The timelines of the U.S. and Soviet programs are remarkably similar, given that they happened at different times, in very different countries, and with different resources:

- The time from the critical catalyzing event to the first atomic bomb detonation was approximately 43.3 months for the U.S. program (7 December 1941 to 16 July 1945), and approximately 48.7 months for the Soviet program (6 and 9 August 1945 to 29 August 1949). If the United States benefitted significantly from information, materials, or personnel from the German program as some of the evidence in Section D.14 suggests, an unaided U.S. program would have required several more months and thus would have been even closer to the duration of the Soviet program.

- A fission reactor is a necessary step for a Pu-239 bomb program (unless a country resorts to accelerator-driven electronuclear breeding on a large scale); a fission reactor is optional (though potentially helpful) for a U-235 bomb program. The United States demonstrated its first fission reactor (Chicago Pile 1, or CP-1) on 2 December 1942, approximately 12 months after its critical catalyzing event. The Soviet Union demonstrated its first fission reactor (F-1) on 25 December 1946, approximately 16.5 months after its critical catalyzing event, or approximately 12 months after it was able to begin setting up its spoils from Germany (including at least 300 tons of German-produced uranium oxide, which fueled both F-1 and the larger second Soviet fission reactor).

- For both the U.S. and Soviet programs, significant quantities of Pu-239 were not available until just weeks prior to the first atomic bomb detonation, with a period of several years being required to build and test the infrastructure and equipment necessary to breed and purify Pu-239, and several months required to actually produce it. (An electronuclear breeding program would also require several years to build and operate enough particle accelerators to produce a sufficient quantity of Pu-239 or U-233 for a bomb.)

- For both the U.S. and Soviet programs, significant quantities of highly enriched U-235 were not available until just weeks or months prior to the first uranium bomb detonation, with a period of several years being required to build and test the infrastructure and equipment necessary to do high-level enrichment, and several months required to actually do the enrichment.

By comparison to the U.S. and Soviet programs, the timeline of the wartime German nuclear program is much less clear and much more controversial. Figure D.1025 shows the "minimalist" scenario for the German timeline, based on the widely held conventional historical view that relatively little of significance was accomplished during the program [Bernstein 2001; Cassidy 1992, 2009; Frank 1993; Goudsmit 1945, Goudsmit 1947; Groves 1962; Hentschel and Hentschel 1996; Hoffmann 2023; Irving 1967; Pash 1969; Powers 1993; Rose 1998; Schaaf 2001; von Schirach 2015; Walker 1989, 1995, 2020, 2024a, 2024b]. The minimalist scenario may or may not be the correct view of the actual historical events, but the basic details claimed for the program and its timeline have remained relatively fixed across a wide range of minimalist authors for 75+ years; thus at least in that sense, one may regard the minimalist scenario as fairly well documented and relatively well understood.

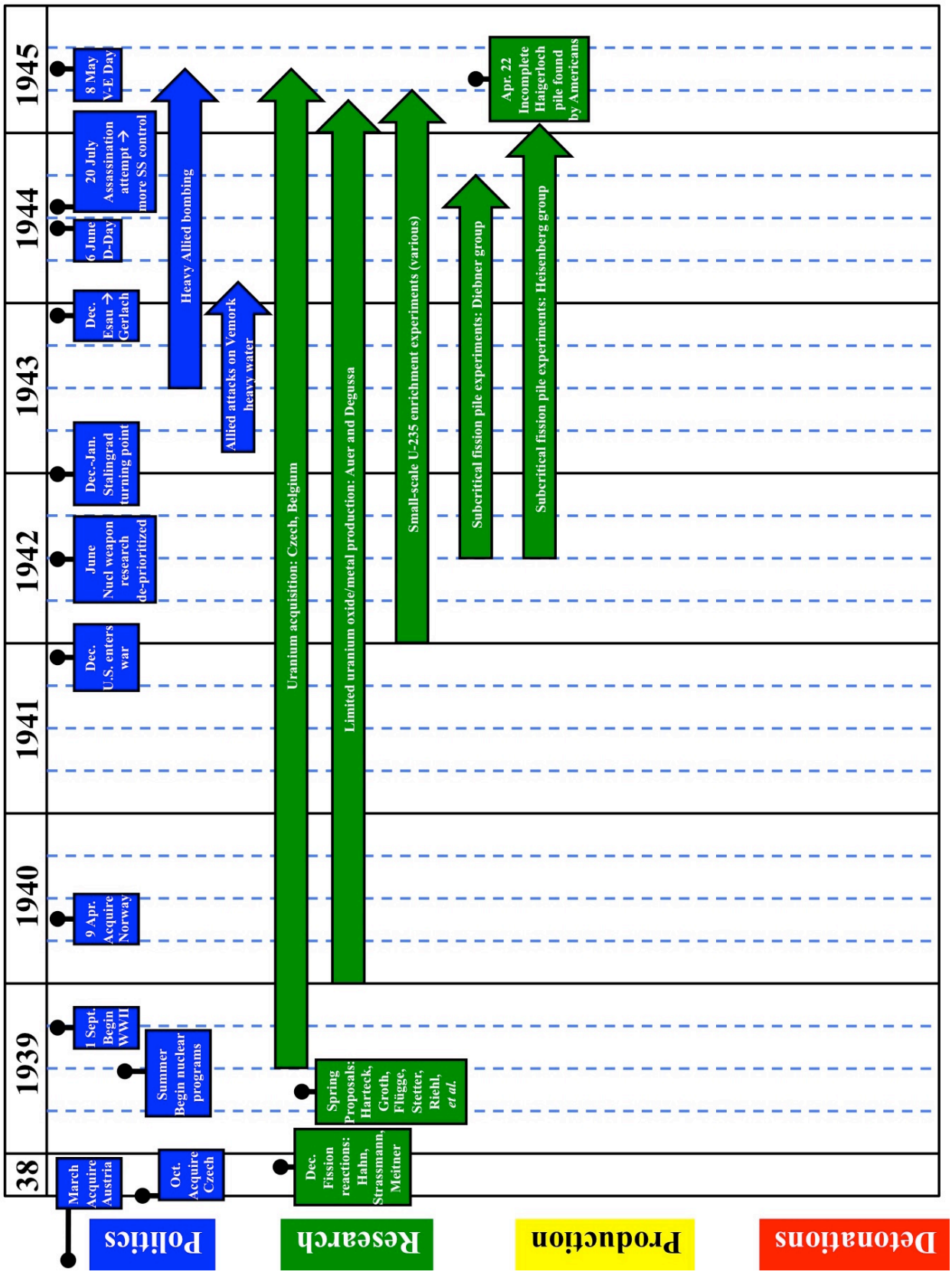

Figure D.1025: Timeline of the German nuclear weapons program, based on the minimalist scenario.

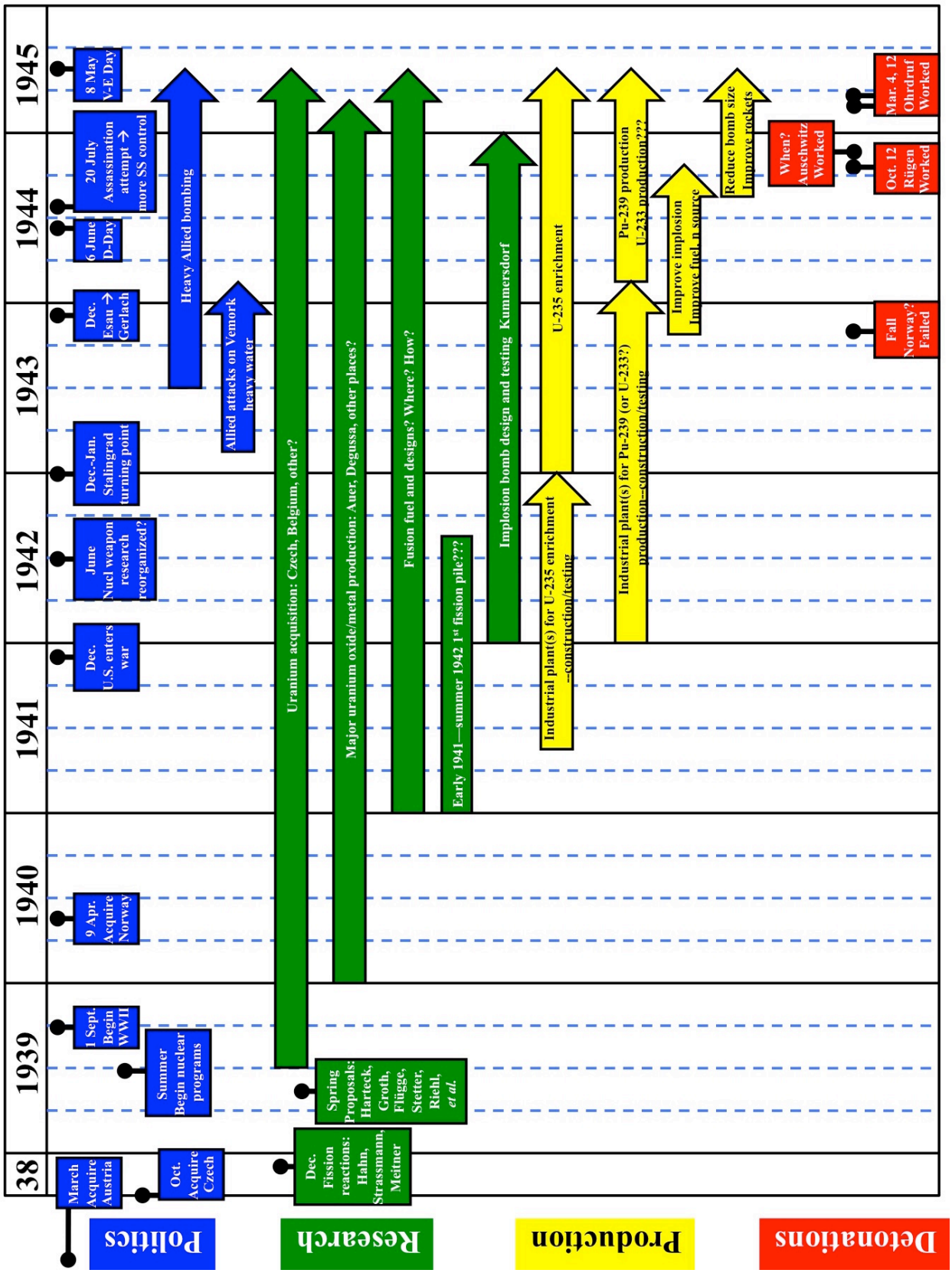

Figure D.1026: Timeline of the German nuclear weapons program, based on the maximalist scenario.

In stark contrast to the minimalist scenario, Fig. D.1026 shows the "maximalist" scenario for the German timeline, based largely on 2000–2002 interviews with Heinrich Himmler's chief adjutant Werner Grothmann, the source that both (a) made specific claims for the greatest amount of progress in the German nuclear program and (b) still had a plausible case for being historically well-informed. From p. 4436, the most profound claims made by Grothmann are that there was a failed nuclear weapons test in autumn 1943 in the North Sea, two successful tests in autumn 1944 (which could agree with the tests on the Baltic coast and in Poland that were reported by several other sources), and a test in March 1945 in Thuringia (or two tests, as reported by Ivan Ilyichev and Cläre Werner), and that Germany developed uranium bombs, plutonium bombs, and bombs apparently incorporating significant fusion reactions. As shown by the other documents quoted in this appendix, there is evidence from other sources that appears to support each of Grothmann's major claims. As was stated for the minimalist scenario, this maximalist scenario may or may not be the correct view of the actual historical events, but it is worthy of serious consideration and scrutiny.

The defining characteristics of the maximalist scenario are its end points—the development of uranium, plutonium, and fusion bombs, and the staging of at least five nuclear weapons tests before the end of the war. Unfortunately the key sources for the maximalist scenario give relatively little information about the program, intermediate steps, and timeline that led to those end points. Nonetheless, by using known historical events and parallels to the early U.S. and Soviet nuclear programs, one may "fill in the gaps" in the maximalist scenario and make plausible conjectures about the steps that would have been necessary for the German nuclear program to arrive at those end points:

1. For the very large and very urgent U.S. and Soviet nuclear programs, the time from the critical catalyzing event to the first atomic bomb detonation was roughly four years. Postwar Allied military accounts stated that the intense Allied bombing of Germany during the last two years of the war delayed Germany's development of new rockets, jets, and other strategic military technologies by at least six months. Coupled with materials shortages due to the Allied bombing and blockades, the total delay may have been more like 12 months. Thus one might expect that the German nuclear program would require roughly five years from its critical catalyzing event to its first successful bomb test. If the alleged 12 October 1944 atomic bomb test on the Baltic coast was indeed real and was indeed Germany's first successful test, one would look for a critical catalyzing event approximately five years before that, and the September 1939 declarations of war appear to be the most obvious choice. Corollaries to this line of reasoning are that:

   (a) If the German nuclear program began around September 1939 and truly did conduct a successful nuclear bomb test within five years (including the delays for Allied bombing and blockades), then during that five-year period, the German nuclear program would probably have had a size and urgency comparable to the U.S. and Soviet programs.

   (b) If the German nuclear program had been significantly smaller or less urgent than the wartime U.S. and postwar Soviet nuclear programs, it seems unlikely that it could have succeeded before the end of the war.

2. If Germany developed Pu-239 (or U-233) bombs, it would have needed to construct and operate one or more fission reactors (or a large electronuclear breeding program, which would have required a comparable amount of time). For the U.S. and Soviet programs, processed uranium oxide was already available prior to the critical catalyzing event (from earlier work for the U.S. program, and from German work for the Soviet program), and the first fission reactor became operational 12–16 months after the catalyzing event. A second, alternative criterion is that for both the U.S. and Soviet programs, the first fission reactor became operational approximately 32 months before a functional plutonium implosion bomb, due to the time required to transition from a small laboratory reactor to a large industrial reactor, create and optimize the plutonium extraction process, and actually produce enough plutonium for a bomb. Using the first criterion, if Germany had a critical catalyzing event in September 1939 and began processing uranium ore into uranium oxide at the beginning of 1940, one would expect the first fission reactor to become operational no earlier than the beginning of 1941. Using the second criterion, if Germany had a functional plutonium bomb ready no later than April 1945, one would expect the first fission reactor to have become operational no later than August 1942. How much evidence is there that Germany had one or more functional fission reactors? Is there any evidence that Germany's first fission reactor became operational sometime between early 1941 and summer 1942? If that actually happened, Germany would have demonstrated the world's first fission reactor sometime before the U.S. CP-1 became operational. Corollaries to this line of reasoning include:

   (a) If Germany did not have a functional fission reactor (or a very large electronuclear breeding program), it could not have had a serious plutonium bomb program.

   (b) If Germany had a functional fission reactor but it first became operational much later than August 1942 (or if the electronuclear breeding program became operational too late in the war), any plutonium bomb design would probably have still been waiting to receive a sufficient mass of Pu-239 when the war ended.

   (c) If Germany had a plutonium bomb program and operational fission reactors or electronuclear breeders, an industrial plant for extracting Pu-239 from spent uranium fuel (or U-233 from thorium) would have likely been adjacent to one or more of the fission reactors or electronuclear breeders.

3. It took the U.S. and Soviet programs at least 2.5 years to construct and test infrastructure and equipment to enrich U-235 to weapons-grade levels and to produce enough U-235 for their first uranium bombs; even before building that infrastructure, significant time was spent to research and develop the underlying scientific techniques. If Germany had enough enriched uranium to attempt a U-235 bomb test in late 1943, it most likely would have to have begun building industrial enrichment plants no later than early 1941, and to have been researching and developing enrichment techniques in laboratories before that. If Germany did not have enough enriched uranium for a bomb until March 1945, construction of industrial enrichment plants could have begun as late as around September 1942.

   (a) What evidence is there for large-scale, early, and/or high-level uranium enrichment work in Germany?

   (b) What possible industrial uranium enrichment plants began construction in 1941–1942?

4. If Germany conducted a failed bomb test in autumn 1943 but successful tests in autumn 1944, much of the work during the intervening period would have been focused on solving the problem(s) that led to the failure. (The failed autumn 1943 test may also account for the replacement of Abraham Esau by Walther Gerlach as "Plenipotentiary of Nuclear Physics" in late 1943.) The most obvious improvements would be:

   (a) Improving the implosion system to better synchronize and improve the symmetry of the implosion, and/or to increase the degree of compression of the fission fuel during the implosion.

   (b) Increasing the mass and/or purity of the fission fuel.

   (c) Improving the neutron output and/or reliability of the neutron source used to initiate a chain reaction when the fission fuel is maximally compressed.

5. If Germany conducted one or more successful bomb tests in autumn 1944 but still felt the need to conduct more bomb tests in March 1945, the simplest explanation is that the autumn 1944 bomb was so large and heavy (like the U.S. bombs) that it was much better suited to being dropped from an aircraft than carried by a rocket. Most German aircraft had become vulnerable to Allied attacks, whereas rockets could not be intercepted. Thus much of the work between autumn 1944 and March 1945 would have been focused on:

   (a) Reducing the mass and diameter of the bomb.

   (b) Increasing the payload capacity, range, and accuracy of rockets to carry the bomb.

It is important to reiterate that both the minimalist and maximalist scenarios considered here are hypothetical constructs that may be useful in thinking about this murky area of history. Each of these scenarios may or may not actually be true history; certainly both scenarios cannot be simultaneously correct. What were the actual historical events of the real German wartime nuclear program (Fig. D.1027)? Were they some suitably refined version of the minimalist scenario, some refined version of the maximalist scenario, or something intermediate between those two scenarios?

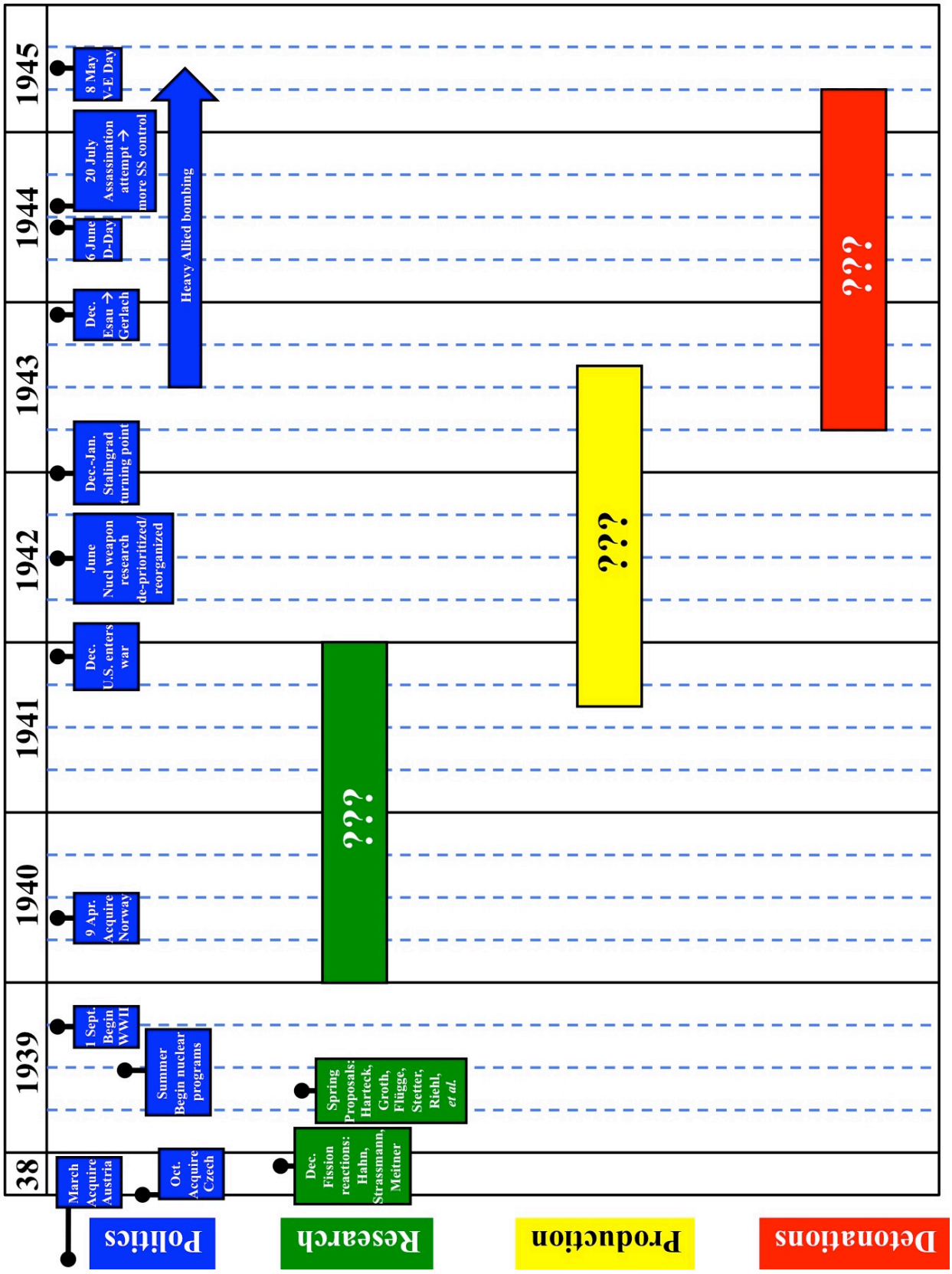

Figure D.1027: Timeline of the German nuclear weapons program, based on actual historical events.

D. Organization of the German Nuclear Program

The German nuclear program was very large and highly compartmentalized. Because so much of the relevant information was destroyed by the Germans at the end of the war or captured and classified by different Allied countries after the war, it is quite difficult for modern historians to accurately reconstruct the organizational details of the program.

Page 5109 presents a tentative organizational chart of the German nuclear program, based on information such as that from pp. 1565–1629 and 3402–3403.

In a nutshell, the overall management of the program was handled by the Army in the earlier years of the war and by the SS in the later years of the war, both with some input from the Reich Research Council.

Those managing agencies oversaw work that was spread over at least a couple dozen different organizations (military groups, other government-run laboratories, companies, and universities), many of which had multiple physical locations.

There was considerable redundancy among those organizations in their work, which may seem inefficient to the modern observer but appears to have served well to make the German nuclear program much less vulnerable to Allied intelligence and bombing.

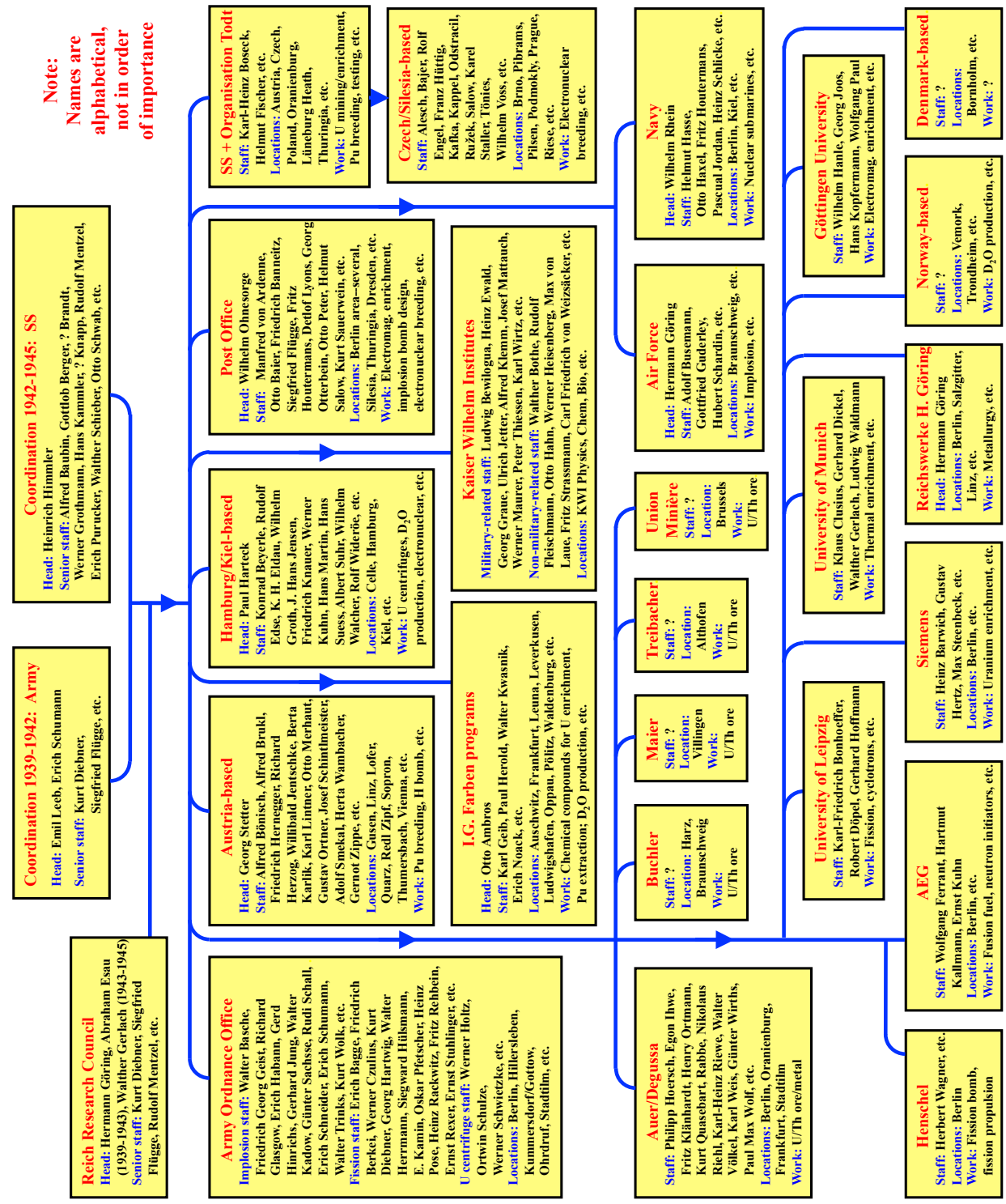

Figure D.1028: Very tentative organizational chart of the German nuclear program.

In order to understand the science of the German nuclear program, it is helpful to look at the program from a different viewpoint other than organizational approach of Fig. D.1028. In the film *All the President's Men*, the advice to "follow the money" was the key to investigating Watergate. Similarly, the key to investigating the wartime German nuclear program should be to "follow the actinides." Actinides are fissionable heavy elements, chiefly thorium, uranium, and plutonium.

Unfortunately, many vital details about the flow of actinides in the Third Reich are presently unknown.

As a guide in understanding the currently available information and in seeking more extensive information, p. 5111 presents a tentative and simplified overview of the actinide pathways and possibilities.

Much more research is needed to investigate and to clarify whether and how these pathways were actually implemented during the war.

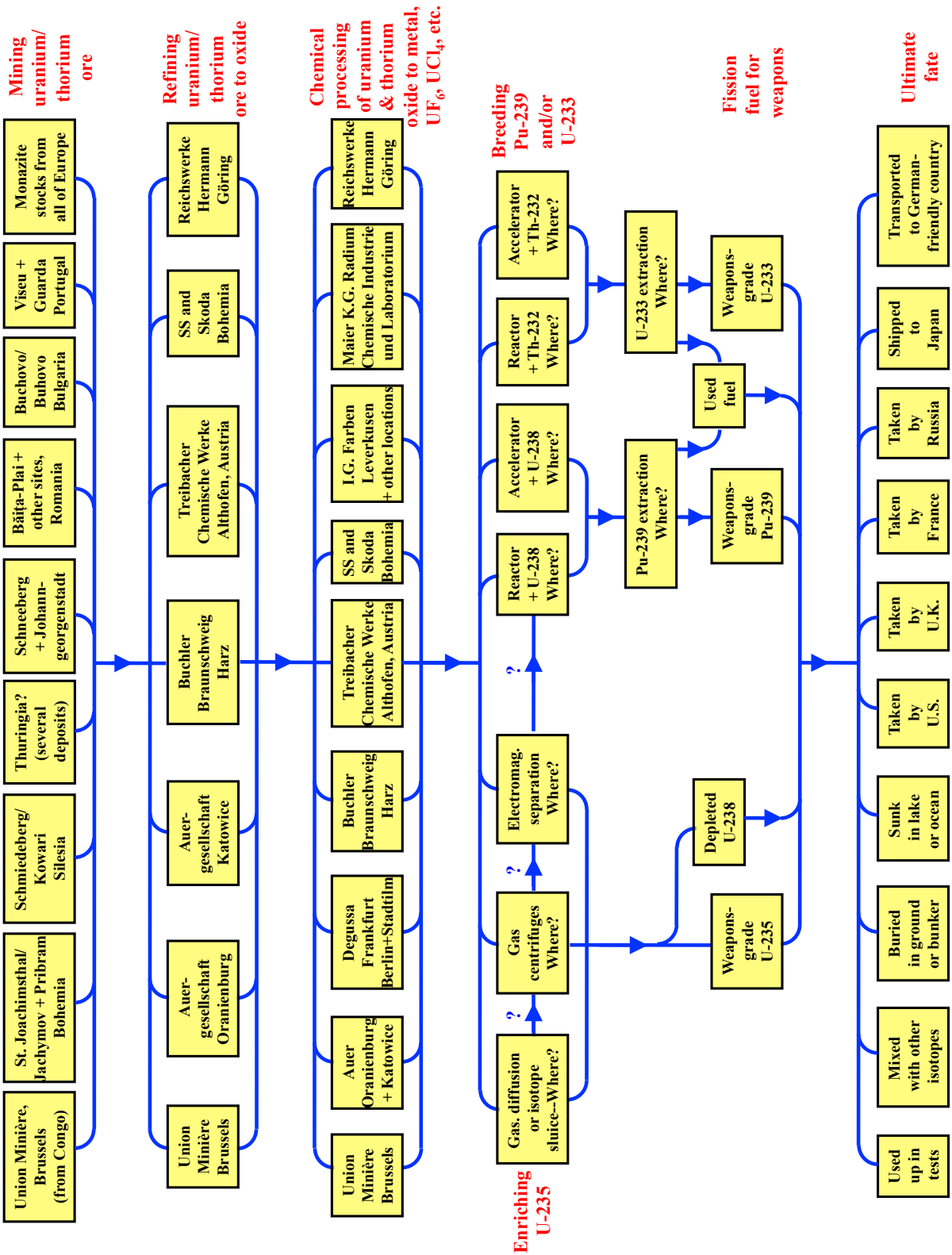

Figure D.1029: Known and extrapolated actinide (thorium, uranium, and plutonium) use in the German nuclear program.

During the war, Germany had access to large amounts of natural uranium and thorium ore by (see map on p. 3405):

- Acquiring at least 1200 tons, and according to some well-informed sources 3500 tons, of uranium compounds (originally mined in the Belgian Congo) from Union Minière in Brussels [e.g., pp. 3335, 3408–3414].
- Expanding uranium mining at St. Joachimsthal (Jachymov), Bohemia [e.g., pp. 3418–3429, 3445, 3469–3470, 4978–4984; Hayes 2004, pp. 132–133, 235, 243].
- Mining uranium at Příbram/Przibram/Pibrans, Bohemia [e.g, pp. 3424, 3470, 3751–3754].
- Mining uranium at Schmiedeberg, Silesia [e.g., pp. 3328, 3424, 3429, 3445, 3471].
- Possibly using any of several uranium deposits in Thuringia [e.g., pp. 3468–3469; Zeman and Karlsch 2008].
- Mining uranium at Schneeberg, Saxony [e.g., pp. 3416, 3424, 3426–3428, 3433–3437, 3445, 3456, 3468–3469, 3708, 4922; Zeman and Karlsch 2008].
- Mining uranium at Johanngeorgenstadt, Saxony [e.g., pp. 3416, 3424, 3426–3428, 3433–3437, 3456, 3468–3469, 3708, 4922; Zeman and Karlsch 2008].
- Mining uranium at Freiberg, Saxony [e.g., pp. 3424, 3426–3429, 3445, 3468–3469].
- Mining uranium at Durrnaul near Marienbad [e.g., p. 3424].
- Mining or planning to mine uranium at Mladkov/Wichstadt, Bohemia [e.g., p. 3425].
- Operating and receiving shipments from Bulgarian uranium mines such as a mine at Buchovo (or Buhovo, a suburb of Sofia), since 1938 [e.g., Hayes 2004, p. 235; https://ejatlas.org/conflict/life-after-the-uranium-mines-in-buhovo-bulgaria]. See also pp. 3446, 3470, 4588.
- Mining uranium at Băiţa-Plai and other sites in Romania [e.g., pp. 3449–3455, 3471].
- Acquiring uranium from mines at Viseu and Guarda, Portugal [e.g., p. 3445; Hayes 2004, p. 235].
- Procuring all available monazite thorium ore in occupied Europe [e.g., Irving 1967].
- Exploiting other possible sources—Spain, Scandinavia, etc.?

One 1946 U.S. intelligence report on Czech uranium mines noted, "The Germans put mining on a high priority and only mining was done throughout the 6 years occupation. The ore was delivered by special planes to Germany and Austria" (p. 3998). Another 1946 U.S. intelligence report added: "The Germans continued operations in this mine to the very last moment" (p. 4981).

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

Germany processed uranium and thorium ore to uranium oxide and thorium oxide, and thence to uranium or thorium metal or to a variety of useful chemical compounds—uranium hexafluoride, uranium tetrachloride, uranium nitrate, etc.—at numerous locations including (see map on p. 3407):

- Union Minière in Brussels [e.g., pp. 3335, 3408–3414; Irving 1967, p. 65].
- Auer in Oranienburg, Katowice/Kattowitz, and other locations [e.g., pp. 3446, 3458, 3461–3463, 3465, 4980; Nagel 2016].
- Buchler in Braunschweig [e.g., pp. 3420, 3430–3431, 3458, 3460–3463, 3465, 4980].
- Treibacher Chemische Werke in Althofen, Austria [e.g., pp. 3420, 3432–3437, 3458, 3460, 4980; Gollmann 1994].
- Degussa in Frankfurt, Berlin, Stadtilm, and possibly other locations [e.g., pp. 3458, 3461–3465; Hayes 2004; Nagel 2016].
- Chemische Fabrik Grünau in Berlin [e.g., pp. 3438–3439, 3461–3463].
- I.G. Farben in Leverkusen and other locations [e.g., pp. 3488–3489, 3492–3493, 3678–3680, 3748–3750, 4440–4477; Mader 1965, pp. 193–202, 229-233].
- Krupp in Essen [e.g., pp. 3458, 3461–3463, 3465–3467].
- W. de Boer in Hamburg and Wittingen [e.g., pp. 3458, 3461–3463, 3465].
- Radium-Chemie AG in Frankfurt [e.g., pp. 3440–3441, 3458, 3465].
- W. Maier KG Radiumchemische Industrie und Laboratorium in Villingen-Schwenningen am Neckar and other locations [e.g., Oleynikov 2000].
- Příbram/Przibram/Pibrans, Bohemia [e.g., pp. 3423, 3751–3754].
- Facilities in Dresden [e.g., pp. 3423, 3426].
- Reichswerke Hermann Göring in Linz and other locations [e.g., pp. 3877–3880].
- Possibly other facilities.

At the end of the war, Allied countries removed over 2800 tons of uranium and thorium compounds from former German-controlled territory (p. 3456). In addition, in 1974, Alwin Urff, deputy technical plant manager of the Asse nuclear disposal site in Germany, stated: "When we began storage in 1967, our company first sank radioactive waste from the last war, that uranium waste which arose in the preparation of the German atomic bomb" (p. 3472).

German scientists developed and demonstrated methods of enriching uranium-235 from natural uranium:

- Konrad Beyerle, Wilhelm Groth, Werner Holtz, Werner Schwietzke, and many others worked in teams that developed gas centrifuges to enrich uranium-235. Centrifugation proved so superior to the U.S. Manhattan Project's enrichment methods that the German gas centrifuge designs are now the worldwide standard for uranium enrichment (p. 3494).

- Manfred von Ardenne, Heinz Ewald, Wolfgang Paul, Wilhelm Walcher, and many others worked in teams that developed electromagnetic separators to enrich uranium-235. These electromagnetic separators were comparable to the Manhattan Project's calutrons (p. 3554).

- Erich Bagge invented and successfully demonstrated a unique uranium enrichment device called an isotope sluice, which combined some features of centrifuges, electromagnetic separators, and gaseous diffusion (p. 3651).

- Erika Cremer, Rudolf Fleischmann, Gustav Hertz, and others developed gaseous diffusion methods suitable for enriching uranium-235 that were comparable to the Manhattan Project's gaseous diffusion technology (p. 3618).

These enrichment methods are analyzed in Section D.15.2.

If Germany scaled up any of these proven uranium enrichment methods in order to produce nuclear weapons, it would presumably have distributed that production capability among a number of small underground locations for protection against Allied bombing. Archival documents mention dozens of highly suspicious sites that might have been used for that purpose and that still have not been properly investigated (p. 3670).

Two or more enrichment methods might have been used together, with one method enriching natural uranium to a level moderately enriched in uranium-235, then forwarding that material to another method to be enriched to a higher level.

Among the few currently available sources, there is some evidence that German scientists were working on breeding plutonium-239 or uranium-233:

- Ludwig Bewilogua, Kurt Diebner, Paul Harteck, Otto Haxel, and many others worked in teams trying to develop fission reactors suitable for breeding plutonium-239 from natural uranium-238 or uranium-233 from natural thorium-232. Two reactors were on the brink of criticality by the end of the war, and there is some evidence that other reactors may have actually become operational during the war (p. 3794).

- Walther Bothe, Walter Dällenbach, Max Steenbeck, Rolf Wideröe, and many others worked on particle-accelerator-driven electronuclear systems suitable for breeding plutonium-239 from natural uranium-238 or uranium-233 from natural thorium-232. There is some evidence that such systems may have been operational during the war (p. 3954).

These breeding methods are analyzed in Section D.15.3.

One or more enrichment methods might have also been used in conjunction with one or more breeding methods, providing uranium somewhat enriched in uranium-235 to a fission reactor or electronuclear breeder to make it easier to produce neutrons and thus easier to breed plutonium-239 from the remaining uranium-238.

Various subsets of the above processes could have produced any or all of these fission fuels for nuclear weapons:

- Uranium-235.
- Plutonium-239.
- Uranium-233.

If the Third Reich ever truly had significant quantities of any bomb-grade fission fuel, as well as the actinide waste products from enriching and/or breeding that fuel, they must have been disposed of in one or more of the following ways:

- Used up in test explosions.
- Smelted together with large enough quantities of natural uranium or other materials to render them effectively unusable.
- Buried in the ground or a bunker, sunk in a lake or ocean, or otherwise hidden so well that they were never found, or were found only after the Soviet nuclear program was already very far along.
- Captured by the United States.
- Captured by the United Kingdom.
- Captured by France.
- Captured by Russia (only small quantities and/or discovered years later[26]).
- Shipped to Japan.
- Sent to other sympathetic countries, such as Switzerland, Spain, Argentina, etc.

[26]While the postwar Soviet program benefited enormously from all of the German scientists, materials, equipment, and information it acquired, it still required four full years after the war to produce enough plutonium for one plutonium bomb test, RDS-1/Joe-1, and even longer to produce enough highly enriched uranium for its first uranium-235-based bomb test, RDS-2/Joe-2. Stalin was desperate to test a nuclear weapon as soon as he possibly could, in order to show the world that the United States was not the only nuclear superpower (p. 4533). Therefore, the timeline of the Soviet nuclear program appears to prove that as many spoils as the Soviets found in Germany and former German-occupied territories, useful quantities of plutonium-239, uranium-233, or highly enriched uranium-235 were not among them, or perhaps were only discovered after the Soviets had produced enough of their own fission fuel.

D.15.2 Enrichment Methods to Produce U-235

Uranium ore in most deposits typically consists of 0.1–2% uranium mixed with other elements. As the first step in processing, the uranium ore is milled or refined to at least 80% U_3O_8; this refined product is called yellowcake due to its color.

By mass, natural uranium contains approximately 0.72% ^{235}U, 99.275% ^{238}U, and just a trace amount (0.005%) of ^{234}U. Natural uranium can be used in fission reactors employing either heavy water or very pure graphite (not contaminated by neutron-absorbing boron) as a moderator to slow down the neutrons and facilitate the chain reaction. For use in reactors using light (ordinary) water as a moderator, the ^{235}U content of the fuel must be increased to 2–4%. For use in fast reactors or fission bombs, the ^{235}U content must be increased to ∼50–90% (the higher the better). The excess ^{238}U that is removed is called depleted uranium or tails; it used for other applications such as military ammunition and nuclear bomb casings, due to its very high density and other properties.

Preferentially accumulating one isotope versus another of the same element is called enrichment. As shown in Fig. D.1030, there are several different methods of enrichment:

A. Electromagnetic separation.

B. Gaseous diffusion.

C. Centrifugation.

D. Laser isotope separation.

The first two enrichment methods were used by the United States during World War II. Centrifugation is the main method used worldwide now. Laser isotope separation has been investigated for potential future use.

There is evidence that the wartime German nuclear program conducted research on all four of these enrichment methods. It is possible that any or all of the first three methods were used to produce enriched uranium for nuclear weapons, although most of the relevant information was either destroyed or may remain buried in classified archives. Much more work is needed to investigate the locations and methods of uranium enrichment that were used in the German nuclear program, as well as the amount and purity of the material that was produced.

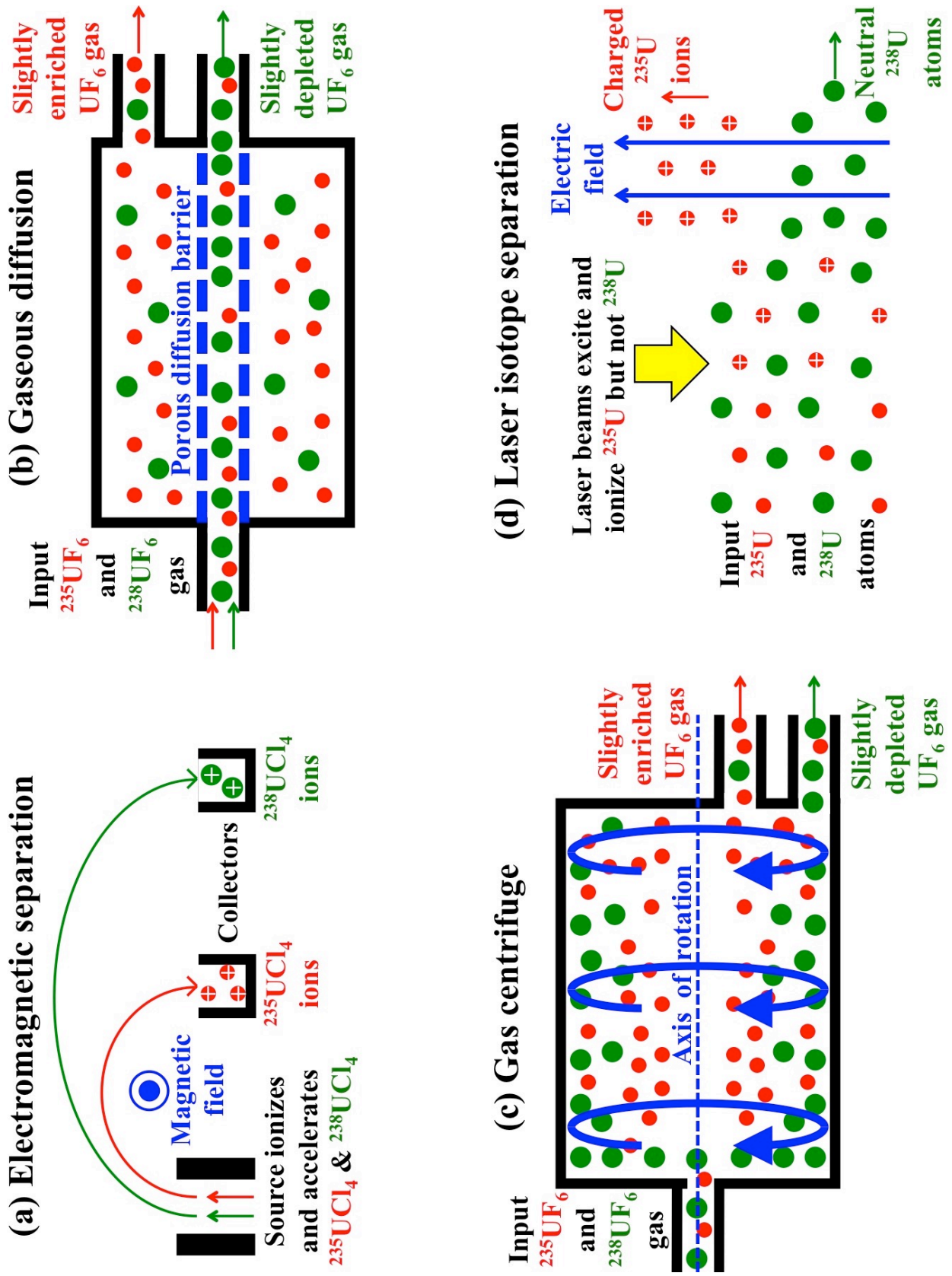

Figure D.1030: Uranium enrichment methods include (a) electromagnetic separation, (b) gaseous diffusion, (c) centrifugation, and (d) laser isotope separation.

A. Electromagnetic Separation

Mass spectrometers or circular particle accelerators can separate particles with different masses, as illustrated in Fig. D.1030(a). If uranium atoms are ionized and accelerated to a certain energy, an applied magnetic field can bend the paths of the uranium ions, with the trajectories of lower-mass ^{235}U ions having more curvature than those of higher-mass ^{238}U ions. This effect creates spatial separation between the two isotopes and thus can enrich the isotopes to very high purities. However, because of the very low particle densities and sophisticated equipment required, this enrichment approach tends to be very expensive for fission fuel. Nonetheless, all highly enriched ^{235}U produced in the United States during and soon after World War II was purified using electromagnetic separators called calutrons. Since the calutrons could produce highly enriched uranium but were limited by how much uranium they could process, they were most effective when they were fed with low-enriched uranium (from a separate gaseous diffusion plant) instead of natural uranium [Bruce Cameron Reed 2015a, 2019].

Manfred von Ardenne, Heinz Ewald, Wolfgang Paul, Wilhelm Walcher, and other German scientists developed methods for enriching uranium-235 via electromagnetic separation that were comparable to the U.S. calutrons (p. 3554). If Germany was secretly able to mass-produce and operate separators copied from those prototypes, it could have enriched enough uranium for one or more implosion bombs, especially test bombs with relatively small explosive yields such as those described by Werner Grothmann (p. 4436) and other witnesses. Indeed, according to Grothmann, the Reichspost built and operated a large uranium enrichment facility somewhere outside Berlin apparently based on von Ardenne's technology (p. 3494).

The physical size of an electromagnetic separator, and the distance by which it can separate uranium isotopes into two different streams, can be estimated from basic physics. The Lorentz force on an ion of mass m, velocity vector $\mathbf{v}$ (magnitude v), and singly ionized charge e in a magnetic field vector $\mathbf{B}$ (magnitude B) is

$$m \, \frac{d\mathbf{v}}{dt} \;=\; e \, \mathbf{v} \times \mathbf{B} \tag{D.17}$$

If the centripetal acceleration of the ion from Eq. (D.17) is the centripetal acceleration v^2/r_c required to go in a circular cyclotron orbit of radius r_c,

$$\left| \frac{dv}{dt} \right| \;=\; \frac{e \, v \, B}{m} \;=\; \frac{v^2}{r_c} \, , \tag{D.18}$$

then one can use the ion's kinetic energy $E = mv^2/2$ and mass A in atomic mass units to calculate the cyclotron radius:

$$r_c \;=\; \frac{\sqrt{2 \, E \, m}}{eB} \;=\; 0.456 \, \frac{\sqrt{E_{keV}}}{B_T} \, \sqrt{A} \;\; \text{cm} \tag{D.19}$$

The diameter d_c of such a circular orbit is twice its radius:

$$d_c \;=\; 2 \frac{\sqrt{2 \, E \, m}}{eB} \;=\; 0.912 \, \frac{\sqrt{E_{keV}}}{B_T} \, \sqrt{A} \;\; \text{cm} \tag{D.20}$$

Two types of ions of masses A_1 and A_2 that begin at the same point with the same energy will be maximally separated by a distance Δd after half an orbit by the difference of their orbital diameters:

$$\Delta d_c \;=\; 2(r_{c1} - r_{c2}) \;=\; 0.912\,\frac{\sqrt{E_{keV}}}{B_T}\left(\sqrt{A_1} - \sqrt{A_2}\right)\;\text{cm} \tag{D.21}$$

The U.S. calutrons used 35 keV beams of singly ionized UCl_4 molecules, which had masses of $A_1 = 378$ for $^{238}UCl_4$ and $A_2 = 375$ for $^{235}UCl_4$. There were two types of calutrons: alpha calultrons with a magnetic field of 0.34 Tesla, and beta calutrons with a magnetic field of 0.68 Tesla. Using these numbers, the separation distance between beams of U-238 and U-235 was:

$$\Delta d_c \;\approx\; 1.2\text{ cm} \qquad \text{for alpha calutrons with B = 0.34 T} \tag{D.22}$$

$$\;\approx\; 0.6\text{ cm} \qquad \text{for beta calutrons with B = 0.68 T} \tag{D.23}$$

The calutrons had to be sufficiently large to contain the orbits of the uranium beams:

$$d_c \;\approx\; 3.1\text{ m} \qquad \text{for alpha calutrons with B = 0.34 T} \tag{D.24}$$

$$\;\approx\; 1.5\text{ m} \qquad \text{for beta calutrons with B = 0.68 T} \tag{D.25}$$

German electromagnetic separators would almost certainly have had roughly comparable sizes and separation distances.

Fundamental physics can also give a ballpark estimate for the number of electromagnetic separators that would be required to achieve a given U-235 production rate. If N is the number of independent uranium ion beams, I is the current per beam in Amps, and $e \approx 1.602 \times 10^{-19}$ Coulombs is the electric charge of singly charged ions in the beam, the total number of ions per second is simply NI/e. Since there are $365 \times 24 \times 60 \times 60 = 3.1536 \times 10^7$ seconds per year, the annual ion production rate is

$$\frac{\text{Separated ions}}{\text{year}} \;=\; 3.1536 \times 10^7\,\frac{N\,I}{e}\;\frac{\text{ions}}{\text{year}} \tag{D.26}$$

Using Avogadro's number $N_A \approx 6.022 \times 10^{23}$ and the mass A of the ions in atomic mass units, there are N_A/A ions per gram of mass in the beam, or $1000 N_A/A$ ions/kg. Combining this information with Eq. (D.26), the annual production rate of mass is

$$\frac{\text{Separated mass}}{\text{year}} \;=\; 3.1536 \times 10^4\,\frac{N\,I\,A}{e\,N_A}\;\frac{\text{kg}}{\text{year}} \tag{D.27}$$

Space charge effects and other phenomena limit practical values of the current in the separated U-235 beam to around half a milliamp, or $I \sim 5 \times 10^{-4}$ A. (The current of the initial beam will be much larger, since most of the beam will be composed of U-238 ions.) Realistically the ion beams might operate at a somewhat lower current and would be taken offline periodically for maintenance and cleaning. Lowering the current to an average value of $I \sim 3 \times 10^{-4}$ A to account for those limitations, and using $A = 235$ for U-235, Eq. (D.27) becomes

$$\frac{\text{Separated U-235}}{\text{year}} \;\sim\; 0.023\,N\;\frac{\text{kg}}{\text{year}} \tag{D.28}$$

In early 1945, the U.S. Y-12 plant at Oak Ridge was producing approximately 0.2 kg U-235 per day, or approximately 73 kg/year. Equation (D.28) predicts a ballpark number on the order of 3200 calutron ion beams would be required for that production rate. In fact, the Y-12 plant used a two-stage process, with 2688 alpha calutron beams ($4 \times 2 \times 96 \ + \ 5 \times 4 \times 96$) enriching to $\sim$ 20% U-235 in the first stage, and then 432 beta calutron beams ($6 \times 2 \times 36$) further enriching that material to $\sim$ 80% U-235 [Bruce Cameron Reed 2015a, 2019]. Lumping the alpha and beta calutrons together, that makes 3120 ion beams, very close to the crude estimate from Eq. (D.28).

The maximum planned electrical power consumption of the entire Y-12 calutron plant was 200 MW (Fig. D.1031 and Table D.8). In practice, Y-12's electrical usage was generally less than that. As shown in Fig. D.1032, the total electrical consumption for Oak Ridge (Y-12 calutrons + K-25 gaseous diffusion + all other nuclear facilities + the town itself) peaked for the month ending 1 September 1945 at 200 GW hr for the month, or 0.269 GW = 269 MW time-averaged. For the 12 months ending 1 September 1945, the total electrical consumption for Oak Ridge was 1659 GW hr for the year, or 0.189 GW = 189 MW time-averaged.[27]

The total production of electrical energy in the United States increased from 161,308 GW hr for the year of 1939, or a time-average of 18.4 GW electric power production, to 271,255 GW hr for 1945, or a time-average of 31.0 GW electric power production.[28]

Thus Oak Ridge's electrical consumption during the peak final war month of August 1945 was 0.868% of the total U.S. electrical power at that time (0.269 GW/31.0 GW = 0.00868). Oak Ridge's electrical consumption averaged over that final year of the war was 0.610% of the total U.S. electrical power at that time (0.189 GW/31.0 GW = 0.00610). These figures disprove the oft-repeated myth that Oak Ridge required a large fraction of the nation's electricity. [See also Bruce Cameron Reed 2015b.]

According to the U.S. Strategic Bombing Survey (USSBS), at the end of 1944 the Greater German Reich (including modern Germany, Austria, Poland, and the Czech Republic) had a total known electrical production capacity of 22 GW, with at least 16 GW of that currently then in use despite territorial losses, extensive bombing, and ongoing repair work.[29] See pp. 2102–2104. BIOS 342 estimated a total of 23 GW for 1944 (pp. 2105–2106). Including secretive or specialized power plants for classified or dedicated projects within the Greater German Reich that were not known to the USSBS (especially in areas occupied by the Soviet Union after the war) plus the electrical production capacities of other countries that were occupied by Germany, allied with Germany, or nominally neutral but exporting aid to Germany, a reasonable estimate of the total electrical production capacity supporting the German war effort is roughly double the 22 GW figure, or ∼44 GW.

[27] Manhattan District History. Book I, Volume 12, Part 1. Clinton Engineer Works: Central Facilities. p. 12.5. https://ia803409.us.archive.org/14/items/ManhattanDistrictHistory/MDH-B1V12P01-General-CEW_Central_Facilities.pdf
Manhattan District History. Book I, Volume 12, Part 2. Clinton Engineer Works. Appendix C-7. https://ia803409.us.archive.org/14/items/ManhattanDistrictHistory/MDH-B1V12P02-General-CEW_Central_Facilities_Appendices_A-C.pdf

[28] United States Census Bureau. 1949. *Statistical Abstract of the United States.* p. 512. https://www.census.gov/library/publications/1949/compendia/statab/70ed.html https://www2.census.gov/library/publications/1949/compendia/statab/70ed/1949-08.pdf

[29] United States Strategic Bombing Survey. 1947. *German Electric Utilities Industry Report.* pp. 1, 4, Exhibit C, Exhibit D. https://books.google.com/books?id=U9Q9TS-FtSgC

Using the average total electrical consumption of Oak Ridge during the final year of the war, Germany could have powered a fully equal facility by using:

- 1.18% of the electrical capacity known to remain in use in the Greater German Reich at the end of 1944 (0.189 GW/16 GW = 0.0118), or
- 0.859% of the known wartime electrical capacity in the Greater German Reich (0.189 GW/22 GW = 0.00859), or
- ∼0.43% of the estimated total electrical production capacity that was available to aid Germany during the war (0.189 GW/44 GW = 0.00430).

The U.S. electromagnetic separation plant was designed to produce so much U-235 because the United States planned to use that uranium in Little Boy, a gun-type fission bomb that needed over 60 kg of fuel because it did not compress the fuel and had a very low efficiency. The U.S. plant provided enough uranium for approximately one bomb of that design per year.

The sources that describe the German fission bomb design all indicate that it was an implosion bomb, which compresses the fuel, is much more efficient than a gun-type bomb, and therefore requires roughly 1/10 as much fuel as a gun-type bomb. If a German enrichment facility were designed to produce enough U-235 for one full-sized bomb per year (or several test bombs with smaller amounts of fuel and smaller explosive yields, as described by the sources), that German enrichment plant could have been roughly 1/10 the size of the U.S. Y-12 plant, as extrapolated in Table D.8. If that same production capacity were distributed among several production plants to minimize the risk of Allied bombing (p. 4400), each plant would have been even smaller.

German enrichment facilities 1/10 the total size of Oak Ridge would have used:

- 0.118% of the electrical capacity known to remain in use in the Greater German Reich at the end of 1944, or
- 0.0859% of the known wartime electrical capacity in the Greater German Reich, or
- ∼0.043% of the estimated total electrical production capacity that was available to aid Germany during the war.

Due to the huge power consumption of the electromagnets, electromagnetic separators like the Y-12 calutrons are the least energy-efficient uranium enrichment method that has been employed on an industrial scale. As analyzed next, Germany developed more energy-efficient enrichment methods (gaseous diffusion and especially uranium gas centrifuges), so plants using those methods would have consumed even less of the total German electrical capacity than has been calculated above.

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

Table D.8: Known characteristics of the U.S. electromagnetic separation plant and extrapolated characteristics of a hypothetical German electromagnetic separation plant.

process requirements (App. A-94). It became evident that an electrical connection would have to be established between the western (Gas and Thermal Diffusion Plant Areas and the Clinton Laboratories Area) and the eastern (Electromagnetic Plant and Townsite Areas) end of the project, in order to make full use of the facilities, to provide interchange, and/or supplements of power, and to coordinate the system for maximum dependability and efficiency. This was accomplished by constructing a tie line between Elza No. 1 substation main buss and the switchyard buss at the Diffusion Plant (K-25) power plant station (App. A-95); and initially this line was connected to a transformer bank temporarily installed to furnish power for construction and testing operations at K-25 until such time as the permanent K-25 substation was completed and ready for service (App. A-320). This is a three phase, 154 kv line on H-frame wood pole structures, 300 MCM, 30 percent conductivity copperweld conductors, approximately 11.3 miles long. Another power supply from the TVA system at Fort Loudoun ties into the switchyard buss in the K-25 Area, thus affording four independent power sources to the project. From the K-25 Area switchyard, a 13.8 kv, 60 cycle, three phase line, wood pole supported, of 1/0 aluminum cable, steel reinforced, ~~feeder~~ serves the Clinton Laboratories (X-10) Area. This line is approximately six miles long. The four sources of power and the primary substation facilities mentioned above provided the project with facilities having a capacity of approximately 310,000 kw to serve loads estimated as follows in the various areas: 200,000 kw to the Electromagnetic Plant Area and its extensions, 23,000 kw to the town, 80,000 kw to the Gas Diffusion Plant Area, 6,000 kw to the Thermal Diffusion Plant Area, and 1,000 kw to the Clinton Lab-

Figure D.1031: Electrical power consumption for U.S. Oak Ridge during World War II. Manhattan District History. Book I, Volume 12, Part 1. Clinton Engineer Works: Central Facilities. p. 12.5. https://ia803409.us.archive.org/14/items/ManhattanDistrictHistory/MDH-B1V12P01-General-CEW_Central_Facilities.pdf

ELECTRIC POWER CONSUMPTION AND COSTS

CLINTON ENGINEER WORKS

OCTOBER 1943 THROUGH DECEMBER 1946

Period Ending	KWH Consumed	KW Demand	Total Costs
1 November 1943	3,912,040	11,400	$ 18,834.08
1 December 1943	9,105,000	18,300	34,171.50
1 January 1944	8,365,000	18,300	33,061.50
1 February 1944	10,725,000	23,100	41,785.50
1 March 1944	17,105,000	31,200	60,103.50
1 April 1944	27,665,000	48,600	94,735.50
1 May 1944	33,970,000	64,500	121,365.00
1 June 1944	41,478,000	73,800	142,671.00
1 July 1944	39,870,000	98,200	166,611.00
1 August 1944	46,140,000	104,200	182,496.00
1 September 1944	52,610,000	125,900	215,637.00
1 October 1944	63,280,000	144,450	251,676.00
1 November 1944	77,700,000	187,760	320,080.80
1 December 1944	90,370,000	222,050	376,119.00
1 January 1945	107,010,000	236,900	417,117.00
1 February 1945	123,668,000	242,633	448,295.64
1 March 1945	117,442,000	253,047	450,203.76
1 April 1945	150,950,000	290,487	540,900.96
1 May 1945	166,170,000	263,626	534,721.08
1 June 1945	179,160,000	269,866	560,945.28
1 July 1945	184,350,000	283,840	583,822.20
1 August 1945	198,870,000	291,800	614,199.00
1 September 1945	200,000,000	298,627	623,267.16
1 October 1945	117,920,000	292,867	493,926.36
1 November 1945	60,290,000	116,227	216,710.16
1 December 1945	48,020,000	122,347	204,914.76
1 January 1946	63,620,000	145,100	252,888.00
1 February 1946	96,587,000	197,540	358,973.70
1 March 1946	113,130,000	220,040	408,088.20
1 April 1946	150,550,000	258,440	505,690.20
1 May 1946	162,400,000	266,127	531,767.16
1 June 1946	171,995,000	261,463	541,122.54
1 July 1946	181,253,000	293,867	590,005.86
1 August 1946	180,771,000	293,200	588,562.50
1 September 1946	167,232,000	259,600	531,966.00
1 October 1946	155,725,000	227,200	479,713.50
1 November 1946	178,100,000	267,600	556,908.00
1 December 1946	154,547,000	259,200	512,506.50
1 January 1947	153,739,000	230,400	480,190.50

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C-7

Figure D.1032: Electrical power consumption for U.S. Oak Ridge during World War II. Manhattan District History. Book I, Volume 12, Part 2. Clinton Engineer Works. Appendix C-7. Electric Power Consumption and Costs, CEW. https://ia803409.us.archive.org/14/items/ManhattanDistrictHistory/MDH-B1V12P02-General-CEW_Central_Facilities_Appendices_A-C.pdf

B. Gaseous Diffusion and the Isotope Sluice

If a gas contains two isotopes with different masses $m_{\rm heavy}$ and $m_{\rm light}$ but the same temperature T, the thermal velocity of the lighter isotope will be $\sqrt{m_{\rm heavy}/m_{\rm light}}$ times faster than that of the heavier isotope ($v \sim \sqrt{k_B T/m}$). If pressurized gas is forced to diffuse through a barrier containing small pores, the lighter isotope will thus diffuse $\sqrt{m_{\rm heavy}/m_{\rm light}}$ times faster than the heavier isotope, permitting a small amount of enrichment per barrier stage, as shown in Fig. D.1030(b). By connecting many such diffusion barriers in series, significant amounts of enrichment can be obtained.

The only compound of uranium suitable for enrichment by gaseous diffusion is uranium hexafluoride (UF_6), which is solid below 56^oC but gaseous above that temperature. UF_6 is very chemically reactive with water and highly corrosive to organic materials (except Teflon) and most metals except nickel and aluminum, so the diffusion barriers are generally formed from porous nickel or possibly porous aluminum. The fluorine mass per molecule ($6 \times 19.0 = 114$) is small enough not to completely obscure the small mass difference between ^{235}U and ^{238}U. Including the fluorine, the ratio of the diffusion velocities $v_{\rm light}$ of $^{235}UF_6$ and $v_{\rm heavy}$ of $^{238}UF_6$ is

$$\frac{v_{\rm light}}{v_{\rm heavy}} = \sqrt{\frac{m_{\rm heavy}}{m_{\rm light}}} = \sqrt{\frac{238+114}{235+114}} \approx 1.0043 \qquad \text{(D.29)}$$

In practice, at least 1000 pressurized barrier stages in series are required to obtain reactor-level (2–4%) enrichment, and many more to obtain bomb-level ($> 50\%$) enrichment. The United States employed this method during and for quite some time after World War II, but it is very cumbersome and energy-intensive, due to the large number of stages and the energy required to pressurize each stage. Thus almost all enrichment nowadays uses centrifugation, which is much more energy-efficient [Benedict et al. 1981; Bruce Cameron Reed 2015a, 2019].

Gustav Hertz pioneered gaseous diffusion enrichment, starting before 1923, continuing to work in Germany throughout the Third Reich (even though he was partially Jewish), and playing a critical role in uranium enrichment in the Soviet Union after the war (p. 3618). Historians should investigate whether there may have been any secret programs in wartime Germany to mass-produce and operate copies of Hertz's technology, either by Hertz or anyone else.

Whereas Erich Bagge's isotope sluice had its own unique method of operation (p. 3651), ultimately its isotope separation was due to the same velocity ratio between light and heavy isotopes as Eq. (D.29) for gaseous diffusion. Thus Bagge's isotope sluice would have required a number of stages or repeated steps comparable to gaseous diffusion in order to achieve large-scale enrichment. Again, historians should dig more deeply to determine if such devices may have been mass-produced and operated anywhere within the Third Reich.

C. Gas Centrifuges

Centrifuges are routinely used to separate liquids of different densities, but specially designed centrifuges can also separate gas molecules of different masses. As with gaseous diffusion, the uranium is in the form of hot corrosive UF_6, so centrifuge components must be made from resistant materials such as aluminum, nickel, and Teflon [Benedict et al. 1981; Glaser 2008; Kemp 2009, 2012, 2017].

Konrad Beyerle, Wilhelm Groth, Paul Harteck, Werner Holtz, Werner Schwietzke, and other scientists and engineers in the German nuclear program developed a succession of improved gas centrifuges during the war (p. 3494). According to official histories, these centrifuges were one-of-a-kind prototypes that were simply used for research purposes. Yet there is evidence that these centrifuge designs were secretly mass-produced and used at other locations in the Third Reich (pp. 3544, 3670). If that was indeed the case, they could have been a highly effective method of producing enriched uranium for both fission bombs and fission reactors.

After the war, German gas centrifuge technology (along with the German experts on that technology) was ultimately adopted by the Soviet Union, western Europe, the United States, and the rest of the world, displacing the much less efficient and much more expensive enrichment technologies that the United States had developed during the war.

Figure D.1030(c) shows a highly simplified illustration of a gas centrifuge. The centrifuge is essentially a long rotating drum, and UF_6 is brought in along the axis of rotation. Heavier $^{238}UF_6$ molecules tend to move toward the outer walls of the centrifuge, while lighter $^{235}UF_6$ is more buoyant and tends to remain closer to the axis. Of course, the two isotopes still intermingle, but gas somewhat depleted of ^{235}U can be removed near the outer wall of the cylinder, and gas somewhat enriched for ^{235}U can be drawn off closer to the axis. The centrifuge operates in a continuous fashion with fresh gas entering the chamber and old gas leaving it.

The enrichment that can be achieved by one such centrifuge can be estimated by a simple model. During operation, most of the gas is in a thin layer adjacent to the outer wall. If the wall is at radius R and rotates at velocity v, gas molecules with mass m immediately adjacent to it will move at the same velocity and have kinetic energy $mv^2/2$. If molecules move to a radial position r closer to the axis, in equilibrium they must assume a rotation velocity $(r/R)v$, or a kinetic energy $(r/R)^2 mv^2/2$. The difference in kinetic energies between molecules at radii r and R is

$$E = \left(1 - \frac{r^2}{R^2}\right) \frac{mv^2}{2} \tag{D.30}$$

From statistical physics, in a thermal distribution the density of particles n with different energies E varies like $n(E) = n(0) \exp(-E/k_B T)$. In the rotating frame of reference at the outer wall, molecules adjacent to the wall have zero energy and molecules that climb "higher" (closer to the axis) have energy E from Eq. (D.30) relative to that. Therefore the ratio of the densities at radii r and R is

$$\frac{n_r}{n_R} = \exp\left[-\frac{mv^2}{2k_B T}\left(1 - \frac{r^2}{R^2}\right)\right] \tag{D.31}$$

By applying Eq. (D.31) first to the densities of light molecules ($^{235}UF_6$) and second to the densities of heavy molecules ($^{238}UF_6$), and then by taking the ratio of those densities, one finds:

$$\frac{(n_{\text{light}}/n_{\text{heavy}})_r}{(n_{\text{light}}/n_{\text{heavy}})_R} = \exp\left[\frac{(m_{\text{heavy}} - m_{\text{light}})v^2}{2k_BT}\left(1 - \frac{r^2}{R^2}\right)\right] \tag{D.32}$$

Note that the amount of separation that can be produced by centrifugation in Eq. (D.32) only depends on the difference of the isotope masses, not their ratio as was the case for gaseous diffusion in Eq. (D.29). The difference in masses between uranium isotopes is several mass units, yet their ratio is only a minute fraction over unity, so centrifugation is inherently superior to gaseous diffusion for uranium enrichment.

To better see the efficacy of centrifugation, one can use Eq. (D.32) with a mass difference of 3 atomic mass units (the difference between uranium-238 and uranium-235) and a temperature of 340^oK (just comfortably above the sublimation point of UF_6):

$$\frac{(n_{\text{light}}/n_{\text{heavy}})_r}{(n_{\text{light}}/n_{\text{heavy}})_R} \approx \exp\left[\left(\frac{v}{1370\text{ m/sec}}\right)^2\left(1 - \frac{r^2}{R^2}\right)\right] \tag{D.33}$$

Using rough estimates of $v = 500$ m/sec (4800 revolutions per minute and $R = 0.1$ m) and $r/R = 0.8$, Eq. (D.33) yields

$$\frac{(n_{\text{light}}/n_{\text{heavy}})_r}{(n_{\text{light}}/n_{\text{heavy}})_R} \approx 1.049 \tag{D.34}$$

As shown by Eq. (D.34) vs. Eq. (D.29), the enrichment that can be obtained by one stage of gas centrifugation is $\sim$ 10x greater than that obtained from one stage of gaseous diffusion. Therefore, enrichment of natural uranium to reactor-grade material can be accomplished by $\sim$ 100 gas centrifuge stages vs. $\sim$ 1000 gaseous diffusion stages.

Each gas centrifuge also uses at least $\sim$ 2x less energy than each gaseous diffusion stage (due to the large pressure loss across each diffusion barrier), so enrichment via centrifuges consumes at least $\sim$ 20x less energy than enrichment via gaseous diffusion.

Because of these advantages, centrifuges are now the worldwide standard for enrichment (pp. 3549–3553).

Actual gas centrifuges are considerably more complicated than indicated by the schematic illustration in Fig. D.1030(c) or the simplified calculations above. Among other complexities, they include mechanisms to induce gas circulation within the chamber to optimize isotope separation while allowing for continuous throughput [Benedict et al. 1981; Glaser 2008; Kemp 2009, 2012, 2017].

Using information from these references and comparing to Table D.8 for electromagnetic separators, Table D.9 shows the extrapolated characteristics of a hypothetical German centrifuge separation plant. For this table, it has been assumed that the plant requires less than 1 worker per shift (3 shifts/day) per centrifuge, and less than 9 m^2 of floor space per centrifuge. For the same uranium enrichment rate, a centrifuge plant should have less than the cost of an electromagnetic separation plant (which has expensive electromagnets and ion beams), and less than 1/20 the electrical

consumption of a gaseous diffusion plant (which in turn has less electrical consumption than an electromagnetic separation plant).

A German centrifuge separation plant as outlined in Table D.9 would have consumed less than 1 MW of electrical power, which corresponds to:

- Less than 0.00625% of the 16 GW electrical capacity known to remain in use in the Greater German Reich at the end of 1944, or
- Less than 0.00455% of the 22 GW known wartime electrical capacity in the Greater German Reich, or
- Less than ∼0.00227% of the ∼44 GW estimated total electrical production capacity that was available to aid Germany during the war.

If that same production capacity were distributed among several production plants to minimize the risk of Allied bombing (as confirmed in 1944 by the leading German industrialist Adolf Schneider, p. 4400), each plant would have been even smaller than indicated in Table D.9.

Historians need to clarify exactly how far gas centrifuge technology progressed in Germany during the war, how many gas centrifuges were used and where they were located, and how much uranium of what enrichment percentage was produced in the Third Reich. The critical role of German scientists and engineers in spreading this technology to other countries after the war also deserves to be much better known than it currently is.

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

Table D.9: Extrapolated characteristics of a hypothetical German centrifuge separation plant.

D. Laser Isotope Separation

By 1930 or earlier, groups of scientists within the German-speaking world began developing two (apparently) separate technologies: (1) photochemical methods of separating isotopes using inefficient plasma lamps (p. 3664) and (2) lasers as an efficient monochromatic light source (Section C.3). During and after the Third Reich, both technologies were transferred to other countries, where decades later they were combined to create laser isotope separation.

The mass of the nucleus has a very small but measurable effect on the energy levels of orbiting electrons, termed the hyperfine interaction in quantum physics, so different isotopes of the same element have slightly different energy levels and thus can be excited by photons at slightly different wavelengths. As shown in Fig. D.1030(d), this principle can be used to separate different isotopes when they are in the form of either individual atoms or molecules:

- In Atomic Vapor Laser Isotope Separation (AVLIS), pure uranium metal is heated to 2300^{o}C to vaporize it. Due to hyperfine interactions, the wavelength to elevate one electron to an excited state is 502.74 nm for ^{235}U but 502.73 nm for ^{238}U. Therefore a dye laser precisely tuned to 502.74 nm can excite ^{235}U atoms in the vapor without affecting ^{238}U. Photons with a wavelength of 262.5 nm from a second laser have enough energy to ionize (completely free the one excited electron) the excited ^{235}U but not the unexcited ^{238}U atoms. Electric and/or magnetic fields can remove the singly charged ^{235}U while leaving the neutral ^{238}U, as illustrated in Fig. D.1030(d). In practice, charge exchange between the two isotopes leads to some neutral ^{235}U and some charged ^{238}U, limiting the enrichment that can be achieved by one pass through an AVLIS system. Even so, natural uranium can be enriched to reactor-grade levels in one or at most a few passes, versus $\sim$ 100 for centrifugation and $\sim$ 1000 for gaseous diffusion. Moreover, AVLIS is precise enough that it can even harvest the small amount of ^{235}U that remains in the depleted uranium tails left by diffusion or centrifugation enrichment plants. For a given quantity of uranium and degree of enrichment, the input energy cost of AVLIS is roughly comparable to that of gas centrifuges, while the equipment cost is potentially lower, since the cheaper cost of a centrifuge vs. the laser setup is outweighed by the far larger number of centrifuges required for comparable enrichment.

- In Molecular Laser Isotope Separation (MLIS), UF_6 gas is used, just as it is for enrichment by diffusion and centrifugation. This is a great advantage over AVLIS, since UF_6 must only be heated to 56^{o}C to become a gas (vs. 2300^{o}C for pure uranium). However, UF_6 molecules must then be cooled to 30–77^{o}K to put them into their vibrational ground state, which largely conflicts with the goal of keeping them in the gaseous phase instead of solid phase [Benedict et al. 1981]. If this can be accomplished, photons from a carbon dioxide laser with a wavelength of 16 μm can be used to boost $^{235}UF_6$ (but not $^{238}UF_6$) molecules to the first excited vibrational state. Photons with a wavelength of 308 nm (or in some implementations, an infrared wavelength) from an excimer laser can then dissociate the excited $^{235}UF_6$ molecules (but not the unexcited$^{238}UF_6$ molecules) into UF_5 plus atomic fluorine. Under these conditions, UF_5 is a solid, so ^{235}U precipitates out in the solid pentafluoride phase, whereas ^{238}U remains in the gaseous hexafluoride phase. An improved version of this process, Separation of Isotopes by Laser Excitation (SILEX) apparently overcomes the previously conflicting requirements of MLIS by using the difference in electrical charge between the two laser-irradiated isotopes to separate them, but details of SILEX are still classified.

Much more archival research is needed to explore how far wartime German programs on photochemical isotope enrichment progressed, how far wartime German programs on lasers progressed, whether there were any connections between those two wartime programs, and exactly how those wartime German programs influenced postwar work in other countries.

D.15.3 Breeding Methods to Produce Pu-239 or U-233

As discussed in the previous section, enrichment of uranium is difficult due to the fact that highly fissionable uranium-235 and relatively inert uranium-238 are chemically identical and very close in mass. In contrast, one can use a fission reactor or a particle accelerator to breed highly fissionable plutonium-239 from natural uranium-238, or highly fissionable uranium-233 from natural thorium-232, then exploit the differences in chemical properties between the bred fission fuel and the natural starting material in order to rapidly purify the fuel for a bomb.[30] This section discusses (a) the fundamental nuclear physics of creating plutonium-239 and uranium-233, (b) how a fission reactor could be used to breed either fuel, (c) how a particle accelerator could be used to breed either fuel, and (d) what chemical processes could be used to separate the bred fuel from the natural starting material.

A. Fundamental Nuclear Physics of Creating Plutonium-239 and Uranium-233

By mass, approximately 99.275% of natural uranium is uranium-238 ($^{238}_{92}$U), which will not fission unless it is hit with high-energy (at least a few MeV) neutrons. However, if uranium-238 is irradiated with low energy neutrons, such as in a fission reactor, it can absorb a neutron (n) and release the excess energy as a gamma (γ) ray, then undergo two successive beta (β) decays to become plutonium-239 ($^{239}_{94}$Pu), which is an excellent fission fuel:

$$^{238}_{92}\mathrm{U} + \mathrm{n} \xrightarrow{(\mathrm{n},\gamma)} {}^{239}_{92}\mathrm{U} \xrightarrow{\beta\ 23.5\ \mathrm{min}} {}^{239}_{93}\mathrm{Np} \xrightarrow{\beta\ 2.36\ \mathrm{days}} {}^{239}_{94}\mathrm{Pu} \tag{D.35}$$

The two beta decays to plutonium-239 happen within a few days, which means that they tend to happen before the fuel is removed from the breeding reactor, or within a few days of being removed from the breeding reactor. Many highly radioactive isotopes with short half-lives are created by fission of uranium-235 in the fuel, so it is customary to let the fuel "cool off" for a month or so after being removed from the breeder reactor before it is processed by people. Since the German nuclear program would have had a great sense of urgency and likely did not value the lives of its low-level workers, it might have processed irradiated fuel with a much shorter cooling off period.

If uranium-238 were irradiated with low-energy neutrons for a long enough period of time, most of it would convert to plutonium-239. Unfortunately, two problems greatly limit how long the uranium-238 can be exposed to neutrons, and therefore how much of it can be converted to plutonium-239. If significant amounts of plutonium-239 build up in the sample, slow neutrons will make them undergo fission reactions and burn up before they can be removed and purified for use in a bomb. Yet even before that effect becomes a problem, a second constraint is even more limiting: plutonium-239 that absorbs a neutron but does not fission becomes plutonium-240:

$$^{239}_{94}\mathrm{Pu} + \mathrm{n} \longrightarrow {}^{240}_{94}\mathrm{Pu} + \gamma \tag{D.36}$$

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

Plutonium-240 is chemically identical to plutonium-239 and only one atomic mass unit different in mass, making these plutonium isotopes even harder to separate from each other than uranium-235 and uranium-238 (with three mass units of difference). Thus most bred plutonium-239 will contain some amount of contaminating plutonium-240.

Whereas plutonium-239 essentially only fissions when hit with a neutron, and therefore will wait to release its energy in a chain reaction in a bomb, plutonium-240 sometimes fissions spontaneously. The neutrons that are constantly emitted by this spontaneous fission of plutonium-240 could initiate a fission chain reaction too soon as the critical mass of a bomb is being brought together, greatly decreasing the net energy release of the bomb. A gun-type (Little Boy) bomb design assembles the critical mass too slowly to overcome this problem; only an implosion (Fat Man) bomb design can assemble the critical mass rapidly enough before the spontaneous fission events hinder the process.

Even with an implosion bomb design, it is important to minimize the amount of plutonium-240 contamination and the spontaneous fission rate, so for weapons production, typically uranium-238 is irradiated with neutrons only until <0.01% of the uranium-238 has become plutonium-239. That means that an enormous amount of (highly radioactive) irradiated uranium must be chemically processed to recover a small amount of plutonium.

In addition to uranium, another actinide that can be mined in useful quantities is thorium, virtually all of which is thorium-232 ($^{232}_{90}$Th). While thorium-232 itself is not a good fission fuel, if it is irradiated with low energy neutrons, such as in a fission reactor, it can absorb a neutron and release the excess energy as a gamma ray, then undergo two successive beta decays to become uranium-233 ($^{233}_{92}$U), which is an excellent fission fuel:

$$^{232}_{90}\text{Th} + \text{n} \xrightarrow{(\text{n},\gamma)} {}^{233}_{90}\text{Th} \xrightarrow[\beta]{21.8\,\text{min}} {}^{233}_{91}\text{Pa} \xrightarrow[\beta]{27.0\,\text{days}} {}^{233}_{92}\text{U} \tag{D.37}$$

The processes for breeding uranium-233 in Eq. (D.37) and for breeding plutonium-239 in Eq. (D.35) are clearly highly similar, though beta decay to uranium-233 takes over ten times longer, mandating that the fuel sit for at least a month or so after being removed from the breeder reactor.

Just as the buildup of an undesirable contaminant limits how much plutonium-239 can be bred from uranium-238, the buildup of another undesirable contaminant limits how much uranium-233 can be bred from thorium-232. Neutron bombardment can actually remove a neutron from the highly desirable uranium-233, converting it to the highly undesirable uranium-232:

$$^{233}_{92}\text{U} + \text{n} \longrightarrow {}^{232}_{92}\text{U} + 2\text{n} \tag{D.38}$$

Uranium-232 undergoes a series of alpha (α) decays with a net half-life of roughly 70 years, producing thallium-208 which emits intense gamma rays. Although that process does not interfere with fission reactions, steady decay of contaminating uranium-232 into gamma-emitting thallium-208 means that bred uranium-233 is intensely radioactive and harmful to people working with it, and remains that way for many years after its creation. Again, if the German nuclear program did not value the lives of its low-level workers, this concern may not have limited their use of this method of fission fuel production.

B. Breeding in a Fission Reactor to Produce Pu-239 or U-233

German scientists knew how to breed plutonium-239 or uranium-233 in a fission reactor, had two reactors on the brink of criticality by the end of the war (the Heisenberg group's Berlin/Haigerloch pile and the Diebner group's Gottow/Stadtilm pile), and may have had other reactors that actually became operational during the war (p. 3794). Such reactors could have used heavy water (D_2O) and/or pure graphite (without neutron-absorbing boron impurities) as a moderator to slow down the neutrons emitted by the fission reactions, so that the neutrons would be much more likely to create a chain reaction and also to breed plutonium-239 (or uranium-233).

In the wartime U.S. nuclear program, the main reactors breeding plutonium were three reactors in Hanford, Washington, dubbed reactors B, D, and F. When fully operational, each of those reactors produced approximately 250 MW of thermal power from approximately 250 tons of natural uranium, or about 1 MW/ton [Bruce Cameron Reed 2015a, 2019]. None of that energy was converted to electricity as in a modern power reactor; water was used to cool the reactor and carry the heat away, so the reactors needed direct access to large quantities of fresh water.

At that power, each reactor bred approximately 0.19 kg of plutonium-239 per day, or approximately 69 kg per year. To limit the production of plutonium-240, the 250 tons of reactor fuel was removed after approximately 100 days, and then the reactor was restarted with fresh natural uranium fuel [Bruce Cameron Reed 2015a, 2019]. Comparing the plutonium-239 production rate of 0.19 kg/day to the rate of using natural uranium, 250 tons/100 days = 2.5 tons/day, the amount of plutonium-239 bred per ton of natural uranium was

$$\frac{\text{Bred Pu-239}}{\text{Natural uranium}} \approx \frac{0.19 \text{ kg/day}}{2.5 \text{ tons/day}} \approx 0.076 \frac{\text{kg}}{\text{ton}} \tag{D.39}$$

Note that the amount of fissionable plutonium-239 produced from a ton of natural uranium is roughly 100 times smaller than the maximum amount of fissionable uranium-235 (7.2 kg) that could be extracted from that same ton of natural uranium via the enrichment methods of the previous section. Again, this low level of production is due to the need to avoid creating much plutonium-240 in the fuel. As a result, a fission fuel breeding program would use ∼100 times more uranium than a fission fuel enrichment program (unless the irradiated uranium were reused in the breeder reactor after the plutonium had been removed, but that would be even more time consuming, and a wartime program would presumably be under extreme time pressure).

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

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

Table D.10: Approximate characteristics of a breeder reactor for producing plutonium-239.

As long as the reactor is large enough to have a self-sustaining fission chain reaction, these characteristics can be scaled up or down in a linear fashion, using the approximate numbers in Table D.10 as a basis for reference [Kemp 2005; OTA 1977]. For example, if each Hanford reactor held 250 tons of natural uranium and produced approximately 69 kg of plutonium-239 per year, a hypothetical German reactor holding approximately 22 tons of natural uranium could produce approximately 6 kg of plutonium-239 per year, enough for one full-sized ∼20 kiloton implosion bomb (like the U.S. Gadget and Fat Man bombs) per year. From Eq. D.39, producing 6 kg of plutonium would require processing approximately 79 tons of uranium.

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

C. Breeding with an Accelerator to Produce Pu-239 or U-233

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

If the target is lithium without uranium or thorium, electronuclear breeding can be used to produce tritium, which would be very useful for fusion boosting of fission bombs or for creating a hydrogen bomb.

Electronuclear breeding was seriously pursued by the United States and other countries after World War II, and even now is of concern as a proliferation risk for how new countries could produce nuclear weapons.[31] German scientists knew how to breed plutonium-239 (or uranium-233) in a particle-accelerator-driven electronuclear system, and built and operated suitable accelerator systems (pp. 3954–4022 and 4504–4510) that appear to have been a high priority part of the wartime German nuclear program.

Simple physics can give a ballpark estimate for the amount of Pu-239 or U-233 that could be produced by electronuclear breeding. If N is the number of particle accelerators, I is the beam current per particle accelerator, and $e \approx 1.602 \times 10^{-19}$ Coulombs is the electric charge of particles (protons, deuterons, or electrons) in the beam, the total number of charged particles per second is simply NI/e. Since there are $365 \times 24 \times 60 \times 60 = 3.1536 \times 10^7$ seconds per year, the annual charged particle production rate is

$$\frac{\text{Charged particles}}{\text{year}} \;=\; 3.1536 \times 10^7 \; \frac{N\,I}{e} \;\; \frac{\text{particles}}{\text{year}} \tag{D.40}$$

Let η be the number of bred Pu-239 or U-233 atoms per accelerated charged particle, or in other words the efficiency of converting accelerated charged particles to neutrons and then letting those neutrons be captured to breed the desired atoms. Thus the atom breeding rate is

$$\frac{\text{Bred atoms}}{\text{year}} \;=\; 3.1536 \times 10^7 \; \frac{N\,I\,\eta}{e} \;\; \frac{\text{atoms}}{\text{year}} \tag{D.41}$$

Using Avogadro's number $N_A \approx 6.022 \times 10^{23}$ and the mass A of the bred atoms in atomic mass units, there are N_A/A atoms per gram of mass, or $1000N_A/A$ atoms/kg. Combining this information with Eq. (D.41), the annual production rate of mass is

$$\frac{\text{Bred mass}}{\text{year}} \;=\; 3.1536 \times 10^4 \; \frac{N\,I\,\eta\,A}{e\,N_A} \;\; \frac{\text{kg}}{\text{year}} \tag{D.42}$$

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

Space charge effects and other phenomena generally limit practical values of the beam current to around a milliamp, or $I \approx 10^{-3}$ amp [Kemp 2005]. For 10 accelerators operating in parallel to breed Pu-239 ($A = 239$) with an efficiency $\eta \sim 1$, Eq. (D.42) becomes

$$\frac{\text{Bred Pu-239}}{\text{year}} \sim 0.78 \frac{\text{kg}}{\text{year}} \tag{D.43}$$

Similarly, for 10 accelerators with $I \approx 10^{-3}$ amp breeding U-233 ($A = 233$) with an efficiency $\eta \sim 1$, Eq. (D.42) gives

$$\frac{\text{Bred U-233}}{\text{year}} \sim 0.76 \frac{\text{kg}}{\text{year}} \tag{D.44}$$

Likewise, for 10 accelerators with $I \approx 10^{-3}$ amp breeding tritium ($A = 3$) with an efficiency $\eta \sim 1$, Eq. (D.42) becomes

$$\frac{\text{Bred tritium}}{\text{year}} \sim 9.8 \frac{\text{g}}{\text{year}} \tag{D.45}$$

From these crude estimates, a year-long electronuclear breeding program could produce ~ 0.8 kg of plutonium-239 or uranium-233, or ~ 10 g of tritium. The equations reveal several ways to improve this output:

- The German program could have built and operated more than 10 particle accelerators in parallel. That is not unreasonable, considering that the United States built and operated 3120 calutron ion beams at Oak Ridge for U-235 enrichment.
- The beam current might have been increased. 1 mA per beam is a representative value but not a hard limit. Increasing the beam current by a factor of two or three would correspondingly increase the amount of bred fission fuel by a factor of two or three.
- The German program might have operated particle accelerators for longer than a year. If the accelerators began operation two years before the end of the war, twice as much fuel could have been produced.
- Most importantly, the efficiency η could have been optimized. Depending on the conditions, the efficiency could be as low as $\eta \sim 0.001$ or as high as $\eta \sim 100$ [Kemp 2005]. Using the highest possible beam energy, choosing the best type of charged particle for the beam (in some cases, deuterons work better than protons or electrons), and using a neutron-multiplying target could give efficiencies toward the upper end of that range. A neutron-multiplying target would essentially be a small, subcritical fission reactor, for example chunks of unenriched uranium metal immersed in heavy water and surrounded by a beryllium reflector. Whereas the reactor would not be large enough to create its own self-sustaining chain reaction of fission events, each neutron generated by the accelerator would trigger a small cascade of additional neutrons in the subcritical reactor, yielding several bred atoms per initial neutron.

Based on this simple analysis, it is evident that electronuclear breeding of kilograms of plutonium-239 or uranium-233 for a fission bomb, or of grams of tritium for fusion boosting a bomb, would be technically challenging but nevertheless quite feasible for the wartime German program. It is important for historians to search for more evidence of such an electronuclear breeding program, both in archival documents and at locations that may have been involved in this work.

D. Chemical Reprocessing to Purify Bred Pu-239 or U-233

In nuclear power programs, chemical reprocessing of "spent" fuel that has been in a fission reactor is used to recover plutonium-239 that has been bred during the time in the reactor, as well as any leftover uranium-235 that was not burned up inside the reactor. Those fissionable fuel components can be repackaged and used again for reactor fuel; uranium-238 can also be recycled. Many other actinides in the fuel can be recycled without adversely affecting the repackaged reactor fuel. For nuclear weapons programs, the same techniques may be used to extract and concentrate the plutonium-239 from a uranium reactor (or from an electronuclear breeding particle accelerator) to make high-grade fuel for fission bombs.

Documents show that German scientists knew how to produce plutonium-239 from uranium-238 (p. 3794) and how to produce uranium-233 from thorium-232 (p. 3832), and knew that both of those fission fuels would be suitable for bombs. If one or more fission reactors were operational before the end of the war (p. 3794), or if accelerators were able to produce a significant amount of fission fuel (p. 3954), it seems likely that Germany would have developed and utilized chemical reprocessing methods to extract and purify the bred plutonium-239 or uranium-233. In fact, in the highly fragmentary documentation that is now available to scholars shows that there was in fact work to develop such reprocessing methods (p. 3826).

Although it is current unknown just how far that work may have progressed during the war, or in what geographic locations, the scientific details of reprocessing constrain where and how it could have been done, and may guide historians in locating relevant documents and geographic sites:

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

- Because of the large amount of spent uranium that would need to be processed for a much smaller amount of plutonium, and because of the great personal danger involved in exposure to the associated high levels of radiation and toxic chemicals, it moreover seems likely that any such work in wartime Germany would have involved slave labor (at least if it advanced beyond small-scale proof-of-concept laboratory experiments).

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

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

The most widely used chemical method for reprocessing spent fission fuel is called the PUREX (Plutonium Uranium Reduction EXtraction) process. Although it is quite complex [Benedict et al. 1981], a very simplified overview is illustrated schematically in Fig. D.1033. This description covers modern reprocessing for nuclear power programs, but a wartime weapons program would use very similar (or perhaps streamlined) steps:

1. Spent fuel rods are soaked in hot nitric acid, which dissolves uranium, plutonium, and fission products, but not zirconium alloy claddings and other hardware. Thus non-fuel reactor materials can be separated out for waste disposal. Gaseous fission products are also removed at this time.

2. Then the polar aqueous nitric acid solution containing uranium nitrates, plutonium nitrates, and fission-product nitrates is mixed with a nonpolar organic solvent, which is a kerosene-like mixture containing *n*-tributyl phosphate (TBP). At this point, uranium is in a hexavalent state (VI) and plutonium is in a tetravalent state (IV), both of which prefer to pass into the nonpolar TBP layer of the immiscible polar-nonpolar fluid combination. In contrast, the fission products are generally in a pentavalent state (V) and prefer to remain in the polar nitric acid layer, so they can be separated out, concentrated, and vitrified for disposal as high-level radioactive waste.

3. The TBP organic solution containing uranium and plutonium is treated with a limited reductant (such as ferrous ions, Fe^{+2}), which reduces plutonium (IV) to plutonium (III) but leaves the uranium (VI) unaffected. The nonpolar organic solvent is again mixed with polar aqueous nitric acid. The uranium (VI) still prefers the nonpolar solvent, but unlike plutonium (IV), plutonium (III) actually prefers the polar solvent. Thus plutonium and uranium can be separated for individual processing.

4. Uranium nitrate is purified from the nonpolar solvent and converted to uranium hexafluoride for enrichment if desired.

5. Plutonium nitrate is purified from the polar solvent and converted to plutonium dioxide for reactor fuel or plutonium metal for bombs.

In practice, up to three rounds of polar-nonpolar solvent purification are used to achieve high purity of the fission product, uranium, and plutonium fractions.

A similar reprocessing method used for separating thorium, uranium, and fission products from spent fuel in thorium-232/uranium-233 fuel cycles is called the Thorex process [Benedict et al. 1981]. By means of this process, one could supply a fission reactor or electronuclear breeding accelerator with natural thorium-232 and produce high-grade uranium-233 for fission bombs.

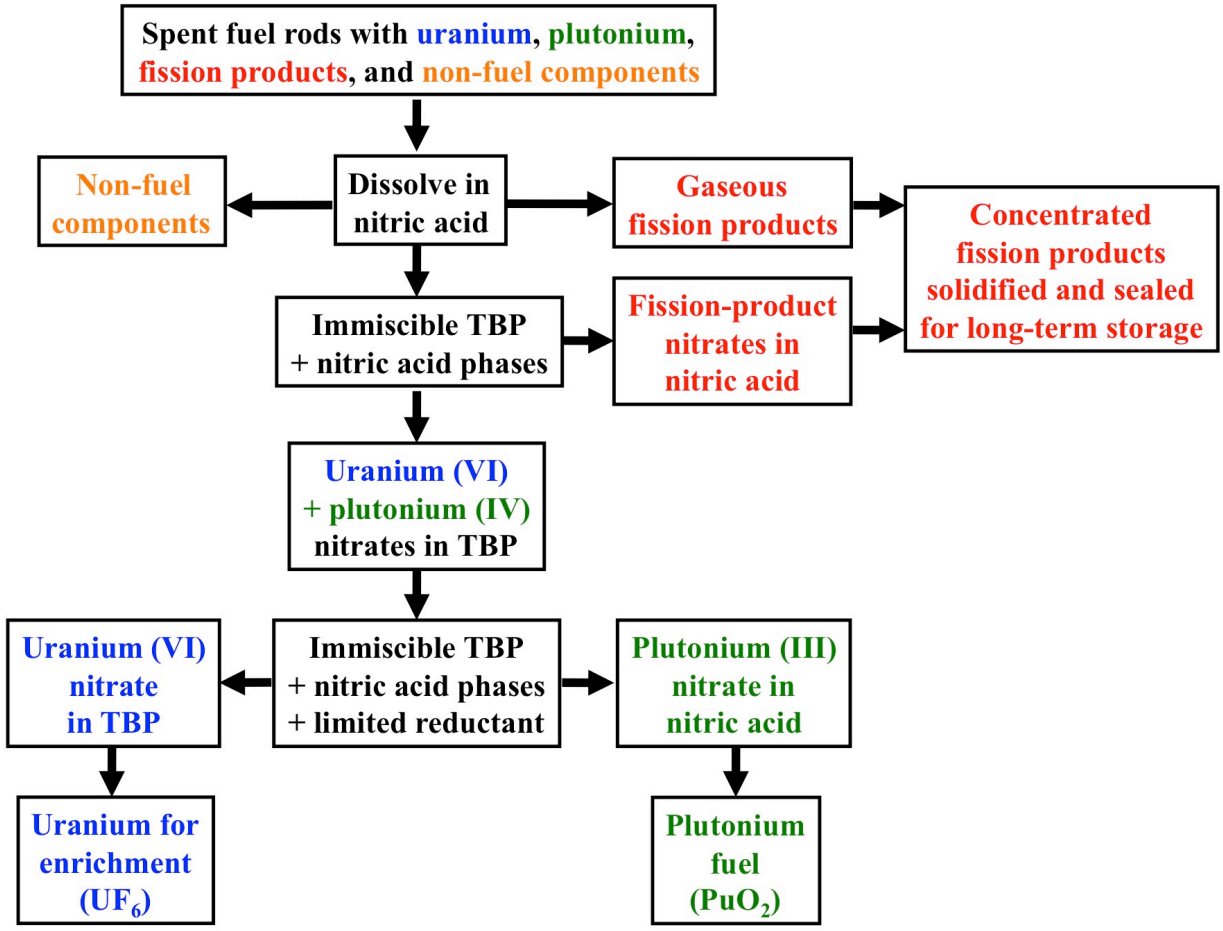

Figure D.1033: Chemical reprocessing of spent fission fuel, often called the PUREX (Plutonium Uranium Reduction EXtraction) process.

D.15.4 Analysis of Test Explosions from Primary Sources

While there are many potential metrics for the progress of the German nuclear program, the definitive litmus test would be a successful wartime nuclear weapons test. Of the alleged Baltic, Polish, and Thuringian test explosions described by the primary sources quoted earlier in this appendix, there is the largest amount of evidence for the Thuringian test, including numerous details that may be subjected to scientific analysis. Without discounting the other possible tests, the remainder of this discussion will focus on analyzing all of the currently available details about that March 1945 Thuringian test.

A. Primary Sources Used for the Analysis

Several of the primary sources provided general background information for the March 1945 Thuringian test. Wartime and postwar documents showed that within the top echelons of the SS, there was a prolonged and intense interest in developing a nuclear weapon, and an expectation around March 1945 that battlefield use of such a weapon was imminent. Likewise, wartime and postwar documents from Diebner, Schumann, Trinks, Guderley, and others confirmed that there were very active research programs on fission reactions, fission fuel production, fusion reactions, fusion fuel production, and spherical implosion bomb designs. How far those programs got, and whether or how they were combined together, is very unclear from the primary sources themselves, but perhaps answerable at least in part by modern theoretical and/or experimental analysis of the available data.

As summarized on p. 4480, at least ten primary sources specifically addressed the Thuringian test:

1-2. Ilyichev's November 1944 and March 1945 Soviet intelligence reports described the preparations for the Thuringian tests, the immediate consequences of the tests, and the detailed design of the nuclear device that was supposedly tested. The authenticity of the documents appears beyond doubt, since they are part of an extended paper trail that includes published responses by Kurchatov and Flerov, and that went all the way to Joseph Stalin. Furthermore, since the documents cast doubt on the Soviet Union's claim to be the second nuclear nation or to have achieved that status by its own scientific strength, there appears to be no incentive for Russians of any time period to have forged or embellished them. Likewise, these reports do not appear to have been a German attempt to bluff the Russians into believing that the Germans possessed a weapon that they did not actually have; a bluff would surely have claimed that the test explosion was much larger, and would not have handed the Russians a highly detailed and very effective design for a fission bomb. Of course, despite the authenticity of these documents, how accurate or inaccurate they may be depends on the competence of the unknown Soviet spy who transmitted the details from Germany.

3-4. Kurchatov's March 1945 letter and Flerov's two brief reports from May 1945 repeated many of the details from Ilyichev's second report, supporting the authenticity of that document. Most of their information was directly derived from Ilyichev's second report (which did not give a specific location for the nuclear test). However, the fact that by May 1945 Kurchatov and Flerov apparently knew of a specific location where they wanted to measure residual artificial radioactivity seems to indicate that they had received additional information not in Ilyichev's November 1944 and March 1945 reports.

5. Robert Döpel's testimony under interrogation by the Russians in 1946 confirms that there was an atomic bomb test on a German military base (such as those in Thuringia) before the end of the war. Unfortunately the only Russian interrogation summary that has been found thus far does not give any further details.

6-7. The testimonies of Werner and Wachsmut described the Thuringian test and its immediate aftermath. Although the 1962 East German transcript's chain of custody is uncertain and hence its authenticity is difficult to prove, the written testimonies by Werner and Wachsmut are consistent with oral testimonies that they each gave later in life, consistent with each other, consistent with details from the other sources that reported the Thuringian test, and consistent in appearance with other East German interrogation transcripts from that place and time. As will be shown, they are also highly consistent with the physics of nuclear weapons, in ways that would not have been possible for Werner and Wachsmut, their interrogators, or a document forger to foresee. Therefore, the testimonies of Werner and Wachsmut will be included in the discussion here with appropriate caution. These two testimonies are the only sources that named a specific location for the Thuringian test, but otherwise the basic facts of the Thuringian test do not depend upon their testimonies.

8. The 1966 East German reports on the interrogation of Erich Rundnagel appear to be authentic and were confirmed by Rundnagel's nephew. Although Rundnagel did not address the actual test, he gave details that seem relevant to the bomb design and preparations.

9. Oscar Koch's 1960s description of a high-level 1945 U.S. intelligence report appears as credible as the Soviet intelligence report. Although it gave fewer details than Ilyichev's reports, those that it did contain are highly consistent with those given by Ilyichev. The most puzzling aspect is that Koch stated that U.S. aerial surveillance photos did not show the blast damage that had been reported in the test area. Some plausible explanations are (a) that the Germans quickly replanted, restored, cleaned, or camouflaged the affected area, (b) that the aerial surveillance photos were not of the correct location, and/or (c) that the Americans were looking for much larger-scale blast damage than the Thuringian test actually produced.

10. The interviews with Grothmann described many details about the Thuringian test, its background, and its aftermath. Major caveats are that the interviews were conducted in private, that they were held 55–57 years after the events in question, and that tapes of the interviews were erased. Nonetheless, historians have been able to independently confirm a large number of obscure details covered in the interviews [Karlsch and Petermann 2007, p. 29; Karlsch 2006; Nagel 2011, p. 64], and scientific details from the interviews are very consistent with known physics and engineering principles, even though Grothmann was not a scientist or engineer. Grothmann provided information that is in excellent agreement with Ilyichev's reports, which were discovered in a Moscow archive only after Grothmann had already died, and Grothmann's statements agree with other sources about the secret wartime programs that have only emerged in recent years. For a more extensive discussion of the reliability of this source, see pp. 3396–3397.

As shown on p. 4480, there is remarkably good agreement among these ten primary sources about the details of the test date, location, organizations or people who were involved, blast, radioactivity, resulting casualties, and device design. Those details will next be used as the basis for preliminary theoretical estimates of the explosive yield, radioactive release, and device design parameters.

Figure D.740 is a map of the Ohrdruf and Arnstadt area that was possibly involved in the March 1945 test. In Fig. D.741, colored lines illustrate clues to the location of the test as described by Werner and Wachsmut. These clues include the approximate boundary of the military base (green), population centers with possible sickness from radioactive fallout (red), the direction in which Werner reported seeing the explosion (yellow), driving distances for Wachsmut from the Ringhofen estate (blue), and the location of an apparent crater on aerial photos from pp. 4541–4545 (purple). Note that those clues place the test roughly in the center of the Ohrdruf military base, which would also make sense from a security perspective.

If information from Werner and Wachsmut is excluded from the analysis, the key facts and data regarding the nuclear test remain the same, except the exact location in Thuringia is then unknown. Based solely on the other sources, the test might have occurred on the Ohrdruf military base, or it might have occurred in some other remote wooded location in Thuringia that could be tightly secured by the SS (likely a military base).

B. Estimating Explosive Yield from Primary Sources

Simple estimates of the relationship between the energy released in an explosion and the radius of damage caused by that explosion can easily be made from first principles. The explosion will be assumed to release an energy E at a point source at radial position $r = 0$ at or very near the surface of the earth, surrounded by atmosphere of initial pressure $p_{\rm atm}$, as shown in Fig. D.1034. For reference, one ton of TNT high explosive is defined to produce an energy of 4.184×10^9 Joules (J) (although the actual yield from real TNT can vary somewhat around this value). The energy of the explosion will be distributed throughout a hemispherical volume of ever-expanding radius R, where the surface at $r = R$ is a shock wave propagating outward into the atmosphere. Using the volume $(2/3)\pi R^3$ of the hemisphere and defining the average energy density deposited within the hemispherical volume as $U_{\rm avg}$, the explosive energy yield may be written as

$$E \;=\; \frac{2}{3}\,\pi\,R^3\,U_{\rm avg} \tag{D.46}$$

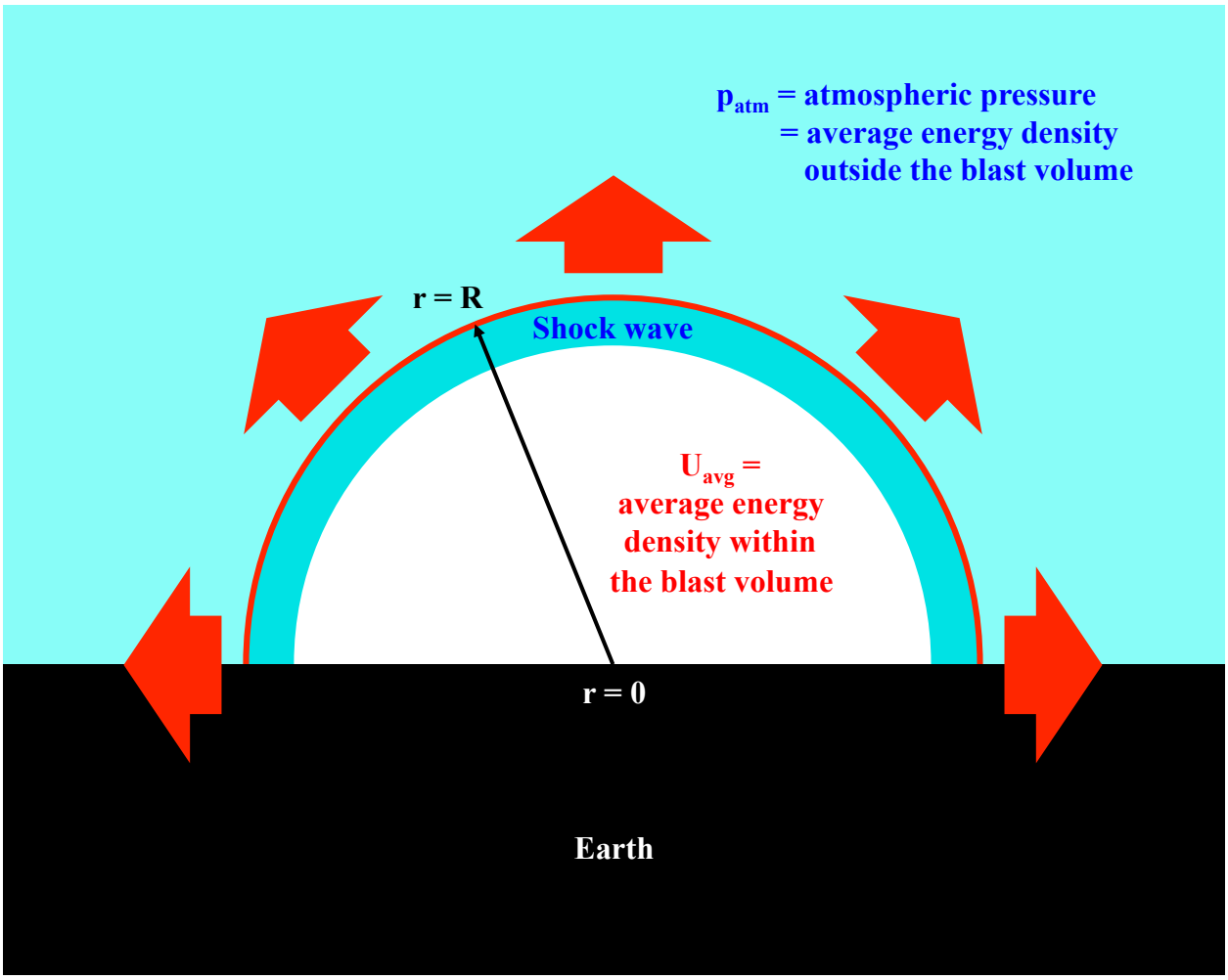

Figure D.1034: Hemispherical shock wave expanding from an initial point on the earth's surface.

Since the total energy E is constant (neglecting any losses), the average energy density U_{avg} of the explosion will decrease as the explosion radius R increases with time. The explosion will be the dominant force in the local environment until its average energy density drops below the pressure-derived potential energy density of normal atmospheric pressure, $p_{\text{atm}} \approx 1.01 \times 10^5$ Pascals (Pa=J/m^3) (using the sea-level average pressure). Of course, the shock wave at the expanding surface contains more energy density than the volume-averaged value, and the explosive energy density can do serious damage to buildings, trees, and people even when it is only a fraction of normal atmospheric pressure.

If one assumes that the explosion will do major damage until the average energy density drops to $U_{\text{avg}} \approx p_{\text{atm}}/10$ at some blast radius $R = R_{\text{blast}}$, the energy from Eq. (D.46) may be written as:

$$\begin{aligned} E_{\text{max}} &\approx \frac{2}{3}\pi R_{\text{blast}}^3 \frac{p_{\text{atm}}}{10} = \left(\frac{2\pi \cdot 1.01 \times 10^5 \text{ J/m}^3}{3 \cdot 10 \cdot 4.184 \times 10^9 \text{ J/ton}} \right) R_{\text{blast}}^3 \\ &\approx \left(\frac{R_{\text{blast}}}{58.3 \text{ meters}} \right)^3 \text{ tons} , \end{aligned} \tag{D.47}$$

in which Eq. (D.47) expresses the explosive energy yield in equivalent tons of TNT.

On the other hand, if one assumes that the explosion will do significant damage until the average energy density drops much further to $U_{\text{avg}} \approx p_{\text{atm}}/100$ at some blast radius $R = R_{\text{blast}}$, the explosive yield from Eq. (D.46) may be written as:

$$\begin{aligned} E_{\text{min}} &\approx \frac{2}{3}\pi R_{\text{blast}}^3 \frac{p_{\text{atm}}}{100} = \left(\frac{2\pi \cdot 1.01 \times 10^5 \text{ J/m}^3}{3 \cdot 100 \cdot 4.184 \times 10^9 \text{ J/ton}} \right) R_{\text{blast}}^3 \\ &\approx \left(\frac{R_{\text{blast}}}{126 \text{ meters}} \right)^3 \text{ tons} \end{aligned} \tag{D.48}$$

For a given measured blast radius, the released explosive energy could vary somewhere between the minimum value given by Eq. (D.48) and the maximum value given by Eq. (D.47), depending on how resistant to blast damage the surround area is, deviations of the actual terrain from the assumed perfectly flat surface, and other factors. Note that Eq. (D.47) gives a maximum energy 10 times larger than the minimum energy of Eq. (D.48), since its assumed energy density is 10 times larger ($p_{\text{atm}}/10$ vs. $p_{\text{atm}}/100$). Within that range, a good single value for a ballpark approximation would be the geometric mean, found by using Eq. (D.46) with $U_{\text{avg}} \approx p_{\text{atm}}/(10\sqrt{10})$:

$$\begin{aligned} E_{\text{geo mean}} &\approx \frac{2}{3}\pi R_{\text{blast}}^3 \frac{p_{\text{atm}}}{10\sqrt{10}} = \left(\frac{2\pi \cdot 1.01 \times 10^5 \text{ J/m}^3}{3 \cdot 10\sqrt{10} \cdot 4.184 \times 10^9 \text{ J/ton}} \right) R_{\text{blast}}^3 \\ &\approx \left(\frac{R_{\text{blast}}}{85.5 \text{ meters}} \right)^3 \text{ tons} \end{aligned} \tag{D.49}$$

Cold-War-era U.S. books tended to specify blast waves in terms of the pounds per square inch (psi) of peak overpressure in the shock wave. Converted into those terms, Eq. (D.49) for the geometric mean of the explosive energy would give the blast radius for 5.1 psi (35 kPa) of peak overpressure, which is generally considered enough to demolish trees or wood-frame buildings. Likewise, Eq. (D.47) for the maximum case would correspond to a peak overpressure of 9.1 psi (63 kPa, enough

to damage or destroy even reinforced buildings), and Eq. (D.48) for the minimum case would correspond to a peak overpressure of 2.9 psi (20 kPa, enough to damage but perhaps not demolish trees or wood-frame buildings). Thus the equations derived here are highly consistent with the standard empirical equations from Cold War atmospheric nuclear tests, and Eq. (D.49) in particular should be a good guide for the level of destruction mentioned by Ilyichev.

Ilyichev described the blast radius as $R_{\text{blast}} = 500$–600 meters. Using Eqs. (D.47)–(D.49), a blast radius of $R_{\text{blast}} = 500$ meters corresponds to an explosive energy somewhere in the range E =63–630 tons, with a geometric mean of 200 tons. Likewise, the larger blast radius $R_{\text{blast}} = 600$ meters corresponds to an explosive energy somewhere in the range $E = 110$–1100 tons, with a geometric mean of 350 tons. These values are consistent with previous estimates based on the same data [Eilers 2007, 2015; Mineev and Funtikov 2007].

Ilyichev also described the bomb as having a total weight of approximately 2 tons and being filled largely with TNT. If such a bomb had exploded in a conventional, non-nuclear manner, its explosive energy would therefore be only ~ 2 tons. The absolute minimum explosive energy consistent with the reported blast radius is 30 times larger than that value, and the actual energy may well have been several hundred times greater than the non-nuclear yield of TNT alone. Thus some sort of nuclear explosion appears to be the only satisfactory explanation for the reported blast size.

An independent method of estimating the explosive energy would be to use the dimensions of the crater it created in the ground. Unfortunately, if the bomb had an explosive energy less than 1000 tons and was mounted on a tower for the test (to facilitate diagnostics, as in the first U.S. fission bomb test in New Mexico on 16 July 1945, and as described by Schumann and Grothmann), it would likely not leave a significant crater [Glasstone and Dolan 1977, p. 255]. If the aerial reconnaissance photos on pp. 4541–4545 do indeed show the correct location of the test, the suggestive ejecta pattern that is visible in the 21 March 1945 and 9 June 1945 aerial reconnaissance photos may have been the only physical trace of the blast, apart from radioisotopes.

C. Estimating Radioactive Release from Primary Sources

In addition to the reported blast radius, the reports of radioactive effects or radiation sickness by Ilyichev, Grothmann, Werner, and Wachsmut seem to suggest some sort of nuclear explosion. In theory, a nuclear explosion could be due to fission reactions alone, fusion reactions alone, or some combination of fission and fusion reactions. In the 75+ years since 1945, scientists have been unable to create a net-energy-producing pure fusion reaction without the assistance of fission reactions [Gsponer and Hurni 2009, pp. 139–141; Winterberg 2010, pp. 297–298, 302], so the possibility that the described 1945 test was a pure fusion weapon seems too remote to consider. Both pure fission and fission-fusion hybrid designs are quite possible however. Even for plausible fission-fusion hybrid weapon designs, the fraction of released energy that comes from fusion reactions is negligible. Therefore the explosive energy yield (calculated from the reported blast radius) may be used to find the amount of fission fuel consumed and hence the amount of radioactive fallout.

Fission fuel consumed

By definition, one mole (6.022×10^{23}) of uranium-235 atoms has a total mass of 235 grams. Upon fission, each atom releases approximately 180 million electron-volts (eV) of energy (not counting energy lost as neutrinos, or energy released in delayed radioactivity), which can be converted into Joules or equivalent tons of TNT energy by the conversion factors 1.602×10^{-19} J/eV and 4.184×10^{9} J/ton. Putting all of this information together, the number of grams of U-235 that must be completely fissioned to produce one ton TNT equivalent of explosive energy is:

$$\frac{(235 \text{ g})\ (4.184 \times 10^{9} \text{ J/ton})}{(6.022 \times 10^{23})\ (180 \times 10^{6} \text{ eV})\ (1.602 \times 10^{-19} \text{ J/eV})} \approx 0.0566 \ \frac{\text{grams}}{\text{ton}} \tag{D.50}$$

Ilyichev specifically said the device used U-235 as fission fuel. In principle, other fission fuels could have been used: uranium-233 (U-233, created by bombarding natural thorium-232 with neutrons), neptunium-237 (Np-237, e.g., created by knocking a neutron out of natural uranium-238), or plutonium-239 (Pu-239, creating by bombarding natural uranium-238 with neutrons). Energy values for those other fission fuels are approximately the same as that for U-235, so Eq. (D.50) can safely be used as the basis for any fission calculations.

For explosive yields in the range of 63–1100 tons with a geometric mean of 200–350 tons, as calculated in Section D.15.4, the mass of fuel completely fissioned is:

$$M_{\text{fissioned}} = \text{3.6–62 grams, with a geometric mean of 11.3–19.8 grams.} \tag{D.51}$$

Thus the best ballpark guess is that the reported explosion would have completely fissioned $\sim$ 10–20 grams of uranium. This is a very small quantity considering that nuclear weapons would normally have many kilograms of fission fuel, but Grothmann reported that only a very small amount of fuel was used in this test device, and that larger amounts of fuel were ready to be used in subsequent devices. For a small test, the total amount of fissionable fuel might have been as little $\sim$100 grams, which is very consistent with the result in Eq. (D.51), since only some fraction of the fuel would have time to fission during the very brief time that the core of the bomb was maximally compressed.

Initial radiation from the explosion

People who were very close to the test site would have been exposed to the initial radiation (gamma, neutrons, and beta) released during the actual explosion. For a fission explosion of 200–350 tons, the lethality (10 Grays or 1000 rads) radius for this prompt radiation is $\sim$ 500 meters, very comparable to the blast radius [Glasstone and Dolan 1977, p. 333]. Thus anyone present on the field where the device was tested would have been either killed immediately or left injured and dying from the blast, radiation, and heat. This is highly consistent with the reports of Ilyichev, Grothmann, Werner, and Wachsmut.

If the blast radius was 500–600 meters as reported by Ilyichev, Wachsmut's estimate of 700 bodies was correct, and those victims had been uniformly spread out within an area $\pi R^2 \sim$ 785,000–1,130,000 m^2 around the device when it was tested, the spacing would have been

$$\sim 1100\text{–}1600 \text{ m}^2 \text{ per person on average} \tag{D.52}$$

or

$$\sim 33\text{–}40 \text{ m between people if uniformly spread out} \tag{D.53}$$

Thus 700 people could have easily fit within the blast radius, even if they were spread out. It seems highly unlikely that the detonation would have been accidentally triggered at an unexpected time before people had had time to take cover. A far more plausible explanation is that the SS scattered POWs around the test area to serve as human guinea pigs to measure the effects at varying distances from the explosion.

Indeed, Ilyichev's report appears to suggest that the SS made detailed correlations of prisoners' positions before the explosion and their conditions after the explosion (p. 4485): "Prisoners of war who were near the epicenter of the explosion died, often without leaving a trace. Prisoners of war who were in the area beyond the center of the explosion have burns on their face and body, the strength of which depends on their position in relation to the epicenter of the explosion."

It is well documented that POWs were used as human test subjects for new nerve agents [Tucker 2006, p. 51] and for new biological weapons.[32] Thus the allegations made separately by Ilyichev and Wachsmut are highly consistent with what is known to have taken place in other Third Reich programs to develop weapons of mass destruction.

In fact, if the statements of Grothmann and Wachsmut are correct, the large size of the explosion and the large number of casualties for the very small amount of fission fuel used apparently surprised even the SS.

[32] Barenblatt 2004; Blome 1941; Michael Carroll 2004; Deichmann 1996; Geißler 1998a, 1998b; Gold 1997; Haagen 1941; Friedrich Hansen 1993; Sheldon Harris 2002; Kater 1989; Keremidis 2013; Klee 2001; Leitenberg and Zilinskas 2012; Posner and Ware 2000; Regis 1999; Reinhardt 2013; Vivien Spitz 2005; Tokyo War Crimes Trial 1950; U.S. Army 1956.

Radioactive fallout from the explosion

From the explosive yield and amount of fuel fissioned, one can also calculate the amount of radioactive fallout. The radioactive fallout decays rapidly, emitting 80% of its total radiation within the first 24 hours, and gradually emitting the remaining 20% over the following days, months, and years [Glasstone and Dolan 1977, p. 397]. Radioactive fallout from a 1 kiloton fission explosion, spread uniformly over a flat area of 1 square mile, would cause a radiation exposure 3 feet above the ground (the approximate center of an adult human) of 2900 rads per hour 1 hour after the explosion, or 21,750 rads total within the first 24 hours after the explosion [Glasstone and Dolan 1977, pp. 390, 395—24 hour cumulative dose is dose rate at 1 hour multiplied by 7.5 hours due to decay]. Converting that information from kilotons to tons, from square miles to km^2, and from rads to Grays (Gy, where 1 Gy=100 rads), one finds:

$$1 \ \frac{\text{ton}}{\text{km}^2} \implies 0.0751 \ \frac{\text{Gy}}{\text{hr}} \ \text{at 1 hour averaged over area} \tag{D.54}$$

$$\implies 0.563 \ \text{Gy} \ \text{within 24 hours averaged over area} \tag{D.55}$$

As calculated in Section D.15.4, the explosive yield had a geometric mean of 200–350 tons. The area over which the corresponding amount of fallout would be distributed could vary significantly depending on local winds and topography, but a plausible ballpark estimate for the affected region might be a ~ 10 km $\times \sim 10$ km area, or ~ 100 km^2. Taken together, those estimates give an average of 2–3.5 tons/km^2, and Eqs. (D.54)–(D.55) can be scaled accordingly:

$$2\text{–}3.5 \ \frac{\text{tons}}{\text{km}^2} \implies 0.150\text{–}0.263 \ \frac{\text{Gy}}{\text{hr}} \ \text{at 1 hour averaged over area} \tag{D.56}$$

$$\implies 1.13\text{–}1.97 \ \text{Gy} \ \text{within 24 hours averaged over area} \tag{D.57}$$

Gamma and beta radiation emitted by fission products in the fallout would begin to produce noticeable symptoms of radiation sickness after a cumulative exposure of ~ 1 Gy, very serious illness at ~ 2 Gy, and fairly consistent lethality (within hours or days after exposure) at ~ 10 Gy [Glasstone and Dolan 1977, pp. 575–587, using 1 rad $\approx$ 1 rem or 1 Gray $\approx$ 1 Sievert for gamma, beta, and neutrons]. Thus the expected average dose from Eq. (D.57) falls perfectly within that 1–2 Gy window for noticeable but readily survivable radiation sickness.

Ilyichev reported that most the civilian population in the surrounding area had been evacuated. Someone who remained in the surrounding area (within the ~ 100 km^2 general area but not at the test site), and who was exposed to the fallout with the first day or so after the test by being outside or consuming water or food that had been outside, might have experienced mild symptoms of radiation sickness that would have resolved themselves within a matter of days. People who remained in the surrounding area but did not have much exposure to the fallout may not have had any noticeable symptoms.

In the area immediately around the test site, the radioactive fallout and dosage would be significantly higher than in the larger surrounding region. Just how much higher would again depend on the local winds and topography, and also on the relative sizes of the areas in question. Data from a number of U.S. nuclear tests suggests that the fallout dosage immediately around a test site is $\sim$ 10–100 times higher than that in the much larger surrounding area that receives significant fallout, with a geometric mean value of $\sim$ 30 times higher [Glasstone and Dolan 1977, pp. 419–439]. Using that mean value to multiply Eqs. (D.56)–(D.57), ballpark values for the radiation dose at the Thuringia test site would be:

$$4.50\text{–}7.89 \ \frac{\text{Gy}}{\text{hr}} \qquad \text{at 1 hour at test site} \tag{D.58}$$

$$33.9\text{–}59.1 \ \text{Gy} \qquad \text{within 24 hours at test site} \tag{D.59}$$

As mentioned, those estimates use the estimated geometric mean from the fallout patterns, and the actual values might have been between $\sim$ 3 times smaller and $\sim$ 3 times larger than the results in Eqs. (D.58)–(D.59). Since a cumulative dose of $\sim$ 10 Gy will cause fairly consistent lethality within hours or days after exposure, even a person who was fully protected from the initial radiation, heat, and blast of the explosion but then visited the test site in the hours after the explosion could rapidly acquire a lethal dose. This factor may help account in part for the lack of later witnesses.

Based on the above analysis (which was derived only from the known physics of fission explosions and Ilyichev's statement that the blast radius was 500–600 meters), the explosion's prompt radiation at the test site, the radioactive fallout at the test site within the first 24 hours, and the radioactive fallout in nearby towns within 24 hours would easily fit Ilyichev's description that a "massive radioactive effect was observed."

Comparison of theoretical results with numerical estimates based on the statements of Werner and Wachsmut

Although the chain of custody and historical authenticity of the written testimonies by Werner and Wachsmut cannot be verified, those testimonies made several specific claims that can actually be tested numerically against the preceding physics calculations.

Werner and Wachsmut (and also Grothmann) reported symptoms of what sounded like radiation sickness among the populations of towns near the test site. Werner specifically listed the towns in which she said people had reported those symptoms, and they are indicated by red circles on p. 4563. The purple circle in that figure is the suspected location of the explosion. Note that the affected towns generally range from north to east of the explosion, which is plausible if the local winds were blowing from the southwest at the time of the test. Based on the distribution of affected towns around the test site, a reasonable estimate for the affected region is a ~ 100 km^2 area. (For reference, the outermost blue circle in Fig. D.741 has a diameter of 10 km.)

Noticeable but readily survivable radiation sickness in that area within a day after the test, as reported by Werner and Wachsmut (and also Grothmann), suggests an average dose of

$$\text{1–2 Gy within 24 hours averaged over area of} \sim 100 \text{ km}^2 \tag{D.60}$$

Thus the area-averaged dose in Eq. (D.60), which was derived from the testimonies of Werner and Wachsmut, agrees extremely well with the prediction from Eq. (D.57), which was derived from Ilyichev's report and the physics of fission explosions.

A completely independent estimate of the radioactivity at the test site may also be derived from the testimony of Werner and Wachsmut. Werner stated that the test occurred at 9:30 p.m. on 4 March and that a large SS group came by at 2:00 p.m. on 5 March on their way to dispose of the bodies. Wachsmut testified that he worked to burn bodies at the test site from sometime in the afternoon until sometime before 11:00 p.m. on 5 March, with a break of unstated length in the middle for decontamination at the Ringhofen estate some distance away. Wachsmut also stated that he and his fellow workers were unable to eat for at least a couple of days afterward, which suggests moderate radiation sickness in the $\sim$ 1–2 Gy cumulative dose range. (An alternative interpretation is that the inability to eat for days was simply a psychological reaction to what they witnessed. That explanation is possible, but seems insufficient to account for the symptoms as Wachsmut stated he and his fellow workers were already very experienced at disposing of badly tortured prisoners' bodies, and that the inability to eat affected all of his work crew.)

To take nice round numbers as a very simple approximation, one could assume that Wachsmut was exposed to the fallout at the test site from $\sim$ 3:30 p.m. until $\sim$ 9:30 p.m. on 5 March, or in other words from 18 to 24 hours after the test. The cumulative dose from fallout between 18 and 24 hours after an explosion is equal to the dose rate 1 hour after the explosion multiplied by approximately 0.25 hours [Glasstone and Dolan 1977, p. 395, 7.5 hours - 7.25 hours = 0.25 hours for the multiplier]. Thus if Wachsmut received 1–2 Gy between 18 and 24 hours at the test site, the dose rate at the test site 1 hour after the explosion would have been

$$\frac{\text{1–2 Gy}}{\text{0.25 hr}} = \text{4–8}\ \frac{\text{Gy}}{\text{hr}} \qquad \text{at 1 hour at test site} \qquad \text{or} \tag{D.61}$$

$$\text{30–60 Gy} \qquad \text{within 24 hours at test site} \tag{D.62}$$

Therefore Eq. (D.61)'s completely independent estimate of the dose rate at the test site immediately after the test, derived from the testimonies of Werner and Wachsmut, agrees extremely well with the prediction from Eq. (D.58), which came from Ilyichev's report and the physics of fission explosions. The corresponding cumulative dose rate at the test site for the first 24 hours is given by Eq. (D.62), which may be compared with Eq. (D.59).

Furthermore, one should note that Werner and Wachsmut's statements suggest that the fallout dose at the test site, given by Eq. (D.62), was $\sim$ 30 times larger than the average fallout dose received by the larger community, given by Eq. (D.60). That is in excellent agreement with typical fallout patterns for nuclear weapons [Glasstone and Dolan 1977, pp. 419–439], and is quite remarkable considering that this ratio was derived purely from unrelated details given in Werner and Wachsmut's statements.

In making these numerical assessments of details from the written statements of Werner and Wachsmut, one should bear in mind several very important caveats:

- These equations are simply **ballpark estimates** for the average exposure, based in turn on both a ballpark estimate for the explosive yield and also a ballpark estimate for the size of the affected region, so the actual average exposure could have been significantly higher or lower.

- The relative distribution of fallout at the test site and in the larger surrounding area would depend greatly on the local winds and geography, so again these are simply ballpark estimates.

- Since the numerical results derived from Ilyichev's report are ballpark estimates, and those derived from the statements of Werner and Wachsmut are ballpark estimates, at best one can say that the agreement between those two independently derived sets of numerical results is simply in the right ballpark. The fact that the numbers happened to be so similar is not of any physical significance, beyond confirming that the independent ballparks overlap well.

- This physics analysis cannot address whether the written statements of Werner and Wachsmut are authentic, or whether they might have been forged or altered. This analysis can only conclude that the statements of Werner and Wachsmut are highly consistent with the known physics of nuclear weapons, and with physics estimates derived from Ilyichev's report, which was not released until after the written statements of Werner and Wachsmut had already been published.

Expected radioisotopes after 75+ years

After 75+ years, the radioactivity of the fallout would have dropped to $\sim 2{\times}10^{-9}$ of its radioactivity 1 hour after the explosion [Glasstone and Dolan 1977, p. 393]. Using Eqs. (D.56) and (D.58) with this information, the residual radioactivity would be

$$\text{Averaged over area:} \qquad 3.0\text{–}5.3 \times 10^{-10} \ \frac{\text{Gy}}{\text{hr}} \ \text{at 75 years} \tag{D.63}$$

$$2.6\text{–}4.6 \times 10^{-6} \ \frac{\text{Gy}}{\text{yr}} \ \text{at 75 years} \tag{D.64}$$

$$\text{At test site:} \qquad 8\text{–}16 \times 10^{-9} \ \frac{\text{Gy}}{\text{hr}} \ \text{at 75 years} \tag{D.65}$$

$$7\text{–}14 \times 10^{-5} \ \frac{\text{Gy}}{\text{yr}} \ \text{at 75 years} \tag{D.66}$$

Since typical radioactive background from terrestrial, solar, and cosmic sources is at least $1\text{–}2{\times}10^{-3}$ Gy/yr, the residual radioactivity at the test site would be at least $\sim$ 10–30 times smaller than the natural background and hence extremely difficult to detect.

Put differently, the estimated initial values that went into calculating this final value of the residual radioactivity would have to be off by a factor of $\sim$ 10–30 times, and in the right direction, in order for the residual radioactivity to be detectable above the natural background level. For that to have been the case, the explosive yield would have to have been $\sim$ 10–30 times larger than was estimated here, or $\sim$ 2–10 kilotons, which seems highly unlikely given the descriptions of the test, and also the German military's logical desire to minimize the fission fuel consumed and the radioactivity produced on German soil by the test. Alternatively, for the residual radioactivity to be detectable with the explosive yield estimated here, the fallout would have to have been confined to an area $\sim$ 10–30 times smaller than has been assumed here, which also seems highly unlikely. In fact, after 75+ years of water, wind, and human activity, the fallout could easily have become scattered over a significantly larger area than the initial area assumed here, and/or become buried to varying depths in the ground, making it even harder to detect than has been calculated here. As discussed above, the radioactivity in the larger surrounding area would be even lower than that at the test site, by a factor of $\sim$ 10–100.

From fundamental physics, one must therefore conclude that measurements of residual radioactivity cannot be used to try to prove or disprove whether the March 1945 Thuringian nuclear test occurred. This same conclusion, for the same reasons, also applies to the Baltic, Polish, or any other possible wartime German nuclear tests.

Nonetheless, it is possible that methods other than radiation sensors might be used to detect residual products left by the test. For that approach to have some chance of success, the residual products should be (a) unique to the nuclear test, and (b) present in the largest quantities possible. The first criterion rules out common explosives such as TNT and RDX, as well as common metals such as aluminum and iron, that presumably would have made up large fractions of the nuclear

device, but that could also have been left by conventional weapons that have been stored, tested, or used at that location for more than a century.

In addition to the radioactive fallout from fission products, any unfissioned uranium would be scattered by the explosion. If only $\sim$ 100 g U-235 was used (and only a faction of that was fissioned) and was surrounded by only non-uranium materials (gold, tungsten, rhenium, etc.) in the device, as little as $\sim$ 100 g of unfissioned uranium may have been scattered. On the other hand, if the device used a $\sim$ 100 kg natural uranium tamper as was reportedly used in the 1945 U.S. Gadget and Fat Man implosion bombs, as much as $\sim$ 100 kg of unfissioned uranium may have been scattered. Again assuming that the explosion and winds initially scattered the fallout over a $\sim$ 100 km^2 area, the expected amount of unfissioned uranium could be anywhere in the range:

$$\sim 1 \text{ g} - 1 \text{ kg of unfissioned uranium per km}^2\text{, or} \tag{D.67}$$

$$\sim 10^{-6} - 10^{-3} \text{ g of unfissioned uranium per m}^2 \tag{D.68}$$

As with the other explosion products, that is only the expected initial amount in 1945. After 75+ years, any unfissioned uranium could have become spread over a much larger area and/or seeped down into the ground, so the current amount could be far lower than this initial estimate.

Thus the residual radioactivity from a 1945 nuclear test of the magnitude described would now be far smaller than the average natural background radiation and therefore undetectable. Nonetheless, it might be possible to detect fission products or unfissioned fuel from the test by analyzing soil samples via mass spectrometry, particle-induced X-ray emission, neutron activation analysis, or other highly sensitive methods. Unfortunately, even these methods might have difficulty distinguishing the small amount of remaining telltale products from a background that would include not only naturally occurring isotopes but also fallout from the 1986 Chernobyl fission reactor accident and contamination from decades of Cold War military exercises (including both nuclear materials and depleted-uranium conventional projectiles).

Uranium-235 tends to fission into a light fragment with mass number $A_1 \sim 95$ and a heavy fragment with $A_2 \sim 140$. The sizes of the resulting light and heavy fragments vary somewhat, creating a double-peaked mass distribution [Fig. D.1035(a)]. Fig. D.1035(b) shows that for different masses of the fissioning nucleus, the heavy fragment mass peak remains essentially fixed, while the light peak is left to shift with the changes in total mass. If there is very little energy initially put into the fission reaction, the trough between the light and heavy mass peaks is quite deep. Yet as the input energy increases, the trough becomes less and less deep [Fig D.1035(c)]; the fissioning nucleus becomes able to fall into almost any final state, not just the energetically lowest ones.

In general, fission products are inherently β emitters due to their excess of neutrons inherited from the massive original nucleus, with some γ emission as well. Most fission products have half-lives less than a couple of years or so and thus will largely decay to more stable isotopes within a few years. Of the vast array of fission products, only a handful do not decay within a few years; these are listed in Table D.11 [using data drawn from Benedict et al. 1981]. (Note that actinides are not included.)

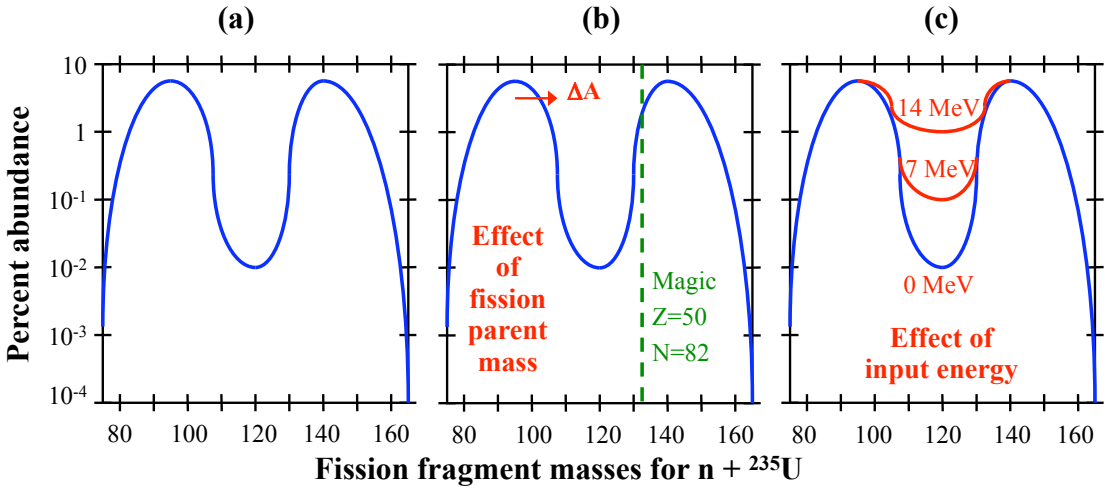

Figure D.1035: Mass distributions of nuclear fragments resulting from fission. (a) Low-energy neutron-induced fission of ^{235}U. (b) Effect of increasing the initial mass of the nucleus undergoing fission by ΔA. (c) Effect of input energy on neutron-induced ^{235}U fission.

Nuclide	Half-life (years)
Europium-154	16
Strontium-90	29
Cesium-137	30
Samarium-151	87
Technetium-99	2.1×10^5
Selenium-79	1.1×10^6
Zirconium-93	1.5×10^6
Cesium-135	2.3×10^6
Iodine-129	1.6×10^7

Table D.11: Major long-lived radioactive fission products.

Despite background contamination and the passage of time, the use of three approaches in combination might be able to provide good evidence of a wartime German nuclear weapons test:

1. Ion mass spectrometry, particle-induced X-ray emission, neutron activation analysis, or other highly sensitive methods could detect very low levels of fission products, even non-radioactive fission products or other bomb components, and identify not just elements but specific isotopes and their relative concentrations.

2. Analyzing numerous samples from suspected test sites as well as surrounding regions could determine what background levels of which isotopes are present (from Chernobyl, Cold War military programs, or natural sources), and how much variation there is in those background levels. If multiple samples from a suspected test site contain fission products that generally agree with each other but are well outside the range expected of background contamination, that finding would be of great interest.

3. From Fig. D.1035, the relative quantities of different fission products depend on whether they came from highly enriched U-235, low-enriched reactor-grade U-235, Pu-239, or U-233. The relative quantities also depend on the neutron energies used in the fission reactions—fast neutrons for weapons and slow neutrons for reactors (although could there have been significant fast fission during the Chernobyl event?). Thus the relative quantities of various isotopes in the sample could indicate the specific type of fission fuel and fission reactions from which they originated. However, there may not be enough fission products to detect (for a 200-ton explosion, $\sim$ 10 grams of fission products scattered over the area). In that case, the most promising component to detect would be the tamper (likely $\sim$ 100 kg of mostly U-238 scattered over the area), if that could be distinguished from U-238 background contamination.

D.15.5 Estimating Device Design Parameters from Primary Sources

Very tentative design parameters for the device that may have been tested in Thuringia in March 1945 may be estimated from the primary sources, simple physics, and unclassified documents about the United States' first implosion bombs (Gadget, shown in Fig. D.1036, that was detonated in New Mexico on 16 July 1945, and its fully packaged version, Fat Man, shown in Fig. D.1037, that was dropped on Nagasaki on 9 August 1945) and other nuclear weapon designs [Coster-Mullen 2012; Goncharov 1996a, 1996b; Goncharov and Riabev 2001; Gsponer and Hurni 2009; Chuck Hansen 1988, 2007; Bruce Cameron Reed 2015a, 2019; Rhodes 1986, 1995; Serber 1992; Smyth 1945; Sublette 2019; Wellerstein and Geist 2017; Winterberg 2010].

Of the primary sources, by far the most detailed and most authoritative is Ilyichev's March 1945 intelligence report, so it will be relied upon heavily here. Details from that report are supported by more general comments from Ilyichev's November 1944 intelligence report and the documents of Schumann, Trinks, Diebner, and Guderley. The most relevant design details from these sources are summarized on p. 4157.

The results of the following analysis are consistent with those of previous analyses [Eilers 2007, 2015; Mineev and Funtikov 2007].

(Can any information on wartime German work be extrapolated from the postwar Soviet program, especially RDS-2/Joe-2 (or later tests)? Soviet rockets were highly derivative of German rockets. The Soviet nuclear program and designs were likely highly derivative of German work as well, although RDS-1/Joe-1 was directly copied from the U.S. Fat Man design.)

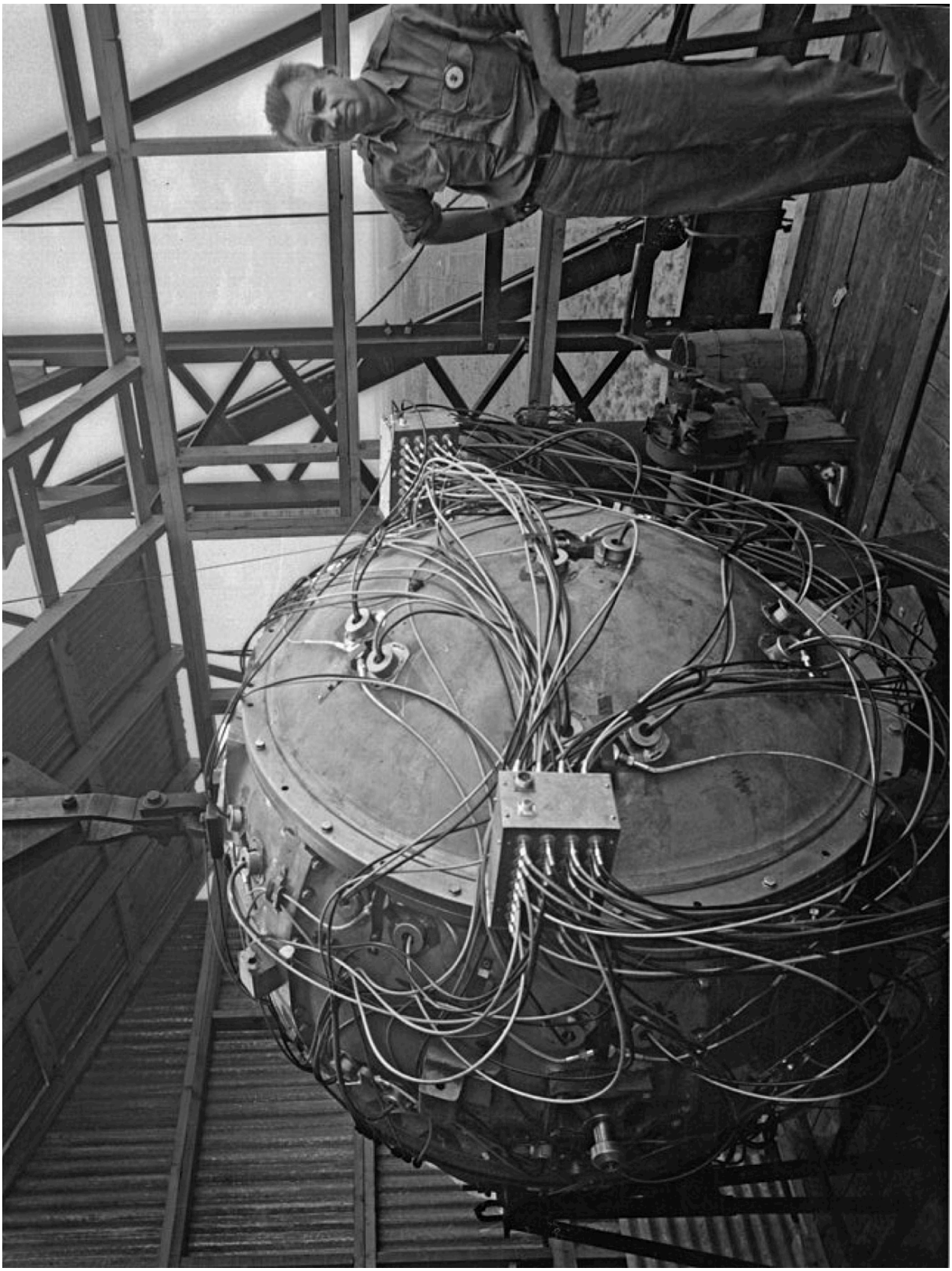

Figure D.1036: Gadget device being prepared by Norris Bradbury for 16 July 1945 test in New Mexico.

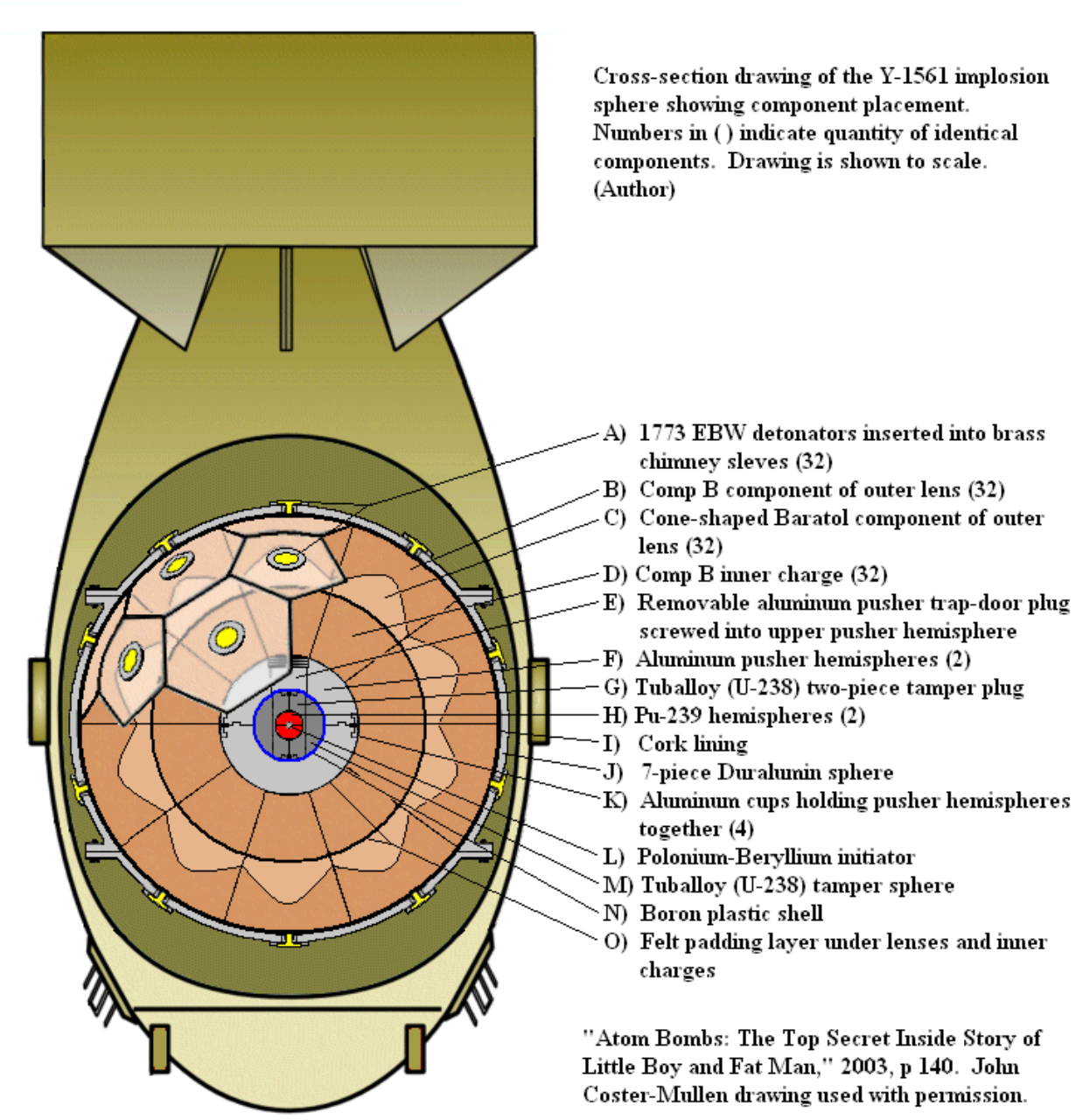

Figure D.1037: Scale drawing of Fat Man design according to unclassified sources [https://commons.wikimedia.org/wiki/File:Fat_Man_Internal_Components.png].

Table D.12 compares the Gadget/Fat Man design details from unclassified sources with extrapolated parameters for what the March 1945 Thuringian device design may have been. Each major component will then be discussed briefly.

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

Table D.12: Comparison of the U.S. Gadget/Fat Man implosion design (from unclassified sources) with extrapolated design parameters of the March 1945 Thuringian device.

A. Neutron Initiator

According to the unclassified references, fission bombs are generally equipped with a neutron source or initiator, which provides neutrons to initiate a fission chain reaction just as the fission fuel is being compressed toward its maximum density by implosion with conventional explosives. These references also indicate that the Gadget/Fat Man design used an internal polonium-210/beryllium initiator nicknamed the "urchin" that produced neutrons when crushed at the center of the bomb, and that modern bombs use an external (not inside the imploding part of the bomb) tube filled with deuterium and tritium gas that produces high-energy "fast" fusion neutrons when high voltage (several thousand volts) is applied.

There are at least five possible neutron initiators that could have been used in the Thuringian device, and there is some evidence for each one. Perhaps combinations of these were used to provide redundancy (in case one failed) or to increase the number of initial neutrons, or perhaps they were intended to be used in different versions of the bomb:

1. **Fusion fuel with high voltage at the center of the bomb.** Ilyichev's March 1945 report gave three similar descriptions (p. 4485):

   (a) "1. High-voltage discharge tube, which is charged by special generators."

   (b) "Initiator or bomb fuse: Consists of a special tube, which creates fast neutrons. It is charged by special generators, which create high voltage inside the tube. As a result, fast neutrons attack active material."

   (c) "The bomb ignition is carried out with the help of a high-voltage discharge tube. It forms a flow of neutrons, which attack the active material. When the flow of neutrons impacts upon uranium, element 93 fissions, which speeds up the creation of a chain reaction."

   These three descriptions seem to refer to a high-voltage tube that is filled with fusion fuel (deuterium, tritium, and/or lithium) and produces fast neutrons when a high voltage is applied to the tube. Those neutrons initiate fission reactions in the uranium, releasing more neutrons and starting the fission chain reaction. (The term "Element 93" was widely and scientifically loosely used in the German nuclear program to mean uranium that had absorbed a neutron, sometimes meaning neptunium and sometimes plutonium. Here it simply seems to mean the excited uranium compound nucleus, just after it has absorbed a high-energy fusion neutron and just before it fissions.)

   Ilyichev made it clear that the neutron initiator was at the center of the bomb; he described the core of the bomb as a

   > uranium 235 [...] sphere with an opening into which an initiator is inserted. Once this is done, the opening is sealed by a cork made of uranium 235.

   Due to the constraints of the small volume available at the center of the fission fuel pit, the requirement to avoid including any materials that could hinder the nuclear reactions, and the need for the electrical connections to the central neutron initiator to be functional during the implosion process, the internal high voltage fusion neutron source would need to have a very ingenious design. In fact, after the war Kurt Diebner obtained a patent on just such a high voltage fusion neutron source at the center of an implosion bomb (p. 4261).

2. **External fusion fuel with high voltage.** Since this neutron initiator would be external to the imploding part of the bomb and not be at the center of the bomb, there would be far fewer constraints on its design, which is why the unclassified references report that most modern bombs have used this method. High-voltage tubes that used fusion fuel to produce neutrons were well known and used in the wartime German nuclear program (pp. 3958–3970, 4281–4327).

3. **Internal fusion fuel (without high voltage).** Even without high voltage, fusion fuel placed at the center of the bomb might experience sufficient compression and heating during the implosion process that it would undergo some fusion reactions. While these fusion reactions would not create a measurable amount of released energy (as confirmed by the efforts of Schumann, Trinks, and others to implode pure fusion fuel), they might produce enough neutrons to initiate a fission chain reaction in the surrounding, imploding fission fuel. After the war, Schumann and Trinks and also Diebner published diagrams showing fusion fuel (without high voltage) at the center of an imploding uranium sphere (pp. 4229–4267).

4. **An internal polonium-210/beryllium urchin-like neutron initiator.** Although such an initiator was used in the early U.S. fission bombs, it is not mentioned in existing documents about German bomb designs. However, general use of an alpha emitter (such as radium, polonium, etc.) plus beryllium to produce neutrons was well known and widely practiced in the German nuclear program (see for example pp. 3374 and 4327). Many tons of beryllium were produced (p. 4096). A special installation also produced polonium-210. In fact, on 28 February 1945, just four days before the 4 March test in Thuringia, Kurt Diebner and Walther Gerlach appropriated Germany's entire stock of prepared polonium for a purpose that was too secret to specify (p. 4540).

5. **An external compact betatron directing electrons with energies of at least 6 MeV toward the center.** The >6 MeV electrons would produce <6 MeV gamma-ray photons in the uranium via bremsstrahlung and other absorptive processes, the photons would induce photofission reactions in the uranium, and neutrons would be released. Ilyichev's March 1945 report seems to indicate that the fission bombs tested in Thuringia used this process (p. 4487):

   > Ahead of this, before the explosion, the uranium sphere is irradiated with gamma-rays, the energy of which does not exceed 6 million electron volts [MeV], which many times increases its explosive qualities.

   The more initial neutrons are provided via the betatron or other methods, the larger the resulting fission chain reaction that can occur during the brief time before the bomb core blows apart—thus the betatron-induced radiation "many times increases its explosive qualities" as stated by Ilyichev. The betatron would also need "special generators, which create high voltage," so that part of Ilyichev's description could apply to betatron and/or high-voltage fusion neutron initiators.

   Werner Grothmann also appeared to refer to this type of neutron initiator (p. 5041).

   The basic physics of this process has been described in detail [Wagemans 1991, pp. 103–197]. Remarkably, documentation demonstrates that German scientists were aware of this process mediated by 5–6 MeV gamma rays no later than 1941 (p. 3814). In one of the most detailed

yet unclassified modern references on nuclear weapons, Carey Sublette described the use of this process as a neutron initiator for fission bombs [Sublette 2019, Section 4.1.8.2]:

> An additional type of ENI [External Neutron Initiator], not based on fusion reactions, has been successfully tested but apparently never deployed. This is the use of a compact betatron, a type of electron accelerator, to produce energetic photons (several MeV). These photons cause photon induced fission, and photon → neutron reactions directly in the core.

Intriguingly, when Diebner fled Stadtilm ahead of U.S. forces, among the papers he left behind was a whole folder worth of papers on betatrons (p. 3862). A number of betatrons were available for the wartime German nuclear program (Appendix C). In particular, a betatron model produced by Siemens-Reiniger Werke in Erlangen was specifically described as having an energy of 6 MeV (pp. 3088–3089, 3957–3970). That betatron weighed a relatively modest 272 kg, and lighter versions may have been constructed too.

The United States did not begin any serious work on betatrons as neutron initiators until 1946. Could that postwar work have been based on what U.S. investigators learned about the wartime German nuclear program? The *Manhattan District History* reported [Supplement to Manhattan District History Book VIII, Los Alamos Project (Y) Volume 2, Technical, pp. IV-13–IV-14. https://ia803409.us.archive.org/14/items/ManhattanDistrictHistory/]:

> THE BETATRON GROUP [...] 4.55 Experiments were conducted throughout 1946 on photo fission thresholds in normal uranium, U^{235}, U^{238} and plutonium. The most dependable results have come from the use of a shielded paraffin geometry about five feet from the betatron. These findings indicate that all fissionable materials (such as plutonium, normal uranium, and U^{238} have thresholds at about 5.2 Mev. However, this work is not conclusive as it has been observed that the threshold for the production of neutrons from the betatron is also 5.2 Mev. Therefore, there is a doubt as to whether the fission observed is neutron produced fission or gamma fission.

According to further information from Carey Sublette, the United States actually successfully demonstrated a betatron neutron initiator in a fission bomb on 1 June 1952 in the George test of Operation Tumbler-Snapper [https://nuclearweaponarchive.org/Usa/Tests/Tumblers.html]:

> This device (code named XR2) used a Mk 5 bomb assembly. The test was intended to gather additional data on the initiation time vs yield curve. A novel feature of this test was the use of an external initiator—in this case employing a device called a betatron (which is a circular electron accelerator). In this test the high energy electrons were used to generate high energy X-rays that induced photo-fission in the core to initiate the chain reaction. The betatron allowed very accurate control of initiation time. The test device had a diameter of 40 inches and weighed 2700 lb, the predicted yield was 30 kt.

Whatever other neutron initiators may have been present or considered, if Ilyichev's description is correct, at least a small amount of fusion fuel was at the center to serve as a neutron source when triggered with high voltage. If that fusion fuel was deuterium + tritium or deuterium + lithium (but not pure deuterium, which is harder to fuse), it may have produced further high-energy neutrons

once the surrounding fission fuel reached high enough temperatures and pressures. If so, those additional fusion neutrons could have significantly increased the number of fission reactions that could occur in the fission fuel before that fuel was scattered by the explosion.

In previous experiments, Schumann and Trinks had tried unsuccessfully to initiate reactions in pure fusion fuel by imploding it with conventional explosives [Irving 1967, pp. 193–197; Karlsch 2005, pp. 144–155; Nagel 2016, pp. 220–242]. If the designers of the Thuringian device did not expect further reactions from the central fusion fuel after the momentary high voltage, yet fusion reactions in the center and fission reactions in the surrounding U-235 mutually aided each other, the yield of the device could have been boosted to be significantly larger than the designers had expected, especially if only a small amount of fission fuel was used. This could explain comments from Wachsmut and Grothmann that the energy yield and casualties were much larger than expected. Potentially this might also explain why there may have been a second and apparently less dramatic test on 12 March 1945 (according to Werner), if the scientists wanted to run the experiment again but without the boosting effect, in order to make sure they fully understood how much difference the boosting effect had made and/or how well their design imploded under more controlled conditions.

On the other hand, perhaps the designers intended for fusion reactions to continue in the center and for fusion neutrons to boost the number of fission reactions in the surrounding fission fuel. In that case, the experiments imploding pure fusion fuel might be viewed merely as preliminary tests before imploding the full fission-fusion design. If one makes some allowances for Ilyichev's specific wording, the center might have been filled with a significant amount of fusion fuel, potentially up to several grams:

- Deuterium-tritium gas would be the most effective [Gsponer and Hurni 2009, p. 10]. Gram quantities of deuterium could easily have been spared from the heavy water production programs. Alfred Klemm mentioned that there was apparently some sort of secret wartime production and use for tritium (p. 4346). Tritium could have been produced by bombarding either deuterium (or heavy water) or lithium with neutrons, in either a fission reactor or a particle accelerator.

- Solid lithium-6 deuteride might also be effective [Gsponer and Hurni 2009, p. 10]. Alfred Klemm produced gram quantities of lithium-6 in his laboratory (pp. 4344–4347), and his process could have been replicated elsewhere. A number of documents show that there was wartime work using lithium and deuterium together as fusion fuel (pp. 4305–4341). Because lithium deuteride is solid and not a gas or cryogenic liquid, it makes a very convenient material for bombs.

- Pure deuterium might conceivably have worked in the high-voltage neutron initiator, but probably would not have been useful for producing further fusion neutrons during the implosion [Gsponer and Hurni 2009, p. 10].

B. Pit

According to the unclassified sources, "pit" is the customary name for the fission fuel in a bomb. Ilyichev's March 1945 report described the pit of the Thuringian device: "Active bomb material is uranium 235. It represents a sphere with an opening into which an initiator is inserted. Once this is done, the opening is sealed by a cork made of uranium 235. ...A shock from the explosion of the external layer of TNT mixed with liquid oxygen takes place, which is directed toward the center. This allows the uranium to reach a critical mass."

Although Ilyichev described the fission fuel as uranium-235, uranium-233, neptunium-237, or plutonium-239 might conceivably have been used instead, so we will consider all four possible fission fuels. Table D.13 gives the critical masses for spheres of uranium-233, uranium-235, neptunium-237, or plutonium-239 under various ideal conditions. Critical masses assuming no compression from implosion, no surrounding neutron reflector/tamper, and no fusion neutrons are taken from unclassified information [Bruce Cameron Reed 2015a, 2019; Sanchez et al. 2008]. At most, a single ideal shock wave could compress the fission fuel density by a factor of 4, or reduce the critical mass by a factor of $4^2 = 16$ [Sublette 2019, Section 2.1.4]. Similarly, at most an ideal neutron reflector could reduce the critical mass by a factor of $2^3 = 8$ [Serber 1992, p. 31]. Neutrons from fusion reactions at the center could also significantly reduce the critical mass; the exact factor of improvement depends on a number of details, but some theoretical predictions of the fusion-assisted critical mass are as low as 10 grams [Winterberg 2010, pp. 36, 206–208]. Of course, these are theoretical minimum values for the critical mass under absolutely ideal conditions. Real systems would have various inefficiencies and design tradeoffs and hence larger critical masses. Nonetheless, the critical masses in Table D.13 give some idea of the range of design possibilities that may have been involved in the Thuringian device.

The fission pit in the Thuringian device could have used one of these possible fuels, or it could have combined two or more of the possible fuels. If Germany only possessed a very limited supply of any individual fission fuel, it may have seemed especially attractive to combine them to produce a functional device (or as many functional devices as possible).

Conditions	Uranium-233	Uranium-235	Neptunium-237	Plutonium-239
No compression No reflector No fusion	14.2 kg	45.9 kg	57.0 kg	16.7 kg
Max compression No reflector No fusion	0.888 kg	2.87 kg	3.56 kg	1.04 kg
Max compression Max reflector No fusion	0.111 kg	0.359 kg	0.445 kg	0.130 kg
Max compression Max reflector Fusion neutrons	< 0.111 kg	< 0.359 kg	< 0.445 kg	< 0.130 kg

Table D.13: Critical masses for spheres of uranium-233, uranium-235, neptunium-237, or plutonium-239 under various ideal conditions.

While Table D.13 assumed that the U-235 was 100% enriched, that would not be required. In fact, the Little Boy bomb that the United States dropped on Hiroshima used 64 kg of 80% enriched U-235, which obviously worked. 70% enriched U-235 would also work but would require approximately twice the critical mass of 100% enriched U-235 under the same conditions (compression, reflector, fusion boost, etc.). Similarly, 45% enriched U-235 would require approximately four times the critical mass of 100% enriched U-235 under the same conditions [Sublette 2019]. Bomb performance would become much worse or impossible with enrichment levels significantly lower than those levels.

Grothmann reported that the device was tested with a very small amount of fission fuel but ready to be deployed with a much larger amount. Possible numbers might be < 1 kg for the tested version and ∼5–10 kg for the version to be deployed. Rundnagel specifically mentioned 8 kg for what was apparently the fission pit stored in a safe. Based on information about implosion device designs from the unclassified sources, it seems likely that the pit would have had a deployed mass in the range

$$M_{\text{pit}} \approx 5 - 10 \text{ kg} \tag{D.69}$$

For the implosion of the test version to function as intended in the deployable version, any amount of fission fuel (U-235, or possibly U-233, Np-237, Pu-239, or some combination thereof) that was omitted from the test version would have been replaced with a less precious but similarly dense material for the outer pit, with the remaining true fission fuel at the inner surface of the pit. By far the best and most logical replacement would be low-enriched uranium, which may have been available, or natural uranium, which certainly was available. Considering that the density of uranium is 19.1 g/cm^3 and that of plutonium is 19.8 g/cm^3, other possible replacement materials include gold (19.3 g/cm^3), tungsten (19.3 g/cm^3), and rhenium (21.0 g/cm^3). Any of those materials would have also made a good neutron reflector to keep as many neutrons as possible within the small amount of fission fuel. Natural or low-enriched uranium would have acted as a good neutron reflector and also to some degree as additional fission fuel.[33]

Since U-235 makes up only 0.0072 of natural uranium, 13.9 kg of natural uranium would need to be completely processed to obtain 100 g of pure U-235, or 694–1390 kg of natural uranium would need to be processed to obtain 5–10 kg of pure U-235. (Of course, the U-235 may not have been enriched to 100% purity.) Any strategically useful nuclear weapons program would require multiple bombs and hence at least a few tons of completely processed natural uranium. Exactly how far did uranium enrichment programs progress during the war (p. 5116)?

Alternatively, could enough U-233 fission fuel have been produced from thorium-232, or enough Pu-239 or Np-237 fission fuel have been produced from uranium-238, using an operational fission reactor somewhere and/or particle accelerators (p. 5129)?

[33]Large amounts of gold were available in the German-speaking world during the war, as shown by the large stashes of gold that were found at the end of the war.

Large quantities of tungsten were also available, as indicated for example by BIOS 684, *Production of Molybdenum & Tungsten for Radio Valves & Electric Lamps, Metallwerke Plansee, Reutte, Tyrol,* p. 16: "During the war the finished Tungsten production [from this factory] was stated to be 1½ tons per month for which they required 3 tons of Oxide. For carbide manufacture they used about 4 tons per month of metal powder made from oxide." For another example of tungsten production, see BIOS 1356, *Grinding and Treatment of Minerals.*

Rhenium was available but much more scarce and therefore unlikely to have been used for this purpose [FIAT 697, 750].

C. Reflector/Tamper

According to the unclassified sources, the reflector serves both to reflect neutrons back into the pit and also (if it has much more mass than the pit) as a tamper to slow the explosion of the pit long enough to allow more fission reactions to occur. The most logical reflector/tamper material would be natural or low-enriched uranium. Although Ilyichev's March 1945 report did not specifically mention a reflector or tamper, it may have simply lumped the uranium pit and uranium reflector/tamper together in describing the inner part of the bomb as being "filled with uranium." Intriguingly though, Ilyichev did initially list a "delay mechanism" between the "sphere made of metal uranium 235" and the aluminum "protective casing," then go on to give more detailed descriptions of the uranium-235 and the protective casing but not the delay mechanism between them. Considering the imperfections inherent in translating from specialized scientific language to common language and also from German to Russian in a spy's brief report, "delay mechanism" would actually be a fairly accurate succinct description of the tamper's function.

According to the unclassified sources, the Gadget/Fat Man reflector/tamper was 108 kg of natural uranium. It seems reasonable to assume that the Thuringian device also had a tamper with a mass in the neighborhood of:

$$M_{\text{tamper}} \approx 100 \text{ kg} \tag{D.70}$$

If for some reason it was decided not to use uranium for the reflector/tamper, the same alternative materials that might have formed the outer pit for the test version would also make good alternative materials for the reflector/tamper: gold, tungsten, and rhenium. Thorium (11.7 g/cm^3) and lead (11.3 g/cm^3) are lower density but might also be possibilities. Beryllium (1.85 g/cm^3) has a very low density and would not make a good tamper (unless combined with a heavier element), but it is an excellent neutron multiplier/reflector.

All of those candidate tamper materials would have been readily available in sufficient quantities in wartime Germany, with the possible exception of rhenium.

D. Neutron Absorber

According to Ilyichev's March 1945 report: "The uranium sphere is encased in a protective aluminum casing, which is covered by a layer of cadmium. This significantly impedes thermal neutrons emanating from uranium 235, which can cause premature detonation." According to the unclassified sources, in the Gadget/Fat Man design, the inner surface of the aluminum pusher was lined with a 3.2-mm-thick layer of plastic that was rich in boron-10. The boron-10 was intended to absorb any fast neutrons escaping from premature spontaneous individual fission events in the pit, so that they would not enter the hydrogen-rich conventional explosives, slow down to "thermal" speeds that are much more effective at inducing fission reactions, and find their way back into the pit to cause even more premature fission events.

Cadmium is also an excellent neutron absorber and would have served the same purpose in the Thuringian device. It seems likely that it was on the inner surface of the pusher, as the boron-10 was in Gadget/Fat Man, although that is somewhat unclear from Ilyichev's report.

Erich Schumann also mentioned a layer of cadmium in implosion bomb designs (p. 4254). After the war, a "capable young engineer" in Poland told the U.S. embassy there that "one of the best if not the only material for atomic bomb containers is cadmium" (p. 4255), which may have reflected knowledge that he gained from the construction and/or testing of a German fission bomb in Poland.

Cadmium was produced in large quantities in wartime Germany and widely used as a neutron absorber in the German nuclear program (p. 4148). Because cadmium is so dense (8.65 g/cm^3) compared to the density of boron or plastic (< 2 g/cm^3), only a very thin layer of cadmium would have been needed, probably less than 1 mm. German cadmium is known to have been produced in foils of thickness 1 mm or less, which could have been suitable for covering the aluminum pusher. For even better uniformity of coverage, especially to avoid any asymmetries during the implosion process, the cadmium could have been electroplated onto the aluminum. Technologies for electrodepositing cadmium, and electroplating layers onto aluminum, are documented to have existed in wartime Germany (p. 4148).

Assuming that the cadmium layer was on the inner surface of the aluminum pusher and had a radius of 11 cm (comparable to the inner pusher radius in Gadget/Fat Man), thickness of 1 mm, and density of 8.65 g/cm^3, its mass would have been:

$$M_{\text{cadmium}} \approx 4\pi\,(11\text{ cm})^2\,(0.1\text{ cm})\,\frac{8.65\text{ g/cm}^3}{1000\text{ g/kg}} \approx 1.3\text{ kg} \tag{D.71}$$

E. Pusher

Ilyichev's March 1945 report stated: "The uranium sphere is encased in a protective aluminum casing." From the unclassified sources, the Gadget/Fat Man design used a 130 kg aluminum "pusher" between the conventional explosive and the uranium reflector/tamper, so it seems reasonable to assume a comparable mass for the Thuringian device's aluminum pusher:

$$M_{\text{pusher}} \approx 130\text{ kg} \tag{D.72}$$

Because the aluminum pusher's density (2.70 g/cm^3) is higher than that of the explosive (~ 1.6 g/cm^3) but lower than that of the uranium (19.1 g/cm^3), the pusher helps to efficiently transfer the imploding shock wave from the explosive to the uranium.

There is some evidence that the aluminum pusher and aluminum explosive case spherical shells for fission implosion bombs were produced on Usedom peninsula (p. 4270), but if not, suitably sophisticated aluminum production and machining was widespread in wartime Germany (p. 4126).

F. Explosive

Ilyichev's March 1945 report stated: "After the layer of cadmium, it is placed inside explosives that consist of porous TNT saturated with liquid oxygen; TNT is made up of bars of a specially chosen shape. The inner surface of the bars has a spherical curvature, which is the same as that of the external surface of the cadmium layer. Each of the bars is supplied with one detonator or two electrical fuses. ...Liquid oxygen is pumped through the opening inside a protective casing, which covers the TNT. ...The detonating mechanism detonates the explosive matter, after which a shock from the explosion of the external layer of TNT mixed with liquid oxygen takes place, which is directed toward the center."

Most of the interior of the Gadget and Fat Man bombs was filled with TNT-based explosives (composition B and baratol) with shapes and a segmented design intended to optimize the creation of a spherical implosive shock wave. Thus one would expect something very similar in the Thuringian device, especially given the participants' extensive experience designing and testing implosion devices powered by conventional explosives [Irving 1967, pp. 193–197; Karlsch 2005, pp. 144–155; Nagel 2016, pp. 220–242]. Erich Schumann and Walter Trinks demonstrated a sophisticated knowledge of TNT, hexogen/RDX, other explosives, and explosive lenses using combinations of those

explosives (pp. 4187–4255). There were also many other experts on implosion techniques, such as Rolf Engel, Rudi Schall, and Hubert Schardin.

Ilyichev said the Thuringian device used TNT, although that might possibly mean any of several TNT-related explosives as in the Gadget/Fat Man design. The average density of solid TNT is 1.654 g/cm^3. If the TNT-based explosive were porous to allow for liquid oxygen penetration, its density would be somewhat lower, say perhaps $\rho \approx 1.4$ g/cm^3.

Assuming that the Thuringian device's explosive layer had an outer radius of approximately $R_o = 63$ cm (slightly less than Ilyichev's stated 65 cm outside radius for the case), an inner radius of approximately $R_i = 23$ cm (if the pusher had an outer radius similar to that in Gadget/Fat Man), and an average density of $\rho = 1.4$ g/cm^3, the explosive layer's mass would be:

$$M_{\text{explosive layer}} = \frac{4}{3}\pi \left(R_o^3 - R_i^3\right) \rho \approx 1400 \text{ kg} \tag{D.73}$$

TNT molecules ($C_7H_5N_3O_6$) contain relatively few oxygen atoms and normally release their explosive energy by decomposing into a number of smaller oxygen-deficient molecules. Without providing added oxygen, detonation releases 4.184 GJ of energy per ton of TNT.

If enough liquid oxygen were provided, all of those TNT decomposition products could be fully oxidized, and significantly more explosive energy would be released. With complete oxidation, detonation releases 14.5 GJ per ton of TNT, 3.47 times as much energy as without added oxygen.

Thus the provision of liquid oxygen might make the ∼1400 kg of explosives in the Thuringian device comparable to up to ∼4850 kg of explosives without added oxygen. Depending on the detailed chemical composition of the explosives (the relative amounts of TNT, hexogen, etc.) and the efficiency with which the liquid oxygen was utilized, the ∼1400 kg of explosives in the Thuringian device could easily have been quite comparable to or even significantly more powerful than the 2500 kg of explosives in the Gadget/Fat Man design.

G. Explosive Case

According to Ilyichev's March 1945 report: "TNT is covered by a protective layer made of a light aluminum alloy. A blasting mechanism is attached on top of this casing." From the unclassified sources, the Gadget/Fat Man design used a cork-lined aluminum case to enclose the explosives. The aluminum case of the Thuringian device may have been unlined, or the Soviet spy may have simply not known about or considered it worth mentioning the lining. If the aluminum explosive case had an outside radius of $R = 64$ cm (just smaller than Ilyichev's quoted radius for the outer steel case), a thickness of 1 cm, and a density of 2.70 g/cm^3, its mass would have been

$$M_{\text{aluminum case}} \approx 4\pi \, (63.5 \text{ cm})^2 \, (1 \text{ cm}) \, \frac{2.70 \text{ g/cm}^3}{1000 \text{ g/kg}} \approx 140 \text{ kg} \tag{D.74}$$

As already mentioned, the aluminum pusher and aluminum explosive case spherical shells for fission implosion bombs may have been produced on Usedom peninsula (p. 4270), but in any event, suitable aluminum production and machining was widespread in wartime Germany (p. 4126).

H. Ballistic Case

Ilyichev's March 1945 report stated: "An exterior casing of armored steel is installed above the blasting mechanism." It is not clear if the steel case was actually installed on the Thuringian device

as tested, or if it only would have been installed on deployed versions. The tested Gadget bomb did not include a steel case, but the deployed Fat Man bomb had an outer 4.5-mm-thick steel case.

Steel alloys have densities in the range of 7.75–8.05 g/cm^3, so one may use an average density of 7.9 g/cm^3. If the Thuringian device had a steel ballistic case with an outside radius of $R = 65$ cm and the same thickness as Fat Man's case (0.45 cm), the mass of the case would have been:

$$M_{\text{ballistic case}} \approx 4\pi\,(64.8\text{ cm})^2\,(0.45\text{ cm})\,\frac{7.9\text{ g/cm}^3}{1000\text{ g/kg}} \approx 190\text{ kg} \tag{D.75}$$

I. Overall Radius

Ilyichev's March 1945 report stated that the bomb diameter was 1.3 m (65 cm radius). On the other hand, his November 1944 report gave the bomb diameter as 1.5 m. That difference in numbers might mean that the Soviet spy's November details were more approximate (consistent with the much shorter and much less detailed November report). Alternatively, it might mean that the Germans had been able to reduce the bomb diameter from 1.5 m to 1.3 meters between November 1944 and March 1945, for example by adding the liquid oxygen to reduce the amount of TNT required.

J. Total Mass

Ilyichev's March 1945 report gave the bomb's weight as "approximately two tons." The weight was not stated more precisely, and it is not entirely clear if the weight given includes the outer steel ballistic case or not.

Adding up all of the extrapolated Thuringian device component masses from Table D.12 (including the ballistic case) yields a total mass of:

$$M_{\text{total}} \approx 2000\text{ kg} \tag{D.76}$$

Thus the total mass is in excellent agreement with Ilyichev's reported estimate.

K. Delivery System

According to Ilyichev's March 1945 report: "A fairing made of a light alloy can be installed on top of the armored casing for future installation on a rocket of the V-type." This fits very well with all known data. V-2/A-4 rockets had become fairly reliable methods of delivering a payload to a target up to several hundred km away and could not be shot down by air defenses (unlike bomber aircraft or V-1 cruise missiles). Rockets with much longer ranges (A-4b, A-9, A-9/A-10) were apparently under development. The maximum payload fairing diameter for all of these rockets was approximately 1.37 meters, so a bomb with a diameter of 1.3 m would have been the largest implosion device that could fit within that space. (Alternatively, the bomb might have been placed in the middle of the rocket at the center of gravity, but space between the propellant tanks there would also be quite constrained.) These rockets used liquid oxygen as oxidizer for propulsion, and hence liquid oxygen would have been readily available to supplement the TNT in the bomb. The standard payload for the V-2/A-4 was one ton. If the Thuringian device was two tons, that would explain why it was never deployed militarily in the well tested standard V-2/A-4 rocket. It would have required either a modified V-2/A-4 with a larger payload capacity or one of the more advanced rocket designs, and such improved rockets were apparently still in the experimental phase (see Appendix E).

L. Explosive Yield

As discussed in Section D.15.4, the blast radius of 500–600 m stated in Ilyichev's March 1945 report suggests that the explosive yield of the Thuringian device as tested was around 200–350 tons. However, the device diameter, mass, and design details given by Ilyichev seem like those of a full-fledged fission bomb comparable to the 20-kiloton Gadget/Fat Man design, as shown in Table D.12. If the Thuringian device had been furnished with a full-sized ($\sim$ 5–10 kg) pit of high-quality fission fuel (U-235, U-233, or Pu-239) comparable to that in Gadget/Fat Man, it seems likely that it would have had a comparable explosive yield in the $\sim$ 20-kiloton range. If the pit was smaller and/or the fission efficiency was lower than in the U.S. design, the explosive yield may have been only a few kilotons. If the pit was $\sim$ 5–10 kg of high-quality fission fuel and significant fusion neutron boosting occurred from the deuterium-tritium (or deuterium-lithium) neutron initiator at the center, or if the center was deliberately filled with deuterium-tritium (or deuterium-lithium) fusion fuel, the device could have fissioned far more of its fission fuel and hence achieved far larger yields—potentially $\sim$ 100 kilotons or more for a $\sim$ 10 kg pit with $> 50\%$ efficiency.

These estimates from physical considerations are supported by a number of historical sources that stated the expected blast radius of the deployed fission bomb. The estimates from these sources were in the range of 1–4 km, depending on how much fission and fusion fuel were used and what the fission efficiency was. Using Eq. (D.49), those blast ranges correspond to an expected explosive yield of $\sim$1.6–100 kilotons, as summarized in Table D.14.

Note that these estimates are for the $\sim$1.3-meter-diameter spherical implosion bomb that was described by many sources and analyzed in this section. Other sources mentioned a nonspherical fission bomb that was much smaller and had a yield of less than 1 kiloton (p. 5170). There were also many sources that mentioned an H-bomb weighing 6 tons that would have been far more powerful, with a 10-kilometer blast radius and $\sim$1.6 megaton explosive yield (p. 5171–5172).

Historical sources	Expected blast radius	Corresponding yield
pp. 4590, 4600, 4602, 4605, 4894	$\sim$1 km	$\sim$1.6 kiloton
pp. 4600, 4703	$\sim$1.5 km	$\sim$5 kilotons
pp. 4605, 4674	$\sim$2 km	$\sim$13 kilotons
pp. 4400, 4595, 4674, 5011, 5012	$\sim$3 km	$\sim$40 kilotons
pp. 4176, 4595, 5011	$\sim$4 km	$\sim$100 kilotons

Table D.14: Expected blast radii and corresponding explosive yields for the German fission bomb as stated by various historical sources. The different expected blast radii originated from different assumptions about the amount of fission and fusion fuel used in the bomb and the expected efficiency of fission fuel consumption during the explosion.

D.15.6 Possible Evidence for Other Device Designs

The wartime German rocket program developed and demonstrated dozens of different types of missiles with a wide variety of designs, sizes, and applications. The German jet program produced designs, prototypes, and in some cases production-line models for jet aircraft with a similarly wide range of designs, sizes, and applications. Likewise, wartime German programs on submarines, electronics, chemical warfare, biological warfare, directed energy technologies, and other areas all pursued a wide variety of developments in each of those areas. If a wartime German nuclear program had been run with determination and methods at least comparable to all of those other wartime scientific programs, one would expect it to have developed or at least investigated a whole range of designs, sizes, and applications for nuclear weapons. Indeed, Werner Grothmann stated that there were at least five different nuclear weapon types under development (pp. 4271–4273).

While Ilyichev reported that a 1.3-meter-diameter spherical implosion bomb was tested at Thuringia (p. 4485), and that report seems plausible from the preceding physics analysis, there is considerable evidence to support Grothmann's assertion that the German nuclear program was also working on other nuclear weapons designs.

A. Larger Spherical Implosion Bombs

A spherical implosion bomb is mostly filled with TNT-based explosives, which have an average density of approximately 1.654 g/cm^3. The average density due to the smaller amount of other materials in the bomb does not deviate much from that density; for example uranium tends to be present in much smaller amounts, and its higher density is typically offset by hollow spaces. Thus one may take 1.654 g/cm^3 as an approximate average density for a spherical implosion bomb. For the 65-cm radius of the Thuringian device, that density predicts a total bomb mass of 1900 kg, very close to the 2000 kg estimate reported by Ilyichev in March 1945.

Larger implosion bombs could compress the fission pit to a higher degree, decreasing the probability of failure and increasing the fission efficiency and explosive yield. Larger bombs could also use more fission fuel for a larger explosive yield. The Thuringian device appears to have been limited to a 1.3-meter diameter simply to allow an A-4 or similar rocket to accommodate its size and mass.

1.5-meter-diameter bomb. Ilyichev's November 1944 report gave a bomb diameter of 1.5 meters, or a radius of 75 cm (p. 4481). That may have just been a less accurately reported estimate of the actual 1.3 meter bomb diameter. However, it seems at least as likely that the 1.5 meter value was indeed the correct diameter of the German implosion design as it existed in November 1944, prior to the final push to reduce its size by supplementing the TNT with liquid oxygen. The U.S. Gadget/Fat Man implosion bomb design had a radius of 75 cm (not counting the bomb shell and fins), so the number reported by Ilyichev in November 1944 seems extremely reasonable. At an average density of 1.654 g/cm^3, a 75-cm-radius implosion bomb would have a total mass of 2900 kg, very close to the 3000 kg approximate mass of the U.S. Gadget. Thus one version of the German implosion bomb may have had a diameter of 1.5 meters and a mass of approximately 3000 kg. That would make it more challenging to deliver via rocket, but still quite reasonable for an air-dropped weapon to be delivered by aircraft. Any nuclear weapons design program would have begun earlier in the war, when rockets were still an unproven technology and Luftwaffe aircraft were making routine bombing runs over Allied territory, and would probably have expected the first nuclear weapons to be delivered by aircraft.

1.8-meter-diameter bomb. Reports of earlier German programs producing and testing spherical aluminum shells for secret purposes indicated a diameter of approximately 1.8 meters (p. 4270). If those reports are accurate (and not a misremembering of 1.3-meter- or 1.5-meter-diameter spheres), they would suggest a spherical implosion bomb design with even more conventional explosives, a larger fission pit, and/or a larger hollow space in the center of the pit. At an average density of 1.654 g/cm^3, a 90-cm-radius implosion bomb would have a total mass of approximately 5 tons. If the radius were slightly larger or if the average density (due to larger amounts of uranium and other dense materials) were slightly higher, the bomb mass could be closer to 6 tons. Intriguingly, there were multiple reports of a new type of German bomb that weighed 6 tons, was radioactive, and would be delivered to the United States by a giant rocket (see pp. 4338, 4350–4363, and 5343). The 1.8-meter-diameter spherical aluminum shells were reportedly being produced and tested in Anklam and Friedland, not far from Peenemünde. As already covered, a spherical implosion bomb design could be used with U-235, U-233, or Pu-239 fission fuel, and with or without a small amount of fusion fuel at the center to add neutrons and boost the overall efficiency of the fission explosion. Therefore, even for spherical implosion bombs, there could be a number of variations with different sizes, fuels, and explosive yields.

B. Nonspherical Implosion Bombs

Spherical implosion gives the greatest efficiency and highest explosive yield for a given amount of conventional explosives and fission fuel, since the fission fuel is uniformly compressed from all sides. Likewise the larger an implosion bomb is, the more efficient it tends to be, as discussed above. However, very large spherical shapes are not particularly well suited for air-dropped bombs or for ballistic projectiles. Thus there would be a strong motivation to consider smaller and/or non-spherical implosion bombs, even if their explosive yield would be considerably less than that of a large spherical implosion bomb. Whereas a large fission implosion bomb can have an explosive yield of tens of kilotons and destroy an entire city (like Nagasaki), a smaller non-spherical fission implosion bomb might have a yield on the order of one kiloton or less, but that could still make it useful for destroying certain tactical military targets, especially considering the radioactive as well as the blast effects. As a further motivation, smaller bombs would require less fission fuel than larger bombs; fission fuel would be in short supply in the early phases of any nuclear weapons program, as Werner Grothmann specifically stated that it was for the German program.

In fact, several sources discussed the wartime development of a smaller fission bomb. It was described as a tactical, nonspherical, two-point-ignition, fission implosion bomb that was externally similar to a standard German 250 kg bomb, had a full yield likely less than one kiloton, and was potentially ready for deployment before the end of the war (pp. 4246–4248, 4271–4277, 5030).

C. Gun-Type Fission Bomb

German scientists also appear to have been aware of the gun-type fission bomb design [Karlsch and Walker 2005; Thirring 1946]. However, any development seems to have been focused on the implosion design, since it requires much less fission fuel and has a much higher efficiency than the gun design. The U.S. gun-type fission bomb, Little Boy, had a mass of 4400 kg, diameter of 71 cm, and length of 300 cm. That is far larger than the SC-250-like bomb described by Grothmann, and descriptions of other bombs alleged by Grothmann, Ilyichev, and other sources to have been constructed have geometries very different than Little Boy. Thus from the available evidence, the gun design appears to have been understood but not developed, probably due to its inherent disadvantages relative to implosion designs.

D. Radiological Dirty Bombs

As discussed in Section D.5, several sources stated that Germany possessed one or more operational fission reactors before the end of the war. If that were true, it would have been technologically very straightforward to remove highly radioactive spent fission fuel from a reactor, pack it around a modest amount of conventional explosives in a bomb, and detonate such a device over a target to scatter highly radioactive isotopes over the target area. Such a bomb would have no required critical mass and could be made as large or small as desired, so it could easily be carried by an A-4 or other rocket, missile, or aircraft. Because that approach would be so straightforward once a reactor was operational, and because there was such strong political and military pressure for Germany to develop powerful new weapons, it seems highly likely that this approach would have been pursued. During the war, high-level officials in the United States and United Kingdom wrote classified memos about the possibility of the Germans using such a radiological dirty bomb, although it is not clear if that was purely speculation or based on actual intelligence from Germany [TNA AB 1/608].

E. Layer Cake H Bomb

As summarized in Sections 8.8.9 and D.9 (see especially p. 4280), a large number of declassified and publicly available sources appear to describe a six-ton H-bomb with a planned yield around 1.6 megatons that used a fission implosion device to initiate fusion reactions in lithium deuteride fuel and was expected to be tested in 1945 or 1946 if the war had continued.

Many documents show that there was prewar and wartime work using lithium and deuterium together as fusion fuel (pp. 4281–4349). Because lithium deuteride is solid and not a gas or cryogenic liquid, it makes an ideal fuel for hydrogen (H) bombs. There were multiple reports that the Germans were developing a weapon with a 6-mile blast radius (pp. 4365–4367). From Eq. (D.49), a 6-mile or 10-km blast radius corresponds to an explosive energy of at least $(10,000/85.5)^3 \approx 1{,}600{,}000$ tons of TNT equivalent, or at least 1.6 megatons. This is well beyond the kiloton ranges of fission bombs, as the German scientists knew from basic calculations of fission energies, and suggests that they were developing much more powerful H bombs. Knowledgeable German sources expected to complete a deliverable version of such a weapon later in 1945 or in 1946 (pp. 3401, 4272, 4367, 4334, 4359). If true, that was a feat that the United States and Soviet Union did not actually accomplish until 1953–1955 (Soviet Joe-4/RDS-6s, U.S. Castle Bravo, and Soviet RDS-37).

According to unclassified references, there are two major types of functional H-bomb designs [Goncharov 1996a, 1996b; Chuck Hansen 1988, 2007; Rhodes 1995; Sublette 2019; Wellerstein and Geist 2017]. The simpler one to build is what the Soviets later called a "layer cake" (*sloika*), a spherical implosion bomb with layers of fusion fuel interspersed with layers of fission fuel. The fusion reactions contribute only a modest amount of energy, but a huge number of neutrons that enable the consumption of far more fission fuel than would otherwise be possible.

Since the German program was producing fusion fuel such as deuterium and lithium, building spherical bombs with a diameter of at least 1.8 meters (significantly larger than even the U.S. Gadget/Fat Man fission implosion bomb), and expecting a blast radius corresponding to a megaton-level explosive yield, it is possible that a layer cake H bomb design was under development. (See also p. 4372.) This view might also be supported by the multiple reports of a new type of German bomb that weighed 6 tons, was radioactive, and would be delivered to the United States by a giant rocket (see pp. 4338, 4350–4363, and 5343). Furthermore, the postwar Soviet nuclear program was heavily dependent upon German scientists, materials, and ideas, and the first Soviet H bomb (Joe-4 or RDS-6, tested on 12 August 1953; see p. 1638) employed the layer cake design.

Joe-4 is reported to have weighed 4.5 tons, had a diameter of 1.5 meters, and produced an explosive yield of 400 kilotons; it is also reported that the bomb's yield could have been higher if its surrounding layer of conventional explosives had been better able to compress the layers of fission and fusion fuel [Wellerstein and Geist 2017]. (Joe-4's size was apparently constrained by the Soviet desire to make it no larger than the Joe-1 fission bomb, in order to facilitate delivery by aircraft). If there was a wartime German design that was very similar but had 1.5 tons more of surrounding conventional explosives (total weight of 6 tons), its diameter would have been around 1.8 meters, and its explosive yield could easily have been in the 1.5-megaton range.

F. Two-Stage H Bomb

According to unclassified references [Goncharov 1996a, 1996b; Chuck Hansen 1988, 2007; Rhodes 1995; Sublette 2019; Wellerstein and Geist 2017], the second major type of H bomb is a "two-stage" design, in which the dense outer bomb casing surrounds both a fission implosion bomb (the first stage) and a neighboring mass of fusion fuel (the second stage). When the fission bomb detonates, its heat and pressure ignite fusion reactions in the adjacent fusion fuel. If the outer bomb casing is made of fission fuel (even natural uranium), high-energy neutrons from the fusion reactions can trigger extensive fission reactions in the outer bomb casing, making it effectively a third stage of the explosion.

Friedwardt Winterberg, who worked very closely with Kurt Diebner after the war and never worked in the U.S. nuclear program, produced a book of designs for two- or three-stage fusion explosive devices that look rather different than publicly available U.S. H bomb designs but that are deeply steeped in earlier German hydrodynamics and physics research [Winterberg 1981]; see p. 4373. Whereas the outer casing of a U.S. H bomb design is generally depicted as cylindrical in the unclassified references, the outer casing of the Winterberg or Diebner H bomb design has a pronounced Prandtl-Meyer ellipsoidal shape. A surviving 1944 sketch from Walther Gerlach shows an ellipsoid in conjunction with nuclear reactions involving deuterium, which seems to support the wartime origin of Winterberg's ellipsoidal H bomb design (p. 4377). In addition to the more straightforward fission bomb designs, Werner Grothmann mentioned that an H bomb was being developed during the war, and that it was of an entirely different design that "looked like a swollen bomb" (p. 4272). The ellipsoidal H bomb design would seem to fit Grothmann's description perfectly. The multiple reports of a 6-ton bomb (pp. 4338, 4350–4363, and 5343) and a bomb with a 6-mile blast radius (pp. 4365–4367) could also describe this type of bomb.

In 1947, when Edward Teller was trying unsuccessfully to invent a workable design for the U.S. hydrogen bomb, he sent a highly unusual, specific, and urgent request for Siegfried Flügge to help him with a "physics... program... of interest and importance to the national security," stating that Flügge would "be of marked assistance in carrying out the aforementioned program" (p. 4996). Flügge was indeed brought to the United States, and it has never been publicly revealed what he worked on. In fact, late in the war and after the war, there was a large influx of scientists and engineers who came to the United States and/or United Kingdom and who were from or had knowledge of the German nuclear program (p. 1608). Many of those scientists appear to have been closely tied to the wartime German work on H-bombs, and may have especially aided the U.S. H-bomb development program between 1945 and 1954.

If enough archival material can be found, declassified, and released, it would be extremely interesting to find out how far German work on H-bombs may have progressed during the war, and how much that work (and the associated scientists, materials, and plans) influenced postwar work on H bombs in the United States, Soviet Union, or other countries.

D.15.7 Conclusions and Recommended Further Research

This appendix concludes by considering the plausibility of the primary source evidence, nuclear vs. non-nuclear explanations of that evidence, different possible nuclear devices, the reasons for not using any nuclear weapons in the war, the technological state of the German nuclear program relative to that of the United States, and recommendations for further research.

A. Plausibility of the Primary Source Evidence

The fundamental question underlying this appendix is the accuracy of the conventional historical view that Germany made little progress toward nuclear reactors and weapons during the war. While there are many types of potential documentation that Germany may have made significantly more progress than has been commonly acknowledged, the most dramatic proof would be the successful test explosion of a nuclear device. There is at least some evidence of several test explosions: one on or near the Baltic coast in October 1944, one in Poland during or around November 1944, and one or two in Thuringia in March 1945. Of those possible tests, currently there is the greatest amount of evidence for the early-March 1945 Thuringian test.

Wartime and postwar documents show that within the top echelons of the SS, there was a prolonged and intense interest in developing a nuclear weapon, and an expectation around March 1945 that battlefield use of such a weapon was imminent. Likewise, wartime and postwar documents from Diebner, Schumann, Trinks, Guderley, Harteck, Stetter, and others confirm that there were very active research programs on spherical implosion bomb designs, fission reactions, fission fuel production, fusion reactions, and fusion fuel production. The surviving documents do not indicate whether or how those research programs were combined or ultimately tested.

At least ten primary sources specifically address the March 1945 Thuringia test:

1. Ivan Ilyichev's November 1944 intelligence report to Stalin.
2. Ilyichev's 23 March 1945 report to Stalin.
3. Igor Kurchatov's 30 March 1945 response to Ilyichev.
4. Georgy Flerov's two brief May 1945 reports to Kurchatov and 1983 interview.
5. Robert Döpel's 1946 interrogation by the Russians.
6. Cläre Werner's testimony in 1962 and later in life.
7. Heinz Wachsmut's testimony in 1962 and later in life.
8. Erich Rundnagel's 1966 testimony.
9. Oscar Koch's 1960s testimony about a 1945 U.S. intelligence report.
10. Werner Grothmann's 2000–2002 testimony.

The details described in these ten primary sources are remarkably consistent with each other, as shown on p. 4480. The details are also consistent with other wartime and postwar primary sources that reported German work on a fission implosion bomb (see for example p. 4157). As shown in Section D.15.4 above, the details from all of these primary sources agree to a striking degree with the now well-established physics of nuclear weapons.

This may seem like an unacceptably small amount of evidence for such a dramatic historical claim as a German nuclear weapons test. However, even if the claim is true, it is not surprising that there is not more evidence. It is well known that Germans destroyed or buried documentation of military technologies at the end of the war.[34] Motivations for those actions included denying that technology to Allied nations, using that information as a bargaining chip, and/or avoiding imprisonment or execution for war crimes associated with the development, testing, use, or intended use of that technology. It is also well known that Allied nations vacuumed up as much documentation as they could find, and then kept it secret from the other Allies, or claimed it as their own technology, or simply lost the information within their large bureaucracies and the vast amount of material removed from Germany.[35]

Likewise it is not surprising that there is not more witness testimony. According to the ten primary sources, the test occurred in a sparsely populated area, most of the residents who did live there were evacuated ahead of time, and most of the residents who remained were sent to air raid shelters by warnings shortly before the test. Virtually all of the prisoners involved in the test or the preparations were worked to death, died in the test, or were killed afterward by the SS. Anyone else who spent much time at the test site in the hours immediately after the explosion would likely have received enough exposure to die of radiation sickness that would have been unrecognized in the chaos and hardship shortly before and after the end of the war. Scientists and military personnel who were involved would be strongly motivated to permanently conceal the test for fear of being executed for war crimes. Any others involved were threatened by the SS and sworn to secrecy or killed, and would have remained fearful of reprisals from former SS members for the rest of their lives if they revealed what they knew.

The Soviet intelligence reports from Ilyichev, Kurchatov, Flerov, Zhukov, and Döpel seem to prove that there was definitely some sort of test event, even if one might argue about the details of that event. The intelligence reports began at least as early as 15 November 1944, continued into 1946, went all the way to Stalin, and led to the commitment of major Soviet scientists, forces, and resources to investigate. These are certainly not forgeries, and it does not seem plausible that they are merely faulty intelligence about a completely nonexistent event.

[34]See for example: Huzel 1962, pp. 138, 151–162; Petersen 2008, p. 491; Simon 1971, pp. 4–8; p. 4670 in this appendix.

[35]See for example Albrecht et al. 1992; Bar-Zohar 1967; Bower 1987; Buyer and Jensen 1948; Byrd 1948; Crim 2018; DOW 1945b, 1946; Gimbel 1986, 1990a, 1990b, 1990c; Goudsmit 1947; Glatt 1994; Hall 2019a; Linda Hunt 1985; Morton Hunt 1949; Jacobsen 2014; Jensen 1948; Jösten 1947; Matthias Judt and Ciesla 1996; Kurowski 1982; Lasby 1971; Mick 2000; Nagan 1947; Nagel 2016; O'Reagan 2014, 2019; Simpson 1988.

B. Nuclear vs. Non-nuclear Explanations of the Primary Source Evidence

All possibilities for what that test event might have been can be considered. Most of those possibilities can be rejected unless the primary sources are greatly in error:

- A conventional bomb would not have the blast radius reported by Ilyichev and Koch, the radioactive effects reported by Ilyichev, Werner, Wachsmut, and Grothmann, the design reported by Ilyichev, Döpel, and Grothmann, or the intense security reported by Ilyichev, Rundnagel, Grothmann, Werner, and Wachsmut.

- A fuel-air explosive device might have caused blast damage to an area as large as reported, but it would not have had the radioactive effects reported by Ilyichev, Grothmann, Werner, and Wachsmut, or the design reported by Ilyichev, Döpel, and Grothmann.

- A chemical agent test might have killed, burned, or sickened as many people as reported, but it would not have the blast radius reported by Ilyichev and Koch, or the design reported by Ilyichev, Döpel, and Grothmann.

- A fuel-air explosive device that dispersed a chemical agent might theoretically account for both the blast damage and the symptoms of the casualties, but would not be consistent with the design reported by Ilyichev, Döpel, and Grothmann, and a fuel-air explosion would be far more likely to incinerate a chemical agent than to efficiently disperse it.

- A radiological "dirty bomb," with radioactive elements packed around and dispersed by a conventional explosive, might explain the radioactive effects, but would not have the blast radius reported by Ilyichev and Koch, or the design reported by Ilyichev, Döpel, and Grothmann.

- A "hydrodynamic" test of a nuclear bomb without any of its nuclear fuel, purely to scientifically validate the design details, would have the outward appearance of a conventional bomb explosion; it would not have the blast radius reported by Ilyichev and Koch, or the radioactive effects reported by Ilyichev, Grothmann, Werner, and Wachsmut.

- A pure fusion device, with fusion fuel at the center of an implosion design powered by conventional explosives, would not produce a significant amount of nuclear reactions, radiation, or energy. Even with over 70 years of effort and steadily improving technology, scientists have not been able to trigger significant fusion reactions with conventional explosives [Gsponer and Hurni 2009, pp. 139–141; Winterberg 2010, pp. 297–298, 302]. Thus such a device would not have the blast radius reported by Ilyichev and Koch, or the radioactive effects reported by Ilyichev, Grothmann, Werner, and Wachsmut. It would also not contain uranium as reported by Ilyichev, Döpel, and Grothmann.

- A pure fission device would be highly consistent with the blast radius reported by Ilyichev and Koch, the radioactive effects reported by Ilyichev, Grothmann, Werner, and Wachsmut, and the design reported by Ilyichev, Döpel, and Grothmann.

- A hybrid fission-fusion device could also be highly consistent with the blast radius reported by Ilyichev and Koch, the radioactive effects reported by Ilyichev, Grothmann, Werner, and Wachsmut, and the design reported by Ilyichev, Döpel, and Grothmann.

C. Type of Nuclear Device

Therefore the only possibilities that seem consistent with the evidence from the primary sources appear to be either a pure fission device or a hybrid fission-fusion device. If it was a fission-fusion device, the fusion reactions would not have made a significant direct contribution to the energy output, but their neutrons could have greatly reduced the critical mass of fission fuel required.

If the device tested had an explosive energy yield of a few hundred tons or so (as found in Section D.15.4), that would make its energy $\sim$ 100 times larger than that of a conventional bomb of the same size, yet $\sim$ 100 times smaller than that of well-known fission bombs such as the Gadget and Fat Man bombs that the United States detonated in July and August 1945. Even in March 1945, Igor Kurchatov was puzzled by the reported energy yield (p. 4496). If the explosive energy of the test was indeed in the few-hundred-ton range, there are three possible explanations:

- The most likely explanation is that the device was a full-sized bomb capable of an energy yield in the range of tens of kilotons if used with a pit containing several kilograms of U-235, but was tested with a pit containing very little U-235, perhaps as little as $\sim$ 100 grams. Any U-235 that Germany had produced would be a highly precious commodity that would be saved for battlefield deployment of such devices, not used up in a test. The Germans would also be reluctant to create a very large blast and very large amount of radioactivity deep in the heart of Germany, especially just for a test. (For the same reasons, several of India's 1998 Shakti nuclear detonations tested devices that produced explosions of less than 1 kiloton each yet successfully demonstrated their designs would have much higher yields if deployed.) This explanation fits well with Grothmann's statements that the test deliberately used only a very small amount of fuel. It is also very consistent with all of the other primary sources.

- A less likely but still possible explanation is that the device was a full-sized bomb, tested with the full amount of U-235, but misfired (for example if the neutron initiator failed or if the implosion was not spherically symmetric), causing the energy yield to be much smaller than expected. Evidence against this explanation includes the statements of Grothmann and Wachsmut that the energy yield was actually larger than expected, the comments of Grothmann that only a small amount of fuel was used, and the military undesirability of using up too much scarce U-235 or making too large of a mess purely for a test.

- Another unlikely but possible explanation is that the device was a small-sized "mini nuke" design, never intended to have a large yield even if deployed on the battlefield. Evidence against this explanation includes the large bomb diameters given in both of Ilyichev's reports, the large bomb mass given in Ilyichev's second report, the statement of Rundnagel that the bomb was designed to use at least 8 kg of fuel, the statements by Grothmann that these late-war efforts were focused on developing a large strategic nuclear weapon that could be delivered by rocket, and the military futility of testing or deploying a low-yield tactical weapon at that late stage of the war.

D. Reasons for Not Using a Nuclear Weapon in the War

One might try to argue that if Germany had really developed a nuclear bomb, it would have immediately used it during the war, so the fact that such a weapon was never used proves that it never existed. However, there are several reasons why Germany may not have used a nuclear weapon even if it had one in its possession. Conceivably any or all of these reasons might be true:

- The weapon may have been developed too late to be deployed. This seems quite plausible if the weapon was still being tested in March 1945 and the area was overrun by Allied forces on 4 April.

- A suitable delivery system for the weapon may have been developed too late or not at all. This also seems quite plausible if—as described by Ilyichev, Schumann, Grothmann, and others—the weapon was intended for delivery by rocket but weighed two tons. Existing A-4 or V-2 rockets were designed to carry a one-ton payload, and any rocket with a larger payload capacity would have still been in the experimental stage.

- There may have been only enough fission fuel for one or a very small number of weapons, and German leaders may have realized that even if those were used, they could not halt the advance of Allied forces into Germany from all sides. This seems very plausible, especially in light of Grothmann's comments about the uncertain political effect of any battlefield use of the weapon, and Grothmann's and Rundnagel's comments about the small amount of fuel.

- German leaders probably realized that if they used a nuclear weapon, Allied forces would respond by killing tens of millions of German civilians with crude but effective WWI-style chemical weapons (mustard agent and phosgene) or other means (pp. 2632–2651). This explanation is highly plausible, since that same reasoning seems to have prevented German leaders from employing the large amounts of advanced nerve gas that the country had in its arsenal (pp. 2632–2651).

- To extend the previous two points, German strategic plans may never have involved the use of just one or two nuclear weapons:

  - In the final years of the war, Allied forces were approaching Germany from all sides; it would have been obvious throughout those final years that destroying one or two Allied cities with nuclear bombs would never halt all of those Allied forces, let alone an Allied counterattack dropping mustard agent, firebombs, etc. on millions of German civilians.

  - Accordingly, the strategic thinking behind the German nuclear program may have been to mass-produce and stockpile nuclear weapons and the means to deliver them. Those weapons would have only been used once their numbers surpassed a capability threshold that would have enabled many simultaneous nuclear attacks [quite possibly in parallel with simultaneous attacks using German nerve agents and other chemical weapons (p. 2651), biological weapons, and/or fuel-air explosives] on Allied targets and the credible threat of further attacks if the Allies launched any counterattacks or if German demands were not met.

  - That approach appears to be supported by Grothmann and other sources that described mass-production or attempts at mass-production for nuclear weapons as well as their delivery methods.

  - Indeed, German officials spoke of plans to end the war within a matter of hours by such an overwhelming attack with their stockpiled weapons of mass destruction. Moreover, after studying German technologies after the war, Allied officials described exactly the same scenario of a massive German nuclear attack. See for example pp. 4549–4550, 4587, 4621, 4627–4665, 4679–4681, 4766, 5038, 5218, 5380, 5454–5466, 5658–5659.

  - If that was indeed the German strategy in the final years of the war, it suggests that the scale and level of advancement of the nuclear weapons/delivery programs may have been quite extraordinary, and that the world may have narrowly escaped a level of devastation that was unthinkable, at least until much later in the Cold War.

- Individual political or military leaders in charge of the deployment of a nuclear weapon may have realized that Germany would lose the war very soon regardless, and feared that they would be executed as war criminals if they actually used the weapon. That same reasoning may have prevented them from employing their nerve gas. For example, according to a 1 April 1945 Allied intelligence document, Luftwaffe General Albert Kesselring mentioned deliberations among Hitler's top staff about whether to use a final secret weapon, referred to as the "desperation weapon," that would cause a "terrible blood bath"; "Kesselring said if Fuehrer gave him order to use weapon he would surrender his command" (p. 4670). Grothmann confirmed this line of reasoning in the high command.

- Individual political or military leaders in charge of the deployment of a nuclear weapon may have realized that Germany would lose the war very soon, and come to individual decisions that they had more to gain personally by secretly offering the nuclear weapons technology and other advanced technologies to Allied countries than by employing the weapon against Allied forces. This is quite plausible since SS General Hans Kammler seems to have been directly in command of all advanced weapons (including any nuclear weapons) in the final stages of the war, and he secretly disappeared to America after faking his death—see pp. 4931–4959 [Agoston 1985; Döbert 2015; Döbert and Karlsch 2019; Karlsch 2014; Michalski et al. 2019; Reuter et al. 2019; Sulzer and Brauburger 2014, 2019a].

E. Technological State of the German Nuclear Program vs. the U.S. Program

Much more work is needed to gather and analyze relevant data from primary sources and physical evidence in order to verify that the Germans indeed tested a nuclear device, and to work out the design details of that device. With that large caveat, the extrapolated design details above and further details in the works of Schumann, Trinks, Diebner, Guderley, and others suggest that the wartime German nuclear program was actually ahead of the wartime and postwar U.S. nuclear programs:

- The implosion design reported by Ilyichev seems very detailed, physically feasible, and deeply grounded in experimental and engineering details. While similar to the U.S. Gadget design, it does not appear to be a carbon copy of that design, suggesting that it was arrived at independently and not by any German espionage of the U.S. program. It seems to be much more than an abstract concept never reduced to practice, or a hasty idea thrown together at the end of the war. It appears to be the end product of a well-funded, long-running, highly scientifically skilled nuclear weapons development program.

- As stated by Werner Grothmann (pp. 4271–4273) and supported by other evidence as discussed in Section D.15.6, the German program appears to have developed not just one nuclear weapon design, but rather a whole range of specialized designs for a variety of strategic and tactical applications. The United States did not have comparable diversity in its own nuclear arsenal until many years after World War II.

- German nuclear scientists appear to have been aware of the gun design, but seem to have focused their work on the implosion design from early on, since that would use much less fission fuel and offer much higher efficiency, which is why the implosion principle is still used in modern bomb designs. In contrast, the U.S. Manhattan Project spent most of its time and resources developing the gun-type design (called Thin Man in the early versions and Little Boy in the final version), and only began a serious program to develop an implosion design (Gadget/Fat Man) in July 1944.

- Germany appears to have conducted a test explosion of a nuclear device on 4 March 1945, four and a half months before the first U.S. test, and the German test appears to have been of a device that, if deployed, would have had a yield comparable to or even greater than the first U.S. fission bombs. If the reported October 1944 Baltic test explosion was real and was a successful nuclear test, that would have been over 9 months before the first U.S. test.

- The United States had produced no functioning nuclear weapons whatsoever by V-E Day, and only three by V-J Day (those detonated at Trinity, Hiroshima, and Nagasaki). In contrast, there is evidence that before V-E Day, Germany may have produced at least three nuclear weapons that were used in successful tests (Sections D.10, D.11, and D.12), and apparently several more that were held in a stockpile for possible military use (e.g., pp. 4182, 4436, 4667, and 4670). If that information is correct, then by the end of the war, Germany held an enormous lead over the United States in the world's first nuclear arms race.

- If allegations are true that the United States removed nuclear weapons technologies from Germany, used enriched uranium and bomb detonators obtained from the German submarine U-234, and relied at least in part upon those captured nuclear weapons technologies, captured

enriched uranium, and captured experts for the first U.S. fission bombs (Section D.14.5), the German program was even further ahead of the U.S. program.

- The German nuclear program accomplished as much as it did despite the tremendous handicaps and setbacks of years of heavy Allied bombing, sabotage, and blockades, which the U.S. program did not have to endure.

- If the Thuringian device used a high-voltage fusion neutron source as an initiator, that was a more advanced solution than the U.S. polonium-210/beryllium initiator, and was ultimately adopted much later after the war by the United States.

- If the Thuringian device used a compact betatron as an initiator, that was also a more advanced solution than the U.S. polonium-210/beryllium initiator. The U.S. did not demonstrate a betatron neutron initiator for a fission bomb until the 1 June 1952 George test of Operation Tumbler-Snapper [https://nuclearweaponarchive.org/Usa/Tests/Tumblers.html].

- If the Thuringian device and other proposed German designs used neutrons from fusion fuel in the center to greatly "boost" the yield of the fission fuel, that was a major advance that could increase the energies of fission bombs by a factor of ~ 10 (from tens of kilotons to hundreds of kilotons). Officially, fusion boosting was first considered in the U.S. by Edward Teller in 1945 and in the Soviet Union by Andrei Sakharov in 1948, was first tested by the U.S. in 1951 and by the Soviet Union in 1953, and is commonly used in modern bombs [Goncharov 1996a, 1996b; Chuck Hansen 1988, 2007; Rhodes 1995; Sublette 2019; Wellerstein and Geist 2017].

- The Thuringian device appears to have been designed to be launched on a rocket (perhaps even the intercontinental A-9/A-10), which the United States was not prepared to do until 1958 (after help from hundreds of German-speaking scientists and engineers it had acquired). See p. 5821.

- The Thuringian device appears to have packed a full-fledged implosion design (and presumably an explosive yield to match) into a bomb with a total deployed mass less than half that of the first U.S. fission bombs (2000 kg for the Thuringian device vs. 4670 kg for Fat Man). Grothmann reported that Germany possessed tactical nuclear bombs that were even smaller. It took the United States several years to reduce the size and mass of fission bombs.

- Whereas the U.S. program relied heavily on a very inefficient and expensive gaseous diffusion process to help enrich uranium, the German program developed and employed (among other techniques) gas centrifuges, which were much more efficient and therefore subsequently became the preferred modern method. There is also evidence that the German program studied "photochemical" methods of uranium isotope enrichment, many decades before laser isotope separation was perfected in the United States.

- There is evidence that the German program developed electronuclear breeding of fission fuel (p. 3954), a technology that the United States did not seriously pursue until years after the war, and that is still of concern for nuclear weapons proliferation in the modern world.

- The German nuclear program appears to have produced and perhaps even used lithium-6 deuteride as readily storable solid fuel for producing fusion reactions in nuclear bombs (Section D.9), as an alternative to the much more troublesome cryogenic deuterium and tritium. Officially, lithium-6 deuteride was first considered in the United States by Edward Teller in 1947 and in the Soviet Union by Vitaly Ginzberg in 1949, was first tested by the United States in 1954, and is commonly used in modern H bombs [Goncharov 1996a, 1996b; Chuck Hansen 1988, 2007; Rhodes 1995; Sublette 2019; Wellerstein and Geist 2017].

- A 1948 U.S. intelligence document stated that Austrian and German scientists such as Josef Schintlmeister had produced and identified transuranic elements through element 104; if true, that is a feat that was not accomplished until 1969 in the United States (p. 4335).

- In addition to possibly using fusion fuel to improve a fission bomb design, there is significant evidence that the German program was working on full-fledged H-bomb versions with megaton-level yields (pp. 3401 and 4271–4273 and Sections D.9 and D.15.6). German sources stated that they expected to complete a deliverable version of such a weapon later in 1945 (see p. 4367) or in early 1946 (see p. 3401). If true, that was a feat that the United States and Soviet Union did not actually accomplish until 1953–1955 (Soviet Joe-4/RDS-6s, U.S. Castle Bravo, and Soviet RDS-37).

F. Final Perspective and Recommendations

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

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

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

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

4. Extensive and meticulous industrial archaeological digs should be conducted at sites suspected to have been involved in developing or storing nuclear materials or nuclear weapons. Even

> if much of the material at those sites had been removed by German or Allied forces, any remaining evidence could provide conclusive proof about the nature and extent of the wartime nuclear program.

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

An analogous historical mystery may be the 1960s Soviet program to land a cosmonaut on the moon. Prior to the U.S. manned landing on the moon, it was widely believed that the Soviet Union was very close to achieving the same goal. Yet once the United States had achieved victory, the Soviet Union denied that it had ever even attempted a manned lunar program. Soviet denials continued for two decades, and concrete proof of a Soviet manned lunar program could not be found. Most historians ignored the Soviet program, and only a handful of authors sifted through the small amount of available evidence and speculated about the program [Oberg 1981; Phelan 2013]. In 1990, Soviet officials finally revealed the entire former program and put five of the LK manned lunar landers that had been built for it on display in various museums [Siddiqi 2000].

Similarly, for most of World War II, it was widely believed that Germany was developing a nuclear bomb and might well beat the United States to that goal. Yet once Germany was defeated, there were denials that it had ever even attempted to develop a nuclear bomb. Those denials have continued for decades and concrete proof has not been found. Most historians have ignored the German nuclear weapons program, and only a handful of authors have sifted through the small amount of available evidence and speculated about the program. Whether those authors are correct, and whether concrete proof of the program will ever be released, remains to be determined.

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

Likewise, if the German nuclear weapons program was successful, one can also understand why the major countries involved might want to preserve that secret even 75+ years later. Germans and Austrians might not want yet another Third Reich offense from their past for which they would need to apologize. Former Allied countries might not want to admit that their wartime and postwar technological prowess was not as great as they had boasted for so many years, or that that of their vanquished enemy was greater than they had claimed for so long. In any event, routine security classification rules would prevent the release of archival documents with useful details about nuclear weapons designs and production methods, no matter what their age, history, and country of origin might have been.

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

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

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

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

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

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

6. All nations would benefit tremendously by learning exactly how such revolutionary technologies were created then, so that they could employ similar methods of innovation to create and enjoy the benefits of new revolutionary technologies in the future.