assured him that they were using the cyclotron only for nonmilitary research. The *Alsos* mission was left with a mixed impression. They felt Joliot had been evasive about his work with the Germans; on the other hand, would the Germans have made such intensive use of Joliot's laboratory in Paris if they had not launched some sort of uranium energy project at home?

Throughout their six-month stay in Paris, a constant flow of information passed across the *Alsos* mission's desks. The mission moved into the Hotel Royal Monceau, which later became the main U.S. Navy officers' billet as well. Close contact was established with the other Intelligence missions and agencies, and in particular with the OSS, their only real "competitor." The most embarrassing circumstance for Goudsmit was that the uranium project had had to be kept secret even from very high-level Americans, apart from one or two officials in each organization. Thus while *Alsos* reported officially to G-2, American Military Intelligence, and was not in any way a branch of Groves's organization, there was only one officer in G-2 who was aware of the mission's task: he was Colonel Charles P. Nicholas, a peacetime professor of mathematics. Again, only one of Eisenhower's staff officers knew about the mission. When the OSS started atomic intelligence in Europe, on their own initiative, there was some friction which was only finally resolved by a high-level decision that the OSS should conduct atomic intelligence in neutral countries only; in this way a onetime baseball-player, Moe Berg, was sent by the OSS to cover Sweden and Switzerland.

Most of the OSS reports forwarded to Goudsmit were ominous and circumstantial, reporting explosions and fires and linking them with atomic energy research in Germany. In retrospect they would now seem to have been accidents involving hydrogen peroxide or liquid air. The British Intelligence authorities were similarly troubled by reports of "heavy water" which turned out to be hydrogen peroxide — a not unreasonable mistake. One OSS report spoke of rumors that a "uranium bomb" had blown up in a Leipzig laboratory, killing several scientists.

The total intelligence gained from their Paris investigations was fragmentary and disappointing. The *Alsos* mission had, on the other hand, learned that Diebner and Schumann held key positions in the uranium project, which was unexpected.

Documents found in various Paris offices of German firms yielded the latest addresses of some lesser targets; clues had been extracted from desk calendars, lists of telephone calls and a doorman's check list; and a piece of carbon paper had revealed the names and addresses of all French employees of a German scientific espionage group, not unlike *Alsos* in its composition.

The most unexpected find in Paris was a 1944 catalogue of the Reich University of Strasbourg, from which it was discovered that some of the most important names on their "target" list, including von Weizsäcker and Fleischmann, were now located there. For the time being, Strasbourg was still in German hands.

Before Goudsmit had time to exploit all the targets he wished to investigate in Paris, a far more important target became available as Brussels was liberated by the Allies. On the evening of September 9, he and Major Calvert entered Brussels. The offices of Union Minière were raided on the same day, and they were given complete access to the files. To his chagrin, Goudsmit discovered that he was not first; there were already two officers independently investigating rumors of "uranium bombs" for U.S. Army and Navy Intelligence missions. Goudsmit took one of them, the Dutch-born mechanical engineer and Harvard professor Commander J. T. Den Hartog, into his own mission; the other, he sent away. From the firm's books, Goudsmit and Calvert learned of Auer's initial purchase of sixty tons of uranium compounds in 1940, and of smaller quantities shipped to *Degussa* during 1941. They also learned that unusually large shipments had gone to the German front firm, Roges GMBH, in June 1942: about 115 tons of refined and partially refined uranium compounds had been bought, together with 610 tons of crude materials, 17 tons of uranium alloys and 110 tons of rejects from the refining processes. They saw too that during 1943 a further 140 tons of refined uranium products had been shipped into Germany.

Now they were really worried. The Germans might have wanted a few tons of uranium for purely commercial purposes, but these books showed purchases of over a thousand tons, and much more had been seized besides. From Brussels, he moved on September 22 into Holland. At Eindhoven, he visited the huge Philips works, and from their files he learned about the big electrical equipment ordered by the Reich Research Council for the University of Strasbourg, and the particle accelerator ordered by the German Post Office for its laboratory at Miersdorf. The mission returned to Paris headquarters to await the fall of Strasbourg.

In Paris they now had time to search the deserted offices of the Société des Terres Rares. After the city's occupation by the Germans, the Auer company had taken over the firm and had delegated the director of their Oranienburg Rare Earth Factory, Dr. Egon Ihwe, to run it for the duration. In practice, Ihwe only rarely visited Paris, leaving his deputy, a Dr. Jansen, in charge. Ihwe's name had already been encountered during the *Alsos* mission's examination of Union Minière's files in Brussels; that there should be a direct link with the Auer company in Paris was surely a stroke of great fortune.

The office was raided at once. Its files were few and far between, but one fact that was discovered threw Goudsmit's mission into confusion: Germany had seized France's entire stocks of thorium, a possible alternative to uranium in the construction of atomic bombs. Goudsmit and Fred Wardenburg, a scientist who had just been sent out to join him, wrote an immediate report — "Thorium Products Taken to Auer-Gesellschaft, Germany" — on October 17, and asked what possible commercial uses there could be for thorium. They were told that the element could be used in gas mantles, in the ceramics industry, and as a catalyst in an obsolete petrol-synthesis process; but each application needed only a minute quantity, and the Germans had seized many tons. This seemed proof that they were far ahead of their enemies, for they had acquired thousands of tons of uranium too. What possible alternative explanation could there be? "I felt," wrote Goudsmit at this stage in the investigation, "like a new District Attorney who prosecutes his first case." Suddenly his mission had assumed a responsibility and importance far greater than he had anticipated.

Some time back, Goudsmit had been directed by the Washington *Alsos* office to collect a sample of Rhine water at the earliest opportunity. With the same brand of romantic unrealism as had led the Americans to assume that if the Germans were at Hechingen, they must be using the Hohenzollern castle there as their atomic lair (Goudsmit had destroyed this notion by pointing out that the castle had no lavatories), Washington had deduced that if the Germans were running a plutonium-producing pile, they must be using a river to cool it, and the river must be the Rhine. As soon as the Rhine was reached, one of Pash's officers, Captain Robert Blake, collected a few bottles of the water, and brought them to Paris headquarters. Major Furman, who had an educated sense of humor, included a bottle of Rhône wine in the crate of bottles going to Washington, and labeled it: "Test this for activity too." The joke backfired. Washington passed both samples through laboratory tests, and telegraphed *Alsos* headquarters in Paris that the wine showed radioactivity: "Send more. Action." One of Goudsmit's physicists had to waste ten valuable days collecting bottles of wine for dispatch to Washington; and only then did the American analysts realize that the radioactivity was natural to the waters of that region of France.

One of the secrets of the success of Goudsmit's *Alsos* mission was the flexibility of its program. While it did have target lists, they were flexible; in the course of their investigations, names that had seemed important were crossed off and others, of people who had at all costs to be found, were added. In short, the attack was mounted not against sites and establishments so much as against a widening circle of scientists and those they in turn considered to be of importance. A sequence of events touched off by a find among the papers of the Paris office of the Société des Terres Rares shows the tenuous but rewarding trail of clues that often had to be followed. Among the files of Dr. Jansen, Goudsmit found a small brown register listing the outgoing registered mail since the beginning of 1943; the last entries were for two registered letters to Ihwe at Oranienburg, and one to "Hermanns" at Eupen.

What interested Goudsmit was that the last item had not been franked by the post office, so the packet must have been taken to Eupen — a town on the Belgo-German frontier — by some other means. Washington was by now clamoring for the mystery of the seizure of the thorium to be investigated. As soon as Eupen fell to American troops, Colonel Pash left Paris in a Jeep with two men to search the town for Fräulein Hermanns, who was now known from correspondence found at the office to have been Jansen's personal secretary.

The search brought to light not only Fräulein Hermanns but also Dr. Jansen himself. He had been sent back from Oranienburg to locate a thorium consignment which had not arrived, and was still at Eupen when the town surrendered. Pash telephoned the news to Goudsmit in Paris, and followed shortly afterward with Jansen. Jansen had been carrying a document case when captured, and his pockets were full of oddments. After a fruitless interrogation of the man, Goudsmit retired to bed to study the captured papers. All at once, everything began to fall into place: a tram ticket and a hotel bill showed that both he and Fräulein Hermanns had been in Oranienburg only recently, and a further hotel bill showed that Jansen had been in Hechingen as recently as September.

Oranienburg and Hechingen: these were two localities which, mentioned separately, were enough to prick the ears of any *Alsos* officer; combined, their effect was dramatic. But no sooner had the clues been found than they were demolished by Jansen himself. He admitted having visited the Auer company at Oranienburg, but he had no knowledge of its production program. As for Hechingen, his mother lived there, and he had been visiting her. One item did catch the officers' attention, a remark in a letter found among Jansen's papers: for some reason Hechingen was a "restricted area."* The photographic reconnaissance of the whole area was revived.

Wing-Commander Douglas Kendall, who was already directing the Allied photographic intelligence attack on the German V-weapons, was summoned to London and briefed by Dr. R. V. Jones, chief of the Air Scientific Intelligence branch, on the Allied atomic program. Jones gave Kendall a sketch of what a German atomic bomb plant might look like, and stressed that for the production of atomic explosives two things were essential: an abundance of electric power and water. The plant would also inevitably be conspicuous.

The electric production capacities of most of the European power plants had been thoroughly checked against their visible

* This was another instance of reaching the right conclusion from the wrong arguments. The *Alsos* mission concluded that the German word "*Sperrgebiet*" meant "restricted military area"; in fact, it meant that Hechingen had taken its full complement of evacuees, and was closed to further influx.

outlets, and no discrepancies had been found. The most direct check in Germany could be provided by tracing the enemy electricity grid along all its ramifications. Kendall was given high priority to make the search. He briefed a handful of men at the Allied Central Interpretation Unit to search for transformer stations larger than a certain size, and report to him whether they were supplying any plants not previously accounted for. A flight-lieutenant who had been a German subject was put in charge.

Jones also requested Kendall to obtain photographic coverage of a certain building to which scientists of the Kaiser-Wilhelm Institute were known to have removed from Berlin, outside Stuttgart. Nothing unusual was found there, apart from a small transformer station; the building itself was singularly inactive.

Stuttgart was an area of Germany where there was a gap in recent photographic cover, and Kendall laid on the necessary sorties to fill in this gap. It was now that Allied Intelligence had, in General Groves's words, "its biggest scare to date." By the end of the third week in November 1944, the gap had been filled. Excited photographic interpreters brought into Kendall's office the first of a number of photographs showing that not far from Hechingen a number of medium-sized industrial plants were being erected on high priority in a string of valleys about twenty miles long. The plants had a standard layout, including a small factory building and a couple of storage tanks, two chimneys and a grid of pipes laid out on the ground.

What most disturbed Kendall, and Dr. Jones in turn when he was shown the photographs, was the priority attached to the project: a number of forced-labor camps had been erected with incredible speed, railway spurs had been rushed across the countryside, power lines were being set up, and large quantities of materials moved in.

Jones hastened to bring this to his superiors' attention. He showed the photographs to Lord Cherwell at noon on November 23, and on the following day Cherwell wrote to the prime minister in the following terms:

> You may wish to know that Jones has discovered on some photos taken last week that three similar medium-sized factories are being rushed forward in a region south of Stuttgart in which we suspect [German atomic] work may be going on. They are of unusual type, but we should not have connected them with [atomic development] had it not been that the scientist who might be expected to be called in on this work* is known to infest this region. One plant might be experimental, but *three similar ones* look as though they expect to produce something worthwhile for this war.

Lord Cherwell had already spoken to Sir Charles Portal, Chief of Air Staff, about this new threat; and Portal had agreed with him that when the factories had advanced a bit further it might be well to bomb them. In the meantime, plans were laid to photograph the region at reasonably short intervals, and the existing photographs were rushed to America in the expectation that those who had built the uranium isotope separation plants there might be able to recognize what the German factories were for.

On Sunday afternoon, November 26, the Deputy Chief of Air Staff, Air Marshal Bottomley, telephoned through to Jones's office and asked for the photographs to be sent round to him.

* Presumably Heisenberg.

They were rushed round to Sir Norman Bottomley in Whitehall immediately, and when Cherwell saw Mr. Churchill at Chequers some days later he learned that the matter had been brought to the attention of the Chiefs of Staff Committee in secret session on the morning of the twenty-seventh.

When General Groves saw the photographs, on which fourteen of these unusual factories had by now been detected, he could only ask himself one question: was this the start of Germany's "Oak Ridge"?

Wing-Commander Kendall had by now noticed one strange feature of the several factories: not only were they all in the same string of valleys, but they were on the same contour as well; there seemed to be a geological clue to their function. One of his flight-lieutenants suggested a visit to the Geological Museum in South Kensington, and a close study of German geological records there showed that, before the war, a German geologist had reported very low-grade oil shales in that region, and on that very contour. Lieutenant-Colonel Edwin V. Foran, the *Alsos* mission's shale-oil expert in Paris, saw the connection at about the same time. It seemed that this was the end of the scare, but a few days later the Intelligence authorities received a further jolt when it was secretly reported from Sweden that the oil shales there had been found to bear uranium. Soon after, the mysterious factories were positively identified as simple but inefficient plants for extracting oil from shales. They were bombed nevertheless. The current state of the German war economy was such that the production of oil by any means was enjoying the same kind of priorities as the manufacture of atomic weapons in the United States.

[III]

THE MYSTERY of the thorium had a stranger origin. Early in 1944, the possibility that thorium might in fact prove of importance in nuclear physics had set Dr. Nikolaus Riehl, Auer's chief chemist, trying to devise means of procuring for his company the entire stock of thorium in occupied Europe. Even if the metal should prove of no nuclear value, there were other peaceful applications in which the company was equally interested: it was used for luminous products, gas mantles, metallurgical purposes and a patent Auer polishing process. Above all, in the early 1930s the company had marketed a brand of toothpaste, Doramad, containing thorium hydroxide. Their advertisements showed little armies of radioactive men chasing away the evil bacteria which are still a feature of toothpaste advertising today: "I am the radioactive substance. My rays massage your gums. Healthy gums — healthy teeth." In short, thorium was the "chlorophyll" of the 1930s.

Auer's "radioactive" toothpaste — with special thorium ingredient

When Riehl learned from Dr. Ihwe that there was a quantity of thorium in France, he had proposed to the firm's relatively new deputy chairman, one Maier-Oswald, that it should be acquired for postwar toothpaste manufacture. Maier-Oswald, who was a poor scientist but a good businessman, agreed, and all the thorium had been acquired and moved into Germany on this pretext.

Late in 1944 German war research underwent its final upheaval. When the Reich Research Council had been controlled by Minister Rust, the reservation from call-up of scientists had been frowned on; increasing inroads had been made into their ranks as more scientists were drafted to the front. In 1943 Professor Carl Ramsauer had warned that while 3,000 fewer soldiers would not weaken the armed forces, 3,000 more physicists might well decide the war. Professor Werner Osenberg, a naval research scientist, had written a barrage of memoranda to ministers, generals, admirals and gauleiters, stressing the vital importance of sustaining Germany's scientific effort, even in wartime.

Osenberg's main purpose had been to bring back scientists from the front. On December 18, 1943, the High Command had agreed to release 5,000 scientists from active service. The measure was strongly opposed by Albert Speer, who found himself confronted with Göring, Bormann and Himmler over this issue. Himmler ordered a further mass reservation of scientists in July 1944. He had written to SS-General Jüttner:

> I hear that it is intended to include 14,600 of the personnel reserved for German military research in the present draft (SE-IV induction operation).
>
> I direct you to cease this induction operation in the military research sector forthwith, as I consider it madness to dismantle our scientific research.
>
> H. HIMMLER

Professor Osenberg was told of his victory by the Party's chancellery in the middle of August; and a few days later he was finally commanded by Göring to set up a War Research Pool, the first positive effort to link the armed services with German science. On September 3, Martin Bormann decreed that all scientists, including those brought back from the fighting, were to be shielded from any kind of special service outside their immediate neighborhoods. Copies of the Bormann decree were telegraphed to all gauleiters.

The worsening war situation in Germany brought the atomic research project almost to a halt. Factories were bombed and laboratories evacuated.

In mid-September, Frankfurt was again heavily raided by RAF Bomber Command. The *Degussa* uranium-refining plant was gutted by fire, and the machinery was evacuated to Rheinsberg near Berlin. Some time later, the remaining uranium raw materials were removed from Frankfurt to Rheinsberg and to Grünau, where the second uranium-reduction plant began metal production during December. Before the Rheinsberg plant could resume production, however, the Soviet invasion had broken in the east and it had to be moved again. The equipment was loaded onto lorries and sent off to Stadtilm in Thuringia; it never arrived.

In the late summer of 1944, Dr. Kurt Diebner, director of Gerlach's office and head of the rival team to Heisenberg's, had been obliged to evacuate his uranium-pile research from Gottow to the village of Stadtilm in Thuringia. His team of physicists had moved into an old schoolhouse with a cellar that seemed virtually bombproof. In the middle of the cellar they excavated a pit to house a projected heavy-water pile surrounded by graphite and uranium oxide briquettes, of which *Degussa* had manufactured ten tons under a contract given in about May. Diebner set up his laboratories in the upstairs rooms.

During November, work on the pilot uranium-235 enrichment factory at Kandern, "Vollmer's Furniture Factory," was also stopped. Such a possibility had been envisaged almost from the outset and provision had been made for the evacuation of all the costly equipment early in September. Harteck and Beyerle had then realized that "the possibility must be taken into account that the Freiburg-Kandern region may become dangerously close to the front." Despite this, the ultracentrifuge Mark III-A had stayed on at Freiburg for a while, and construction work on the Kandern plant had continued, in case the war took a turn for the better. But on November 24, Harteck agreed that a mechanic should be sent to Freiburg to collect all the parts necessary for the new laboratory he was now setting up near Hanover. The evacuation of Freiburg was only just complete when the whole city was destroyed on the night of the twenty-seventh; the Hellige factory, where many components for the Mark III-B mass-production prototype were being manufactured, was badly damaged.

Harteck and Groth had moved their new ultracentrifuge laboratory into a parachute-silk spinning mill at Celle. Harteck wisely ordained that the ultracentrifuge prototypes were never all to be concentrated under one roof; several would be stored in a shelter at Hamburg to avoid further loss from air raids. As a general direction, Harteck, Groth, Beyerle and Suhr — the four scientists primarily concerned with the ultracentrifuge — decided at a Hamburg conference at the end of the year that "Celle is to start production with the Mark III-A as soon as humanly possible." Dr. Diebner telephoned on December 13 with the news that Professor Gerlach had promised to apply for priority *Z-I* —

the new maximum priority — for the ultracentrifuge, in the new year.

In the middle of December, Heisenberg, von Laue and several others working at Hechingen, Haigerloch and Tailfingen, were drafted into the *Volkssturm*, the people's militia being raised for a last-ditch stand. Professor Gerlach wrote to Martin Bormann on December 16 to protest: had not Bormann himself decreed that scientists were to be shielded from "special tasks"? Of course all his personnel had "volunteered" for the *Volkssturm*, but they had been inducted into formations liable to be sent into action outside their immediate neighborhoods, and this Bormann had specifically forbidden:

> The personnel has been kept to the very minimum [Professor Gerlach advised] and the least withdrawal would be synonymous with shutting the project down altogether. And these are researches that are among the most important research and development projects in my sector. It is my concern that they continue unhindered, under all circumstances. You are without doubt aware that these are researches which might unexpectedly prove of decisive importance for this war; you are also aware that the most strenuous efforts are being made by America in the same field; but I am convinced that both in research and development we are at present well ahead of America although we are working with a vanishingly small percentage of the manpower America is using.

Gerlach urged Martin Bormann to direct the local Party authorities, and in particular Gauleiter Murr in Stuttgart, to see that no special tasks were allotted to the *Volkssturm* units in which the precious scientists were. Bormann did not reply, but

Murr was certainly warned in the way that Gerlach had intended.

[IV]

TOWARD THE END of November, Strasbourg was captured in a move so swift that the local gauleiter had time to warn only a select few of the city's most prominent German citizens to escape. Colonel Pash and an advance party from the *Alsos* mission joined the task force in Strasbourg on November 25, while Goudsmit stayed in Paris briefly to see Dr. Vannevar Bush. Pash's first telegram to Paris reported that none of the scientists they were looking for could be found. Just as Goudsmit was about to tell Bush of this disappointment, a further telegram arrived: the nuclear physics laboratory had been found in a wing of a Strasbourg hospital, and staff who had at first been thought to be doctors had turned out to be physicists. Goudsmit and Fred Wardenburg prepared to drive to Strasbourg at once. In Europe it was "disagreeably cold," and riding in a draughty command car the scientists were so exposed that they took to wearing pajamas underneath their uniforms. They set out on December 2, and took two days to reach Strasbourg; flying was out of the question, as fighting was still raging round the city.

Now Goudsmit was confronted by fellow scientists on the enemy side. Writing to his wife, he referred to this as a part of his work that was "very, very grim." And on the tenth, he again wrote: "The grim part of the venture was that I had to face for the first time a small number of people like myself, but on the other side. Thank God I didn't know them personally, and I kept my own identity hidden until the very end, when I had them put on a truck and taken to a camp."

The biggest catch was Professor Fleischmann himself, whom we have met in earlier pages working on gaseous and thermal diffusion methods of uranium isotope separation. Professor von Weizsäcker and Professor Haagen, a German virus research expert, had both left in good time. The *Alsos* mission requisitioned the home of Haagen, whom Goudsmit courteously referred to in his letters as "an enemy colleague." A few days later, he wrote: "They had left in a hurry. I slept in the room of a little boy; all his toys were still there — an electric train, a movie projector, an old microscope of his father's, an aquarium with snails, books, tools, but also a lot of Hitler Jugend insignia, flag, etc. Still, it was only a child of 11 or 12, and I was thinking whether he missed his toys now. . . . I am too soft for this game, and especially when I was leading the small party to prison did I feel awful. But they haven't learned yet, they are still so arrogant."

The *Alsos* mission had interned seven physicists and chemists at Strasbourg, but all of them were uncooperative and Fleischmann in particular. This was a disappointment for Goudsmit; he had thought that all that would be necessary would be to capture one or two scientists, and to obtain from them complete information about all their colleagues, "either through interrogation or better still from their documents."

This still left the University proper. The door to von Weizsäcker's office refused to open, no matter how hard they pushed. An axe was brought and the door — which was unlocked but designed to open *outward* — was smashed down. The room was just as von Weizsäcker must have left it, several weeks before.

The files were all removed to Goudsmit's billet. While the Germans began shelling the city from afar, and with a background of wailing air-raid sirens, Goudsmit and Wardenburg began to read through von Weizsäcker's papers, by the guttering light of candles and a gas lamp. At once, the intelligence picture seemed complete. Among the files, Goudsmit found postcards from important scientists, including one from Professor Bothe mentioning the slow progress being made with the production of large uranium plates, and a letter giving the first reference to work by Harteck and Groth on an ultracentrifuge. There was also a letter from Groth to Fleischmann mentioning uranium hexafluoride. In the waste-paper basket there were the remains of a letter von Weizsäcker had drafted to Heisenberg, at about the same time that Vögler had written to Gerlach about the disappointing progress Heisenberg was making with his uranium pile. Von Weizsäcker had written a letter sharply criticizing some of his master's calculations, but he had thought better of sending it and torn it up. (Among Heisenberg's files, Goudsmit later found the letter finally sent, in a more moderate vein.) "Security with the Germans was not too good on that project," Goudsmit commented.

The most startling security breach was the disclosure of all the main institutes' exact addresses. Gerlach's letters had a somewhat ambiguous letterhead which read: "Reich Research Council — The Plenipotentiary of the Reichsmarschall for Nuclear Physics — Professor Doctor W. Gerlach," and which included the full address in Berlin and the telephone number. Each of the other institutes and laboratories used the same general letterhead, but with a subheading indicating the designation and address of the research group concerned. In fact, almost on this same day, Gerlach was informed by Göring's office that he was to discontinue using these indiscreet letterheads; but it was too late, for the *Alsos* mission now knew the exact location of most of the targets in which they were interested. All in all, the Strasbourg papers "gave an authentic picture of the uranium research program as of the summer of 1944," as Goudsmit reported. They revealed that Hitler had been told of the possibilities of a nuclear weapon in 1942, and that "large-scale" uranium pile experiments had taken place at Gottow, but that even as late as August 1944 the experiments were still at an early stage. "I worked hard for four days by candlelight, no gas, no electricity, water only got a few hours, nightly air raids, shelling and continuous loud artillery," Goudsmit wrote.

It was in an uncomfortable Jeep — "a Jeep is not a proper method of travel for the 4-F and over draft-age, desk-type and blackboard scientists," Goudsmit complained to Washington at this stage — that he, Wardenburg and Fleischmann journeyed back to Paris with their haul. The complete set of Strasbourg documents was sent back to Washington, where it was thoroughly examined by both General Groves's Manhattan Project experts and the OSRD. Washington was inclined to suspect that the haul had been too easy, and that in particular the torn-up letter to Heisenberg might be a plant. The papers were translated, indexed, and even statistically analyzed for certain word-groupings, to ascertain just how genuine they were. Over Christmas, Goudsmit himself flew back to Washington to discuss the Strasbourg Report — as it came to be known — with Dr. Richard T. Tolman, scientific adviser to General Groves. Tolman upbraided Goudsmit for allowing the Rhône wine joke to be played on the unsuspecting Washington scientists. In general, however, all were agreed that even if there was no bomb, the German nuclear energy project was no myth.

CHAPTER ELEVEN

To the Brink of Criticality

PROFESSOR WALTHER GERLACH was a man who moved in mysterious ways, and there were few in the uranium project in Germany who fully understood his motives. In particular, there were those who failed to understand why he permitted two research groups to compete with each other for the necessary materials to build uranium piles. Was it designed to promote a spirit of rivalry? To insure that neither group had sufficient of the scarce materials? Or to spare the maximum number of nuclear physicists from the front?

Gerlach's real reason seems to have been a reluctance to pass a final, and possibly wrong, verdict in deciding between Diebner's and Heisenberg's groups. While Diebner's group had obtained some strikingly successful results, he was not prepared to downgrade the other group so long as it was headed by a Nobel Prize winner and world-famous physicist. A Party leader or general, confronted with the same decision, would not have hesitated. Gerlach did, for just too long.

That Gerlach admired Diebner's work had become evident when he had tried to promote his *Habilitation* — an important qualification for recognition as an academic physicist — some months before. Diebner had been secretly derided in Göring's office as "not even *habilitiert*." Diebner's work on the geometry of uranium piles had been so outstanding that Gerlach took the matter up with Professor Winkhaus, of the Berlin Technical University; and Diebner's career would have enjoyed this satisfying accolade had Gerlach's proposal not met with the roundest denunciation from the existing academics, and from Heisenberg's group in particular. Diebner was denied the honor.

At Stadtilm, Diebner's group was preparing a further improvement on their earlier experiment with uranium cubes at Gottow. Diebner had calculated that hollow uranium spheres would be more efficient fuel elements than cubes, and an order had been placed for the manufacture of enough to perform a low-temperature pile experiment. On Professor Harteck's suggestion, the spheres would be embedded in solid carbon dioxide, the substance he had used in Hamburg in 1940. They also had a quantity of heavy water, which they intended to use for interim experiments as soon as the uranium spheres could be manufactured.

So long as it was necessary to get his own way, Gerlach continued to refer obliquely to "explosives." When he needed to extract from a Dresden factory the last surviving high-voltage particle accelerator, ordered for other purposes, he felt justified in stressing at a Berlin conference in October that the equipment was needed "for experiments on explosives physics for which no other equipment is available." But he would promise nothing.

When the head of Göring's private office asked him whether an explosive would ever be produced by this uranium research, Gerlach confidently answered that it could not. Why then was the project not stopped immediately, he was asked. The professor replied that he assumed that the Reich wanted to win the peace as well as the war. If Germany were to neglect research on such a vital subject as nuclear energy, the other nations would quickly pass her and then the peace would be lost. "It was a very emotional interview," said Gerlach later.

He thought it politic to summarize the progress his Research Group had made so far in this field in a secret printed report containing five papers by the leading scientists. He himself drafted the foreword, in which he surveyed the conclusions so far:

> 1. Cube configurations are better than plate configurations. Using half a ton of uranium metal, the former gave a neutron increase of 2.06, while using 1.5 tons of uranium metal and the optimal plate thickness the latter yielded an increase of only 2.36 — in other words relatively less in view of the very much larger size. It is not yet known whether the size of the cubes employed is the optimum.
>
> 2. An extrapolation of the theory in connection with the experiments makes it seem highly probable that hollow [uranium] spheres suspended in heavy water will yield a significantly greater neutron increase, and it can be expected that different cube-sizes will also result in a larger increase. Neither experiment has yet been put in hand.
>
> 3. The amount of heavy water available has been restricted for years to come because of the loss of the Norwegian plant. A sure way of mini-

> mizing the heavy-water requirement and of reducing the reactor's volume is manufacturing uranium metal enriched in the 235 isotope. The development of the ultracentrifuge is complete and a working plan for the production of uranium with the necessary 235-isotope enrichment is under construction. Other processes are being developed to the same end, to lead to simpler plants. The production of the necessary uranium compounds and experiments to produce suitable compounds are in hand.
>
> 4. Despite the utmost difficulties, we are attempting to set up heavy-water production in Germany by developing novel processes.

Gerlach concluded by mentioning the research into other processes designed to obviate the use of heavy water, including the Harteck/Diebner low-temperature pile planned at Stadtilm, and into uranium fuel element shapes, uranium alloys and other subjects.

In the last weeks of 1944, the underground bunker laboratory at the Kaiser-Wilhelm Institute of Physics at Berlin-Dahlem was the scene of the last uranium pile experiment in Berlin, *B-VII*. Built under the direction of Dr. Karl Wirtz, the pile was surrounded by a graphite "reflector" for the first time; hitherto, all the pile experiments had used ordinary water as a reflector, but Heisenberg (in October 1942) and Bopp and Fischer (in January 1944) had shown that the use of a carbon reflector would result in considerably higher neutron multiplication.

From Bamag-Meguin an aluminum cylinder was obtained, 210.8 centimeters in diameter and 216 centimeters tall. The magnesium-alloy vessel used for the earlier Berlin pile experiments was suspended inside this, and the 43-centimeter space between them tightly packed with graphite — ten tons of long graphite slabs cut and shaped to fit — as a reflector.

The whole assembly was lowered onto a wooden scaffold resting on the floor of the water-filled concrete reactor pit in the main underground laboratory. All together the pile contained 1.25 tons of uranium — still in the form of one-centimeter-thick metal plates — with 18 centimeters of heavy water between each layer, a total of about one and a half tons of heavy water. There was still no provision of regulator rods to control any chain reaction should one have begun; Professor Wirtz now states that the pile was planned largely as a sub-critical assembly, in which case regulator rods would not have been needed.

This time the neutron multiplication rose to a figure of 3.37, although not much more material was used than in the best of the previous series. The improvement must have been brought entirely by the graphite reflector. That graphite had functioned so well should at this stage have thrown immediate doubt on Professor Bothe's fatal 1941 calculation of graphite's neutron absorption characteristics, for the two constants were closely connected, but the physicists still did not notice the error.

They might now have just enough heavy water to build a critical pile. On January 3, 1945, Wirtz's group reported that the minimum size of a self-sustaining pile "has been over, rather than under, estimated." For one last time nevertheless, Professor Harteck journeyed northward to Rjukan; on January 9 he and another scientist visited Norwegian-Hydro to investigate the possibility of obtaining heavy water again from that source. Upon their return, they recommended devious ways of getting the heavy water to Germany without the knowledge of the Norwegians. Above all there must be no question of endangering the firm's nitrogen production, which was vital for the explosives industry.

There was still time, the scientists thought, to build a critical uranium pile before the war ended. With the last plate experiment the theory was complete. Professor Gerlach spent the second week in January in Berlin, where the scientists under Wirtz were now working feverishly to construct their first zero-energy heavy-water pile, using uranium cubes for the first time in Berlin. The conditions were appalling, with the capital suffering nightly air raids, the telephones out of order and frequent power breakdowns. Gerlach returned to his institute in Munich and found the city heavily damaged, and the flowers in his office all killed by the frost. Night after night the air raids continued. In the middle of January, the Soviet Army unleashed its invasion on the eastern frontiers, and within days it was clear that Berlin would soon be under siege. Professor Gerlach saw little point in allowing work to continue on the heavy-water pile at Dahlem. It was time to move the rest of the institute to Hechingen in southern Germany. On January 27, he telephoned the decision to Hechingen, then telephoned Berlin and said he would travel up overnight. He arrived in the city at noon, and talked at length with Diebner about the future. Even as they were conferring, a heavy air raid began, breaking many windows in the Kaiser-Wilhelm Institute building. In the bunker, Wirtz's technicians had nearly completed setting up the biggest heavy-water pile experiment so far, *B-VIII*, using hundreds of uranium cubes and a ton and a half of heavy water. Preparations were being made for the vital criticality experiments in the next few days; but it was a time when all the scientists would willingly have been anywhere else than in Berlin. If the pile did go critical, and a controlled nuclear chain reaction did start, Gerlach, Wirtz and Heisenberg knew it would have been a tremendous achievement for a nation at war and suffering such body blows

— her brain would have been functioning to the last. By January 29, all was ready.

By now, the Soviet armies were advancing westward with alarming speed, and the evacuation of two million people from East and West Prussia was in full swing. There was a perceptible mood of panic in the Reich capital, and a general exodus began. Gerlach and Diebner realized that there was no time to be lost. The professor called in his close friend, Dr. Rosbaud, early on January 29 and told him that he was planning to leave Berlin within the next day or two, and that he was planning to take "the heavy stuff" with him. Rosbaud asked whether that meant he was taking heavy water to Heisenberg, by now in southern Germany, and Gerlach did not deny this. When pressed by Rosbaud as to what Heisenberg wanted with the liquid, Gerlach answered only: "Perhaps business."

At 5:30 P.M. on the thirtieth, Professor Gerlach issued the order to dismantle the uranium pile. Everybody was to be ready to leave Berlin next day, regardless of all the decrees to the contrary. Gerlach and Rosbaud discussed at length the danger that the heavy water might be destroyed.* The professor told Rosbaud that he had asked Heisenberg for an assurance that there would be no attempt to destroy the heavy water. That evening, Gerlach telephoned the local gauleiter, Sauckel, to tell him of the move that was planned to Stadtilm, and arranged to see him two days later.

Late on the afternoon of January 31, Professor Gerlach, Dr. Diebner in Army uniform and Dr. Wirtz left the Harnack building in a car bound first for Kummersdorf. Several lorries,

* Relating this episode to the *Alsos* mission, Rosbaud asserted that the heavy water had been produced in Norway, "under false pretext, to be used in a most dreadful war machine against the civilized world."

laden with the heavy water, uranium and other equipment followed soon after. Gerlach was "pale, excited and depressed." His secretary, Fräulein Guderian, accompanied them. Rosbaud could not find out, try as he might, their ultimate destination. Left in Berlin, he tried to inform Professor Blackett and Dr. Cockcroft through his secret Norwegian channels that the uranium and heavy water had left Berlin. This message was followed by an appeal to Blackett to come as soon as possible after the capitulation to secure these precious materials. It is not known whether either message reached England.*

Gerlach, Wirtz and Diebner reached Stadtilm after a night traveling down an autobahn made treacherous by black ice. On Gerlach's instructions, the convoy of lorries was unloaded at Stadtilm, because he believed that preparations at Diebner's laboratory were further advanced than at Haigerloch. Dr. Wirtz, considerably put out, telephoned Professor Heisenberg in Hechingen. On February 2, Gerlach went to Weimar and persuaded the local gauleiter, Sauckel, to guarantee the Stadtilm laboratory the electricity it needed, and to release its personnel from any *Volkssturm* and Labor Service liabilities. When Heisenberg telephoned him that evening, however, it was clear that the nuclear physicist had no wish for the critical pile to be built at Diebner's laboratory, and certainly not with materials that had so recently been used by his own team at Berlin-Dahlem.

* Professor P. M. S. Blackett, who was a friend of Rosbaud's, has informed the author that the messages did not reach him. General Groves later wrote, however: "We had learned from . . . a Berlin scientist, who got word to us through the Norwegian underground, that research on uranium had been moved, presumably to a safer location, but where he did not know. Until that time, our intelligence had come in on a fairly regular basis, but then it virtually ceased. We were confronted with the problem of finding out where the Kaiser-Wilhelm group had moved to and what they were up to." *Now It Can Be Told*, p. 216.

Gerlach told the professor to come and see him in Stadtilm about it.

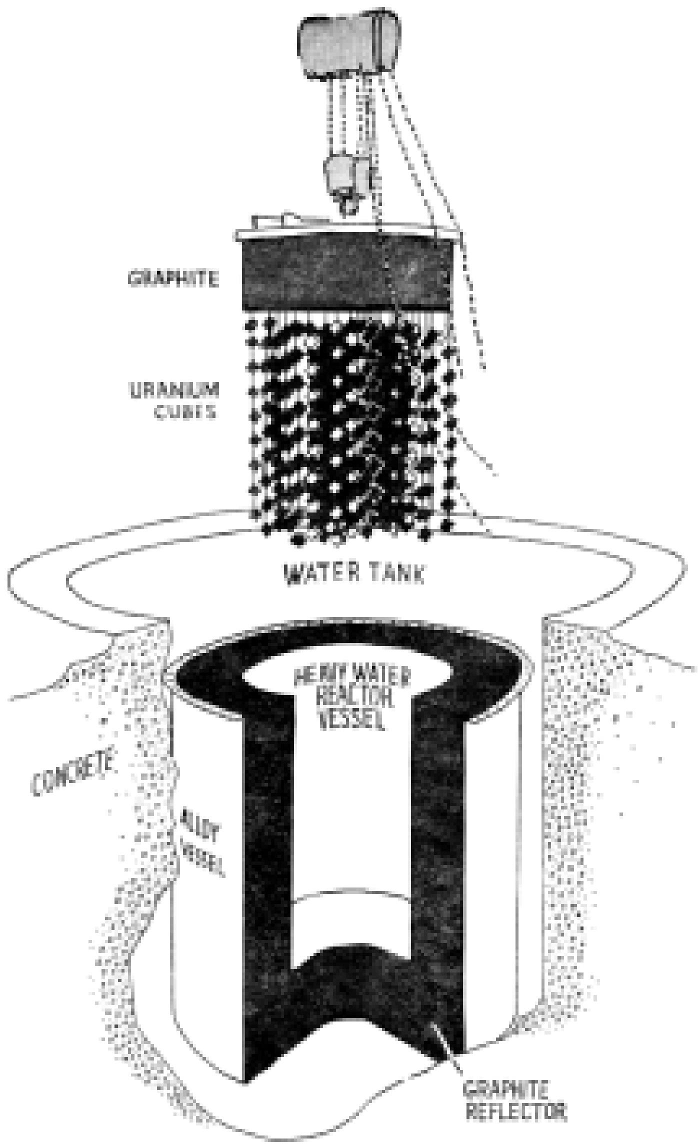
Heisenberg did not come alone; he brought Professor von Weizsäcker, the political expert, with him too. The two scientists set off on bicycles, and after a long and hazardous railway and motorcar journey reached Stadtilm during the afternoon of February 5. There was a continuous air-raid alert in Stadtilm, and the sky seemed full of airplanes. Heisenberg urged Gerlach to arrange for the transportation of most of the uranium and heavy water to Haigerloch. Gerlach agreed to look into the transport possibilities, after spending most of February 6 alone with Heisenberg.

On the following day, he telephoned Gauleiter Sauckel, with whom he had established a working relationship, and asked to arrange an interview with Gauleiter Murr of Württemberg — the area covering Haigerloch and Hechingen — on the twelfth. When Gerlach and Heisenberg drove down to Stuttgart, however, Murr refused to see them, probably in consequence of the letter Gerlach had written in December to Bormann protesting about the Party's demands on his nuclear scientists. The professors saw his deputy, *Staatssekretär* Waldmann, instead, and arranged for a number of trucks and men to be provided to transport the uranium and heavy water from Stadtilm to Haigerloch. Dr. Fritz Bopp had already flown down from Berlin bringing 500 milligrams of radium-beryllium with him for Haigerloch. Gerlach drove Heisenberg on to Munich, then went on himself to Haigerloch to inspect the arrangements being made there, before returning to Stadtilm on the fourteenth.

On February 23, Dr. Erich Bagge set out from Hechingen in charge of a column of lorries, heading for Stadtilm to remove the Kaiser-Wilhelm Institute's uranium and heavy water. "Dramatic journey," he wrote in his diary. "Fighter bombers, bomber formations. Journey mostly by night." Wirtz transferred to Haigerloch with the convoy, having succeeded in insuring, as he now puts it, "that the Kaiser-Wilhelm Institutes' materials were not used in an experiment at Stadtilm." The return to Haigerloch was not without incident either, as one of the lorries crashed into a ditch and had to be rescued. But by the end of February the necessary materials were assembled at Haigerloch, four weeks after they had left Berlin.

The reconstruction of the pile *B-VIII* now began. The building work in the bunker was complete, and a diesel generator had been set up in the inn opposite the cave to power the laboratory. All together, Heisenberg's scientists now had one and a half tons of uranium cubes, one and a half tons of heavy water, ten tons of graphite blocks, and a lump of cadmium metal which could be dropped into the pile if the chain reaction threatened to get out of hand. The remaining uranium, heavy water and some uranium oxide briquettes were at Stadtilm, where Professor Gerlach had now set up his headquarters as Plenipotentiary for Nuclear Physics.

Ideally, the uranium cubes should have been between six and seven centimeters in size. The cubes left over from Diebner's Gottow experiments were only five centimeters, however, a consequence of his having had to improvise his early cubes from the uranium plates used by Heisenberg. Heisenberg and Bothe decided that rather than have a new set manufactured to the ideal size, they would have more made of the old size; a total of 664 cubes was now available. As in Berlin, the large alloy vessel was lowered into a water-filled pit in the center of the underground laboratory. Ten tons of graphite blocks lined this vessel, leaving a cylindrical cavity for the magnesium-alloy reactor vessel proper. The 78 chains of uranium cubes would be suspended in eights and nines from the lid by fine alloy wires — the system devised in the last Gottow experiment under Diebner's direction. The lid itself was also filled with graphite, sandwiched between magnesium plates; through a chimney in the lid the neutron source and heavy water could be introduced. At the end of February, experiment *B-VIII* began.

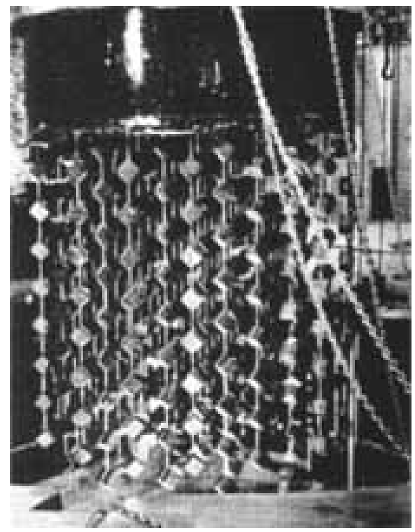


This was the pile with which the Germans attempted their last criticality experiment, B-VIII, in a cave in Haigerloch in southern Germany. The uranium cubes were lowered into the reactor vessel and a large alloy lid bolted into place. A neutron source was introduced at the pile's centre, and heavy water poured in stage by stage while measurements of neutron intensity were taken at a set distances from the centre of the pile.

At the end of January, Hitler had signed an "Emergency Program" decree, designed to meet Germany's war requirements without emasculating her vital military research. During the afternoon of February 26, Gerlach discussed the decree with the Reich Research Council in Berlin, and recognized that if the uranium project were to survive he would have to axe at least half of the research contracts. On the same day, he formulated a carefully phrased letter to the council's economics section, entitled: "Emergency Program. Energy Generation Project." In this letter, in which he talked of the "final development" stage reached by his nuclear research group, he asked for complete protection for the Kaiser-Wilhelm Foundation's institutes at Berlin-Dahlem, Heidelberg, Hechingen and Tailfingen, and for his own groups at Stadtilm, Haigerloch and Munich. Professor Harteck's isotope-separation work and the work of Professor Stetter and Professor Kirchner on fast neutrons were also of great importance, as were the heavy-water projects at I. G. Farben and Bamag-Meguin, and uranium production at Auer and *Degussa*, and the cyclotron and betatron research projects. "These projects are to enjoy complete energy-, material- and personnel-protection in accordance with the Führer's Emergency Program," Gerlach ruled. All else was to lose priority forthwith.

For one last time Professor Gerlach, who returned to Stadtilm on February 28, fell back upon the pretext that his scientists were working on explosives. He seriously feared for the health of Diebner's group, exposed as it was to X-ray, gamma-ray and neutron radiation, particularly because all the scientists were by now seriously undernourished, and lack of food made them prone to blood diseases caused by radiation. Gerlach wrote to the Weimar Food Office, applying for the "explosives allowance" for his group — an extra food allowance granted to workers in that industry.

By this time, the whole uranium pile assembly at Haigerloch was ready for its final experiment. The scientists assembled warily in the narrow confines of the underground laboratory. The graphite lid and chains of uranium cubes were lowered into place inside the reactor vessel, and the dished top-plate of the vessel was firmly bolted into position. Ordinary water, containing an anti-corrosive, was pumped into the pit and the watertight joints tested for the last time. Finally, the neutron source was lowered through the shaft to the heart of the pile, and the one and a half tons of irreplaceable heavy water slowly pumped in. At frequent intervals, the pumping was stopped, and the neutron multiplication levels inside and outside the aluminum boiler were checked. As the heavy water reached further and further up the inside of the cylinder, the readings increased, and it really seemed as though the pile might now go critical. Professor Heisenberg and Dr. Wirtz, directing the experiment, became increasingly uneasy as the readings showed mounting neutron multiplication; the pile's efficiency had already surpassed all the previous experiments' results.



A photograph of the Haigerloch pile showing the 664 cubes of uranium ready to be lowered into the heavy water

Plotting the reciprocal of the neutron intensity against the quantity of heavy water already pumped in — a Heisenberg suggestion — they could see the point at which the pile must go critical and suddenly start producing energy independent of the neutron source in its center.

Wirtz was uncomfortably aware now of their lack of experience with uranium piles. Above all, they had ignored the most elementary safety requirements, they knew too little about the pile's time constant, and the apparatus was desperately under-instrumented. Would the cadmium block suffice to shut the chain reaction down if the pile suddenly went critical? But — unaware of Fermi's achievement in Chicago two years before — all were determined that Germany should have produced the world's first chain reaction in uranium, before the war ended.

At last, all the heavy water had been pumped in. The infinite neutron increase had not been reached — so they had failed. For every 100 neutrons the source had "injected" at the center, their pile had emitted only 670 at the surface. It was the best result so far, but not enough. The theoretical physicists calculated that if they could increase the pile's size by 50 per cent, using the same geometry, a self-sustaining chain reaction would definitely occur. That meant that from somewhere Heisenberg had to procure 750 kilograms of heavy water, and not much less than that weight of uranium. There might be enough at Stadtilm, 200 miles to the north.

The Allied armies were pouring into Germany now from east and west. Gerlach returned to Berlin on March 22 and stayed for a week winding up his office there. Dr. Berkei and the rest of the staff had already left to join their families in Stadtilm.

Gerlach was in Berlin when the highly misleading news arrived from Haigerloch that the uranium pile was on the brink of criticality. He telephoned Rosbaud and asked him to call round. When Rosbaud entered Gerlach's office at 1:00 P.M. on March 24, he found Gerlach very excited. Gerlach began at once by proclaiming: "*Die Maschine geht!* The pile works!" Rosbaud later confessed that the news stunned him. He asked Gerlach how he knew. The professor replied that word had just come from Hechingen that the latest measurements were in full agreement with theory. Rosbaud interrupted him: there was a world of difference between having established the theory, and having proven it by practice. He reminded Gerlach how long it took Bosch to make an industrial process out of the theories of Haber; but Gerlach was unshakably confident, talking of carrying out the first "chemical reactions" within the next six months and the possibility that their research would be evacuated to the Führer's Alpine redoubt. Rosbaud was severely shaken by the change that had come over his friend and colleague, and later compared him with a child who refused to be taken away from his playthings. In this respect artists and scientists were so similar: "When they are obsessed by an idea, they ignore reality."

To Gerlach this was a great triumph: there would be no need for petrol, no need for radium now; Rosbaud unpatriotically answered that "Thank God it was coming too late." Gerlach refused to accept this. A wise government, he said, conscious of its responsibilities, could use this immense discovery to bargain for better conditions; now Germany knew something of extreme importance, which other nations did not. But he added: "We have a government which is neither wise nor ever had any feeling for responsibility." Rosbaud destroyed the professor's illusions: if he were the enemy, he said, he would either kill any scientists who tried to enter into such bargains with him, or send them into imprisonment until they had confessed "everything they knew about the reactor or the bomb."* In all probability

* This section is based on a report made by Rosbaud to the Allied authorities before the news of Hiroshima was announced. His remarks about "a bomb" are very interesting, therefore. See the footnote on p. 316.

the Americans and the Russians were already far advanced in this field anyway.

Gerlach left Berlin for the last time on March 28 and drove to Stadtilm for the day. The news arrived that the American troops were not far away. All work stopped, and the scientists resolved to meet their fate together. Gerlach left that night by car for Munich. After a brief stop at the Bavarian capital, he drove on to Hechingen and Haigerloch where the last great experiment had been. He conferred with Heisenberg, drank coffee with Max von Laue, and met Professor Otto Hahn. At Hechingen he learned from Heisenberg of the steps the physicist now proposed to take to make one last effort to get their reactor critical: all maddening theory was to be thrown to the winds. In addition to such heavy water and uranium as he could still obtain from Stadtilm, he now planned to introduce uranium oxide into the actual graphite shield, using the briquettes that Diebner had obtained for this purpose. Dr. Wirtz had already observed that their measurements of neutron intensity outside the graphite reflector during the recent experiment strongly suggested that graphite would have proved better as a moderator than Professor Bothe had so disastrously predicted four years before.

By now, the American troops were held up only five miles from Stadtilm. On April 3, Gerlach reached Munich and tried to contact Stadtilm. It was impossible. He wrote in his diary: "Radio communications with Thuringia interrupted," and added "All my chrysanthemums are flowering on the balcony." He tried to contact the group through the local army headquarters, again with no fortune. He resolved to drive to Stadtilm, but the military situation made this impossible. Gradual paralysis was overtaking Germany's internal communications. He could not even contact Erfurt, the nearest big city to Stadtilm. On April 8 he tried again through the local army headquarters, but they could not contact northern Germany at all, not even Berlin.

In Berlin, meanwhile, two SS officers had visited Dr. Graue at the Reich Research Council's headquarters and asked whether there were any vital research groups near the enemy fronts; Graue told them that the unit at Stadtilm would have to be evacuated at once. The SS officers said they would organize a column of lorries, and set off from Berlin. Early on April 8, the SS unit arrived at Stadtilm and told the startled scientists that the Führer had ordered that all bearers of secrets were to be evacuated to the south — the Alpine redoubt — and that those who refused were to be shot. Diebner's staff did not care to test their resolve on this latter score. Fortunately the SS troops had had an uncomfortable journey through the night, and one by one fell asleep in chairs in the schoolhouse, with their machine guns across their knees. While their guards slept, Diebner and Berkei arranged that those who were most mobile and had little property should escape to the south, while those who could not well move should stay at Stadtilm, whether "secret bearers" or not. Berkei would stay, for example, while Diebner would accompany the uranium and heavy water on its final odyssey.

Several lorries were feverishly laden with all the uranium metal, heavy water, radium and instruments; a few hours later the convoy was ready to leave. The column of lorries rumbled from Stadtilm to Ronneburg, and then to Weida, where the Bureau of Standards had last been evacuated, and made generally for Munich. At 7:30 A.M. on April 8, Professor Gerlach received a wireless message from Berkei announcing that Diebner was heading south. Gerlach sent a courier to Mentzel telling him this news.

[11]

THE *ALSOS* MISSION resumed its operations in Europe toward the end of February 1945, entering Germany near Aachen. The mission had had little to do since its coup in Strasbourg in December. Its operations promised to be complicated, however, for most of the really important research establishments were in sectors of Germany that had been assigned to France and the Soviet Union.

The Strasbourg papers had confirmed the part played by the Auer company's metal refining works at Oranienburg, outside Berlin, in producing the metallic uranium. But Oranienburg would lie in the Russian zone; there was no possibility of seizing and dismantling the factory before the Russians occupied it. This was in any case forbidden by their international agreements. Early in March, General Groves, director of the U.S. atomic bomb project, recommended that the Auer company's plant be bombed out of existence. General Marshall approved, and the commanding general of the American Strategic Air Forces in Europe was directed to attend to this target. Early in the afternoon of March 15, over 600 Flying Fortresses executed a saturation bombing attack on the factory that was so severe that even now, twenty years later, the city still has a "Catastrophe Commission" charged with removing the scores of unexploded bombs hidden in the ground. Casualties were very heavy, but post-raid reconnaissance showed that the factory had been completely destroyed.

Aware, as he was, of the concentrated efforts being made by the *Alsos* mission, Sir John Anderson proposed to Mr. Churchill that special steps be taken to prepare to investigate the German uranium research as soon as Allied troops crossed the Rhine. He made certain proposals, and Mr. Churchill was privately advised that it seemed unlikely that the British could do more than Anderson proposed without exciting unwelcome comment from the Russians. In any case, Dr. R. V. Jones, head of the Air Scientific Intelligence branch, had already made arrangements to send the appropriate people out to Germany, as soon as "places of interest near Stuttgart" — i.e., Hechingen, Haigerloch and Tailfingen — had been reached.

In the last days of March, American troops entered Heidelberg, and officers of the *Alsos* mission occupied the Kaiser-Wilhelm Institute of Physics on the thirtieth. Dr. Samuel Goudsmit, scientific chief of the mission, searched the laboratories together with Fred Wardenburg and Dr. James A. Lane. They found Professor Walther Bothe, and Goudsmit, who knew the professor well, had the delicate duty of interrogating him. Bothe was pleased to show the American his institute's new cyclotron and discuss his pure research, but he declined to give any information at all on the military research upon which he had been engaged.

The *Alsos* mission also located Dr. Wolfgang Gentner, who had worked on the Paris cyclotron. Neither he nor Bothe was taken prisoner. On April 5, Goudsmit drew up a report on the Heidelberg operations and an investigation of the *Degussa* works at Frankfurt, carried out on the third. They now knew that Professor Otto Hahn was at Tailfingen, south of Stuttgart, that Heisenberg and Max von Laue were at Hechingen, and that the last uranium pile had been evacuated from Berlin-Dahlem to Haigerloch, near Hechingen. The size of the whole project was small, consisting only of Heisenberg, the Döpels, Kirchner, Stetter, Hahn and a number of assistants; Professor Gerlach's role in allocating, jointly with Speer, the necessary priorities was also understood. Above all, Gentner had told them that the Haigerloch pile was not self-sustaining, so German research was evidently at a very early stage still. A subsequent Heidelberg interrogation revealed that there was in fact a second research group, at Stadtilm, under Dr. Diebner; but Gentner suggested that Diebner's work was not as good as that performed under Heisenberg.

No sooner had Goudsmit returned to Paris than he learned that General Patton's army was progressing with such speed that Stadtilm might fall any day. Goudsmit alerted Pash at Heidelberg, and after a couple of days' waiting at nearby Eisenach, the *Alsos* mission moved in on Stadtilm. The village was captured without a fight at about 4:00 A.M. on April 12, and the mission's officers, including Wardenburg and Lane, followed soon after.

This time the *Alsos* mission were in no doubt of the importance of their capture. In Paris, Samuel Goudsmit received a hastily scribbled note rushed by courier from Wardenburg.

> Stadtilm, 12 April 1945
>
> Sam:
>
> "*Alsos* struck again" — Pash.
>
> After three hours here, it is obvious we have a gold mine. Diebner and all the personnel (except one) who worked on the project, together with material, secret files, etc., were carted away from here on Sunday [April 8] by the Gestapo, destination unknown.
>
> However, we have:
>
> 1. Dr. Berkei, who has been in on the project from the beginning and who is telling all. He is also up to date on Hechingen.
>
> 2. Sets of revealing files.
>
> 3. Parts of the U-machine [i.e., uranium pile].
>
> 4. Much equipment, counters, etc.
>
> I think you should get here post haste. Mike Perrin should also be here. We will certainly learn

the broad outlines of the whole project here and in the south fill in the technical details.

See you soon,

FRED.

Alsos had also struck in northern Germany. At Lindau, Dr. Charles P. Smyth secured Professor Osenberg and a staggering quantity of files of the Reich Research Council; and on the seventeenth, Smyth — joined now by Dr. Colby, Major Furman and Dr. Goudsmit himself — had found Dr. Groth's centrifuge laboratory in the silk-spinning mill at Celle. Twenty years before, Groth and Goudsmit had been roommates while studying in Germany, and it was a painful confrontation for them now. Only one day before, Anschütz & Co. had put in a final tender worth over a half a million Reichsmarks for the construction of an ultracentrifuge uranium-enrichment factory; the tender never reached the Reich Research Council, however. It was a sad meeting for Goudsmit. Groth took him through the centrifuge laboratory, but Goudsmit kept the visit as brief as possible. He wrote Groth a letter after he had gone, and Groth replied thanking him and telling him of the hopes he had for the future, and also of his sorrow at all that had come to pass in the last few years. Groth was flown straight out to London and installed in an hotel. He was interrogated perfunctorily by British Intelligence officers, but he could see that they knew more about the whole German project than he did.

This was very much the achievement of Commander Welsh and Michael Perrin; although Welsh had many critics, nobody disputed that he had a highly developed flair for Intelligence work, and a "nose for clues." The British nuclear Intelligence effort had been formalized late in 1944, after agreement had been reached by Sir John Anderson and the Intelligence authorities in London, and General Groves and others in Washington, that nuclear Intelligence should be treated separately from the rest of scientific Intelligence, presumably as an elaborate security measure. Sir John Anderson had issued clear directives to this effect, and in November 1944 a special Anglo-American nuclear Intelligence committee had been established in London, consisting of Perrin, Welsh, Dr. R. V. Jones, Major Furman and Major Calvert, the latter two being the American representatives.

The British Intelligence authorities laid extensive plans for bringing operations to a triumphant conclusion, as the time for the capture of Hechingen and Haigerloch approached. Colonel Pash had in the meantime drawn up plans for a parachute assault on Hechingen to kidnap the scientists and their documents. Goudsmit was able to scotch this, and a similar plan to bomb Hechingen, by saying that in his view the German uranium project was not worth one sprained Allied ankle.

Great though the verve and impetus of the American officers in the *Alsos* mission was, the British had one thing that the Americans lacked: air transport. When the news of the document finds at Stadtilm and Lindau reached London, Dr. R. V. Jones charged one of his principal assistants in the scientific Intelligence section, Wing Commander Rupert Gascoigne Cecil, to arrange for an RAF aircraft to fly a team of officers out to link up with the *Alsos* mission. Together they called on Marshal Bottomley to procure the Dakota aircraft necessary.

Commander Welsh was to fly in with this advance party as well; Michael Perrin, deputy director of the "Tube Alloys" project, would follow later. The Dakota took them out to Frankfurt, and they proceeded by road from there to Stadtilm. Goudsmit and Wardenburg were already in the gloomy schoolhouse which had served as the headquarters of Professor Gerlach's operations. From Gerlach's files, they built up a complete sketch outline of the German project from the first military interest in uranium fission in the first months of the war until the construction of *B-VII* in Berlin-Dahlem.

By now, the remainder of the British mission had flown out to Paris, on their way to join the final cleaning-up operation. Michael Perrin had come out from London with Sir Charles Hambro, now representing the Combined Development Trust, the Anglo-American-Canadian body founded to control the world's uranium deposits. Professor Norman, Dr. R. V. Jones's linguist expert, joined the plane at Paris; it flew on to Reims, where there was a final conference with General Bedell Smith on the military operation planned to seize the region round Hechingen. Finally, they joined up with the *Alsos* mission — Colonel Pash, Dr. Goudsmit, and Major Furman — at Heidelberg. General Groves had even sent his chief of security, Colonel Lansdale, to represent his interests in these final stages.

The major difficulty was that the whole area of Germany into which German atomic research had been concentrated — the area around Freiburg, Stuttgart and Friedrichshafen — was to be occupied by the French, and there were no American units near the zone. "My recent experiences with Joliot had convinced me that nothing that might be of interest to the Russians should ever be allowed to fall into French hands," wrote General Groves later. The possibility that the Russians might somehow benefit from the German uranium research project was clearly uppermost in Mr. Churchill's mind in April, as the Soviet Army began to flood westward across Europe. He told Eden on April 19 that he considered that while the western Allies seemed now not to be in the position to force their way into Berlin, they should set themselves two main objectives: the capture of Lübeck, and "thereafter, but partly concurrent, it is thought well to push on to Linz to meet the Russians there, and also by an American encircling movement to gain the region south of Stuttgart. In this region," Mr. Churchill continued, "are the main German installations connected with their atomic research, and we had better get hold of these in the interests of the special secrecy attaching to this project."

The bulk of the German uranium ore still had to be found. In the previous autumn Calvert had traced it to a salt mine near Stassfurt operated by the government-controlled Industrial Research Association (*WiFo*). A British-American mission was hastily formed, comprising Colonel Lansdale and Calvert, and Sir Charles Hambro and David Gattiker, Perrin's assistant; the British officers all wore military uniforms. Stassfurt lay between the American and Russian armies, but the group attached itself to the 83rd Infantry Division and quickly seized the plant, which had suffered badly from bombing raids. With the assistance of the German plant manager, eleven hundred tons of the Belgian ore were located, stored in rotting barrels in a shed. Fortunately a barrel factory was found close by, and under American military supervision some 20,000 new barrels were turned out to transport the vital uranium ore. Within three days the entire tonnage had been shipped westward across the line of the future Iron Curtain and stowed in an airport hangar at Hildesheim.

Uranium production in Germany had finally stopped on April 15. The uranium-reduction plant at *Degussa*'s affiliated "Chemical Factory" at Grünau, whose construction had begun early in 1942, had finally begun production in December 1944, during which month it had produced 224 kilograms. Its equipment and capacity — 1,000 kilograms of uranium or thorium metal per month — were the same as the bombed-out Frankfurt works, but by mid-April 1945 it had produced only 1,500 kilograms of uranium. In January 1945 the melting, casting and rolling of uranium was removed from *Degussa*'s other Frankfurt works to Auer's plant near Berlin, where a further 400 kilograms had been rolled by the end of the war. Of the 14.3 tons of uranium metal manufactured during the war in Germany, only 5.5 tons had been cast in plates or cubes. All the rest was in powder form.

On April 23, General Groves was able to report to General Marshall in Washington that the possibilities the Germans might have atomic weapons were now nonexistent. He explained:

> In 1940 the German Army in Belgium confiscated and removed to Germany about 1,200 tons of uranium ore. So long as this material remained hidden under the control of the enemy, we could not be sure but that he might be preparing to use atomic weapons.
>
> Yesterday I was notified by cable that personnel of my office had located this material near Stassfurt, Germany, and that it was being removed to a safe place outside of Germany where it would be under the complete control of American and British authorities.
>
> The capture of this material, which was the bulk of uranium supplies in Europe, would seem to remove definitely any possibility of the Germans making any use of an atomic bomb in this war.

On the same day, April 23, troops under Colonel Pash captured Haigerloch. Two days before, the French had crossed the line where they had been ordered to halt, apparently heading for Sigmaringen where the survivors of the Vichy government were known to be located. Pash had been given immediate operational command of the 1279th Engineer Combat Battalion of U.S. troops to forestall them; General Eugene Harrison, chief of Intelligence in the Sixth Army Group, accompanied them as Haigerloch was taken. Michael Perrin flew in from London, and on the twenty-fourth the door to the cave housing the Haigerloch pile was forced. The whole party, including Welsh, Perrin, Lansdale, Furman and the others, trooped in. The cave and tunnel were damp and ill-lit, and candles had to be fetched. The pit in the floor of the tunnel was covered over, and there was some anxiety as to whether they would be met by a burst of radiation as they opened it up. Perrin was probably the only one to have seen a near-critical atomic pile — the huge graphite pile being built by Fermi at Chicago, in the spring of 1942. The first thing that struck him was the complete absence of any kind of radiation protection. The pile could not possibly have gone critical; if it had, the Germans concerned would now have been very sick men indeed. Perrin ordered the pile to be opened up

British and American Intelligence officers dismantling the Haigerloch pile in April 1945 and it was completely dismantled on the twenty-fourth. The uranium and heavy water had gone, but a few drums of heavy water were found standing round, and these were laden onto Army lorries together with the quantities of graphite blocks that had surrounded the pile. So that the French should find no trace of the Haigerloch experiments when they occupied the village, one of the two colonels suggested that the ancient chapel atop the cliff be blown up, so that the ruins would completely block the entrance to the cave. The local priest protested, and the plan was dropped.

The atomic pile's cave was blown up by the engineers after the mission had withdrawn from Haigerloch. Perrin and the others went on to Hechingen to join Goudsmit there. The town had been occupied at about 4:00 P.M. on Sunday, April 22, by French and Moroccan troops. The *Volkssturm* had been disbanded two days previously, after the local Party officials had fled, and there had been no fighting. Von Weizsäcker was still working in the Institute, but the French had had little interest in it. All documents and the uranium and heavy water at Haigerloch had been hidden where it was hoped they would never be found. Heisenberg had already escaped in the early hours of the previous Friday, and after three days' and three nights' hard cycling had reached his family home at Urfeld in the Bavarian mountains, where he waited for the end. At about 8:30 A.M. on April 23, four American armored cars and several lorries of the T-Force of the Sixth Army Group had rolled into Hechingen. Colonel Pash and General Harrison forced their way into the German laboratories in Weiher Strasse and Tübinger Strasse, and found Heisenberg's office in the wing of the Grotz textile factory which had been taken over by the Kaiser-Wilhelm Institute. Pash was amazed to find a photograph showing Heisenberg with none other than Dr. Goudsmit — taken at the dockside as Heisenberg was leaving America in 1939. Pash set up *Alsos* headquarters in the factory.

To prevent the French from removing any personnel or equipment from the laboratory, the Americans furnished the Germans with written orders safeguarding their laboratories from search. Two American officers called on Dr. Bagge and searched his home, removing all his papers later than 1942, promising to return them. Bagge's prototype apparatus for separating uranium-235 had been set up, together with a similar machine designed by the young Dr. Korsching, in a room of the Grotz building; it was running so well that its isotope-separation factor for a single stage was about four times better than for a single stage of the gaseous diffusion adopted by the Americans.

His "isotope sluice" had had a checkered career: twice bombed out in Berlin, and three times evacuated, it had begun its final trials only in these last few days. The ugly iron bottles of uranium hexafluoride had been sent across by the I. G. Farben firm, and experiments were about to begin. By April 24 it was already too late. At 4:00 P.M. Bagge was fetched by American soldiers and taken to the factory to be interrogated by Dr. Goudsmit. Before his eyes, simple American soldiers began to dismantle his isotope-sluice machine, the poisonous uranium hexafluoride fumes rising from its innards. Bagge was obliged to help them dismantle his machine and pack it into crates: "One of the men doing this shrugged his shoulders and said: '*C'est la guerre, monsieur*.' You could see he hated doing it. He was an American. Toward seven o'clock, I left the Institute."

He had been at home only a few minutes, when an American arrived and warned him to stand by to leave next morning for an undisclosed destination. He was to be prepared for an absence of several weeks. The unhappy Bagge promised to drop all further work on the "isotope sluice" but his entreaties fell on deaf ears.

The same happened to Dr. Korsching. His machine was dismantled and loaded onto lorries; a German mechanic took him aside and suggested that they remove some of the more vital equipment, so that the Americans could not piece the machine together again. The idea had never even occurred to Korsching, but he agreed and the parts were removed. For four days the interrogations of the Hechingen scientists continued. Professor von Weizsäcker and Dr. Wirtz were repeatedly questioned by Goudsmit, and were successfully tricked into revealing the hiding place of the uranium and heavy water used at Haigerloch. They would be needing it, after all, when they resumed their experiments under Allied auspices. On the twenty-sixth, a special group of British and Americans drove the ten miles to Haigerloch and found the heavy water hidden in petrol cans in the cellar of an old country mill, and the hundreds of uranium cubes buried in a field outside the village. Professor von Weizsäcker and Dr. Wirtz signed a rather superfluous authorization for the Americans to remove the uranium and heavy water; Michael Perrin wielded a shovel to unearth the uranium cubes. Upon returning to Hechingen, he and Commander Welsh composed and encoded a full report on the operation, which was transmitted by the special radio apparatus they had with them to their HQ in London, who forwarded it through Mr. Wallace Akers to Sir John Anderson.

In the meantime, Colonel Pash had driven out to Tailfingen, together with Wardenburg and Lane. A passerby pointed out the laboratory of the Kaiser-Wilhelm Institute of Chemistry, in an old school building; the school was surrounded, and two of Pash's officers walked in and asked for Otto Hahn. The elderly chemist looked ill and emaciated — he had lost thirty pounds in the last year. When asked for all the secret reports and documents known — from receipts found at Stadtilm — to have been sent to him, Hahn said simply: "I have them here." Professor von Laue was found there as well.

Otto Hahn was taken away from his wife and son — who had lost an arm on the eastern front and was lying seriously ill in a local hospital — and driven with von Laue to Hechingen. Hahn's first action was to write a letter to America, to Clara Lieber, the girl who had assisted him in his famous discovery six years before. He gave the letter to Goudsmit to forward, but like all the letters written by the German prisoners at this time it was seized and never reached her.

The Americans' method of selection of German scientists to accompany them caused some friction; von Weizsäcker complained about the decision to pick up physicists like Bagge and Korsching, who were certainly not important enough, in his view. As the party was about to leave Hechingen, von Weizsäcker suddenly blurted out that the remaining records of the German research program were in a sealed canister suspended in the cesspit of his home. The cache was retrieved, and the unwholesome task of examining the find was delegated to Dr. Goudsmit. Now the Intelligence picture really was complete, for they had the complete set of secret research reports, and with Gerlach's files they knew the story of the whole project.

Unaware of the special arrangements that had been made between Britain and America over atomic Intelligence, Professor Norman and Wing Commander Cecil advocated that a complete copy of the *Alsos* documents should be obtained by the regular British Intelligence service during the documents' one-night stop in London en route to Washington. They transmitted a signal to Dr. R. V. Jones in London, using the same radio link as had been used for the earlier report. In the Intelligence headquarters there was a special document-copying service, and Jones arranged for the entire department to stand by to photograph the *Alsos* papers and for several other Ministries to cooperate on the vast one-night effort as well. He telegraphed the British officers accompanying the mission to this effect.

Hechingen was evacuated early on April 27.

Professor Norman, the linguist expert, went in Colonel Lansdale's Jeep. Lansdale was Groves's chief of security, and as such he was fully informed on the American program's progress. He advised Norman that everything would have to be kept quiet for three more months; then the bomb would have been used, and the need for secrecy would be past.

> *Friday, 27 April 1945*: Shortly after 8 A.M. I was called for in a motorcar [wrote Bagge]. I said goodbye to my family, briefly but affectionately; at the last minute there was a lot of weeping and I was able to restrain myself only with difficulty. Soon after nine, a long procession of motorcars left the Institute heading for Heidelberg, with Professors Hahn, von Laue, von Weizsäcker, Doctors Wirtz, Korsching and myself. Arrived at Heidelberg at 4 P.M. Put up in a house in the Philosophen-Weg. There is a wonderful view across the city and the Neckar. Far away on the horizon we can make out the spires of Speyer cathedral.

It remained only to await the arrival of the German research documents in London for the British Intelligence effort to reach its triumphant conclusion. But it was at this stage that the two factions in the British portion of the *Alsos* mission fell out, for during Wing Commander Cecil's absence, arranging the details of the RAF Dakota's flight home, it was decided that the *Alsos* documents should not stop over in London but should proceed straight to Washington. Cecil and Norman were confronted with this development soon after, and found it most disturbing. To them it could only seem that two British officers — Welsh and Perrin — were working hand in glove with the Americans to deprive the regular British Intelligence services of this series of papers. Neither could know that atomic Intelligence was such a vitally important field — it will be remembered that Mr. Churchill had spoken of the "special secrecy" attaching to this subject — that special arrangements had been made between Sir John Anderson and General Groves for the handling of this particular field of Intelligence.

All this was unknown to the two officers from Jones's office. Cecil and Norman retired for a long discussion of their tactics, and then returned; by candlelight — Heidelberg still had no electricity supplies — a heated argument developed in the villa, mostly between Cecil and Colonel Lansdale. At 2:00 A.M., when the angry meeting broke up, it seemed clear that the Americans had won. Perrin and Welsh were unable, of course, to explain to their British colleagues the real reason for their action. Perrin and the others flew back to London on April 28, with the atmosphere in the aircraft decidedly tense. To Norman and Cecil it seemed a shocking end to a mission which had set out with such high hopes.

Some mornings later, a strained meeting was called by the deputy head of the regular Intelligence services to hear the protest which had been lodged on Jones's behalf about this apparent betrayal of British Intelligence interests. Jones and Cecil represented one side of the issue, and Perrin and Welsh attended in person. Whether the deputy was as fully apprised of the special directives issued by Anderson as was his chief is a matter for speculation. At any rate neither Perrin nor Welsh received anything but the highest praise for the way in which they had handled the Intelligence attack on the German atomic research project, bound up as it was so tightly with the whole delicate relationship between Britain and America in the field of atomic research.

This is not to say that the suspicion did not remain firmly rooted in Jones's mind that Michael Perrin and Commander Welsh had engineered this situation only so that they could remain the sole channel through which nuclear intelligence could reach the British authorities.

The interrogations of the German scientists continued. On April 29, Bagge wrote: "Summoned by Goudsmit with Wirtz and von Weizsäcker. Main question: 'Where is Diebner?' — Nobody knows."

The search also began in earnest for Heisenberg. On May 1, Walther Gerlach was hauled into the net as he sat at work in the physics laboratory of Munich University. On April 19, he had learned that an SS warrant for his arrest had been issued, and he and an assistant had filtered into the Bavarian mountains to await developments. He had made repeated attempts to contact Diebner's convoy by telephone and telegram, but to no avail. On April 22 — the day of Hitler's final appeal for the defense of Berlin — Gerlach had been ordered to drive down to Innsbruck to prepare accommodation for Diebner's laboratory and staff. After an exciting three-day search in the mountains, during which he was arrested on suspicion of being a British spy, he had located the convoy in a village between Tölz and Tegernsee. Most of its SS escort had been captured by the enemy in an incident some days before. Gerlach had split the convoy up into sections early on the twenty-fifth, and sent some of them on to Garmisch-Partenkirchen, while he had returned to his old institute in

Munich with part of the uranium and heavy water. He had located the Reich Research Council's evacuated head office, and drawn a final half million Reichsmarks in cash to settle salaries and outstanding bills.

In Munich, there was peace: "Mother's *genista* are blooming," he wrote in his diary. He paid the half million Reichsmarks into his bank account in Munich and it was still there, converted, when he returned from internment in England in 1946. Munich was captured late on April 30. At 5:00 P.M. on the following day, Gerlach had a visitor — Dr. Baumann of the *Alsos* mission. It began to snow heavily. Gerlach looked haggard and ill.

Dr. Diebner was picked up soon after, at a village about twenty miles southeast of Munich; he had all of 80,000 Reichsmarks on him. On the following day, Colonel Pash called on Professor Heisenberg's home at Urfeld. The physicist's bags were already packed. Heisenberg was marched to an armored vehicle, and placed between two armed American soldiers. The vehicle moved off down Urfeld's main street, with a large tank in front and another tank and several Jeeps behind. The crowds of villagers lining the street agreed that even Stalin could not have been better escorted. Heisenberg and Diebner were brought to the new *Alsos* headquarters at Heidelberg.

The Americans found Diebner an uncooperative and sullen prisoner compared with the others. The hostility of Heisenberg and his colleagues toward Diebner was so marked that even the Americans noticed it: "Their conversations with him were limited to monosyllables," wrote Goudsmit.

On May 2, Mr. Winston Churchill was told of the results of the combined Anglo-American sweep of the "suspect sites near Stuttgart," and of the haul it had yielded: the officers had found practically all the German uranium, and some one and a half tons of heavy water. Particularly pleasing was the capture of the German scientists and most of their records. "It is satisfying to find," Lord Cherwell told the prime minister, "that they are at least three years behind the Americans and ourselves in their investigations." What Cherwell did not add, in writing of this to Mr. Churchill, was that the Germans had perfected most of the theory three years before anyway, since when they had virtually marked time.

At the beginning of 1945, Dr. Rosbaud, the collaborator with the British, went for the last time to see Manfred von Ardenne's laboratory at Berlin-Lichterfelde. It had been completely repaired after the bomb damage it had sustained two years before, with the magnificent laboratory now built underground and heavily reinforced against bomb damage. The Van de Graaff machine, the cyclotron and the prototype electromagnetic isotope-separation equipment were among the most advanced in Germany. Rosbaud called on Professor Gerlach the same day, and told him what he had seen. He said that von Ardenne had forgotten one thing: when the Russians came, they would dismantle everything and send it to Russia. Gerlach had rejoined that the Russians would take von Ardenne to Russia too; there he would rebuild everything, ten times larger, and continue as before.

Gerlach was not far wrong. At the end of the war, the Russians rounded up the uranium-project scientists, and removed very many of them, including Bewilogua, Döpel, Geib, Hertz, Vollmer, Wirths, Herrmann, von Ardenne, Thiessen, Timofeeff, Riehl and Zimmer to the Soviet Union. Most went freely under good contracts. The Russians knew exactly whom they wanted, and those whose work was already obsolete. As an expert in the processing and refinement of uranium, Dr. Riehl was invaluable to the Russians and worked for the next ten years on their project.

The Russians quickly realized that the Americans had bombed Oranienburg to deny the Auer works to the Soviet Union. Riehl was escorted out to see the factory by Russian officers, and he gathered that they knew the reason for the attack from remarks he overheard. Again, the Russians soon discovered that the Americans had, contrary to all their written agreements, removed the uranium from Stassfurt, for the Soviet atom minister, A. P. Savenyagin, told this to the German scientists working under him. All that the Russians obtained from Oranienburg was several tons of very pure uranium oxide. They did, however, capture *Degussa*'s uranium-smelting plant, which had been evacuated to Stadtilm. At Rheinsberg — now the site of East Germany's first atomic power station — they captured the rest of the uranium, including five tons of metal powder and a quantity of the uranium cubes sent there. It was with these stores, and about twenty-five tons of unrefined uranium oxide and uranates discovered in the various Auer stockpiles, that the Soviet Union began work on the atomic bomb.

The Russians stripped the Kaiser-Wilhelm Institutes in Berlin-Dahlem of all their familiar equipment, including the impressive high-voltage linear accelerator, which was last seen by Dr. Czulius at the Russian atomic establishment at Obninchoye. But much of the less familiar nuclear physics equipment was thrown out and was still lying there when Dr. Goudsmit himself inspected the Institute of Physics On July 30, *Alsos* found that the building was being used as the headquarters of an American Intelligence command, "apparently unaware," as Goudsmit reported to Washington, "of the importance of the target." The Americans had dumped the few remaining pieces of equipment in the back garden, including blocks of uranium oxide, graphite and lead. In the famous bunker Goudsmit found the reactor pit, covered with wooden boards, and the remote-control handling mechanism for handling the radium-beryllium neutron source and lowering it into the center of the pile. Goudsmit found Riehl's secretary, Fräulein Blobel, at Auer's head office. She told him that the Russians had removed all the company's records, contracts and process details. She also said they would never see Riehl himself again, as the Russians had got him too.

This was the end of the story of the German uranium project. Riehl, Hertz, Döpel and the other leading uranium scientists were being paraded before General Beria in Moscow. Dr. Geib, Professor Harteck's brilliant research pupil who had evolved the revolutionary hydrogen sulphide dual-temperature exchange process for manufacturing heavy water, had also been removed to Russia. He arrived at the Canadian Embassy one day and applied for asylum, giving the name of Professor E. W. R. Steacie as a reference in Canada. The inept Embassy officials told him to come back next day. The young German never returned; his wife was sent his personal effects a few days later and told that he was dead. Nor did Professor Döpel — who with Heisenberg had achieved the first positive neutron-production in a uranium pile in 1942 — see Germany again.

What happened to the rest? Dr. Albert Vögler, president of the Kaiser-Wilhelm Foundation, survived to the last few days of the war, but not much longer. Vögler was morally one of the most upstanding characters in Germany. He had become increasingly critical of his government during the latter years, but he had drawn the line at any kind of sabotage of the war effort so long as his country was fighting for survival. Vögler now saw British troops looting his home of a lifetime's collection of *objets d'art*; he took poison and killed himself in a nearby church. Dr.

Basche, Diebner's original superior at the Army Ordnance Department in Berlin, was killed in the fighting for Kummersdorf in the last five days of the war. Nobody knew what had happened to Professor Erich Schumann.

As the German nuclear scientists settled down for an uncomfortable sojourn in Paris — worried for their families, their homes and their probable fates — one man was still at large. Without British permission, two *Alsos* officers drove up to Hamburg in the British zone and located him there: Professor Paul Harteck, the bachelor scientist who, given the funds, the men and the materials, could certainly have produced an atomic bomb for Germany. The Americans sat him in the back of their Jeep and smuggled him out of the British zone, with Major Russell Fisher at the wheel.

Harteck — his spirits high and his courage unshaken — saw that he was being driven to Paris. In his tunic and beret, and with his clipped military mustache, he looked dignified and not unlike an Allied officer. As the French countryside unfolded past him, he recalled all that had happened since he and Willi Groth had written that letter to the War Office in April 1939 — the Berlin conferences, the heavy-water crises, the ultracentrifuge project, the hopes gradually raised and dashed. The streets of Paris were hung with flags, and spring was at last in the air. There were crowds of Frenchmen lining the streets as the little Jeep sped Harteck through the suburbs to join his captive colleagues: there must have been some parade on later that day. The crowd began to cheer as they saw the Jeep, with its imposing insignia and major at the wheel, and its anonymous passenger sitting in the back. Harteck stood up and saluted, acknowledging the cheers.

CHAPTER TWELVE

The German Achievement

DURING THE LAST few days of the war, wild rumors began to circulate in southern Germany: Party officers went from house to house in Munich spreading the word that the German atomic bomb was about to be used. It was a rumor that many people believed. Colonel Geist, Speer's chief of technical research, met his wife as both were fleeing before the enemy. She begged him to tell her whether Hitler had any more "miracle weapons" with which to snatch victory from defeat, even at this hour. Geist told her that there were none. For a time, he said, there had been some hope of manufacturing an atomic bomb; but Germany's scientists had let her down.

For a long time, it was difficult for people to believe that Germany had done virtually no work toward making an atomic bomb. Rumors continued to persist that there had been an atomic bomb factory on Bornholm Island,* which had been captured by the Russians. Some Latin countries still believe that the bombs dropped on Hiroshima and Nagasaki in August 1945 had been stolen from German arsenals.

Reichsminister Speer, the Munitions Minister, was interrogated about the German uranium project soon after his internment. He admitted: "Just as in America, our scientists have also been engaged for a long time on a study of atomic fission. You are much further advanced in America than we are: you have the big cyclotrons. It was only during my régime that all that got any support, and I ordered the construction of several smaller cyclotrons to be put in hand; there is now one in Heidelberg. But in my own view we were a long way behind the stage you have reached in America." He was asked: "Can it be said that 'heavy water' played some role in the development you planned later to exploit as a source of energy?"

Speer replied: "We never got beyond primitive laboratory experiments, and even these were not ready for decision." A week later, he was again interrogated on this subject, and apart from mentioning the names of Professors Bothe and Heisenberg as being those responsible, and again stressing that he believed American work on the atomic bomb was far advanced on that in Germany, he could add nothing: "Ten more years were needed," he professed.

That the German nuclear scientists should have failed to fire Speer's imagination with the possibilities of atomic fission

* Cf. Gerlach diary, August 7, 1945: "The newspapers state that we have a uranium-bomb factory on Bornholm. The Major [Rittner] tells me that they know all about Bornholm — it was partly V-weapons and partly radio-controlled bombs that were being developed there." Professor Gerlach was subsequently questioned by a British officer about the Bornholm atom-bomb factory rumors. Cf. also S. A. Goudsmit, *Alsos*, p. 32.

was their greatest shortcoming. They had had the opportunity at their meeting with him in Berlin in June 1942 (Chapter 5, section III) but they had wasted it. Academic physicists are notoriously shy, and it was not surprising that they failed to establish *rapport* with great men of government or industry. Some scientists, like Professor Harteck, were unafraid of making great demands on industry; but in the uranium project it was the academics who held the reins. Asked by Speer how he could best help in June 1942, Heisenberg and von Weizsäcker had complained that they could make no headway as they lacked the necessary building quotas; but when Speer asked how much they needed, von Weizsäcker tentatively suggested the sum of about 40,000 Reichsmarks. Field-Marshal Milch recalls: “It was such a ridiculously low figure that Speer looked at me, and we both shook our heads at the artlessness and naïveté of these people,” By all accounts, Dr. Vögler was hideously embarrassed by this *faux pas*, and he and Speer left the meeting with a negative impression of the whole uranium project. Speer told the scientists that they could have any funds they wanted, but he did not bother himself much more about the nuclear project.

The scientists concerned would now suggest that this was their intention — that they had no desire to work on a uranium bomb. Certainly Heisenberg succeeded in impressing upon his audience the virtual impossibility of Germany’s producing such a weapon; but he admits that during the war he and his colleagues overestimated the difficulty of actually producing the necessary fissile material. There was accordingly no positive effort to draw attention to the possibility of making atomic bombs. Professor Schumann and Professor Esau both advised against letting word leak out in case they were *ordered* to manufacture such weapons, with unpleasant consequences if they failed. Surprisingly, Dr. Diebner acted similarly when an Intelligence officer appeared at his office one day with the news that somebody had told the Führer of the existence of a research group working on atomic bomb development, about which the Führer accordingly wished to be informed; Diebner had sent the man away.

It is certainly not suggested that in not having made an atomic bomb, German scientists were morally more pure than those in America and Britain. On the other hand, as Professor Heisenberg told Professor Bethe, who had left Germany for America in the 1930s, he did not blame German émigrés for working on atomic bombs in the United States: their hate of everything German was justified, and they had to make some effort to prove their worth to their host countries. He carefully précised the position of the German physicists who remained in the Reich in a letter to Bethe: "German physicists had no desire to make atomic bombs, and were glad to be spared the decision by force of external circumstances," by which he meant the "enormous technological effort" such a project would have involved. To put the position in a nutshell, "German research never came far enough to have to make a decision on the bomb."

Given the time, the Germans would and could have produced an atomic bomb. There is no indication that at any stage in the logical process of development the scientists' moral scruples would have become powerful enough to overcome their natural curiosity to see what came next — a curiosity which is the driving force of scientists throughout the world. This was the force which had spurred Heisenberg and Wirtz to make their last dramatic effort to build a chain-reacting uranium pile before the war ended: not because it would have helped the war, but because they were curious to see whether it could be done. The further stages in the path toward the plutonium bomb were already clearly mapped out ahead, and there is no reason to suppose that the same curiosity would not have impelled these scientists along it. By the late spring of 1945 they had taken no wrong turnings in the inexorable track; they were railroaded, and only an error of the magnitude of Bothe's, in his graphite measurement, could have prevented them from getting to the bomb.

At the slow rate at which they were progressing, it would have taken time, of course. The obvious comparison is with postwar France, which "drifted toward the possession of an atomic bomb without the project ever receiving official sanction at Cabinet level."*

Two forces militated against speed in the German project: the first, that the project was directed by scientists throughout its history, and not by military commanders as in America; and the second, that in Germany the emphasis was on the theory throughout the project. The points must be taken separately.

Professor Esau, the first Plenipotentiary for Nuclear Physics, was characterized as "a good-humored, somewhat blustering" individual by his contemporaries. He was stolid and anything but a visionary. Early in 1944, in a wireless broadcast, he said: "We technicians do not believe in miracles; we believe, that success comes only as the fruit of unrelenting, purposeful labor." An article about him in *Das Reich* six months later described him as a good and modest man, who "knew too much and had achieved too much to want too much." Laudable though these qualities may have seemed to *Das Reich*, they had not been the qualities of the man the German uranium project had needed.

* Lawrence Scheinman, *Atomic Energy Policy in France under the Fourth Republic* (Oxford University Press).

Professor Gerlach, who had replaced him, had even less drive than Esau, although he and Esau were both favored by the SS, and he in particular enjoyed close relationships with Vögler, Speer and the academic world. Gerlach was not primarily motivated by any desire for Germany to win the nuclear race when he accepted his appointment as Göring's Plenipotentiary for Nuclear Physics. Rather, he saw his as a mission to save German physics from the ignominious limbo to which it would be condemned if the best of the physicists and lecturers were to fall on the war's battlefields. How could he believe that the Allies, presumably more rational than the Nazis, were doing anything different? All the greater was his disillusionment when he realized on the day of Hiroshima that, while he had saved German physics, he had lost the greater battle. He wrote in his private shorthand diary on the following day a distracted comment on his feelings:

> All our work training physicists for teaching and industry has been in vain — our whole work during the war in vain. But perhaps the salvaging of German physics will make itself felt one day . . . or perhaps not after all. One can no longer cling to the belief that intellectual labor will be only to the benefit of mankind. Must everything that benefits mankind now result also in its destruction? The situation in our small circle is getting difficult and tense. The most remarkable views are coming to the fore. . . .

In particular Gerlach found himself reproached for having failed Germany in her hour of need: he could have forced the scientists to produce an atomic bomb, but he had not.

In appointing a physicist to direct the German project, Göring had insured that it would not come to fruition. Gerlach had viewed his appointment as a golden opportunity, even in the midst of war, to reestablish German predominance in the field of pure science.

An early Allied analysis of the German military research effort suggested in 1945:

> German science was not without guile, and took advantage of the lack of understanding of science by those in authority to engage in interesting scientific research, under the guise of war-work, that could not possibly help the war effort.

In short, the behavior of the German scientific leaders demonstrated that during war, science cannot be safely left to the scientists.

The second disadvantage under which the German atomic project labored was the predominance of pure over applied physics in Germany. It was no mere fluctuation in fortunes which had led to the great decline in German physics since the 1930s; nor can the popular excuse of Party interference be substantiated. The truth was that the German scientists had lost the art of experiment: "I had the opportunity of working in Rutherford's laboratory in Cambridge from 1933 to 1934," Professor Harteck said years later. "And when I looked at the way people performed their experiments, and overcame experimental difficulties, I got the impression that there was nothing superior in Germany, and that the discovery of deuterium by Urey did not come about by good luck." The Germans had become self-complacent, and had underestimated the ability of scientists in foreign countries, he believed.

In Germany, Heisenberg was the undisputed doyen of the physicists and Heisenberg was a theoretical physicist. He would probably have stood aside in time of war and allowed the experimentalists a greater share in directing the fortunes of the project, had he not been discouraged by the physicists in his entourage, and in particular by von Weizsäcker and Wirtz, who scorned the efforts of those who were not like them. But the theoretical physicists were remotest from the engineering industry. It was this sad gulf between science and industry that had denied German science the big engineering achievements like the cyclotron in 1940.

In consequence of the hegemony of theoretical physics in Germany there was no immediate urgency to get the uranium pile critical. It interested the Heisenberg group more to build up the solid theoretical basis stage by stage, and to compare it with the practical results they then achieved. Academically a very satisfying pursuit, it was not the way to win wars; but it did win Heisenberg and Bothe the acclaim of other academics. In peacetime, they would probably not have acted in this way, as they would have seen how close their rivals were. As Dr. Goudsmit wrote in his final report:

> The evaluation of the intelligence indicated that the Germans believed that they were far ahead of American developments in this field. In reality the Germans, though they started sooner, were far behind. They had given up altogether the idea of making a bomb and were concentrating their efforts on constructing an energy-producing machine, which they called a "Uranium Burner" [*Uranbrenner*]. At the end of the war, they had not even succeeded in constructing a self-sustaining chain reaction or "pile."
>
> Nevertheless, they believed their progress to be so important that they offered to assist United States scientists in their efforts to harness atomic

> energy. They were convinced that their work would help Germany to dominate the world of science, even though the military struggle had been lost.

Not until the news of the atomic bomb reached them on August 6, 1945, did the German scientists realize that they had lost the war of physics as well.

[11]

HOW FAR HAD the Germans really progressed by May 1945? Were they three years behind, as Lord Cherwell wrote to Mr. Churchill? A cool assessment of the entire series of German research papers suggests that they were in fact further advanced than either the British or Americans publicly gave them credit for.

In some aspects of the work on which the Germans with their limited means engaged, they equaled the work done in Britain and America. Other aspects had not been investigated at all. All work on graphite-moderated reactors was choked by Professor Bothe's 1941 underassessment of the diffusion length of thermal neutrons in graphite; nobody had dared to suggest that a Bothe could be wrong. Professor J. W. Beams, the American ultracentrifuge expert, wrote that in 1945 the German ultracentrifuge project was behind the stage reached by his own American project at the end of 1943, when support was cut off; but this was the result of the Allied air offensive, not of any failings in the German scientists under Harteck and Groth who built the ultracentrifuges. The enforced evacuations from Kiel and Freiburg had each caused many months' delay, and it proved difficult to obtain the necessary materials from Essen and

Vienna because of the bombing campaign. The Germans certainly showed much ingenuity in devising the various other methods for enriching uranium-235 in a country weak in electric power.

The most remarkable verdict on the German work on uranium piles was passed in a secret report written by two Oak Ridge scientists* for Dr. A. H. Compton in November 1945. Shortly before, the question had arisen of the advisability of publishing the very comprehensive American *Plutonium Project Report*. Compton was advised that expert analysis of the German *Kernphysikalische Forschungsberichte* — the *Nuclear Physics Research Reports* circulated by Schumann, Esau and Gerlach — showed that the publication of the American volumes would reveal few secrets not already unraveled by the Germans.

The two scientists posed and answered a number of questions. Did the Germans know the correct lattice dimensions for a heavy-water/uranium system? "The answer is an unequivocal yes." In December 1943, Bothe and Fünfer had reported on their experiments on various lattice arrangements measuring the strength of a neutron source with and without the uranium lattice in place; the Germans' main conclusion had been that "a combination of 20 centimeters of heavy water and one centimeter of uranium metal, density 18, is the most favorable." The American physicists remarked: "This conclusion is exactly the same as that reached by us on the basis of calculations in August 1943 (CP-923)." So the German work had been performed, they said, at the same time as theirs.

* Dr. Alvin M. Weinberg and Dr. Lothar W. Nordheim. The former is now Director of Oak Ridge National Laboratory, Tennessee. The author questioned him on the history and motivation of his report to Compton, and was told that he would not modify his opinion of the German project's 1945 status even now.

Further, the Americans noted the repeated German references to the need for about four tons of heavy water for the reactor to go critical: "this figure is essentially correct." The German uranium metal — "and this is important" — was about as pure as that used by the Americans. And the German theorists had introduced the same mathematical system, the "group model reflector calculations," early in 1944, not much after the American scientists had independently done so. Why then had they not succeeded in establishing a chain reaction with heavy water ("Product 9")? "The answer is simple: they did not have sufficient P-9." In short, the Germans' understanding of the principles was "comparable" to that of the Americans. The only important secrets apparently unknown to the Germans were the poisoning of the chain reaction by the fission-product xenon-135 and the properties of plutonium-240.

In conclusion, the two scientists suggested that the *Alsos* mission's capture of the German documents raised a question of ethics. The research papers often contained useful information, and it would not be proper for American authors to be given credit for certain results without credit being given also to their German counterparts who had independently reached the same conclusion. It was not enough to state that the German uranium project was on the right track: "their thinking and development paralleled ours to a surprising extent." The astonishing fact remained, they pointed out, that a small, independent group of enemy scientists had achieved so much in face of such adversity.

There has been much loose criticism of the German nuclear research effort during the war, mostly stemming from an obvious ignorance, although some has come from informed sources who should have known better, and to whom the documents on which this account was based were certainly available. A clear distinction must be drawn, however, between the German achievement in the theoretical field, as stressed by the report discussed above, and the work on uranium reactor technology. In the latter, they were backward to an alarming degree, and the lack of provision of control and regulating mechanisms in their various piles, and the lack of adequate instrumentation, has already been commented upon. The theory of cadmium-sheathed control rods was given not even a cursory numerical treatment. There was not even some simple provision for draining the heavy water quickly through an outlet in the bottom of the vessel, should the reaction have got out of hand. Had the Haigerloch pile reached criticality,* the Germans would have encountered the same unexpected difficulty in shutting it down as did the Americans when their heavy-water pile first went critical in the middle of 1944. Nor had the Germans realized the importance of *delayed* neutrons as the factor in controlling atomic piles.

If one compares the parallel courses of German and Allied atomic research after the parting of the ways in 1939, it is clear that for both parties the turning point had come in 1942. Until then, both sides had covered much the same ground, except for Germany's lack of enthusiasm for devoting research effort to uranium-isotope separation. Indeed, the Germans were the first physicists in the world, with their Leipzig pile L-IV, to achieve a positive neutron production, in the first half of 1942. The Germans had failed to win the support of their government, which may well have felt that a country which had already swallowed most of Europe had no need for such abstruse research. The

* There is a belief that had the geometry of the Haigerloch pile been spherical, and not cylindrical, the materials available would have sufficed to produce a chain reaction.

Americans had thrown themselves wholeheartedly into the project even before the Fermi pile went critical in Chicago in December 1942, and invested a thousand times more effort in their Manhattan Project. After the middle of 1942, Germany virtually marked time until the end of the war, gaining in those three years knowledge that could have been won in as many months had the will been there. Dr. Diebner wrote: "In retrospect one can see that the feasibility of self-sustaining uranium piles had been proven in Germany by 1942, and that all our later experiments just went to confirm this view." Germany's nuclear scientists failed to win the confidence of their government and were left stranded on the shores of the atomic age.

Notes and Sources

AS THIS IS the first history to make extensive use of captured German records, it will be pertinent to describe the existing documentation, both used and unused, on the German atomic project.

There have been three brief published histories: Heisenberg's paper, *Über die Arbeiten zur technischen Ausnutzung der Atomkernenergie in Deutschland* (in *Naturwissenschaften*, Vol. 33, p. 325, 1947), is an accurate summary of the project as its participants viewed it in retrospect after the war; it was published in an abridged translation in *Nature*, Vol. 160, p. 211, 1947. Subsequently, the project's leading scientists wrote a series of papers for the FIAT *Review of German Science*, published in the series *Naturforschung und Medizin in Deutschland 1939-1946*, Volumes 13 and 14 (*Kernphysik und kosmische Strahlen*). Finally, Erich Bagge and Kurt Diebner published in *Von der Uranspaltung bis Calder Hall* (Rowohlt, Hamburg, 1957) a lengthy account, *Zur Entwicklung der Kernenergieverwertung in Deutschland*, based apparently on some of Professor Harteck's papers. The latter publication is notable for its quotations from Bagge's diary (although the published version differs from the original in some respects). In exploring his papers, we even found a wartime diary he had forgotten he had kept; and the same happened with Professor Gerlach in Munich, whose papers yielded three diaries, much to his own surprise. One final publication must be referred to: in 1956, Diebner, under the nom de plume Werner Tautorus, published in *Atomkernenergie*, pp. 368-70 and 423-25, a catalogue of 228 of the German wartime reports, giving their dates. This suggested that Diebner must somewhere have had a collection of wartime documents; but he died in 1964 soon after I first entered into correspondence with him, and my search of his files in Flensburg failed to bring anything to light. I did manage to locate an important 1939-42 file of Professor Harteck's in Kiel and there is believed to be a further important Harteck file (1942-45) at his old Hamburg institute.

The German records captured by the *Alsos* mission were first placed in the files of the Manhattan Project. When the U.S. Atomic Energy Commission succeeded it in 1946, the *Alsos* files were split up among three agencies — the USAEC, the Defense Atomic Support Agency, and the Central Intelligence Agency. In practice, the bulk of the *Alsos* files was retired to archives either at Oak Ridge, Tennessee (the USAEC Technical Information Service), or at Alexandria, Virginia (Military Records Center). Copies of some interim *Alsos* Intelligence reports (1944) are at the Office of the Adjutant General, Washington; the mission's administrative records are in OSRD records in the National Archives, Washington; and *Alsos* mission reports for September and October 1944 are in the USSBS records at the National Archives, under catalogue number 2.a. (envelope 158).

I have made use of the entire series of German papers at Oak Ridge. The 394 German ("G-series") nuclear research items are catalogued and summarized in an excellent USAEC finding-aid, TID-3030, titled *German Reports on Atomic Energy*, which has now been declassified. I have given here the G-serial number of the report where a copy is held at Oak Ridge.

The remaining captured German files, including most of the non-technical and political files, were distributed between the two other agencies; these included all of Gerlach's files and 29 important files of Harteck's. The records of the Reich Research Council (Mentzel and Osenberg) went to Alexandria, but only a few of Osenberg's files have been microfilmed and none of them relates to the atomic project. The files of Görnnert, head of Göring's private office, are similarly available on film but must have been stripped of all atomic research items before filming. (All of Esau's and Gerlach's reports are known to have been passed to Görnnert.) All the important German atomic files not at Oak Ridge are understood to be in the CIA archives, including the Strasbourg Report (now known as the "Goudsmit Book"). Fortunately Goudsmit still has several important files at Brookhaven National Laboratory, New York. There have been some Allied papers which I should have liked to see. Most important, perhaps, would have been the daily transcripts of the conversation of the German scientists interned in 1945 at Farm Hall; the British authorities are reluctant to admit that the transcripts even exist. As the German scientists concerned feel that they have been mistranslated and quoted out of context, I considered it important to see the transcripts, but the request was refused by the authorities, who declined also to state any cause for their refusal. This seems to have been one of the difficulties confronting Mrs. Margaret Gowing, who had hoped to include a chapter on the German atomic project in her official history, *Britain and Atomic Energy 1939-1945* (Macmillan, 1964), but was "unable to trace" the necessary papers. The British refusal to disclose these transcripts is all the more irritating since General Leslie R. Groves quoted extensively from them in his book *Now It Can Be Told* (Harper & Brothers, 1962) and Goudsmit, by now a private American citizen, was allowed to see the original English transcripts at the Military Records Center, Alexandria, Virginia, in April 1963. In general, the British files contain little on German atomic research, with some minor exceptions in the Milch Documents.

1. Solstice

The BBC provided me with copies of the newsreaders' scripts of August 6, 1945. The description of Hahn's discovery of nuclear fission is based on my interviews with Hahn, Strassmann and others. The 1938 and 1939 papers I used have been catalogued in *Review of Modern Physics*, Vol. 12, p. 1 (1940). In addition, I used Lise Meitner's paper in the *International Atomic Energy Bulletin*, December 2, 1962, and Otto Frisch's paper in *British Journal of Applied Physics*, Vol. 5, p. 81 (1954). Hahn provided copies of his private diaries and his dramatic correspondence with Frau Meitner. The description of the Washington conference was given by a letter in *Physical Review*, Vol. 55, p. 416 (1939); *The Times* item was published on February 1, 1939.

2. A Letter to the War Office

The April 1939 meeting in Göttingen was described by Mattauch and Hanle; the subsequent meeting in Berlin is described by Esau in a letter written on October 13, 1939, apparently to General Becker. British reactions to the French physicists' letter can be found in *Sunday Express*, April 30, 1939; Gowing, *op. cit.*, p. 35, and Clark, Tizard, p. 184. Mr. Churchill's letter is published in *The Second World War*, Vol. 1, pp. 344-45. Flügge's important article was printed in *Naturwissenschaften*, Vol. 27, p. 402 (1939) (G-5). Rosbaud's attempts to inform London of developments in Berlin were described by him in a report to the *Alsos* mission, August 5, 1945. Much of the detail about Diebner came to me from his wartime assistant, the late Dr. Friedrich Berkei, who died in East Germany in September 1966. The censored article on atomic research can be found on NARS microfilm T-77, roll 1,001.

Further information came from conversations with Harteck (Troy, New York), Bagge (Kiel), Heisenberg, Riehl (Munich) and von Weizsäcker (Hamburg). Heisenberg's first report (December 1939) is G-39. Heavy-water production techniques are described from interviews with Alf H. Larsen, Rjukan, K. Wirtz's 1942 paper, *Die elektrolytische Schwerwassergewinnung in Norwegen* (G-198) and Harteck's December 1941 paper *Die Produktion von schwerem Wasser* (G-86). See also *Norsk-Hydro 1905-1955* (published by Norsk-Hydro Kvaelstofaktieselskab in Oslo, 1955). Work on the Clusius-Dickel process is described from Harteck's papers, and from a 1940 report by Clusius (G-18).

3. The Plutonium Alternative

Bothe's first measurement of slow-neutron diffusion lengths for carbon is reported by G-12; Heisenberg's measurement for heavy water is in G-23, and for uranium oxide is in G-22. The February 1940 calculation of pile size is in G-60. Heisenberg's mathematical analysis of uranium piles is report G-40. His exchange with Harteck about heavy-water production is in the Harteck papers.

The dry-ice pile in Hamburg is described in the Harteck papers, and by Harteck himself in talks with me; Harteck, H. Jensen, Knauer and Suess wrote a report on it (G-36). The quotation from Harteck on Norwegian heavy-water supplies is from his 1944 *Bericht über den Stand der SH.200 Gewinnung* (G-262).

The quotation from Groves is from p. 5 of his book; he makes no mention here of Hahn and Strassmann as the real discoverers of nuclear fission. The Smyth *Report*, pp. 14-15, is similarly ungenerous. The two Frisch-Peierls memoranda are reproduced in Gowing, *op. cit.*, pp. 389-93, and Clark, *op. cit.*, pp. 214-17, respectively. Von Weizsäcker's paper referring to the possibility of extracting plutonium is G-59; the Schintlmeister and Hernegger paper is G-55. The various reports describing attempts to use the Nernst law are G-18, G-19, G-20 and G-27. Bagge's paper, *Ein rasch arbeitendes Verfahren zur Entmischung von Isotopen*, dated November 24, 1940, is not in the Oak Ridge files, but I obtained a copy from Bagge. Martin described his work on centrifuges in a letter to the Allied military government in Kiel, May 16, 1945. The information on von Ardenne's work came from von Ardenne, who also sent me a copy of his unpublished memoirs. Von Droste's Berlin experiment is reported in G-24. The Virus House is described in Heisenberg's report on the Berlin experiments, G-93. The first Leipzig experiments were reported by the Döpels and Heisenberg in G-74.

The passage describing uranium processing is based on BIOS Final Report No. 675, SECRET, The Production of Thorium and Uranium in Germany; a report by *Degussa*'s Frankfurt plant manager, Dr. Völkel, entitled *Herstellung von Uran bei der Degussa* (G-324); and on the report on *Degussa*'s Rare Metals Division in BIOS Final Report No. 423. Further information was supplied by Riehl and Ihwe.

4. An Error of Consequence

Bothe's (wrong) measurement of graphite's nuclear constants was reported by him in G-17 (cf. *Zeitschrift für Physik*, Vol. 122, pp. 749-55, 1944).

The failure of the Clusius-Dickel process was admitted by Harteck and Jensen in G-89 and reviewed by Groth and Suess in G-83 and by Groth in G-147. Waldmann suggested that the hexafluoride decomposed in G-120, and the properties of the pentachloride were investigated by Martin and Eldau in G-108. Fleischmann's experiment was reported in G-28, and Clusius and Maierhauser reviewed their isotope separation work in G-73. Professor Harteck's report to the War Office is in the Harteck Papers; that the "special applications" he was referring to were atomic explosives was confirmed personally to me. The principle of the "isotope sluice" (*Isotopenschleuse*) was first described by O. Stern in *Zeitschrift für Physik*, Vol. 2, p. 49 (1920). Further detail came from Bagge's private diary and conversations with him in Kiel. J. W. Beams had used his 1938 ultracentrifuge to enrich chlorine gas. General information on the German adaptation of this came from interviews with Groth and Harteck; from Clusius's lecture on May 6, 1943 (G-323); and from Harteck's paper on isotope separation in the FIAT *Review*. Groth also provided a copy of his laboratory diary; in about December 1941 he wrote a progress report on the ultracentrifuge work (G-82), and in the Harteck papers there is a useful letter to the War Office, dated November 1, 1941. See also the monograph by Beyerle, Groth, Harteck and Jensen, *Über Gaszentrifugen* (Verlag Chemie GMBH, 1949). *Alsos* reports G-83, G-95 and G-88 also review the work at this stage.

Houtermans's sojourn in Russia is described by Jungk, *Brighter Than a Thousand Suns*, and by Houtermans in letters to Blackett and Joliot, April 1945. Further information is from von Ardenne. Houtermans's important paper, *Zur Frage der Auslösung von Kernhettenreaktionen* appears in two versions: one dated August 1941 (G-94), and the second, slightly revised by Houtermans, August 1944 (G-267). Jungk suggests that Houtermans voluntarily withheld circulation of this paper on moral grounds, but according to Heisenberg and others it was in fact circulated at the time. Flügge's September 1942 paper was G-142. Jentschke and Lintner put the fast-neutron fission cross-section of uranium-235 at $7 \pm 0.5 \quad 10^{24}$ cm^2 in their 1943 paper *Schnelle Neutronen in Uran* (G-227). The Volz and Haxel paper was G-118. Schintlmeister's proof that the new element was element 94 is given in G-111.

The second uranium-oxide pile experiment was described by Heisenberg and Döpel in G-75. The visit by Heisenberg to Bohr is the subject of some uncertainty, as we have only Heisenberg's version of what was discussed. Margaret Gowing obtained a second-hand account of the Copenhagen talks from Bohr's son, Professor Aage Bohr. I have based my description on the version given by Heisenberg in a letter to B. L. van de Waerden, April 28, 1948.

5. Item Sixteen on a Long Agenda

The initial quotation is from a speech by Speer, April 17, 1942 (NARS microfilm T-175, roll 125). Further information came from the late Karl-Otto Saur, Munich. Schumann's December 5, 1941 letter to the institutes is in the Harteck Papers. General information on the change in direction of the project is from Esau's introductory speech to the German Aeronautical Academy, May 6, 1943 (G-323). The photo-materials shortage was referred to in a War Office letter to Hahn (G-374). Schumann's letters about the War Office's second research conference are in the Harteck Papers, including the agenda illustrated. Himmler's reply to Rust's invitation is in the Goudsmit Papers, and the carbon copy is in the Himmler files as is the agenda of the *scientific* conference (NARS microfilm T-175, roll 125). Keitel's and Raeder's replies are also in the Goudsmit papers. Heisenberg's lecture on February 26, 1942, is to be found, misfiled, in G-323. The episode with "Herr Eckart" was witnessed by Bagge. Döpel's report on *L-III* was G-373. I have not been able to locate a copy of the War Office report on the conference, but it was quoted by Bagge and Diebner in their book, pp. 30-32 and 39, where it is cited as *Tagungsbericht für die wissenschaftliche Tagung der Arbeitsgemeinschaft Kernphysik vom 26.2 bis 28.2.1942*. The complete set of the papers that were read to the conference is G-310. Otto Hahn's comments were made in his private diary; Heisenberg's later statement was quoted by Groves, *op. cit.*, p. 335.

Further heavy-water production difficulties are described from Norsk-Hydro files; from two reports by Harteck — G-86, dated December 1941, and G-262, dated April 15, 1944 — and from information from Professor Brun, who with Professor Wirtz also described to me the visit to Berlin. Reports G-154 and G-160 refer to heavy-water production in Germany. The minutes of the November 22, 1941, conference on the Clusius–Linde process were found in the Harteck Papers. Harteck's recommendation on Såheim was in a letter to the War Office, March 23, 1942. The Harteck Papers hold several items on the construction of heavy-water plants in Germany, including much correspondence between Harteck, Herold and Bütefisch. Detailed information on Vemork's heavy-water output was obtained from *Månedsrapport for drift av Vannstoffabrikken Vemork*, the monthly reports in the Norsk-Hydro files.

Walcher described his mass spectroscope in G-196; Ewald described his work in G-139. Von Ardenne's paper, *Über einen neuen magnetischen Isotopentrenner für hohen Massentransport* (April 1942) is not in the Oak Ridge files; he sent me it. Two uranium accidents were reported by R. Döpel in G-135. The crucial experiment *L-IV* was described by Heisenberg and the Döpels in G-136, *Der experimentelle Nachweis der effektiven Neutronenvermehrung in einem Kugelschichtensystem aus D_2O und Uranmetall* (July 1942).

The important conference in the Harnack building was probably not on June 6, 1942 as Heisenberg stated in *Naturwissenschaften*. Otto Hahn's diary records it on June 4, 1942, and this is supported by Telschow, the then secretary of the Kaiser-Wilhelm Foundation. (Milch's private diary notes the conference on June 5, 1942.) My description of the conference is based on conversations with Heisenberg and Saur, information from Thiessen (East Berlin) Telschow, Hahn, Harteck and letters from Heisenberg to Goudsmit (January 6, 1948 and October 3, 1948) and to B. L. van de Waerden (April 28, 1948), in which latter Heisenberg made the comment attributed to him here. Speer's note on his talk with Hitler is in document FD.3353/45. The confrontation between Riehl and Döpel in Moscow was related to me by Riehl himself.

6. Freshman

Hitler's decree setting up the new *Reichsforschungsrat* is in the Saur Documents, p. 6042; it was published in the *Reichsgesetzblatt*, June 15, 1942. For an excellent general history see *Alsos* Report Vdk/339, "Research under the *Reichsforschungsrat*," September 28, 1945. The extracts from the July 6, 1942, conference are from the verbatim record (pp. 3640–14, Volume 58, Milch Documents). The June 1942 material on ultracentrifuge work is based on Groth's laboratory diary and reports G-146, G-149 and G-158, and a letter from Harteck to the War Office, June 26, 1942, in the Harteck Papers. Esau's report to Göring was on November 24, 1942. Groth went to Sweden in November 1942 to discuss the design of the planned German uranium-235 enrichment plant with ultracentrifuge experts at the University of Uppsala, Professor Theodor Svedberg and Dr. Kai O. Pedersen, the authors of a standard work, *The Ultracentrifuge*, published in 1940. Svedberg and Pedersen advised Groth on the layout, mounting and lubrication of multiple-centrifuge installations, and showed him over their own laboratories. Groth wrote a long report on this for the War Office on December 12, 1940. I asked Pedersen and Svedberg about this episode, but they declined to comment. The report on the mid-July Berlin conference is in the Harteck Papers, dated July 16, 1942. Harteck's objections to the Clusius–Linde process were outlined in G-155. The report on the July 24 and 25, 1942, conferences at Rjukan is in Norsk-Hydro files; the three reports by Brun and Suess were G-337, G-338, G-339.

Mr. W. Akers's letter to Lord Cherwell, reporting Heisenberg's work, is in the Cherwell Papers. The general background to the Intelligence operations and the Special Operations Executive's work in Norway was obtained from a monograph on the subject, *The Heavy-Water Operations in Norway 1942–1944*, compiled by Colonel J. S. Wilson, head of SOE's wartime Norwegian section; it quoted lengthy extracts from operation reports and diaries. I was also able to discuss the operations with Major-General Sir C. M. Gubbins and Colonel Wilson. Brun's escape to London was related to me by Professor Brun himself; see also *Norsk-Hydro 1905–1955*, p. 417. For an official version of the *Freshman* operation, see *By Air to Battle — The Official Account of the British Airborne Divisions* (HMSO, 1945). The execution of the *Freshman* troops was the subject of Nuremberg exhibit US-545. General Rediess's telegram from Oslo was forwarded by *RSHA IV* (Müller) to Himmler at the latter's *Feldkommandostelle*. It is in the Himmler files (NARS microcopy T-175). General Rediess's warning to Berlin of the "importance" of the operations is quoted from his office's *Meldungen aus Norwegen Nr. 49*, dated Oslo, December 15, 1942; these periodic situation-reports are an invaluable source of information on

German counter-SOE operations. (Himmler files.) The report in *The Times* was published on December 24, 1942.

8. An Unexpected Result

Wirtz reported his visit to Rjukan, which lasted from November 13 to 15, 1942, in G-201. Wirtz's report on sources of heavy water was *Zusammenstellung von Wasserelektrolyseuren*, November 24, 1942 (Harteck Papers). Esau's lack of confidence in nuclear research was recounted to me by Harteck personally. Details of the War Office's dropping of the project are in a letter from Schumann to Mentzel, March 31, 1943, and a letter from Mentzel to Esau; further information came from Berkei. Information on the 1943 nuclear research budget is derived from Esau's second 1943 progress report, *Bericht über den Stand der Arbeiten auf dem Gebiet der Kernphysik, 31.12.1943*, written in July 1944; and from a letter from Esau to Mentzel, re: *Antrag auf Forschungsetat für das Rechnungsjahr 1943/44*, dated April 5, 1943 (Goudsmit Papers).

The five speeches at the May 6, 1943 conference were contained in the printed report: *Gkdos. Schriften der Deutschen Akademie der Luftfahrtforschung. Probleme der Kernphysik. Berlin* (G-323). The report is well printed, with many excellent illustrations; there is a poorly legible typescript copy in British official archives, reference FD.2859/48. Ronald Clark, *The Birth of the Bomb*, p. 148, quoted the brief British summary, not the report itself. A curious feature is that Esau's introductory speech reappears word for word as his mid-1943 progress report to Göring: *Bericht über den Stand der Arbeiten auf dem Gebiet der Kernphysik am 1.7.1943*.

The description of the "heavy-ice" pile *G-11* built by Diebner is based on a progress report written by Diebner, Hartwig, Herrmann, Westmayer, Czulius, Berkei and Höcker in April 1943 (G-211), and on their final report, *Bericht über einen Versuch mit Würfeln aus Uranmetall und schwerem Eis*, July 1943 (G-212). The Diebner quotation is from *Von der Uranspaltung bis Calder Hall*, p. 41. Heisenberg's comments were in his speech at the conference mentioned above (G-323). Ramsauer's speech on the status of German physics was to the same body: *Über Leistung und Organisation der angelsächsischen Physik*. Given on April 2, 1943, his speech demonstrated that German physics had declined in both quantity and quality of output: not only were progressively fewer German physics papers published, but — and this was the unkindest cut — progressively fewer German physics papers were being *cited* by later workers on the same subject. Further information on the later May 6, 1943 conference was supplied to me by the Academy's Chancellor, Dr. Adolf Baeumker himself.

The dispute over Einstein is illustrated in correspondence between Mentzel, von Laue and von Weizsäcker (Goudsmit Papers). See also Goudsmit, *Alsos*, pp. 152–54. The file relating to Harteck's troubles with the SS is in the Goudsmit Papers. The department head concerned, Professor Koch, committed suicide after the war according to Jungk. The material on Osenberg comes from *Alsos* report Vdk/339. Osenberg wrote two memoranda of immediate interest, *Allgemein verständliche Grundlagen zur Kernphysik*, May 8, 1943; and that quoted, *Uranbomben* (both in Goudsmit Papers); further information came from Albers.

The communications between Bohr and the British authorities are described in Gowing, *op. cit.*, pp. 246–47. Further information comes from Michael Perrin and the Cherwell Papers. The strained relations inside the Intelligence services are described by Professor Norman. Additional information was derived from a report by Brun on Tronstad, an interview with Goudsmit (particularly about Rosbaud), and from Rosbaud's August 5, 1945 report for the *Alsos* mission. The radioactive poison-gas possibility was investigated by Dr. James B. Conant, "Preliminary Statement Concerning the Probability of the Use of Radioactive Material in Warfare," July 1, 1943. Anderson's subsequent conversation with Dr. Conant is reported in the Cherwell Papers. For German work on genetic effects of radiation, see G-374 ("Miscellaneous German Correspondence on Biological Effects of Radiation, 1944–45") which contains the Rajewsky letter quoted, dated April 9, 1944.

The security-police morale report is in a file of *Meldungen aus dem Reich*, at the Bundesarchiv, Koblenz.

Heavy-water production difficulties in mid-1943 are described from the Norsk-Hydro files; from *Norsk-Hydro*, p. 417; and from Harteck's 1944 report G-262. Material on the arrest of former Norwegian officers is in the German Foreign Office archives and in *Meldungen aus Norwegen* in the Himmler files.

The progress made with the "isotope sluice" is described from Bagge's diary entries of June 28 and August 5, 1943, and on his report on first experiments with it using silver (G-202). The mid-October conference agenda, *Geheim-Vorläufige Vortragsfolge, Kernphysikalische Tagung 1943, 14–16.10.1943* is in the Goudsmit Papers. There is a description of the conference in Fleischmann's diary (G-346) and Bagge's diary, October 14, 1943. The important Fünfer and Bothe experiments, *Schichtenversuche mit systematischer Variation der U- und D_2O-Dicken*, is G-206; the Pose and Rexer report is G-240. Heisenberg's conversation with Harteck was related by the latter to me, and not disputed by the former. There is information about heavy-water and uranium production in Beuthe's report, *Bericht über*

Sitzungen, Tagungen und Besprechungen im November 1943, in the Goudsmit Papers.

Diebner's third pile experiment, *G-III*, at Gottow, was reported in: Diebner, Czulius, Herrmann, Hartwig, Berkei, Kamin, *Über die Neutronenvermehrung einer Anordnung aus Uranwüfeln und schwerem Wasser*, early 1944 (G-210). The report was published, slightly abridged but with all the photographs, in *Atomkernenergie*, 1956, pp. 256–65.

The description of Bohr's escape is based on Gowing, *op. cit.*, p. 249. General German details are found on Nuremberg microfilm B-259. Further information came from Heisenberg. The description of the USAAF attack on Vemork is based on Groves, *op. cit.*, p. 189; *Heavy Water Operations*, p. 27; Jablonski, *Flying Fortress*, p. 204; *Norsk-Hydro*, p. 418; and Esau's progress report for last half of 1943 (Goudsmit Papers). For the general results of the attack, see Speer file 5338/1945. Further information came from Berkei, Larsen, and a letter from Esau to Mentzel dated November 19, 1943, re: *Festlegung von Haushaltsmitteln* (Goudsmit Papers). The dissension between the Allied and Norwegian governments is recounted in *Norsk-Hydro*, pp. 414 and 419. The report on the full-scale Leuna heavy-water plant costs is G-237; associated reports are G-224 and G-235. Further information on the Geib process derived from talks with Harteck. The scarcity of heavy water can be judged from a passage in G-210, the report on pile *G-III*. Discussing the need to eliminate sources of error, it said that experimental confirmation of the error theories would follow "as soon as the necessary heavy water, which is at present being used elsewhere, is available again." Uranium production figures are from BIOS Final Report No. 675 and G-324.

The description of Gerlach's replacement of Esau is based on interviews with Gerlach in Munich, on his 1943 and 1944 diary, and on correspondence between Esau, Mentzel, Görnnert (chief of Göring's private office), Goerner (chief of Speer's private office) and Speer in November and December 1943 (Goudsmit Papers). References to Gerlach's torpedo work are in Himmler's files.

Details of the heavy-water consignment are from *Tungtvann ombord i D/F Hydro ved senkingen 20.2.1944* (Norsk-Hydro Papers); further information is from an interview with Czulius in Erlangen. The SOE attack on the ferry is based on information from *Heavy Water Operations* and on interviews with Haukelid, Larsen, Colonel J. S. Wilson and Michael Perrin. The German security measures were described in a speech by Rediess at the end of 1943 (Himmler files), and from the records of the German 20th Army in Norway, NARS microcopy T-312. The figures for casualties quoted in my footnote are the best available. They come from the files of the German 20th Army in Norway, in report: *Wehrmachtbefehlshaber Norwegen Ic. Nr. 1185/45 geh. v. 22.2.1944. Ic-Lagebericht für die Woche vom 15–20.2.1944 (Nr. 8)* (NARS microfilm T-312). The SOE operation was the subject of a German report, "The Sinking of the Norsk-Hydro Ferry"; but this report now rests in the CIA archives. The 1945 Rediess speech is again an invaluable source of information on SOE in Norway; it makes gruesome reading (NARS microfilm T-175). The final quotation, from Dr. Diebner, is from *Von der Uranspaltung bis Calder Hall*, pp. 35–36.

9. The Cynic in Command

The 1944 consignments of very-low-concentration heavy water are recorded in *Forsendelse av D2O-holdig elektrolytt (kalilut) til Tyskland efter senkingen av D/F Hydro* (Norsk-Hydro papers). The heavy-water production figures given in the footnote are based on Norsk-Hydro's files. There is a slight discrepancy between the monthly figures of December 1942 through May 1943 and the annual total 1942/43.

The German thermonuclear fusion experiments are reported in: Herrmann, Hartwig, Rackwitz, Trinks and Schaub, *Versuche über die Einleitung von Kernkettenreaktionen durch die Wirkung explodierender Stoffe*, 1944 (G-303). There is mention in one source of an obviously related report by Diebner, Sachsse, and others, *Versuche zur Auslösung von D-D-Reaktionen mit Hilfe von konvergenten Detonationsstosswellen*, but it is not at Oak Ridge, and a search of Diebner's papers failed to bring it to light. Sachsse and Trinks, interviewed at the West German Defense Ministry, Bad Godesberg, confirmed to me that such a report was written. Diebner's review of the experiments, *Fusionsprozesse mit Hilfe konvergenter Stosswellen*, was published in *Kerntechnik*, March 1962, pp. 89–93. The introductory quotation from Gerlach was in his *Bericht über die Arbeiten auf kernphysikalischem Gebiet, 1.2–31.3.1944* (Goudsmit Papers); he has confirmed that he was alluding to these fusion experiments. G. Guderley's important paper, *Starke kugelige und zylindrische Verdichtungsstösse in der Nahe des Kugelmittelpunktes bzw. der Zylinderachse*, was published in *Zeitschrift für Luftfahrtforschung*, Vol. 19, pp. 302–312 (1942). F. Hund's paper was *Materie unter sehr hohen Drucken*, published in *Erg.d. exakt. Naturw. XV* (1936). Further information came from Haxel and Bagge.

In connection with the altered dates on Gerlach's report, Gerlach admits that the handwriting is his; but somebody else has also altered the date on Esau's last report from December 31, 1943 to March 31, 1944 — three months after Esau had been dismissed. This complicates the work of the historian to whom dates are of the essence. The nocturnal visit by the SS officers was related to me by Gerlach — before I found among *Alsos* records the 1945 statement he had made to the same effect.

The description of early American Intelligence work, and the *Alsos* mission in Italy, is based on Groves, *op. cit.*, p. 189 *et seq.*; on Thiesmayer and Burchard, *Combat Scientists*, p. 164; on the *Report* by S. A. Goudsmit, as Scientific Chief of the *Alsos* mission, December 7, 1945; and in particular on the secret *Alsos Mission* [to Italy] *Report*, dated March 4, 1944, and its appendix, *Log of Alsos Mission, 14.2.1943–22.4.1944*. The renewed anxieties about German radioactive poisons are described from the Cherwell papers and from Gowing, *op. cit.*, p. 367. Schiebold's lecture, mentioned in the footnote, is report G-284. Further matter comes from General L. R. Groves and his book, *Now It Can Be Told*, p. 199. The final quotation is from an unpublished minute from Anderson to Churchill.

The fact that the Germans suspected the Allies had dropped thermonuclear fusion bombs on Berlin is derived from Gerlach's May 1944 report, and from interviews with him, with Heisenberg, and with Wirtz; and also from the interrogation of Geist mentioned in a footnote, "German knowledge of atomic experiments" (Special Interrogation Brief), File No. 140, dated September 26, 1945, Counterintelligence Branch, Kransberg. Professor Harteck's mid-April 1944 report on heavy-water production dated April 15, 1944 is G-262; its appendices have been misfiled in G-268.

The construction of the underground bunker laboratory at Dahlem is described by Heisenberg and Wirtz in FIAT *Review of German Science*. The quotation about how it looked in 1945 is from Goudsmit, *Alsos*, pp. 125–27. That Vögler was disappointed at Heisenberg's progress was evident from a letter from Vögler to Gerlach, summarized by Goudsmit on May 30, 1945. Details of work on the isotope sluice are from Bagge's diary, May 2 to

September 11, 1944. Information on electromagnetic separators came from Professor Manfred von Ardenne. Hitler's remarks to Mussolini and Miklos, the "visiting foreign statesman," are in the German Foreign Office archives. Information on Haigerloch is from an interview with Gerlach. The Haigerloch acquisition is dealt with in Gerlach's notebook, July–October 1944. The information on the evacuation of ultracentrifuge research to Kandern is from G-330.

For details of I. G. Farben's heavy-water patents wrangle, see G-268, and the Harteck Papers, which contain a note on a Diebner conference of April 30, 1942. The Bütefisch remarks were reported to me personally by Harteck. Goudsmit wrote in an official letter in 1947, "After the sabotage and the bombing, they built a heavy-water plant at Leuna in Germany, but so far as I know it never really started production. The manufacturers were afraid that the heavy-water plant would attract N.S. bombers and as the same plant made synthetic gasoline and other essential war products they wanted to avoid this. The plant in Norway produced ammonia as well as heavy water. The Germans were afraid that rebuilding the heavy-water plant in Norway might eventually cause bombing of the vital ammonia plant" (letter to Lt. Cdr. James D. Roche, U.S. Navy Department, May 20, 1947). Heisenberg recounted the Hans Frank episode to me personally; the Brauchitsch episode he described in a letter to *Physikalische Blätter*, May 1964. The Transozean agency report was published in *Physikalische Blätter*, August 1944. The very interesting fragment of Hitler's conversation with Antonescu is in the German Foreign Office archives.

10. The Alsos *Mission Strikes*

General information on the second *Alsos* mission is from General Groves and his book, *Now It Can Be Told*, from *Combat Scientists*, from Goudsmit's *Report* dated December 7, 1945, and from conversations with Goudsmit himself. Goudsmit's book, *Alsos*, was also employed. His letter about German physicists was to L. A. DuBridge, head of the Radiation (i.e., Radar) Laboratory, June 25, 1943. The rumor about the Leipzig explosion is referred to in Goudsmit's letter to Furman, May 22, 1945.

The "oil-shale scare" is described from interviews with Jones and Kendall, the latter in Toronto. There is reference in several A.D.I.(K.) reports to the search for unexplained German electric power requirements. The letter from Cherwell to Churchill is in the Cherwell Papers; further details were provided by Cecil.

The thorium scare is described in *Alsos* and by Goudsmit; Riehl gave me the real background to the thorium purchases, which were confirmed to me by Ihwe. The Doramad toothpaste advertisement text is from an actual advertisement in a prewar German journal. Reich Research Council and Osenberg information is from Osenberg's papers and from *Alsos* report Vdk/339; further, from FIAT report, "German Academic Scientists and the War," August 28, 1945; and from A.D.I.(K.) report 314/1945, "Research Organizations of the R.L.M." Bormann's September 3, 1944, decree, *Sicherstellung der für Forschungsaufgaben freigestellte Kräfte*, is among Osenberg's papers.

The evacuation of Kandern is described in G-330, and in an unidentified diary, G-355. Gerlach's letter to Bormann is from the Goudsmit papers; Clark, *The Birth of the Bomb*, quotes part of the letter without explaining the context in which it was written.

11. To the Brink of Criticality

The information on the planned uranium/carbon-dioxide pile is from an interview with Gerlach. His comment on "explosives physics" was at a conference between himself, Schumann and Mentzel on October 26, 1944 (Goudsmit Papers). Gerlach's foreword for the planned printed reports is G-244. The statistics in the report make it seem likely that it was written in the late summer of 1944. The pile *B-VII* is described from Bopp Bothe Fischer Fünfer Heisenberg Ritter, Wirtz *Bericht über einen Versuch mit 1,5 t D$_2$O und U und 40 cm Kohlenrückstreumantel*, January 3, 1945 (G-300). Harteck's 1945 visit to Rjukan was described by Goudsmit in a letter to Furman, May 25, 1945. Rosbaud reported his conversations with Gerlach very fully in a report for the *Alsos* mission, dated August 5, 1945. The evacuation of Berlin was described to me by Gerlach, Heisenberg, von Weizsäcker and Bopp.

The construction of the last heavy-water pile, *B-VIII*, was described by Heisenberg and Wirtz in their FIAT Review article, where they mentioned a report by Bopp, Fischer, Heisenberg, Wirtz, Jensen, and Ritter, *Bericht über den Versuch B-8 in Haigerloch*, of which there was no copy at Oak Ridge, however. Gerlach's last list of priority ratings was a letter re: *Notprogramm, Energiegewinnungsvorhaben*, dated February 26, 1945 (G-356). Gerlach's letter to the Weimar Food Office is in G-374. Information on the evacuation of Stadtilm is from Berkei, who lived there until his death in 1966, and from Graue and Gerlach's diary. Anderson's proposals to Churchill were touched upon in the Cherwell Papers. Wardenburg's letter to Goudsmit, April 12, 1945, is from the Goudsmit Papers. Anschütz's final tender, dated April 16, 1945, is in G-330. The British arrangements to join the *Alsos* mission were related by Cecil, Norman and Jones. Churchill's telegram to Eden is reproduced in Churchill, *The Second World War*, Vol. VI, p. 449. After the *Alsos* mission had left Hechingen, Bopp wrote *Bericht des Max-Planck Instituts über die Vorgänge nach der Besetzung*, June 3, 1945 (Goudsmit Papers). Further information on the closing days came from von Weizsäcker, Bopp and Heisenberg; from a letter Heisenberg wrote to Schumacher, May 6, 1945 (Goudsmit Papers); and from Bagge's diary. Hahn's letter to Clara Lieber was dated April 29, 1945 (Goudsmit Papers). The description of Gerlach's capture and the days preceding it are from his diary, which reverted to shorthand at this point, and from interviews with him. The May 2, 1945 letter from Cherwell to Churchill is in the Cherwell Papers.

12. The German Achievement

General Groves, *op. cit.*, p. 335, mentioned the rumors that the Germans were on the point of using the atomic bomb in April 1945. The remark by Geist was told me by his widow in Offenbach. For a typical Latin statement that the Hiroshima bomb was German, see *Pueblo*, Madrid, August 6, 1965: *La Bomba Atomica de Hiroshima era Alemana*. Speer's remarks were made during USSBS interrogation on May 21, 1945, reproduced on a NARS microfilm, and during the SHAEF interrogation of him on May 29, 1945, reported in USSBS files, Washington. The description of the June 1942 meeting between Speer, Heisenberg and von Weizsäcker was given me by Field-Marshal Erhard Milch; it confirms exactly the description given me earlier by the late Karl-Otto Saur, who recalled the bitterness with which Speer rounded on Vögler for having allowed his scientists to make such ridiculously small demands. The assessment of the German scientists' standpoint on the production of atomic bombs is based on talks with Heisenberg and von Weizsäcker, and on Heisenberg's correspondence with Bethe in 1964.

The *Das Reich* article about Esau was published on July 16, 1944. The Harteck remark was made in a lecture published in *Journal of Chemical Education*, Vol. 37, p. 462, September 1960.

Beams's report, "On the Use of the Centrifuge Method for the Concentration of U-235 by the Germans," was dated April 9, 1946 (G-344). Weinberg and Nordheim gave no title to their important three-page evaluation of German uranium pile research. Headed "Monsanto Chemical Company, Clinton Laboratories," it took the form of a memo to A. H. Compton, dated November 8, 1945. It is report G-371 at Oak Ridge.

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