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Physics in Perspective

A Neutronics Study of the 1945 Haigerloch B-VIII Nuclear Reactor

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We present a neutronics study of the German B-VIII nuclear reactor, which was built in Haigerloch, Germany, between February and April 1945. We used the Monte Carlo code MCNP5 to estimate its effective nuclear-multiplication constant k_{eff} and its corresponding neutron-multiplication factor M, its neutron energy-distribution spectrum, and its neutron-flux distribution in its central horizontal and veritical planes for both thermal and fast neutrons. Our calculations agree well with the known measurements the German scientists made, who determined M to be 6.7. We also found that the effect on k_{eff} of impurities in the graphite of its neutron reflector could have been only on the order of few hundredths of a percent.

Key words: Werner Heisenberg; Walther Gerlach; Haigerloch; German nuclear program; B-VIII nuclear reactor; MCNP Monte Carlo code; World War II; nuclear physics; nuclear reactors.

Introduction

We present a neutronics study of the German B-VIII nuclear reactor, which was built in Haigerloch, Germany, between February and April 1945, just before the end of the war in Europe. Our goal is to understand the physical and technical knowledge of nuclear reactors that German scientists had at that time. The United States Manhattan Project was driven to a great extent by fear of the German efforts, but little is known in detail about how far away German scientists were from achieving criticality with their B-VIII reactor, and thus from building a bomb. We present some data that will help to illuminate this question.

The B-VIII nuclear reactor was used in the last of about twenty experiments that German scientists carried out with various nuclear reactors in an attempt to achieve criticality. In retrospect, it seems they understood that they first had to estimate the critical size and mass, that is, the optimal geometrical configuration and quantity of fissionable isotopes that are necessary to sustain a stable neutron population in a given system without external intervention. In general, a system is critical if it maintains over

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time the neutron population that was present at the moment it went critical. A subcritical system is one in which any excess neutrons are reduced more or less rapidly to zero by neutron-capture or absorption processes; it can sustain a stable neutron population if and only if neutrons are continuously supplied to it by an external source – the neutron population increases to a maximum and then decreases if the external source is removed. A supercritical system is one in which the geometrical configuration and quantity of fissionable isotopes are such that the initial neutron population increases exponentially in time, leading to an uncontrollable explosion; a nuclear weapon can be produced by adding more fissile mass to an initially critical configuration. Systems are typically classified according to their effective neutron-multiplication constant k_{eff}. If $k_{eff} < 1$, a system is subcritical; if $k_{eff} > 1$, it is supercritical; if $k_{eff} = 1$, it is both stable and self-sustaining; even an extremely small departure from unity results in either a subcritical or supercritical system. Thus, trying to build a supercritical system without knowledge of the precise conditions and limits beyond which a stable and controllable critical system becomes supercritical can lead to a catastrophic accident.

The physical theory of nuclear-chain reactions is understood extremely well today, and supercritical systems can be designed with no preliminary theoretical and experimental studies of stable, critical systems. That was not the case during World War II, however, when physicists realized that the first step was to understand criticality by building a critical system: Both American and German scientists first tried to build subcritical systems, then critical systems, and only then systems that could become supercritical. The importance of studying critical configurations experimentally also was reflected after the war in the great emphasis that U.S. National Laboratories placed on constructing various critical reference systems between 1950 and 1979; the data obtained from such configurations as Jezebel, Godiva, and Thor,[1] to name just three, are still used to assess integral neutron cross sections, that is, the energy-dependent probabilities that a neutron will produce a given reaction in a collision with a target nucleus.

In principle, the theory and operation of nuclear-power reactors is also helpful in building a fission bomb, which can be classified roughly according to its main fissionable isotope, uranium-235 (U^{235}) or plutonium-239 (Pu^{239}). In the former, natural uranium must be highly enriched in its fissionable isotope U^{235}; in the latter, a sufficiently fast triggering mechanism must be used. Thus, the first step in building a bomb is to understand the physics of critical systems, the second is to obtain either highly enriched uranium or a sufficient supply of plutonium. Efficient and successful procedures for uranium enrichment were beyond the reach of German scientists during the war, because of their extremely high cost, and because of the deteriorating wartime conditions in Germany. Plutonium can be produced efficiently only in reactors that burn uranium. It is sometimes said that German scientists attempted to build only subcritical systems and not critical systems, because they had insufficient time or resources, and because by using an external neutron source with a subcritical reactor they could breed plutonium. In any case, as we will see, the Haigerloch B-VIII reactor was too far away from achieving criticality to be used efficiently to breed sufficient quantities of plutonium: Its neutron flux was several orders of magnitude too small. Nonetheless, we also will see that the B-VIII reactor was not too far away from being a good working critical reactor.

Following a brief historical introduction and a summary of what is known about the Haigerloch B-VIII nuclear reactor,[2] we present the results of a neutronics study of it using the Monte Carlo neutron transport code MCNP5,[3] explaining the geometrical properties and assumptions we used in our simulations. Thus, we used three slightly different configurations and calculated their effective neutron-multiplication constants k_{eff}. We also determined the neutron energy distribution (spectrum) in the reactor and the neutron-flux distribution in its central horizontal and vertical planes for both thermal and fast neutrons, which are its most important parameters for gauging its performance.

The Haigerloch B-VIII Nuclear Reactor

Immediately after the discovery of nuclear fission at the end of December 1938,[4] nuclear physicists everywhere recognized the possibility of producing a self-sustaining chain reaction in uranium by using a moderator to slow down the fast neutrons that are emitted in the fission process to thermal energies, which then produce further fissions.* This eventually led Enrico Fermi (1901–1954) and his team in Chicago to build the first self-sustaining nuclear pile (the famous CP-1), which went critical on December 2, 1942, and the U.S. government to establish the Manhattan Project to develop an atomic bomb, which was first tested at Alamogordo, New Mexico, on July 16, 1945. [5]

German scientists also attempted to build nuclear reactors,[6] with the twofold aim of studying their neutronic properties and of breeding Pu^{239}, which by 1941 they knew was fissionable,[7] and hence could be used to build a bomb.[8] The German Uranium Club (*Uranverein*) consisted of many leading scientists, including Werner Heisenberg (1901–1978, figure 1), Carl Friedrich von Weizsäcker (1912–2007), Otto Hahn (1879–1968), Walther Gerlach (1899–1979), Karl Wirtz (1910–1994), and Kurt Diebner (1905–1964).[9] These scientists and four of their colleagues, Max von Laue (1879–1960), Erich Bagge (1912–1947), Paul Harteck (1902–1985), and Horst Korsching (b. 1915), were captured in Haigerloch and neighboring towns on April 23, 1945, by the American Alsos Mission under the scientific leadership of Samuel A. Goudsmit (1902–1978),[10] and in early July they were interned at Farm Hall, an estate close to Cambridge, England, where their conversations were secretly recorded and remained classified until 1992.[11]

Many of the surviving scientific reports that the German scientists produced are preserved today at the Deutsches Museum in Munich, Germany,[12] from which it can be inferred that they designed and built about twenty small-scale subcritical systems during the war.[13] They gave each of these *Uranmaschinen* a code name that was formed by a letter (for instance, B, G, L) that indicated the city in which they were developed (for instance, Berlin, Gottow, Leipzig), followed by a Roman numeral that indicated the chronological order of their development in the laboratory in that city.

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* In nuclear fission, as physicists soon learned, thermal neutrons, that is, neutrons of energy of about 0.025 eV (electron volt) impinge on the fissionable isotope U^{235}, splitting it into two or more highly energetic fragments with the emission of fast neutrons of average energy 2.5 MeV (million electron volts), which then must be slowed down by a moderator to thermal energies to produce further fissions.



Fig. 1. Werner Heisenberg (1901–1978). *Credit*: Photograph by Friedrich Hund; courtesy of American Institute of Physics Emilio Segrè Visual Archives.

The German nuclear reactor that is known best, performed best, and was tested last was the B-VIII reactor, a subcritical reactor that was built in a former beer cellar beneath the castle church (*Schlosskirche*) in Haigerloch (figure 2), a small town in the Schwabian Alps not far from Tübingen. Its construction was under the overall administration of Gerlach, since 1943 the "czar" of the German nuclear project, and the direct supervision of Heisenberg. The German scientists later reported measurements indicating that the B-VIII reactor attained a neutron-multiplication factor M of 6.7.[14] The neutron-multiplication factor M is defined in terms of the effective neutron-multiplication constant k_{eff} as $M = 1/(1 - k_{eff})$, so that when a system becomes critical ($k_{eff} = 1$), M becomes infinite; M therefore is useful in estimating the neutron-population level of



Fig. 2. The entrance to the beer cellar beneath the castle church (*Schlosskirche*) in Haigerloch where the B-VIII nuclear reactor was located, as it appeared in April 1945 when Samuel Goudsmit and the Alsos Mission dismantled it. *Credit*: Photograph by S.A. Goudsmit; courtesy of American Institute of Physics Emilio Segrè Visual Archives, Goudsmit Collection.

a subcritical system that is asymptotically approaching criticality. When Goudsmit's Alsos Mission reached Haigerloch, he and his men confiscated the documents they found, dismantled the B-VIII reactor, and took some pictures of it. In 1980, the B-VIII reactor was reconstructed to its original scale, and the beer cellar in which it was located was transformed into a museum open to the public (figure 3).

The B-VIII reactor (figure 4), as we know from the documents and pictures upon which its reconstruction was based,[15] consisted of a cylindrical magnesium vessel 124 cm (centimeters) in diameter, 164 cm high, and 3 mm (millimeters) thick that was taken over from the older B-VI reactor to hold the uranium fuel. This was surrounded by blocks of graphite (5 × 10 × 50 cm) to a thickness of 40 cm (total weight 10 tons) to



Fig. 3. The interior of the Haigerloch museum with the reconstructed B-VIII nuclear reactor at the back. *Source*: Stadtverwaltung Haigerloch, *Atom-Museum Haigerloch* (ref. 2), p. 8; reproduced by permission.

reflect neutrons back toward the center, both in the radial and axial directions. The cylindrical magnesium vessel and its surrounding graphite neutron reflector were themselves enclosed in a cylindrical aluminium tank 210 cm in diameter, 210 cm high, and 5 mm thick, which was taken over from the older B-VII reactor, and which in turn was inside a large cylindrical concrete housing to hold light water (H_2O) for cooling the reactor and to serve as a shield against the radiations it emitted.

The inner magnesium vessel was filled with heavy water (D_2O),[16] which could be pumped into and out of it from large storage tanks, and into which cubes of natural metallic uranium, 5 cm on a side, were suspended from two opposite corners and connected together by aluminium wire 5.5 cm in length. There were a total of 664 uranium-fuel cubes, which were divided into 78 uranium-fuel aluminium-wire chains, 40 of which were about 124 cm long and held 9 uranium-fuel cubes, and 38 of which were about 115 cm long and held 8 uranium-fuel cubes, the entire assembly being attached to the roof of a removable watertight lid that could be raised and lowered to cover the magnesium vessel. The chains were arranged in such a way that the minimum distance between the centers of two neighboring uranium-fuel cubes was about 14 cm, which implies some sort of alternation between the 9-cube chains and 8-cube chains, as was

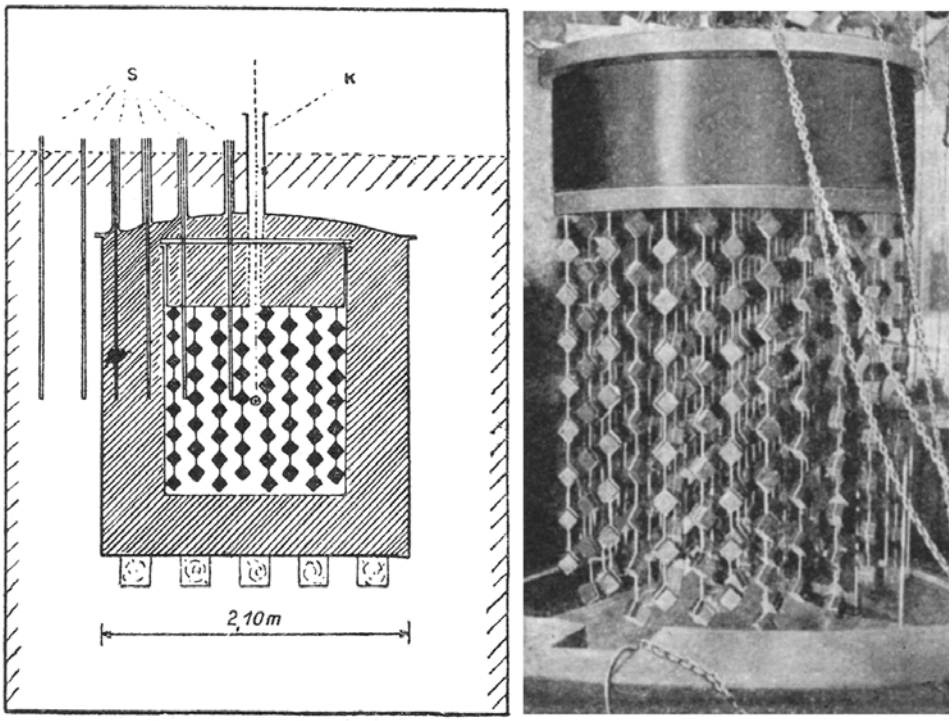


Fig. 4. Schematic picture (*left*) of the Haigerloch B-VIII nuclear reactor. The external neutron source was inserted into its central chimney *K* and placed at the middle of the surrounding uranium-fuel lattice, as indicated by the large black dot. The probes *S* were inserted into the smaller chimneys in the uranium-fuel lattice, into the surrounding heavy-water neutron moderator, and into the external graphite neutron reflector (shaded region, which extends to a diameter of 2.10 meters) to measure the neutron intensities at these locations. The photograph of the reactor core (*right*) shows the uranium-fuel cubes connected together by aluminium wires attached to two of their opposite corners, the entire assembly being suspended from a water-tight lid that covered the reactor core when lowered into place. *Source*: Heisenberg and Wirtz, "Grossversuche (ref. 14), p. 159; Stadtverwaltung Haigerloch, *Atom-Museum Haigerloch* (ref. 2), p. 59.

the case in the earlier G-III reactor.[17] The uranium-fuel cubes thus formed a uniform lattice immersed in heavy water, with a central vertical channel (central chimney) that was kept open so that an external radium-beryllium (Ra-Be) neutron source* could be inserted into it, where the probability that the emitted neutrons would produce fission in the uranium-fuel lattice is highest, and the probability that they would be captured or absorbed is lowest. Whether this was an actual Ra-Be neutron source or one made

* In a Ra-Be neutron source, the isotope ${}_{88}Ra^{226}$ decays radioactively by the emission of an α particle (${}_2He^4$) according to the reaction ${}_{88}Ra^{226} \rightarrow {}_{86}Rn^{222} + {}_2He^4$, and the emitted α particle then impinges on the isotope ${}_4Be^9$, producing a neutron according to the reaction ${}_2He^4 + {}_4Be^9 \rightarrow {}_6C^{12} + {}_0n^1$.

of polonium (earlier called RaF) and beryllium** is unknown; we do know, however, that there was a large polonium breeding plant at the Ronneburg branch of the Physikalisch-Technische Reichsanstalt that was directed by Carl-Friedrich Weiss.[18] Beyond the central chimney, there was a radial series of small chimneys that were used for the insertion of probes,[19] probably of silver or dysprosium, to measure the neutron intensity by neutron-activation techniques, although they also could have been used for the insertion of cadmium rods to quench the reactor by absorbing neutrons before it became supercritical and exploded.

Diebner had introduced the idea of using uranium-fuel cubes in reactors at the beginning of 1944 (reactors G-IIIa and G-IIIb), while Heisenberg had argued for a rectangular arrangement in which slabs of uranium fuel and heavy water were arranged in a wafer-like structure (as in reactor B-VI).[20] The core of the Haigerloch B-VIII reactor thus represented a melding of these ideas and could not have been built before February 23, 1945, when Erich Bagge transported about 1.5 tons of metallic uranium cubes, 1.5 tons of heavy water, 10 tons of graphite, and some cadmium to Haigerloch.[21] Heisenberg and Wirtz included a sketch of a vertical section of the Haigerloch B-VIII reactor (figure 4) in their contribution to the FIAT Review of German Science 1939-1946, which was published in 1948 and reprinted in 1982.[22]

The MCNP Simulations of the Haigerloch B-VIII Reactor

We simulated the Haigerloch B-VIII reactor using the Monte Carlo neutron transport code MCNP, version 5, which is a general-purpose, continuous-energy, generalized-geometry, time-dependent, coupled neutron-photon-electron Monte Carlo transport code that was developed at Los Alamos National Laboratory, and today is one of the most widely used tools in designing and analyzing nuclear reactors.[23]

To create a model of the B-VIII reactor for MCNP simulations, we had to make some assumptions owing both to the lack of detailed knowledge of the reactor and to the necessity of simplifying the system for calculational purposes. First, we assumed that the uranium-fuel cubes, which we took to be made of natural metallic uranium of density 19.05 g/cm^3, and the aluminium-wire links between them could be treated as a kind of homogenized material, that is, that they could be modelled as cylinders of diameter $10/3\sqrt{6}$ centimeters (since the uranium-fuel cubes were suspended from two opposite corners) that were filled with a uniform and homogeneous mixture of uranium fuel, aluminium, and heavy water, with the known masses of these materials placed inside each cylinder. We show in figure 5 horizontal and vertical cross sections at the central plane of the B-VIII reactor, as simulated by the MCNP code for Model C (see below) and as rendered by VISED software. We therefore had to calculate two different compositions of these materials, one for the 8-cube chains and one for the 9-cube chains. This introduced a small underestimation of the effective neutron-multiplication

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* In a Po-Be neutron source, the isotope ${}_{84}Po^{210}$ decays radioactively by the emission of an α particle (${}_2He^4$) according to the reaction ${}_{84}Po^{210} \rightarrow {}_{82}Pb^{206} + {}_2He^4$, and the emitted α particle then impinges on the isotope ${}_4Be^9$, producing a neutron according to the reaction ${}_2He^4 + {}_4Be^9 \rightarrow {}_6C^{12} + {}_0n^1$.

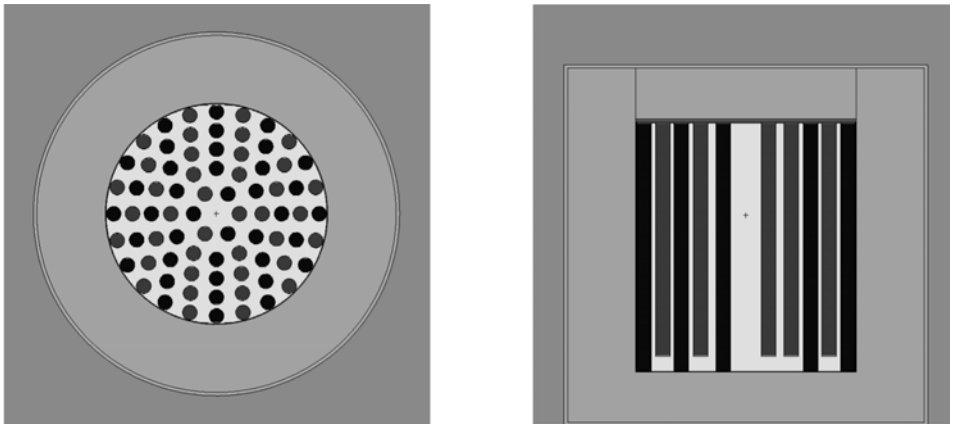


Fig. 5. Horizontal (*left*) and vertical (*right*) cross sections at the central plane of the B-VIII reactor, as simulated by the MCNP code for Model C and as rendered by VISED software.

constant k_{eff}, because the uranium fuel in the B-VIII reactor was lumped in three directions, while in the MCNP simulation it is lumped only in the radial direction.[24] To compensate for this reduction in k_{eff} owing to the absence of lumps of uranium fuel in the axial direction, we assumed that the connecting aluminium wires consisted of double threads 2 mm thick, which we determined would support the weight of the uranium-fuel cubes with a margin of safety, and which we assumed were made of the aluminium alloy Al-5025, one that consists of natural aluminium, a fair amount of magnesium (which has a low neutron-absorption cross section for thermal neutrons), and only trace amounts of copper (which can capture thermal neutrons).

Second, since the purity of the heavy water that was used as a moderator in the B-VIII reactor is unknown (typical purities were 95–99% pure), we assumed that it consisted of 95% heavy water (D_2O) and 5% light water (H_2O) that was distributed homogeneously in the magnesium vessel. Third, we assumed that the thickness of the magnesium vessel was 5 mm,* and that it was made of the magnesium alloy AZ91. Fourth, we assumed that the thickness of the surrounding aluminium tank was 2 cm,** and that it was made of the aluminium alloy Al-1100. We show the elemental compositions of all of these alloys in table 1.

We preserved the geometrical and material symmetries of the B-VIII reactor wherever possible. We did not simulate its concrete housing, however, because that has only a negligible effect on the neutron economy of the system, since to reach it neutrons first have to pass through 40 cm of graphite and a large stratum of light water (which we assumed was 60 cm thick). The purity of the graphite is of fundamental importance, of

* As noted above, its actual thickness was 3 mm; see Heisenberg and Wirtz, "Grossversuche (ref. 14), p. 158; Stadtverwaltung Haigerloch, *Atom-Museum Haigerloch* (ref. 2), p. 58.

** As noted above, its actual thickness was 5 mm; see Heisenberg and Wirtz, "Grossversuche (ref. 14), p. 158; Stadtverwaltung Haigerloch, *Atom-Museum Haigerloch* (ref. 2), p. 58.

Table 1. The elemental compositions (% by weight) of the aluminium alloy Al 5025, magnesium alloy Mg AZ91, and aluminium alloy Al 1100.

Element	Alloy Al 5025	Alloy Mg AZ91	Alloy Al 1100
Aluminum (Al)	95.25	8.0	99.0
Magnesium (Mg)	3.9	90.2	
Silicon (Si)	0.25	0.5	0.5
Iron (Fe)	0.2		0.4
Zinc (Zn)	0.2	1.0	0.015
Chromium (Cr)	0.15		
Copper (Cu)	0.04	0.1	0.085
Manganese (Mn)	0.01	0.13	
Nickel (Ni)		0.07	

course, if criticality is to be achieved in a lattice of lumped uranium fuel dispersed throughout blocks of graphite (as in Fermi's CP-1) to serve as moderators to reduce the energy of the fast neutrons emitted in the fission process to thermal energies so that they produce further fissions. And we know that the graphite the German scientists used was not of the highest purity – it contained boron impurities up to 10 ppm (parts per million) in atomic mass units.[25] In the B-VIII reactor, however, they used graphite only as a neutron reflector and heavy water as a moderator, so its performance was not very sensitive to the purity of the graphite they used. In any case, to evaluate the effect of the purity and density of the graphite they used, we assumed three different models in our simulation, as shown in table 2. Since we assumed that they used natural graphite, as in Model C, we show in table 3 its elemental composition, taking these elements to be present in their natural abundances.

We left the choice of neutron cross sections for the various elements to the MCNP code, which automatically selects them from among those available in the code database based upon the "goodness" of the evaluations. These cross sections were selected from (1) the Acti-A library file for hydrogen (H), oxygen (O), magnesium (Mg), aluminium (Al), sulfur (S), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), and manganese (Mn); (2) the Endf66a library file for deuterium (D), boron (B), and carbon (C); (3) the Endf60 library file for silicon (Si); (4) the RMCCS library file for chromium (Cr), iron (Fe), nickel (Ni), and copper (Cu); (5) the Endl library file for zinc (Zn); (6) the Endf66b library file for molybdemum (Mo) and barium (Ba); and (7) the Endf66c library file for the isotopes U^{235} and U^{238}. The values selected by the MCNP code for low-energy neutron cross sections for hydrogen (H) in light water, deuterium (D) in heavy water, and carbon (C) in the graphite lattice to take account of the excitation of vibrational levels in molecules and bound nuclei were taken from tables in the Sab2002 library file. We felt this was necessary, because the B-VIII reactor was essentially a thermal reactor with high neutron flux below the thermal-energy threshold (which we took to be 0.625 eV). Further, since it was essentially a zero-power reactor, we did not introduce any corrections for temperature effects in the MCNP simulation; all of the cross-sections were evaluated at 296 K.

Table 2. The purity and density of the graphite that was assumed in the MCNP simulations of Models A, B, and C.

Model	Graphite purity	Graphite density (g/cm^3)
A	Pure graphite	2.2
B	Graphite with 1 ppm Boron	1.8
C	Natural graphite	1.8

Table 3. The elemental composition by atomic percentage of natural graphite.

Element		Element		Element	
Carbon (C)	99.925	Vanadium (V)	0.0032	Magnesium (Mg)	0.00057
Calcium (Ca)	0.016	Barium (Ba)	0.0032	Manganese (Mn)	0.00050
Oxygen (O)	0.0154	Aluminum (Al)	0.0032	Molybdenum (Mo)	0.00045
Potassium (K)	0.010	Nickel (Ni)	0.0032	Chromium (Cr)	0.00045
Sulfur (S)	0.010	Iron (Fe)	0.0030	Boron (B)	0.00035
Titanium (Ti)	0.0032	Silicon (Si)	0.0022		

Results

The values of the effective neutron-multiplication constant k_{eff} that the MCNP5 simulations yielded for Models A, B, and C are shown in table 4, together with their standard deviations (SD), neutron-multiplication factors, neutron mean-free paths (mfp) in centimeters over the entire reactor, and the average prompt-neutron lifetimes (l) in seconds. We see that the reactor is subcritical ($k_{eff} < 1$) for all three Models, and that the neutron-multiplication factor for Model C is in reasonable agreement with the value of 6.7 that the German scientists reported for measurements in which they used an external Ra-Be neutron source. We estimate that the effects of differences in graphite purity and density are on the order of a few hundredths of a percent.

The MCNP simulations for Models A, B, and C also yielded the following results: (1) The energy corresponding to the average fissioning neutron lethargy* is between 7.56–7.88 × 10^{-8} MeV. (2) The percentages of fissions produced by neutrons in the thermal, intermediate, and fast-energy ranges are shown in table 5. (3) The average number of neutrons that were produced in each fission is 2.448, that is, greater than 2, so that in principle a chain reaction could be sustained. However: (4) the ratio of the average number of fission neutrons that were produced to those that were absorbed in the

* In the MCNP neutron transport code, the average fissioning lethargy is defined as the average value, over the entire neutron energy range, of the natural logarithm of the neutron energy weighted by the product of the neutron spectrum and fission cross section. We gave the average fissioning lethargy instead of the average energy per fission, because the former is more indicative of the reactor's type of spectrum.

Table 4. The results of the MCNP simulations for the effective neutron-multiplication constants k_{eff}, their standard deviations (*SD*), their corresponding neutron-multiplication factors *M*, the neutron mean-free-paths (*mfp*) in centimeters over the entire reactor, and the average prompt neutron lifetimes (*l*) in seconds for Models A, B, and C.

Model	k_{eff}	*SD*	*M*	*mfp* (cm)	*l* (*s*)
A	0.89454	0.00013	9.482	2.28	5.6530×10^{-4}
B	0.86831	0.00013	7.593	2.28	4.8395×10^{-4}
C	0.85748	0.00013	7.016	2.28	4.1184×10^{-4}

Table 5. The percentages of fissions produced by neutrons in the thermal, intermediate, and fast-energy ranges.

Neutron energy range	Percentage of fissions
Thermal (< 0.625 eV)	92.81–93.11%
Intermediate (0.625 eV–100 keV)	3.73–3.89%
Fast (> 100 keV)	3.17–3.30%

uranium-fuel cylinders is between 1.0194 and 1.0287, and (5) that same ratio for the entire reactor is between 0.8543 and 0.8823, so the reactor is indeed subcritical.

We plot in figure 6 the neutron-energy distribution function $\psi(E)$, that is, the number of neutrons present at each energy E as a function of E, averaged over the entire reactor core. We see that (1) there is a typical Maxwellian distribution at thermal-neutron energies and up to about 10^{-8} MeV (10^{-2} eV); (2) there are small bumps at the lower neutron energies of 1.5×10^{-9} MeV (1.5×10^{-3} eV), 4.5×10^{-9} MeV (4.5×10^{-3} eV), and 9×10^{-9} MeV (9×10^{-3} eV) owing to the excitation of vibrational levels of hydrogen and deuterium nuclei in water and of carbon in graphite; (3) there is an absolute maximum in the neutron-energy distribution at an energy of about 5×10^{-8} MeV (0.05 eV); (4) as the energy of the neutrons decreases to intermediate values, the neutron-energy distribution follows an inverse-energy ($1/E$) dependence; (5) in this region, at neutron energies of 6×10^{-6} MeV (6 eV), 20×10^{-6} MeV (20 eV), 39×10^{-6} MeV (39 eV), 65×10^{-6} MeV (65 eV), 80×10^{-6} MeV (80 eV), and 100×10^{-6} MeV (100 eV), there are dips that correspond extremely well with the first neutron-capture resonances in U^{238}; and (6) above a neutron energy of about 10^{0} MeV (10^{6} eV) there is a kind of fission energy-distribution spectrum.

We emphasize that the above results and neutron energy-distribution spectrum refer only to the B-VIII reactor in its subcritical state; they do not take into account the contribution of an external Ra-Be neutron source. To take that contribution into account would require detailed knowledge of the dimensions, intensity, and placement of the Ra-Be neutron source, but none of these factors are known. If we did know them, we could have used the MCNPX code (a code that is dedicated to the analysis of subcritical reactors) to obtain information on the actual neutron-flux levels in the B-

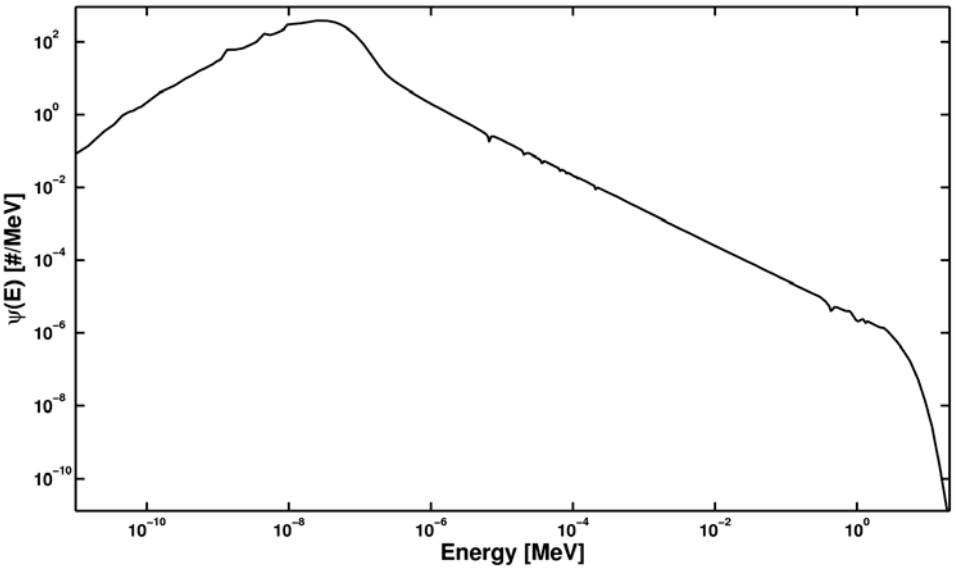


Fig. 6. The neutron-energy distribution $\psi(E)$ *versus* neutron energy E, averaged over the entire core of the B-VIII reactor.

VIII reactor, and thus also on its plutonium-breeding rate, but this actually would have added very little to our understanding of what the German scientists knew about reactor criticality during the war years.

We can obtain a crude estimate of the neutron population in the Haigerloch B-VIII reactor from the asymptotic limit of the solution to the neutron-balance equation,

$$\frac{dN(t)}{dt} = S_0 - \frac{1 - k_{eff}}{l} N(t) \ ,$$

where $N(t)$ is the total number of neutrons at time t in a system with a given effective neutron-multiplication constant k_{eff}, S_0 is the intensity of an external neutron source, and l is the average time required for a fission neutron to either slow down and be absorbed or to leak out of the system. For a subcritical system ($k_{eff} < 1$), the asymptotic stationary solution to the above equation is

$$N = \frac{lS_0}{1 - k_{eff}} = MS_0 l \ ,$$

from which we see that the product of the neutron-multiplication factor M, the intensity S_0 of the external neutron source, and the average lifetime l of a neutron in the system gives the total stationary number of neutrons N in it. If $k_{eff} = 0$, then $M = 1$, so there is no multiplication of neutrons in the system. If $0 < k_{eff} < 1$, then $M > 1$, so the number of neutrons in the system multiplies, and the closer k_{eff} approaches 1, the greater the

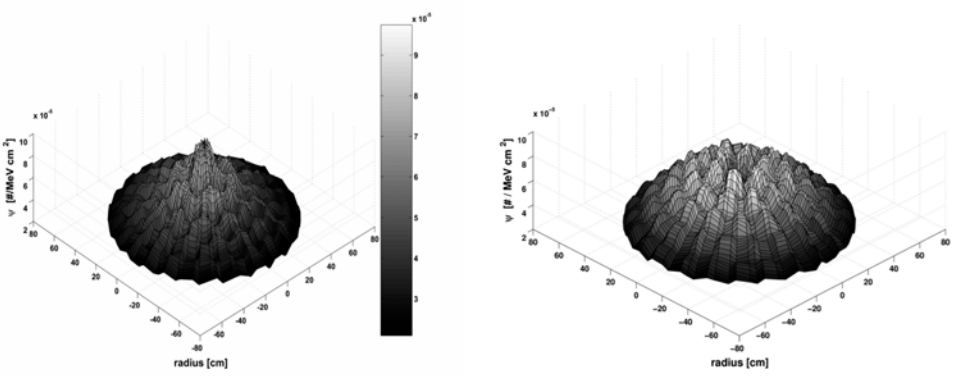


Fig. 7. The radial spatial profile of the neutron-flux distribution Φ *versus* neutron energy E at a horizontal central plane in the B-VIII reactor for thermal neutrons of energies up to 0.625 eV (*left*) and for fast neutrons of energies above 0.625 eV (*right*), as obtained with the MESHTAL feature of the MCNP5 code.

multiplication. If $k_{eff} = 1$, then the system is critical, so if neutrons are added to it by an external neutron source, and if the system is not quenched by a strong neutron absorber like cadmium, they can trigger an explosion. An external Ra-Be neutron source that could have been available to German scientists at the time (which corresponds to roughly 0.5 gram of radium) emits about $S_0 = 10^6$ neutrons per second.[26] We know the neutron-multiplication factor M and average lifetime l from the MCNP simulation, so we find that $N \approx 3500$ neutrons. The corresponding thermal-neutron flux is $\varphi = Nv/V \approx 3.9 \times 10^2$ n/cm^{2}s, since $V = 2.0$ m^3 is the volume of the reactor core,* and $v = 2200$ m/s is the speed of thermal-neutrons of kinetic energy kT, where k is the Boltzmann constant and T the absolute temperature, which is a very low neutron flux indeed for breeding useful amounts of plutonium.

We show in figure 7 the spatial neutron-flux distribution Φ, that is, the number of neutrons present per cm^2 per energy E, as obtained with the MESHTAL feature of the MCNP5 code, in a radial profile at a horizontal central plane for both thermal neutrons (energies up to 0.625 eV) and fast neutrons (energies above 0.625 eV), and in figure 8 in an axial profile at a vertical central plane for both thermal and fast neutrons. We chose the linear mesh spacing to be 2.68 cm, which is a little higher than the neutron mean-free path (2.28 cm), but sufficiently small compared to the radius of the uranium-fuel cylinders ($5\sqrt{3} = 8.66$ cm) to enable us to obtain detailed spatial patterns. We chose the angular binning to have steps of 5.14 degrees (0.09 radian), which is a compromise between having good resolution at large radii and good statistics at the center of the reactor.

We see in figure 7 that there is a sharp maximum in the radial thermal-neutron-flux distribution at the center of the reactor (central chimney) where there is no uranium

* The radius of the magnesium vessel is 62 cm and its height is 164 cm, so its volume V is about 2×10^6 cm^3 or 2.0 m^3; see Heisenberg and Wirtz, "Grossversuche (ref. 14), p. 158; Stadtverwaltung Haigerloch, *Atom-Museum Haigerloch* (ref. 2), p. 58.

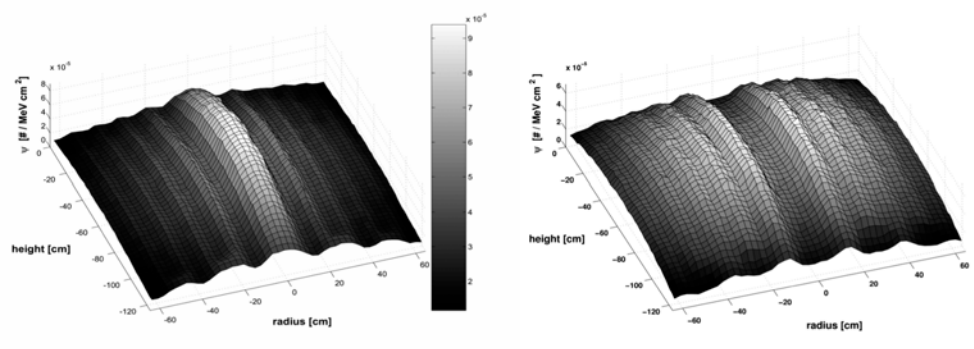


Fig. 8. The axial spatial profile of the neutron-flux distribution Φ *versus* neutron energy E at a vertical central plane in the B-VIII reactor for thermal neutrons of energies up to 0.625 eV (*left*) and for fast neutrons of energies above 0.625 eV (*right*), as obtained with the MESHTAL feature of the MCNP5 code.

fuel for thermal neutrons to produce fission and thereby be absorbed, and small minima at the locations of the uranium-fuel cylinders where thermal neutrons do produce fission and thereby are absorbed. We also see that there are small maxima in the radial fast-neutron flux distribution at the locations of the uranium-fuel cylinders owing to the production of fast neutrons in the fission process. We see in figure 8 these same variations in the axial thermal and fast-neutron flux distributions, with the thermal-neutron flux distribution exhibiting a clear cosine variation with a maximum along the central axis (central chimney) where there is no uranium fuel. In general, there are minima in the radial and axial thermal-neutron flux distributions where there are maxima in the fast-neutron flux distributions, and *vice versa*.

We estimated the decrease in the production of fission if the reactor's central chimney were filled with heavy water and found for Model C a decrease in the effective neutron-multiplication constant k_{eff} of about 0.035 percent. Thus, even if the central chimney were filled with uranium fuel, the reactor would not have reached criticality, since this would have increased its k_{eff} from 0.85748 to only 0.85778, which is still less than 1, with the absolute increase of 0.0003 being less than 0.00039 or 3 standard deviations. For Models A and B we expect the increase in k_{eff} would be about 0.030 percent, so again not enough to bring the reactor to criticality.

Conclusions

We presented a neutronics study of the experimental B-VIII reactor that German scientists constructed between February and April of 1945 at Haigerloch, Germany, using the Monte Carlo code MCNP5 to simulate it and to estimate its effective neutron-multiplication constant k_{eff} for three different models depending upon the purity and density of the graphite they used as a neutron reflector. We found that for all three models the reactor was subcritical ($k_{eff} < 1$), and that the neutron-multiplication factor M

we calculated agrees reasonably well with the value of 6.7 that the German scientists recorded a few weeks before the end of the war in Europe. We also found that the presence of impurities in the graphite used as a neutron reflector would have decreased k_{eff} by no more than a few hundredths of a percent, so that the reactor would not have become critical even in their absence. We also calculated the neutron-energy distribution spectrum and neutron-flux distributions in the radial and axial profiles for both thermal and fast neutrons and found both to be typical of a subcritical reactor.

In general, we found that the design of the Haigerloch B-VIII reactor was a good one for that time. The German scientists used heavy water (D_2O) as a neutron moderator, whose Moderating Ratio (a parameter used to estimate the efficiency of a moderator) is known to be about 100 times greater than that of graphite, and indeed, even about 4 times greater than that of light water (H_2O). Moreover, their use of heavy water avoided using natural graphite as a moderator, which we know was available to them only in a form that was contaminated with boron (B), a highly efficient neutron absorber. Further, their use of lumps of uranium fuel distributed in a regular three-dimensional lattice, instead of in layers, proved to be the correct arrangement, as Fermi found for the Chicago Pile (CP-1). Their idea of using a magnesium-alloy vessel to insulate the heavy-water moderator from the surrounding graphite neutron reflector also was excellent, since this avoided the risk of producing highly exothermic chemical reactions in case the temperature of the reactor rose. The overall cylindrical geometry of the reactor too was rather good, since they designed it to be as compact as possible, with a height-to-diameter ratio of about 1, this being the limiting case of a spherical configuration, which we now know will go critical more easily than a cylindrical configuration. Their idea to use graphite (that is, carbon, an element of low atomic weight) as a neutron reflector also was correct, as was their idea to place an external neutron source in the center of the reactor (central chimney) where it is most effective, although this may just have been common sense.

One major problem with the Haigerloch B-VIII reactor, however, was the low efficiency of its heavy-water moderator: The Slowing Down Length (that is, the minimum length of a substance that is required to slow fast neutrons down to thermal energies by elastic scattering to produce fission) is about 11 cm in heavy water, which actually is a lower limit for neutrons with an energy-distribution spectrum that is shifted toward higher energies, as is the case for neutrons emitted by a Ra-Be neutron source, whereas the shortest distance between the surfaces of two uranium-fuel cubes in the Haigerloch B-VIII reactor was between 5–8 cm (roughly 2–3 mean-free paths), depending upon the direction in which the fast neutrons traveled following fission. To rectify this deficiency, and perhaps to achieve criticality, the German scientists would have needed more heavy water, more uranium fuel, and more time to build a larger reactor, none of which were available to them by the end of the war in Europe.

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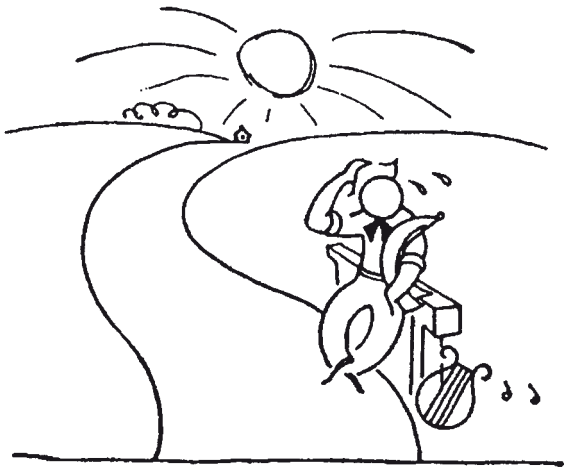
ing its geometry. We also thank Roger H. Stuewer for his careful and thoughtful editorial work on our paper.

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APPRECIATION

Nothing on earth is so sweet
and so worthy to have and hold
as, respectively, cold and heat
in, respectively, heat and cold.

Piet Hein

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