
The Beginning of the Nuclear Age

Albert Einstein
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Nassau Point
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August 2nd, 1939

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

Sir:

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

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quant-

The Einstein Szilard letter to Roosevelt

Aug. 2, 1939

"Because of the danger that Hitler might be the first to have the bomb, I signed a letter to the President which had been drafted by Szilard. Had I known that the fear was not justified, I would not have participated in opening this Pandora's box, nor would Szilard. For my distrust of governments was not limited to Germany."

Rumors or Reality?

American and British nuclear physicists felt they needed to start a A-bomb project to avoid falling behind their German counterparts. They feared Hitler's forces would be the first to have use of atomic arms. This evaluation was based on a number of considerations:

- The pre-war stop of uranium export
- The high caliber of German theoretical and experimental physicists like Otto Hahn, Paul Harteck, Werner Heisenberg, Fritz Strassmann, and Carl-Friedrich Von Weizsäcker;
- German control of Europe's only uranium mine after the conquest of Czechoslovakia;
- German capture of the world's largest supply of imported uranium with the fall of Belgium;
- German possession of Europe's only cyclotron with the fall of France;
- German control of the world's only commercial source of heavy water after its occupation of Norway.

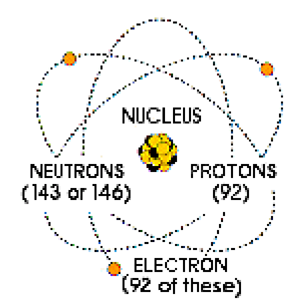
Fission based explosions

Trigger ^{235}U fission through neutron bombardment
Each fission process generates 3 neutrons (- neutron losses)
Required for the success of explosion is:

- High neutron capture probability (cross section)
  (measurements with neutron beams on fissionable material)
- Maintaining high neutron flux
  (measurement of neutron production reactions)

$$Y_{fiss} = \sigma_{fiss}\,[barn]\cdot n_{^{235}U}\,[part]\cdot n_n\,[s^{-1}cm^{-2}]$$

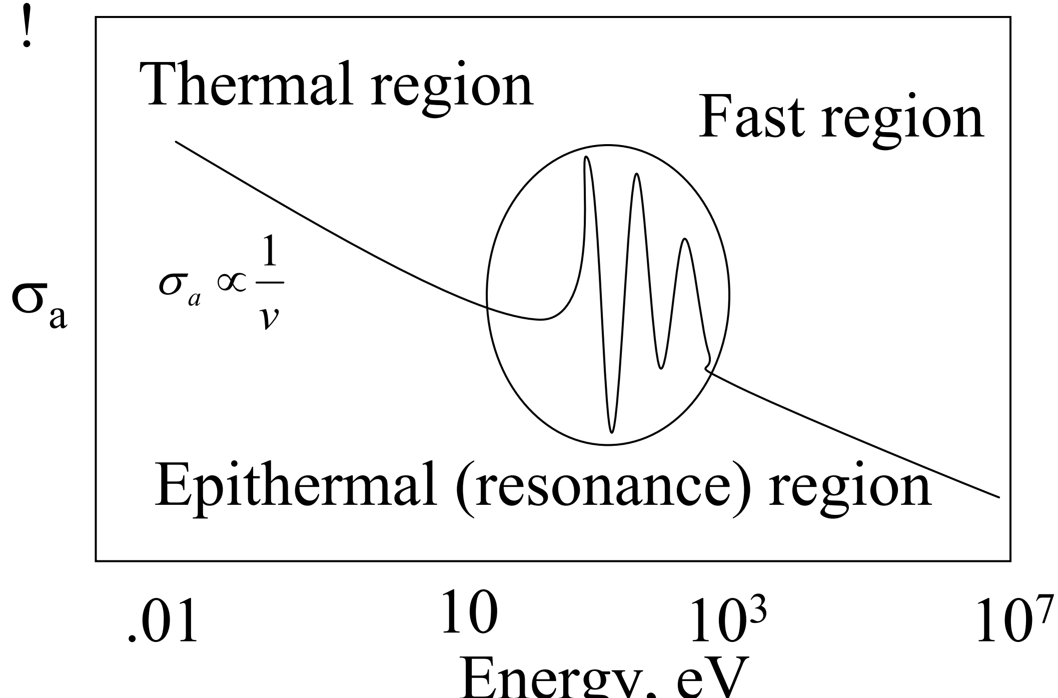
$$E_{fission} = \varepsilon \cdot Y_{fiss}$$



1/v law of neutron capture

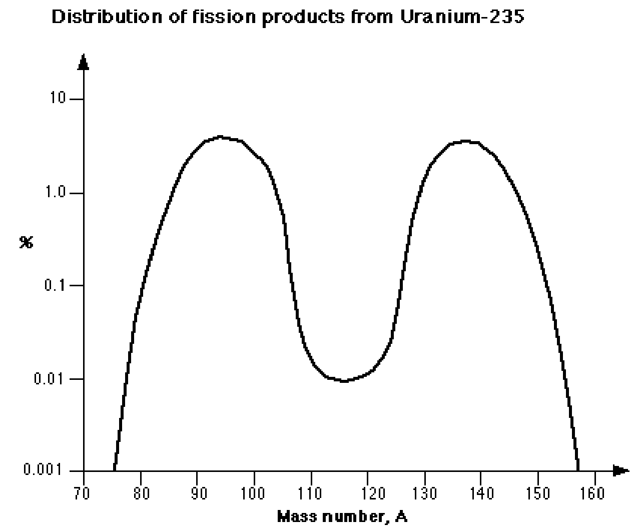
Neutrons have no charge! Neutron capture cross sections are inverse proportional with neutron velocity since no deflective Coulomb barrier is involved. As lower the velocity as higher the reaction probability !

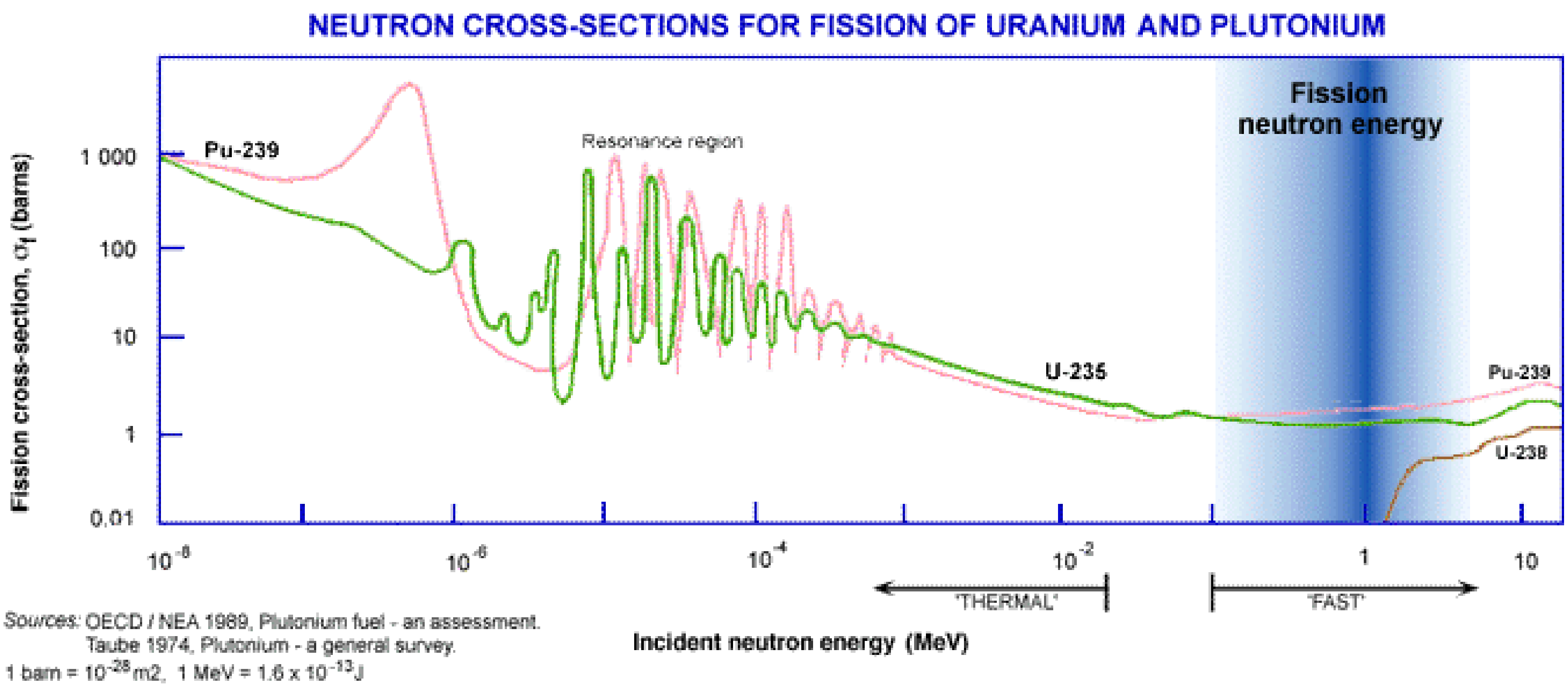
Introduces the need
For "moderating"
Neutrons to low
"thermal" velocities



Fission cross section

Experimental results from fission studies





Moderators

Example: neutron capture probability for 5 MeV neutrons from reaction is ~1 barn (1barn $=10^{-24}cm^2$). What is the capture cross section for thermal neutrons (E=0.026eV)

$$\sigma(E) \propto \frac{1}{v} \propto \frac{1}{\sqrt{E}}; \quad \sigma(E_{therm}) = \sqrt{\frac{E_{fast}}{E_{therm}}} \cdot \sigma(E_{fast})$$

$$\sigma(0.026) = \sqrt{\frac{5 \cdot 10^6}{0.025}} \cdot 1\,barn = 1.4 \cdot 10^4\ barn$$

Four orders of magnitude improvement!!!

Best neutron moderators are light mass materials because of large energy transfer in scattering event: Graphite C, heavy water D_2O (low absorption cross section is crucial!)

Moderators

Graphite: easy to originate from carbon, obvious first choice

Easy to machine for industrial purposes!

Heavy Water is dideuterium oxide, or D_2O or ^2H_2O. Gilbert N. Lewis isolated the first sample of pure heavy water in 1933.

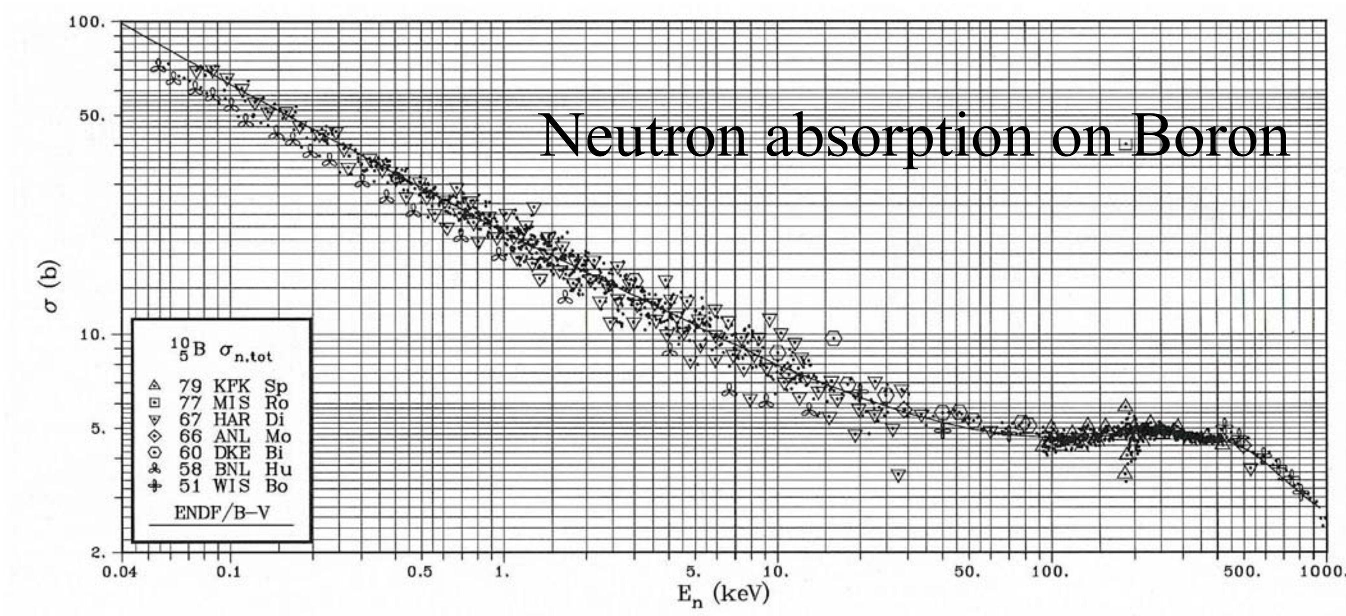
German Choices

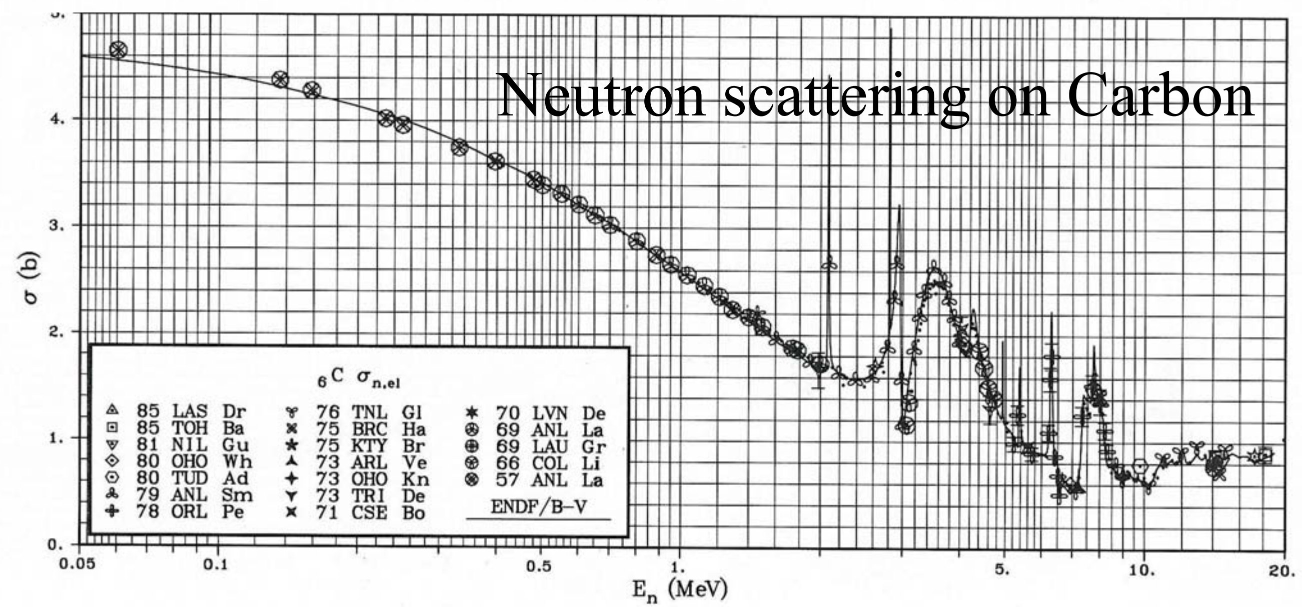
Walter Bothe, the leading experimental nuclear physicist in Germany, did the crucial experiment and concluded that carbon in the form of graphite would not work. In America, Enrico Fermi did a similar experiment and concluded that graphite was marginal. He suspected that an impurity in the graphite was responsible for the problem. Leo Szilard, who was working alongside Fermi, had studied chemical engineering before going into physics. He remembered that electrodes of boron carbide were commonly used in the manufacture of graphite. It was known that one atom of boron absorbs about as many slow neutrons as 100 000 atoms of carbon. Very small boron impurities would "poison" the graphite for use as a nuclear reaction moderator. Szilard therefore went around to the American graphite manufacturers and convinced one of them to make boron-free graphite. Using this pure graphite as the moderator, the American group achieved a chain reaction on 2 December 1942.

The German team, however, needed to use heavy water, D_2O. Ordinary water contains heavy water at a rate of about 1 part in 10 000. The two can be separated by repeated electrolysis, which requires large amounts of electric power in close proximity to a water source. The Germans had this at a hydroelectric plant in occupied Norway, and they set up a separation facility there.

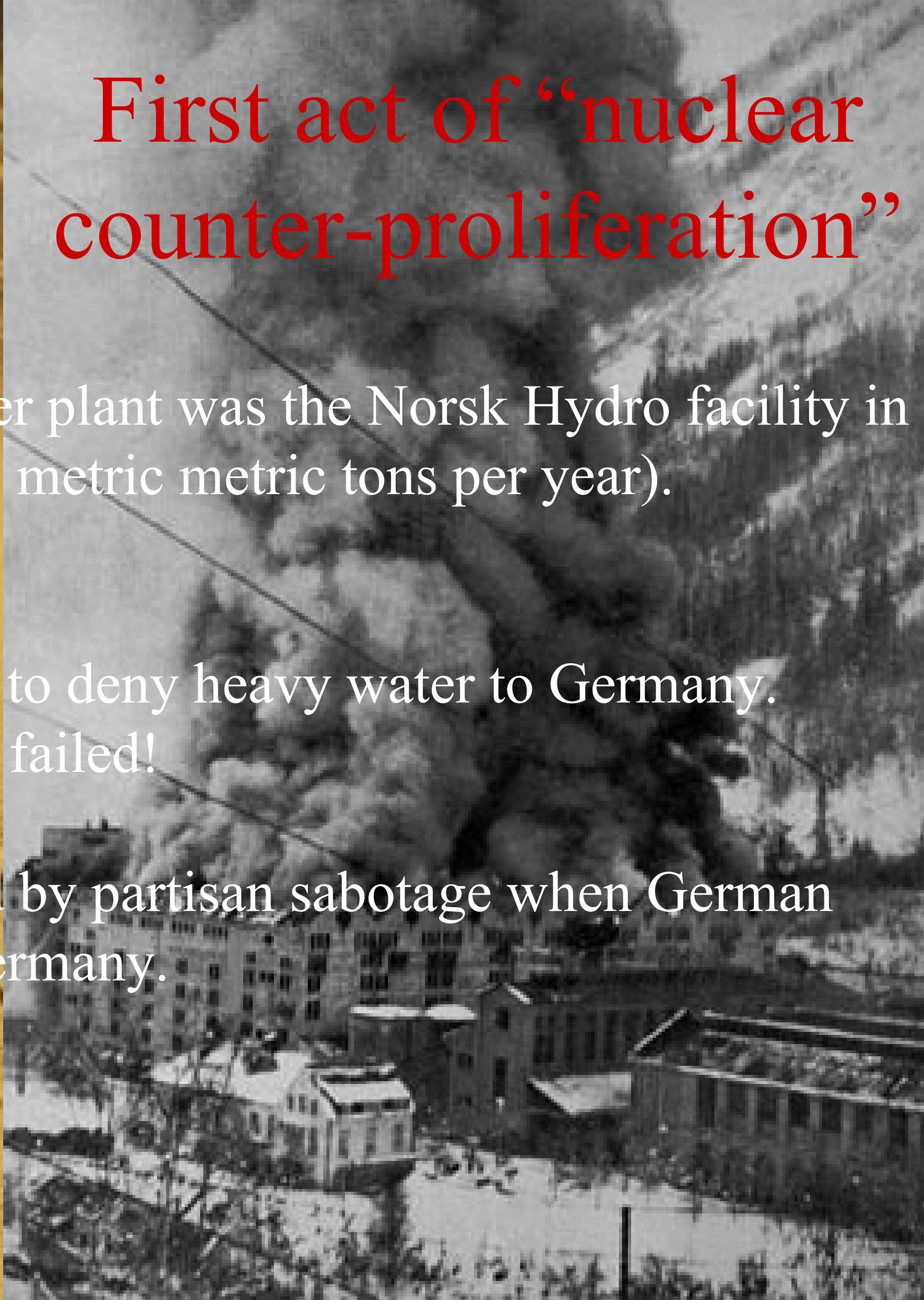
Hans Bethe in Physics Today Vol 53 (2001)

Comparison of cross sections





First act of “nuclear counter-proliferation”



The first commercial heavy water plant was the Norsk Hydro facility in Norway (built 1934, capacity 12 metric metric tons per year).

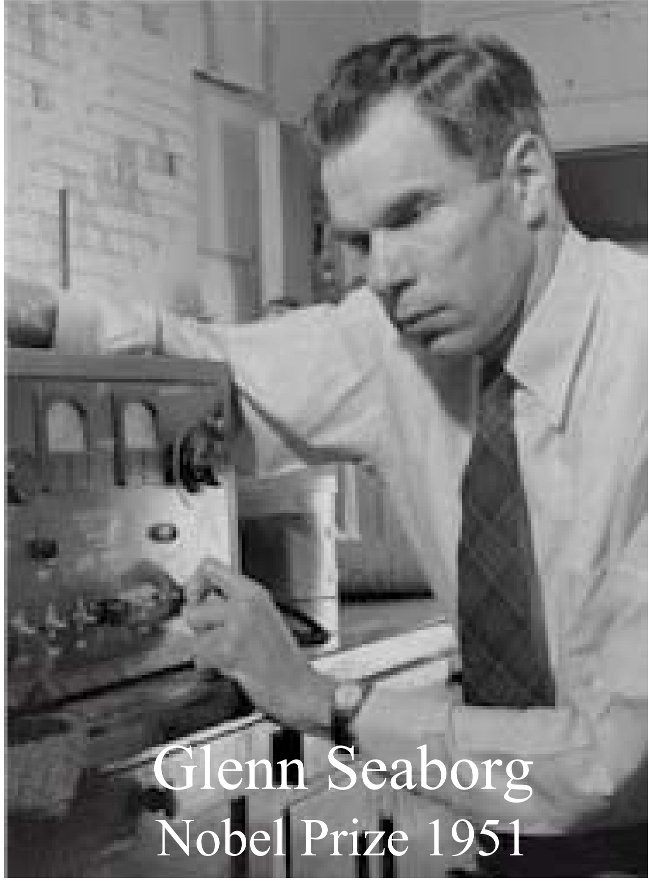
Plant was attacked by the Allies to deny heavy water to Germany. Attacks between 1941 and 1943 failed!

However, D_2O supply destroyed by partisan sabotage when German government tried to ship it to Germany.

Uranium ^{235}U separation

Natural uranium contains only 0.7% of the ^{235}U isotope. The remaining 99.3% is mostly the ^{238}U isotope. To achieve fission of large amounts of ^{235}U separation techniques are required. Reactors operate at 3-4% enrichment, weapons require 90% enrichment. Three methods have been developed :

1. Separation by diffusion through porous membrane; diffusion rate ~ $1/M^2$ (circular separation)
2. Electromagnetic separation in "cyclotrons"
3. Centrifugal separation (developed In 1940, but only applied in 60$^{\text{ties)}}$.



Plutonium

Seaborg discovered plutonium at U.C Berkeley, Feb. 23, 1941.

^{239}Pu also undergoes fission and can be made from ^{238}U.

The "breeding process" requires the exposure of ^{238}U to high neutron flux!

- $^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$ neutron capture reaction
- $^{239}_{92}U \rightarrow ^{239}_{93}Np + \beta^-$ $t_{1/2} = 23.5$ min
- $^{239}_{93}Np \rightarrow ^{239}_{94}Pu + \beta^-$ $t_{1/2} = 2.35$ days

He was discoverer of plutonium and all further transuranium elements through element 102!

The Manhattan Project

The Military Director of the Manhattan Project was General Leslie Groves.

In response to the perceived German threat the United States initiated its own program for the development of an “Atomic Bomb” under the Army Corps of Engineers in June 1942.

Groves projected three sites for the development of nuclear weapon production with the goal of:

1. Enrichment of ^{235}U
2. Generating ^{239}Pu
3. bomb assembling and testing

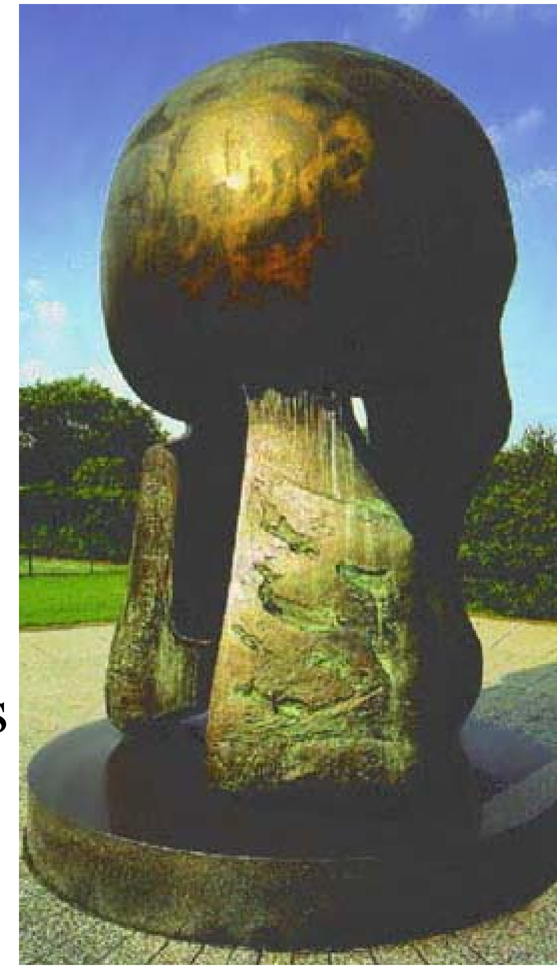
Basic goal was to probe and utilize all of the available technical possibilities!

J. Robert Oppenheimer

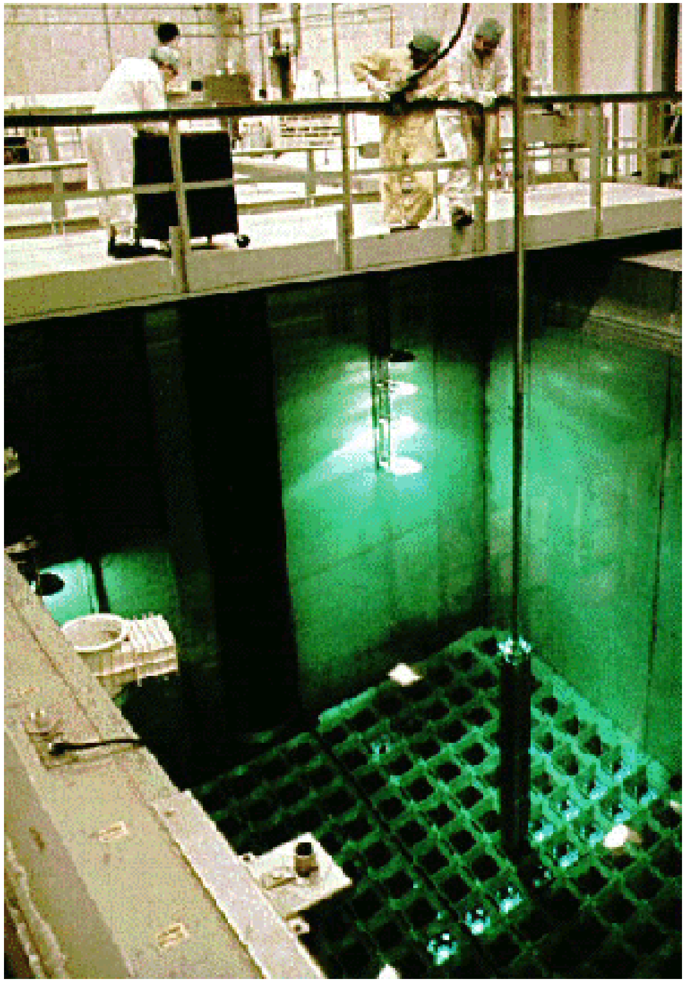
After graduating from Harvard in 1925 and studying (unsuccessfully) at Cambridge under Ernest Rutherford, he obtained his PhD in Göttingen, Germany. In 1929 he returned to the United States to positions at Berkeley and Cal Tech. He was appointed by General Groves in 1942 as the Scientific Director of the Manhattan Project.

Groves said of Oppenheimer, "He's a genius. A real genius...Why, Oppenheimer knows about everything. He can talk to you about anything you bring up. Well not exactly. I guess there are a few things he doesn't know about. He doesn't know anything about sports."

The first operating Reactor



Basic research for understanding fission properties was performed at the University of Chicago. For this purpose Enrico Fermi built the first nuclear reactor, CP-1, in a squash court under the football stadium. The first sustained nuclear reaction occurred on Dec. 2, 1942!



CP-1 Nuclear Reactor

The CP-1 used 235 enriched uranium metal from Iowa State.

As moderator for slowing down the neutrons to thermal velocities the reactor used high purity graphite.

As control rods, for absorbing neutrons and preventing the reactor to become critical CP-1 used Cadmium rods. (Other neutron absorbing materials are e.g. Boron).

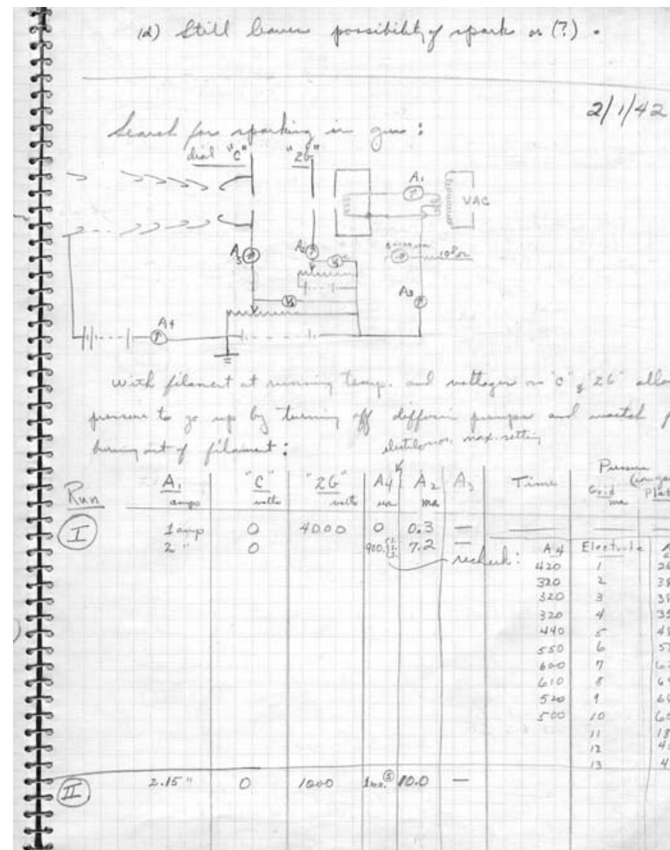
Moderators need high neutron scattering cross section,

Absorbers require high neutron capture cross section.

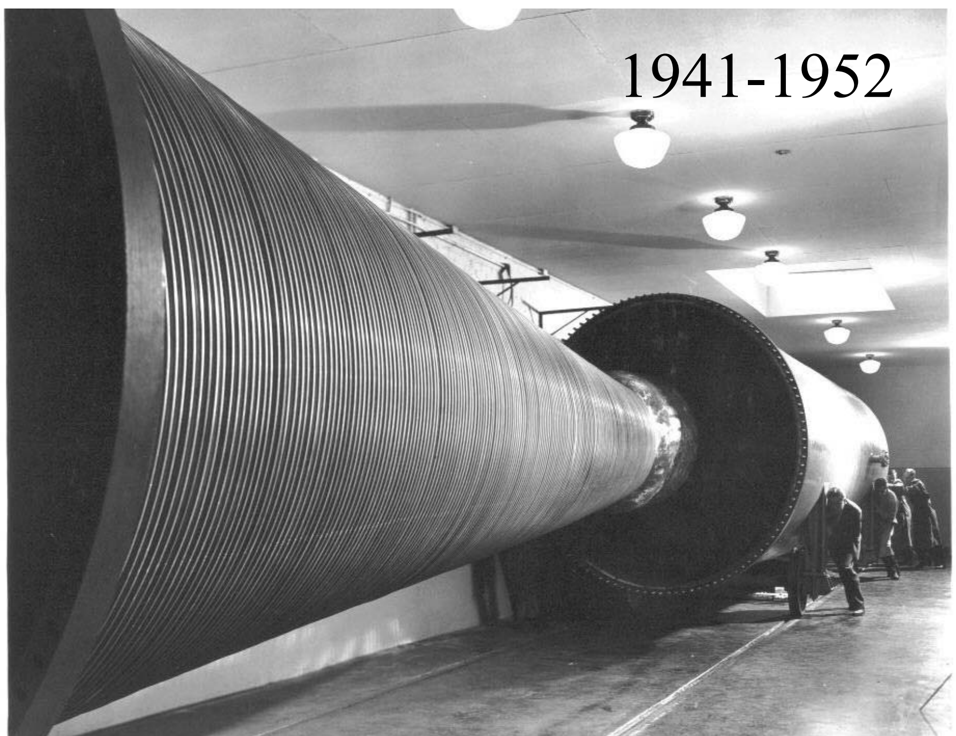
Accelerator based radiation and material test facilities

Wisconsin: neutron production to test material fissibility

Notre Dame: high energy electron beam to test radiation

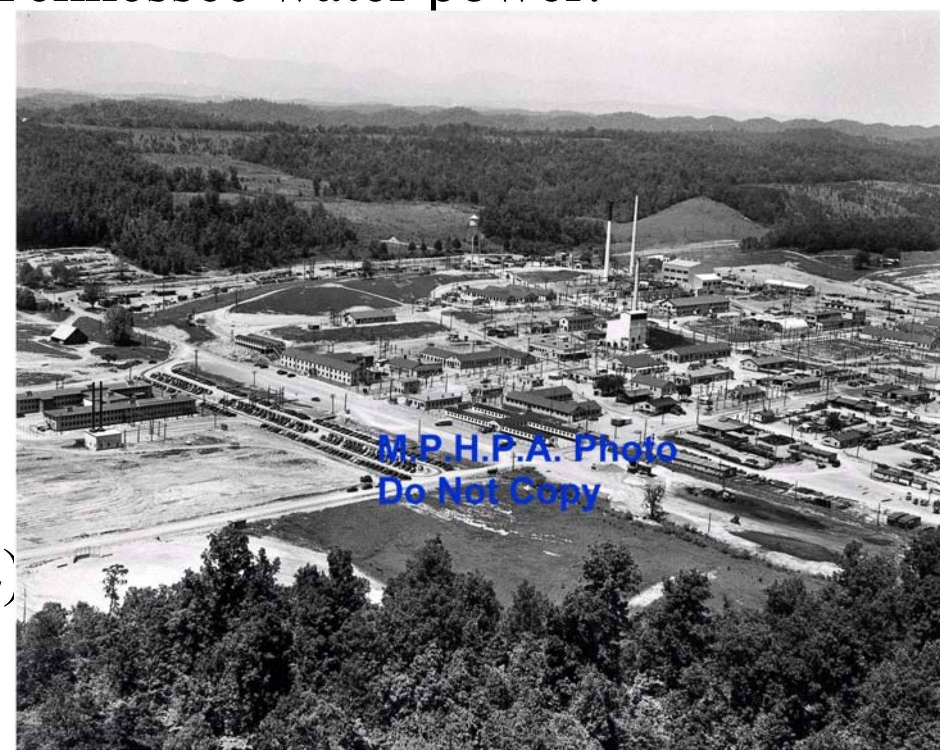


1941-1952



Oak Ridge

In a remote area near Knoxville, Tennessee a secret city was built. The main reason for choice of site was the abundant availability of Tennessee water power.

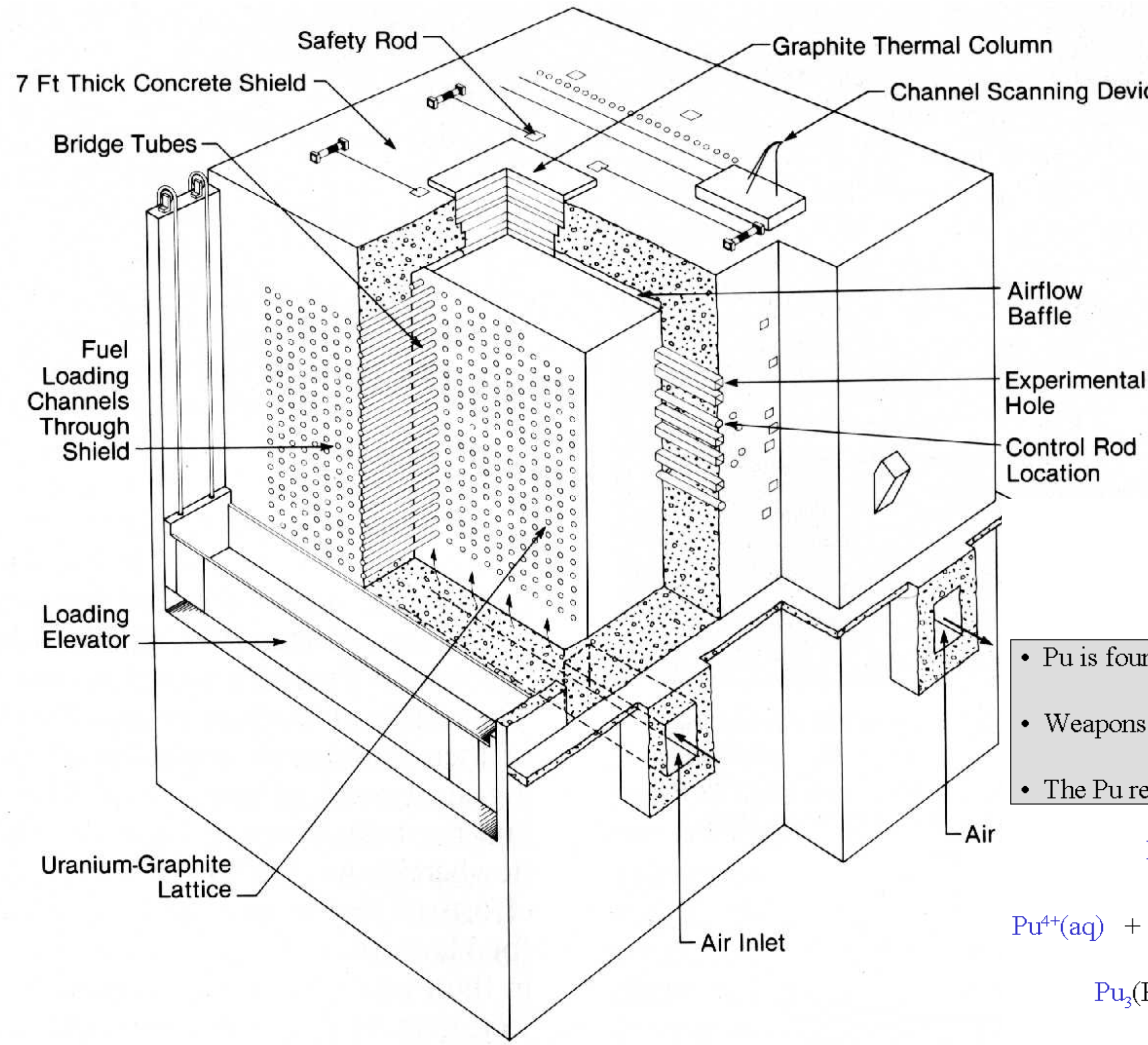


Primary purpose of the Oak Ridge facility was to enrich ^{235}U.

They also built a graphite reactor at site X-10 to study the production of plutonium. (Today site of ORNL)

Construction started in 1942

X-10 plutonium breeder reactor



Chemistry necessary to generate weapon pure plutonium!

Bismuth Phosphate Process
for
Recovery of Plutonium

- Pu is found in low concentrations (<250 ppm) in reactor products.
- Weapons grade Pu must be chemically pure (< 1 part in 10^7 parts Pu).
- The Pu recovery for this process was 95% with < 1 part impurity in 10^7.

$$Pu(s) + X(s) \xrightarrow[H_2SO_4]{HNO_3} Pu^{4+}(aq) + X^{y+}(aq)$$

$$Pu^{4+}(aq) + X^{y+}(aq) + Bi^{3+}(aq) \xrightarrow{H_3PO_4} Pu_3(PO)_4(s) + X^{y+}(aq) + BiPO_4(s)$$

$$Pu_3(PO)_4(s) + BiPO_4(s) \xrightarrow[\text{oxid. agent}]{HNO_3} Pu^{6+}(aq) + Bi^{3+}(aq)$$

$$Pu^{6+}(aq) + Bi^{3+}(aq) \xrightarrow{H_3PO_4} Pu^{6+}(aq) + BiPO_4(s)$$

$$Pu^{6+}(aq) \xrightarrow{H_2O_2} PuO_2^{2+}(aq) \xrightarrow[\text{agent}]{\text{reducing}} Pu(s)$$

X(s) = fission products or uranium; $^{y+}$ = oxidation state

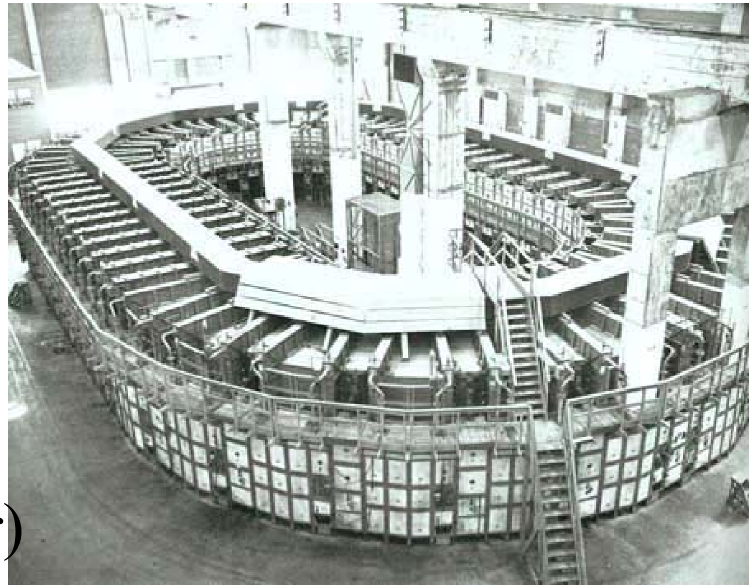
Y-12

Purpose of Y-12 plant:

Magnetic separation of ^{235}U from ^{238}U.

The work was overseen by Lawrence.

Operated 1943-1946
(diffusion based separation was superior)



Magnetic Separation

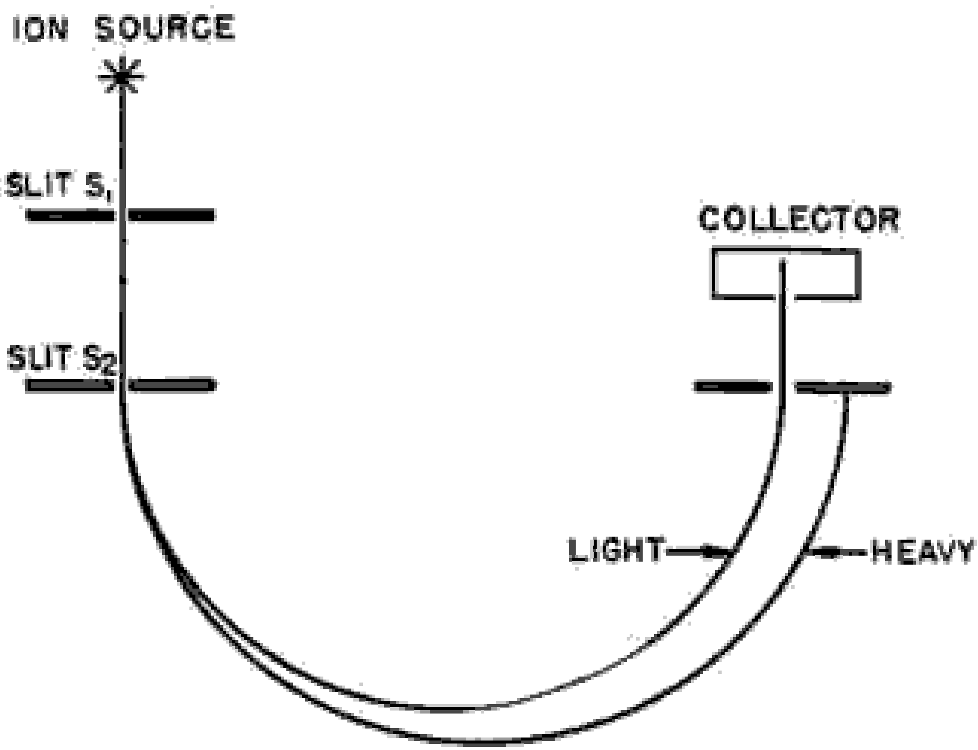
$$m\frac{v^2}{r} = e\cdot v\cdot B; \quad E = \frac{1}{2}m\cdot v^2$$

$$\frac{m\cdot v}{r} = e\cdot B; \quad \sqrt{2\cdot E\cdot m} = e\cdot r\cdot B$$

$$m = \left(\frac{e\cdot r\cdot B}{2\cdot E}\right)^2; \quad \frac{m_1}{m_2} = \left(\frac{r_1}{r_2}\right)^2$$

$$m_1 = 238, m_2 = 235, r_1 = 10m$$

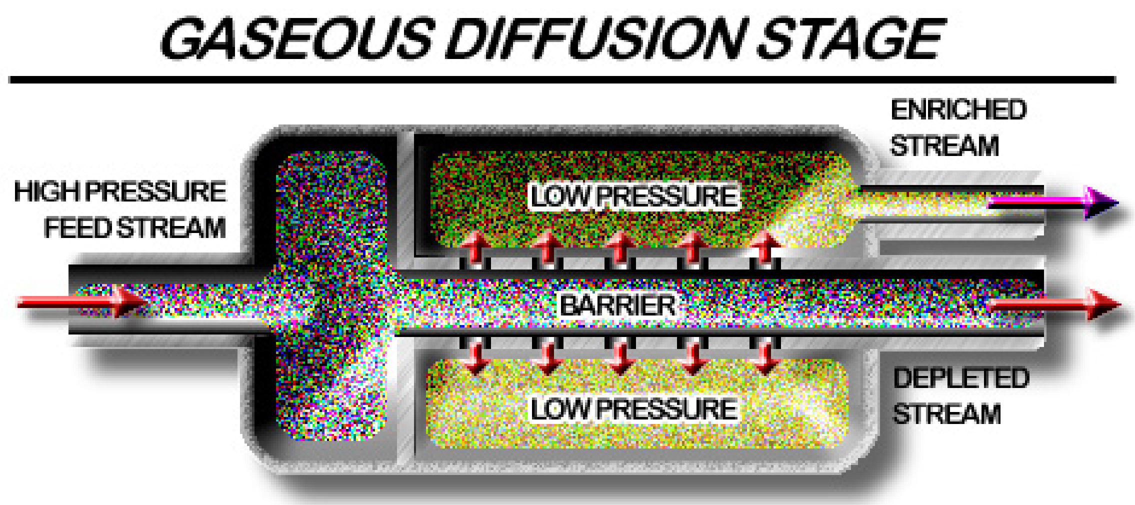
$$r_2 = r_1\cdot\sqrt{\frac{m_2}{m_1}} = 10\cdot\sqrt{\frac{235}{238}} = 9.94m$$

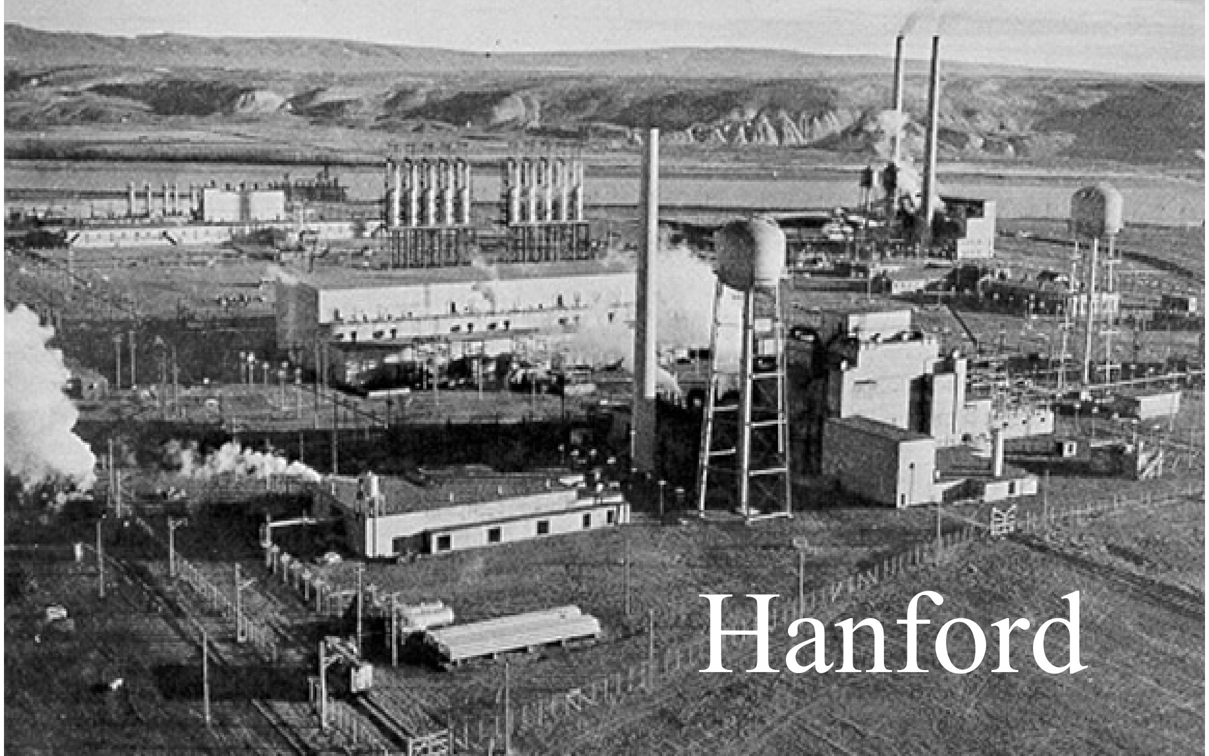


Constructed in 1943
Shut down in 1986!
2004 being dismantled!

Gaseous diffusion plant at Oak Ridge for enrichment of ^{235}U versus ^{238}U.

Based on Graham's Law of Effusion and the oddity that UF_6 is a gas when heated up to 135F.





Constructed in 1943 as follow up on X-10 in Oak Ridge as main site for industrial plutonium production shut-down in 1963! Represents a major nuclear waste problem

Secret City on the Columbia River in Washington State.

- A series of 9 nuclear reactors were designed to produce plutonium.
- A chemical plant to process material and purify plutonium
- Storage site for the resulting nuclear waste

Left-over

Hanford is arguably the most contaminated site in North America. Cleanup costs are projected in the tens of billions of dollars, and requiring a fifty-year effort.

The Hanford Nuclear Site in southeastern Washington state stores 54 million gallons of dangerous high-level radioactive waste containing hundreds of millions of curies from the nation's nuclear weapons production process

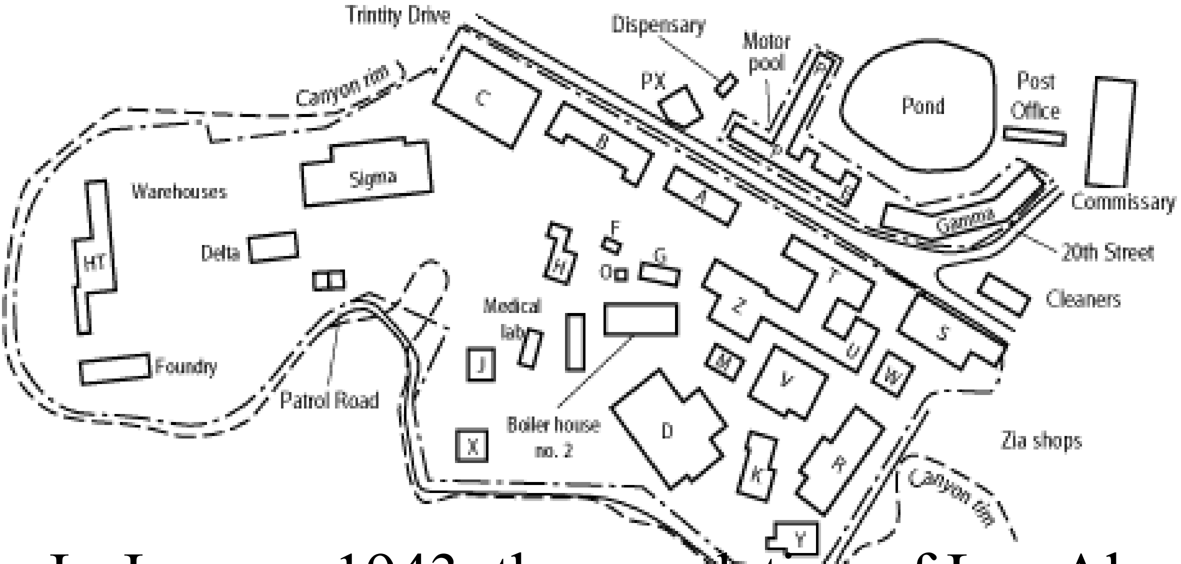
Los Alamos

Construction Secret City in the Sangre de Christo Mountains in New Mexico. The Los Alamos location was picked by Groves and Oppenheimer. On the site of a small boy's school.

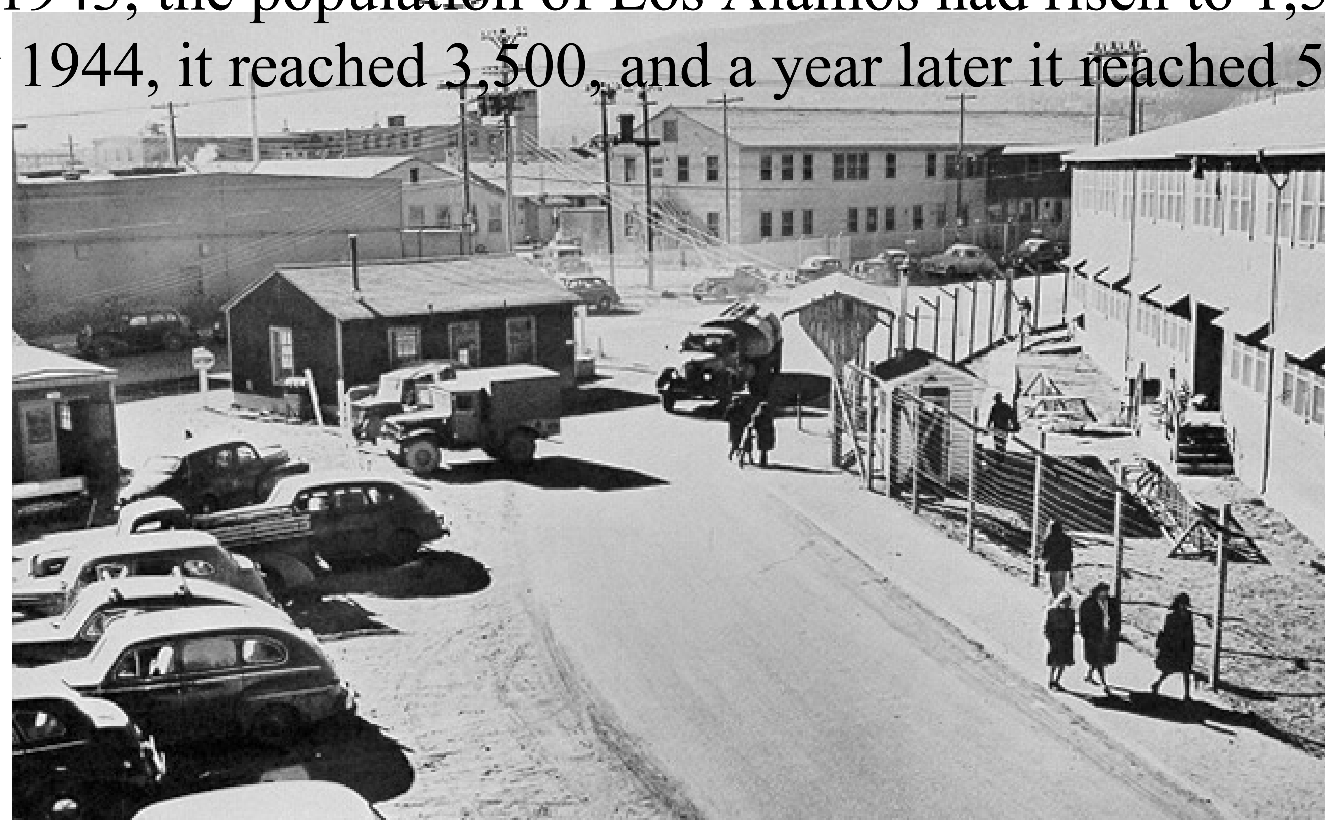
The sole purpose was to design and build the bombs.
Remote area, (Groves, Oppenheimer)
Easily to close off (Groves)
Stimulating environment (Oppenheimer)

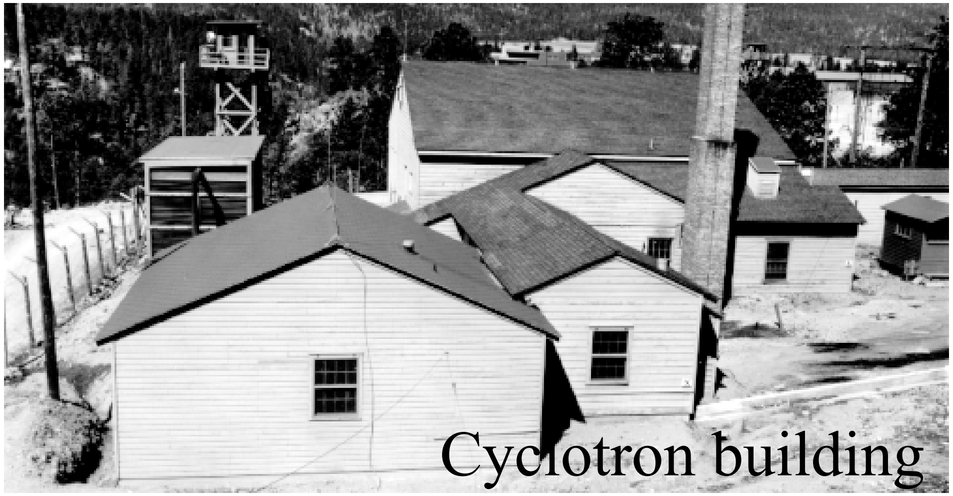
Purchased for ~$ 400,000

Construction started in 1943 on top of Mesa



In January 1943, the population of Los Alamos had risen to 1,500. By January 1944, it reached 3,500, and a year later it reached 5,700.





Cyclotron building

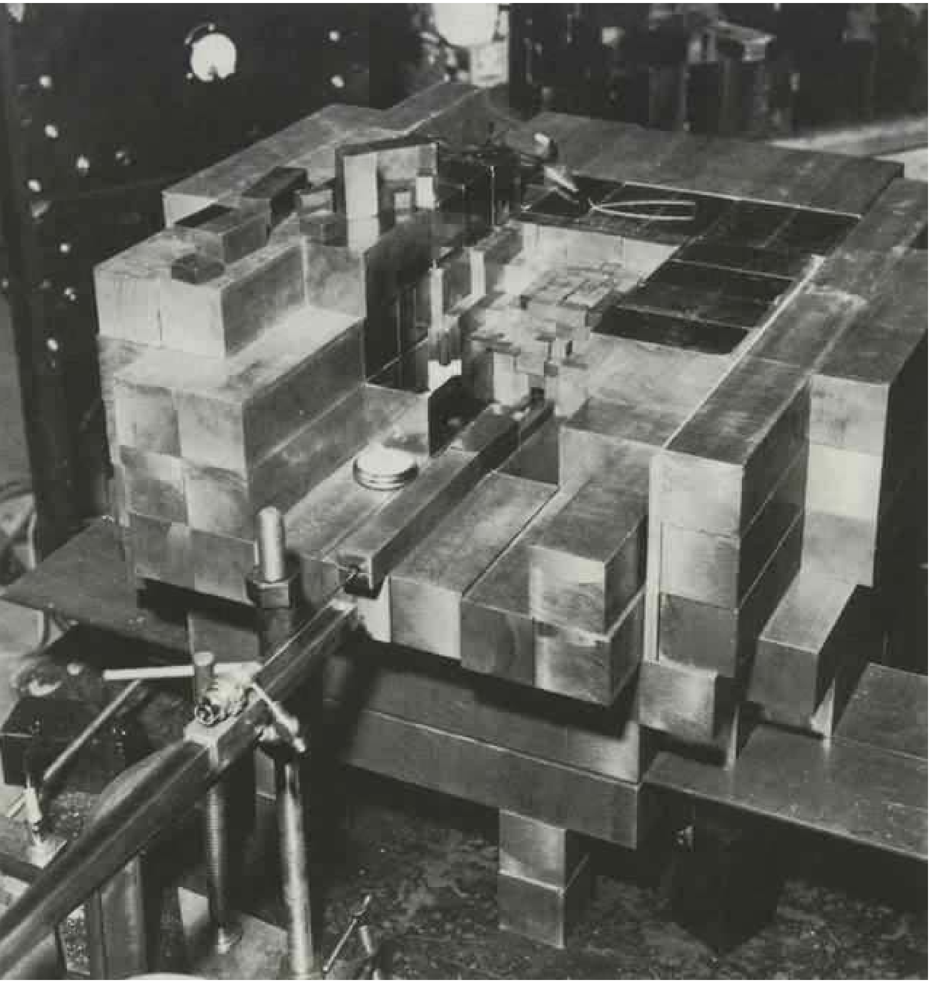
Accelerator test facilities

The largest items were the accelerators. Oppenheimer decided that electrostatic generators (Van de Graaff accelerators), a Cockcroft-Walton machine and a good cyclotron would be required to carry on the experimental measurements that would be transferred to Los Alamos. The Harvard cyclotron was selected as the best. Also selected were the University of Illinois' Cockcroft-Walton accelerator and two Van de Graaff accelerators at the University of Wisconsin: the "long tank," a 22ft long machine and the "short tank," a 17ft long machine.

Electrostatic accelerators

Military or Academic Environment?

Initial plan of “military laboratory” with scientists in uniform failed on refusal of academics which were to be recruited. Final agreement Between Oppenheimer and Groves was academic environment with Oppenheimer as scientific director (Robert Bacher from Cornell (& MIT) would head the experimental section, Hans Bethe (Cornell) the theory (T) division. The ultimate authority over the laboratory, however, would be the Military Policy Committee under General Groves.



Tickling the Tail of the Dragon

The determination of the critical mass for explosion

The exact size of the critical mass was determined by Otto Frisch at Los Alamos. The important input parameters were the fission cross Sections which were measured in accelerator based experiments.

Other parameters were the average neutron yield upon fission, and the mass density which depended on lattice structure of metal and the purity of the available material (absorption of neutrons).

The critical mass?

Depended of neutron flux and neutron release time versus explosion time scale

$$20\,ktons\,TNT = 8.4\cdot 10^{13}\ J$$

$$1\ fission \equiv 3.2\cdot 10^{-11}\ J$$

$$number\ of\ \ fissions : N = \frac{8.4\cdot 10^{13}\ J}{3.2\cdot 10^{-11}\ J} = 2.6\cdot 10^{24}$$

$$235g = 6.02\cdot 10^{23}\,atoms$$

$$m_{^{235}U} = \frac{235\,g\cdot 2.6\cdot 10^{24}}{6.02\cdot 10^{23}} = 1.015\,kg$$

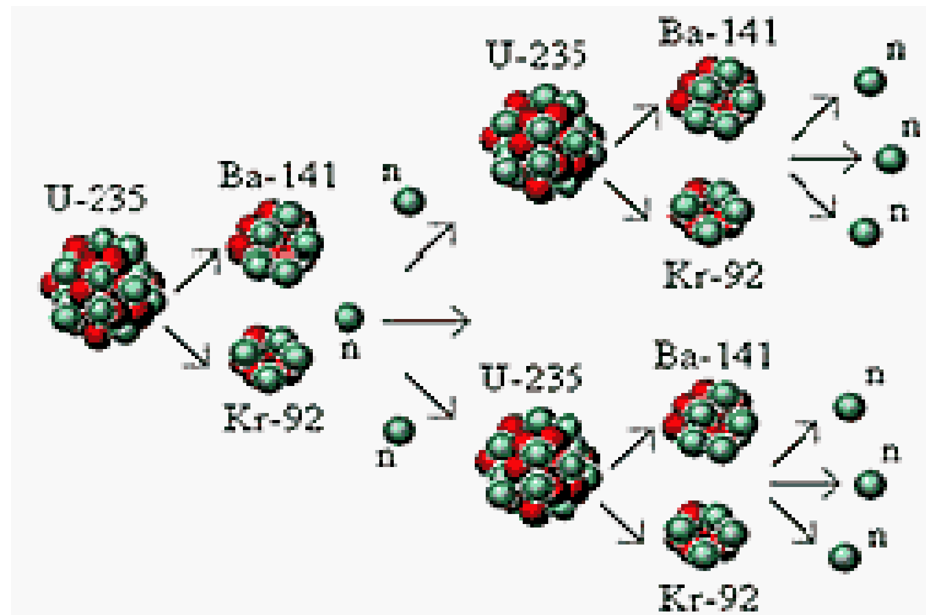
with 10% efficiency 10 kg was estimated.

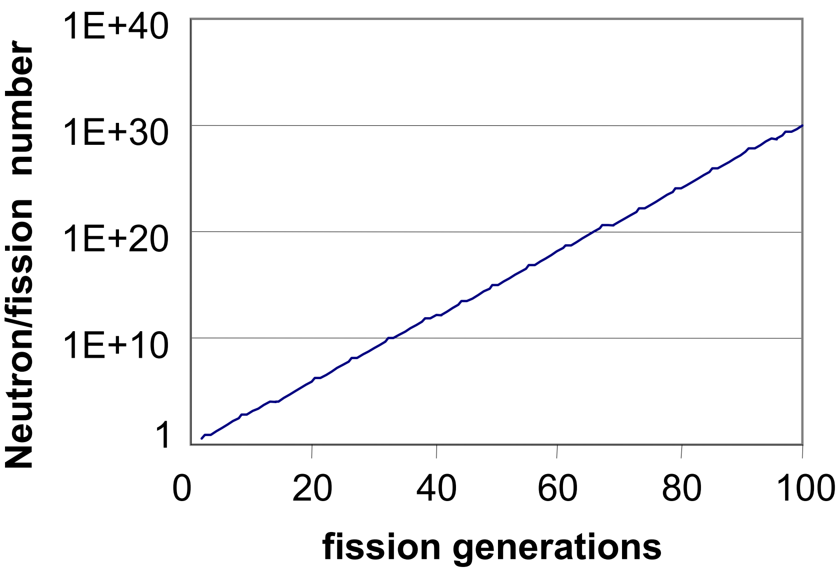
Neutron production for chain reaction

$$N_n = N_0 \cdot e^{(1-k)n}$$

$$N_0 = 1; k = 1.693$$

$$N_n = N_0 \cdot e^{0.693n} \approx 2^n$$





Neutron production factor: *k=1.63* is due to neutron absorption in material impurities (^{238}U)! In ~80 fission generations 10^{24} neutrons for fissions have been produced.

Timing of explosion

Typical neutron velocity: $v = 10^7\ m/s$

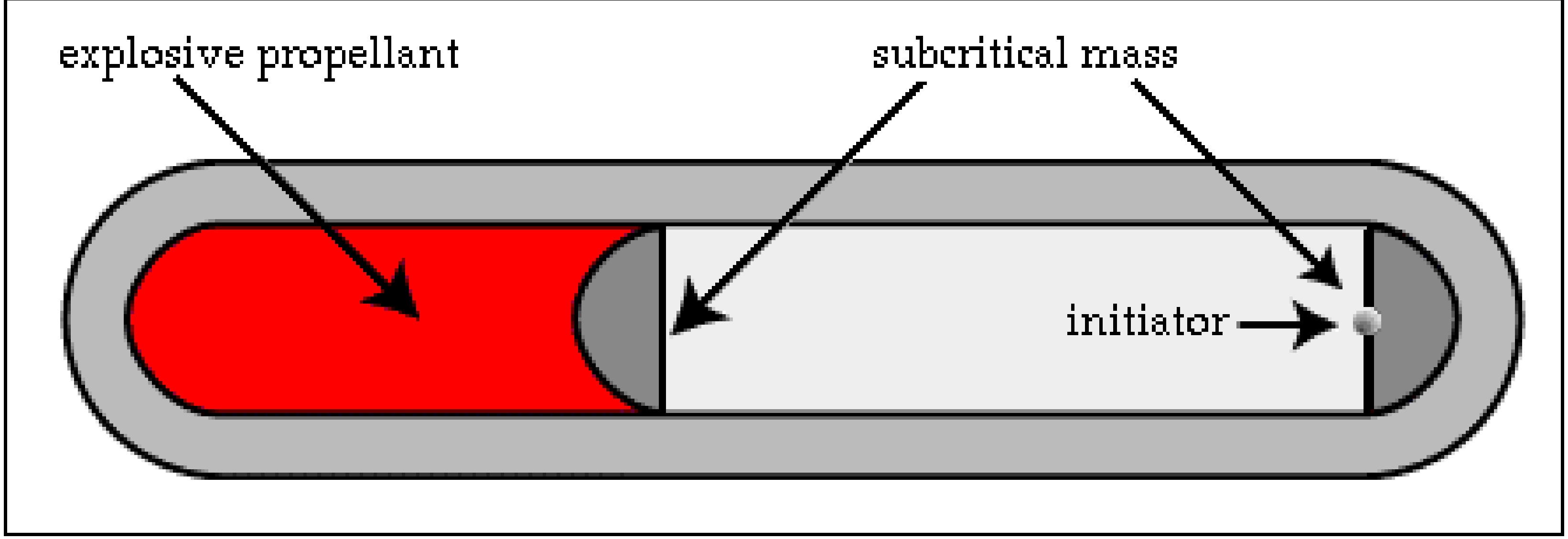
Timing for one generation is travel time of neutrons across Uranium mass with density: $\rho = 1.87 \cdot 10^4\ kg/m^3$.

$$\rho = \frac{M}{V} \quad V = \frac{4}{3}\pi \cdot r^3$$

$$\rho = \frac{3M}{4\pi \cdot r^3} \quad r = \left(\frac{3M}{4\pi \cdot \rho}\right)^{1/3} = 0.05m$$

$$t = \frac{2 \cdot r}{v} = 10^{-8}\ s$$

For ~80 generations ~1μs
Mass must remain confined for ~1μs
since most of the energy production
takes place during last 10 generations

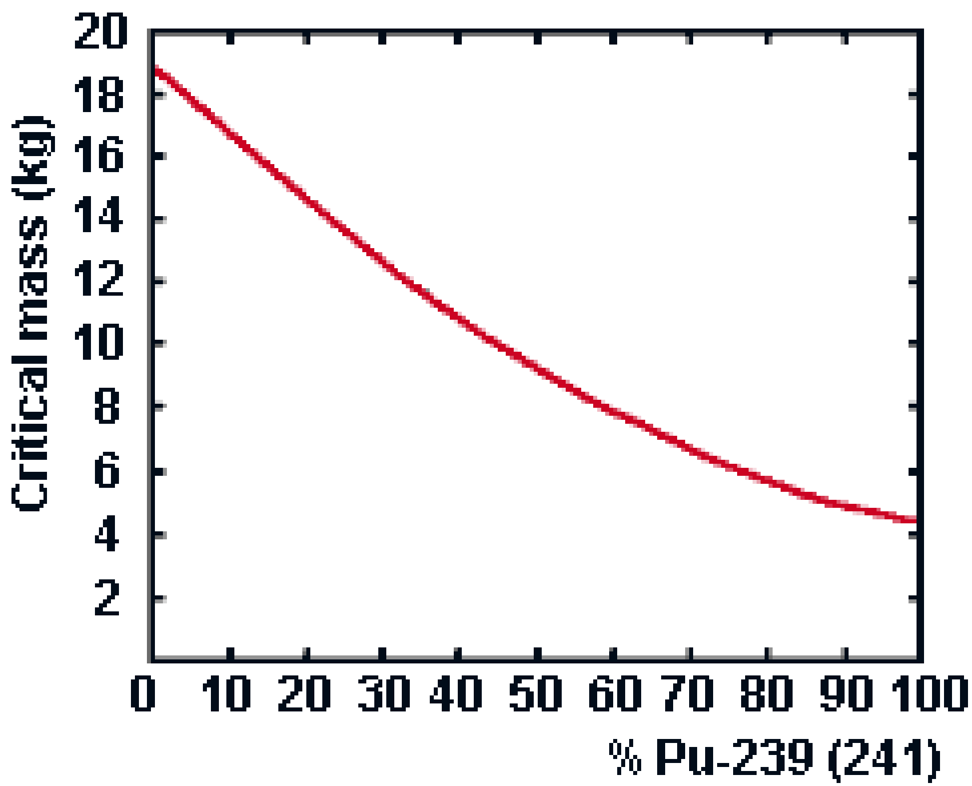


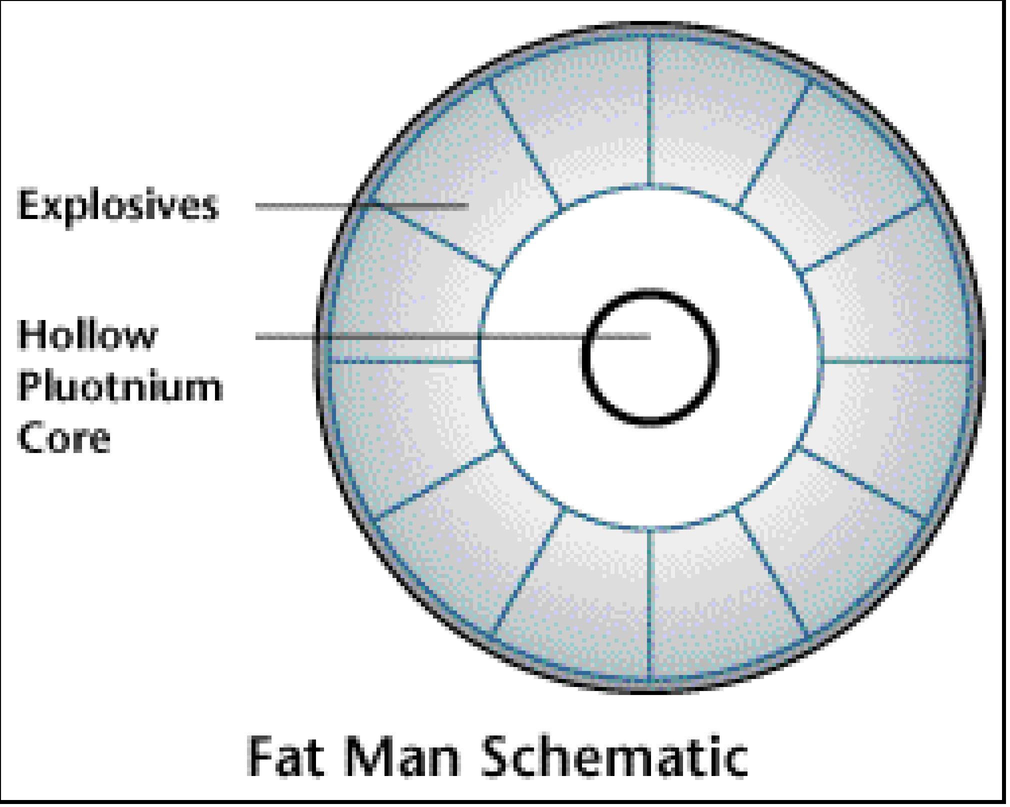
Gun Design

- This design worked with uranium.
- A 2000 lb TNT Blockbuster bomb was used as the “trigger” to bring critical mass together.

Plutonium device

Without a neutron reflecting shield, pure Pu-239 metal has a critical mass of **10 kg**, for a "reactor grade" isotopic mixture this would be 18 kg. Using a 15 cm U-238 shield, the Pu-239 critical mass is only some **4 kg**, while for LWR-produced plutonium this is some **7 kg**.

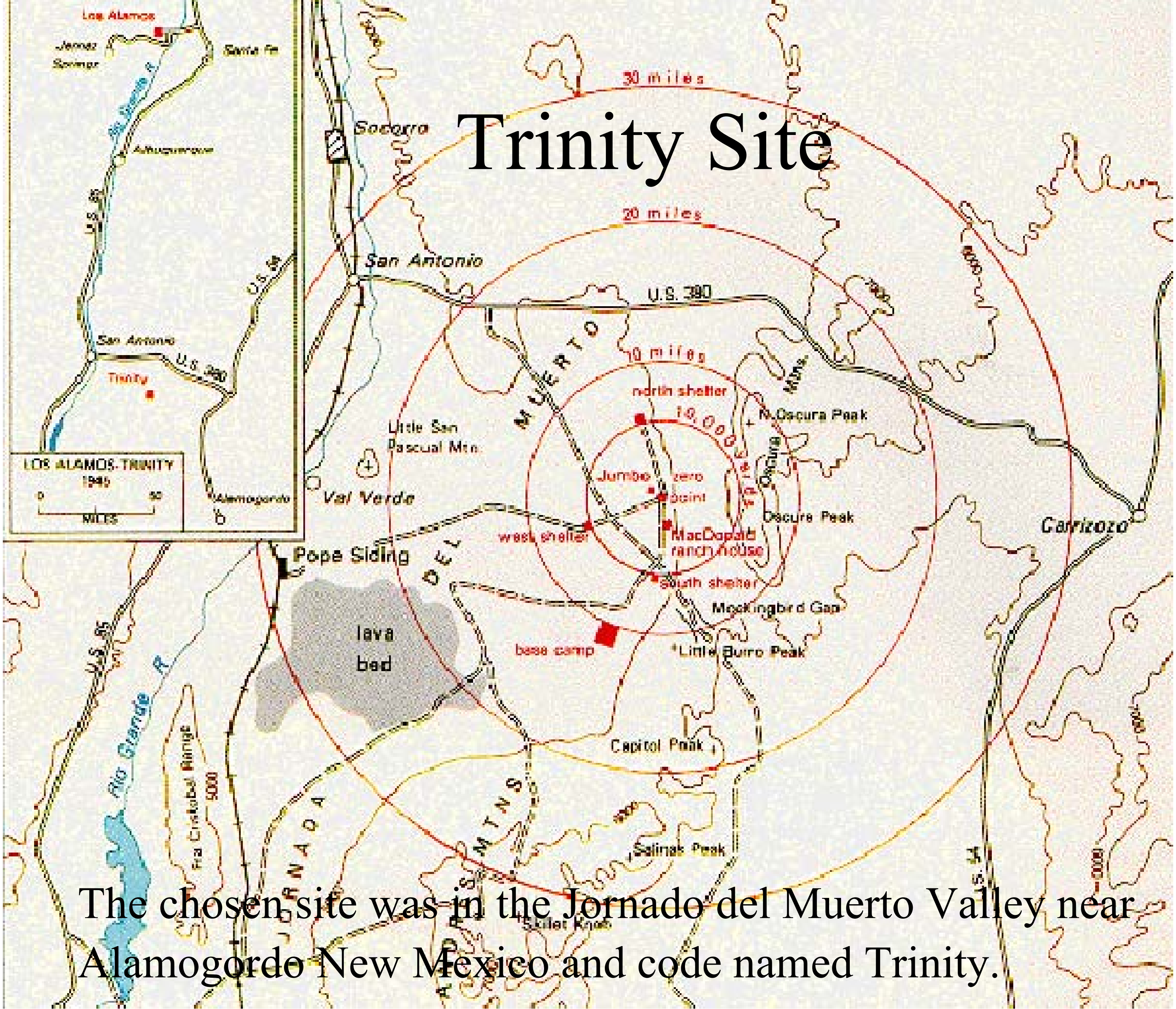




Implosion Design

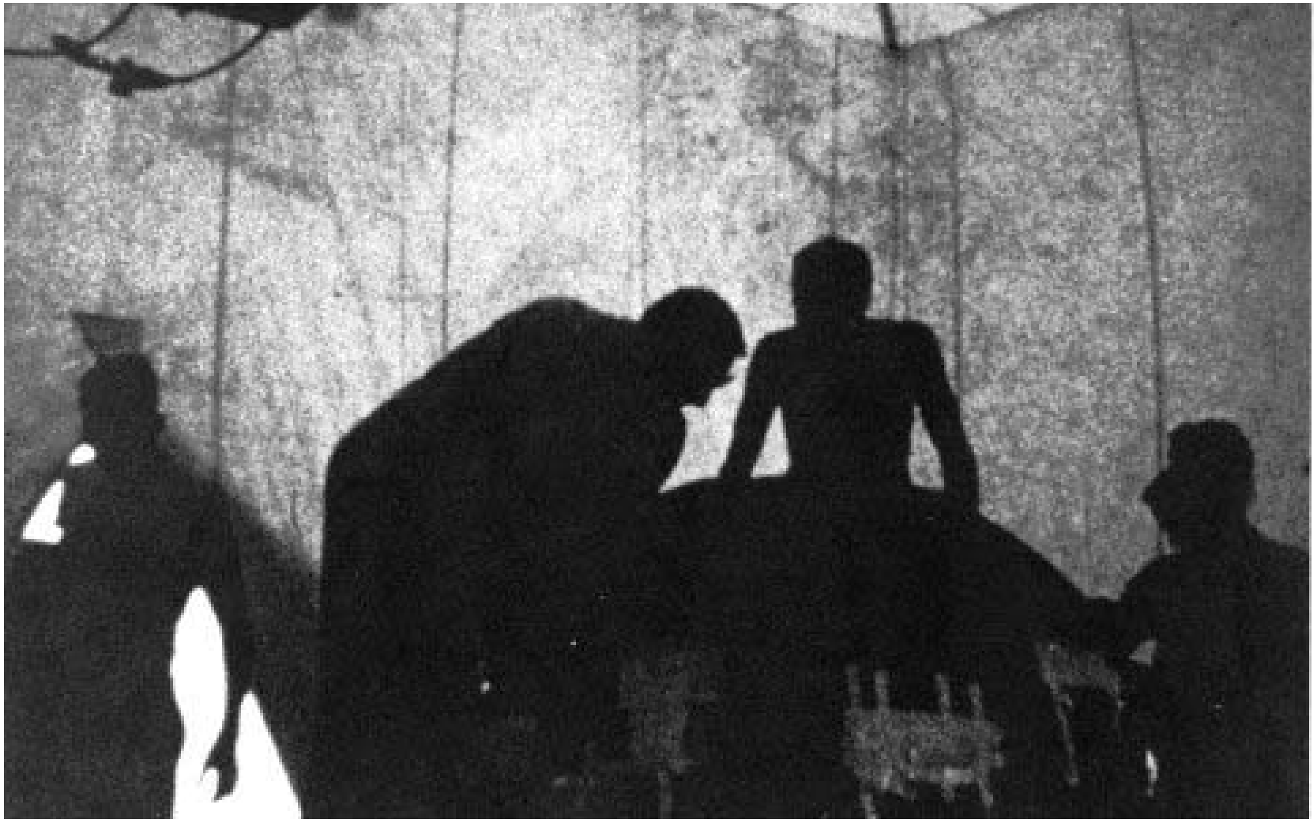
- This design was required for plutonium.
- Impurities of ^{240}Pu would release too many neutrons and cause premature detonation in the gun design. This would lower the yield.
- This design needed testing ⇨ Trinity test

Trinity Site



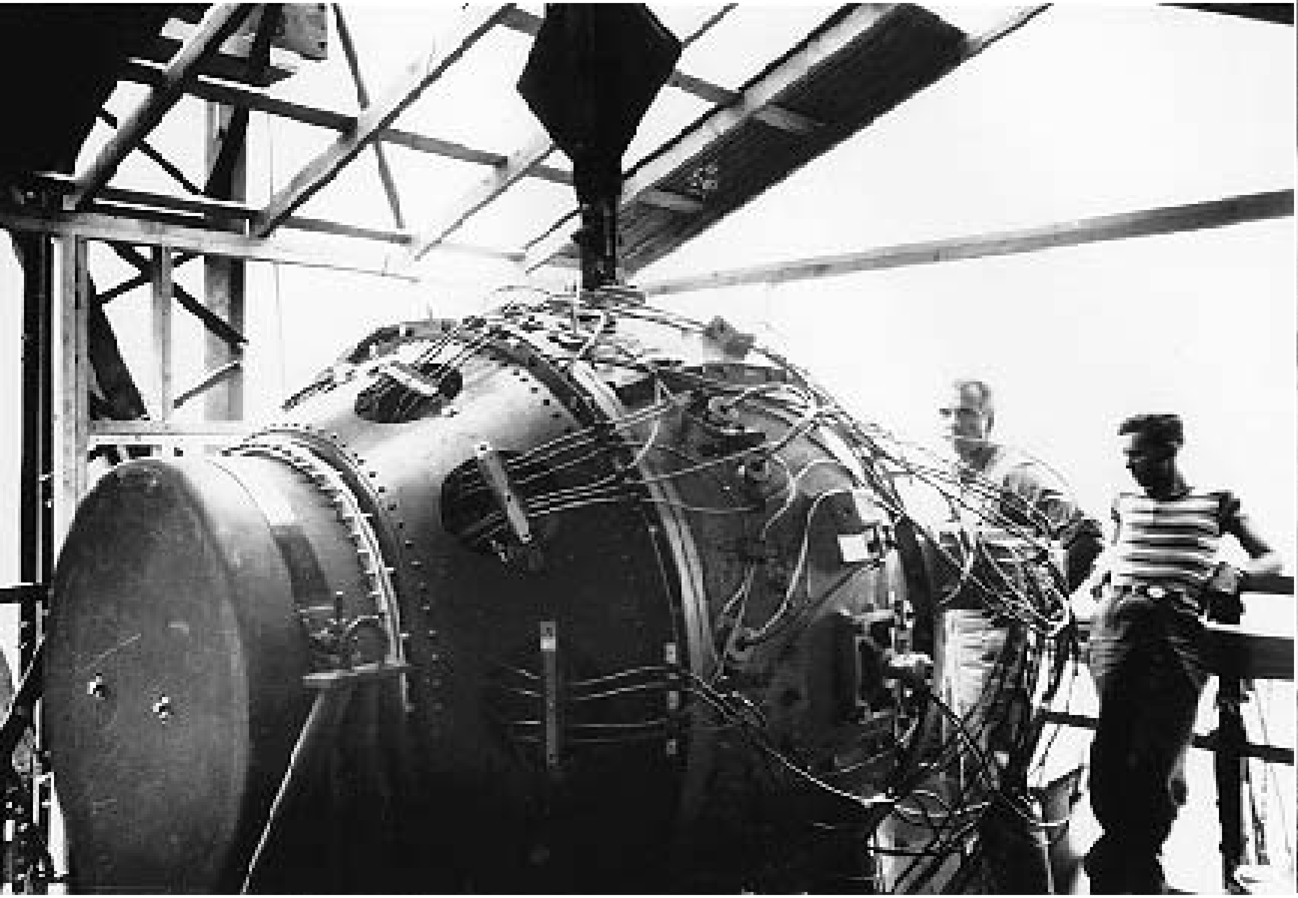
The chosen site was in the Jornado del Muerto Valley near Alamogordo New Mexico and code named Trinity.

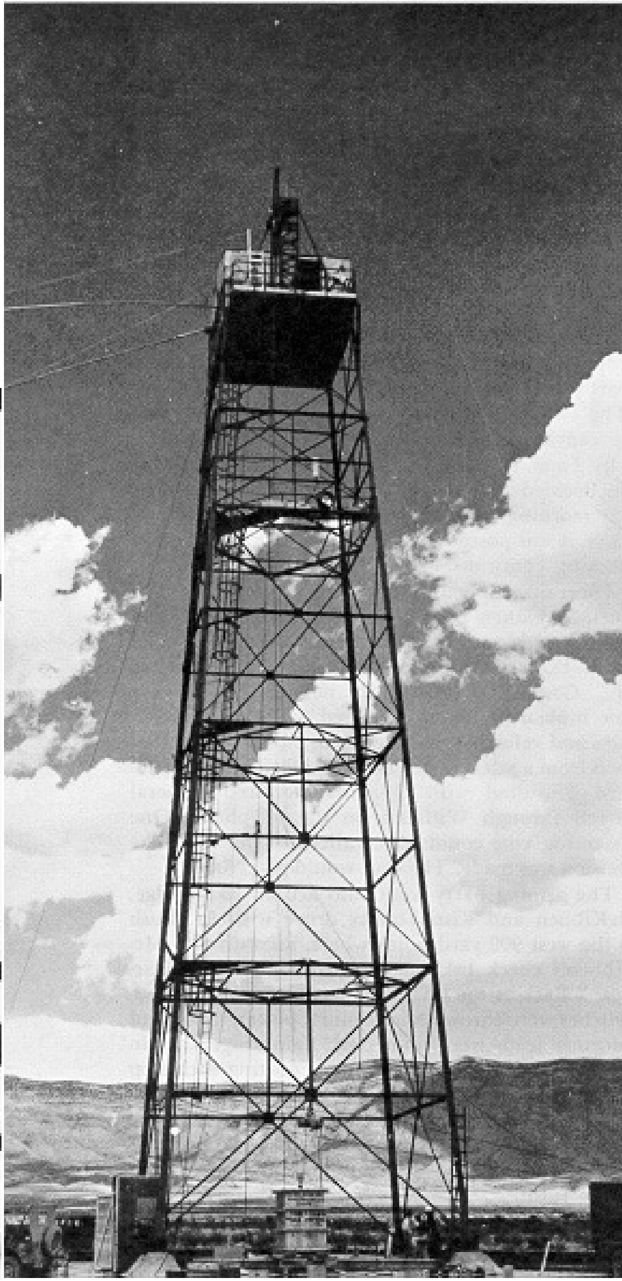
The set-up of the Trinity test



The loading of the Plutonium into the “Gadget”

Gadget





The Dawn of the Nuclear Age

The first nuclear explosion occurred at 5:29:45 am on July 16, 1945 at Trinity.

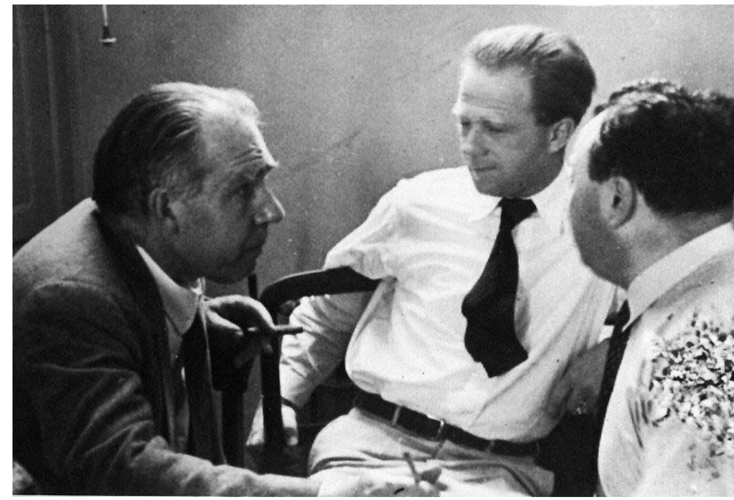
Trinity

At 5:29:45 a.m., the gadget exploded with a force of 21,000 tons of TNT evaporating the tower on which it stood. Groves' deputy, General Farrell, wrote that the "whole country was lighted by a searing light with the intensity many times that of the midday sun. It was golden, purple, violet gray and blue. It lighted every peak, crevasse and ridge of the nearby mountain range with a clarity and beauty that cannot be described but must be seen to be imagined. Seconds after the explosion came first the air blast pressing hard against the people, to be followed almost immediately by the strong, sustained awesome roar that warned of doomsday and made us feel we puny things were blasphemous to dare tamper with the forces heretofore reserved for the Almighty."

- Edward Teller described wearing double welders glasses and was not impressed until he removed his hands from around the glasses.
- Fermi was holding pieces of paper in his hand and waited for the shock wave to estimate the output. He later commented on missing both fission and the first nuclear explosion.

How were the Germans doing?

Meeting between Bohr & Heisenberg
in Copenhagen in September 1941



Looking for help?
Passing on information?
Boasting of German progress?

Heisenberg maintained claim that he was working on reactor
Not bomb design! He was officially head of the German Uranium club.

1942 first reactor design in Leipzig
1943 cancellation of Uranium bomb project
1944 reactor in Haigerloch – remained too small!

The critical mass from German view

The best evidence we have suggests that Heisenberg had no interest in building an atomic bomb. In mid-1942, Albert Speer, the weapons minister, asked Heisenberg whether he could produce a weapon in nine months. With a clear conscience he could answer "No." And he did not know how much fissionable material he would need. When, on occasion, friends asked him, his replies were varied and vague, ranging from 10 kilograms to a few tons.

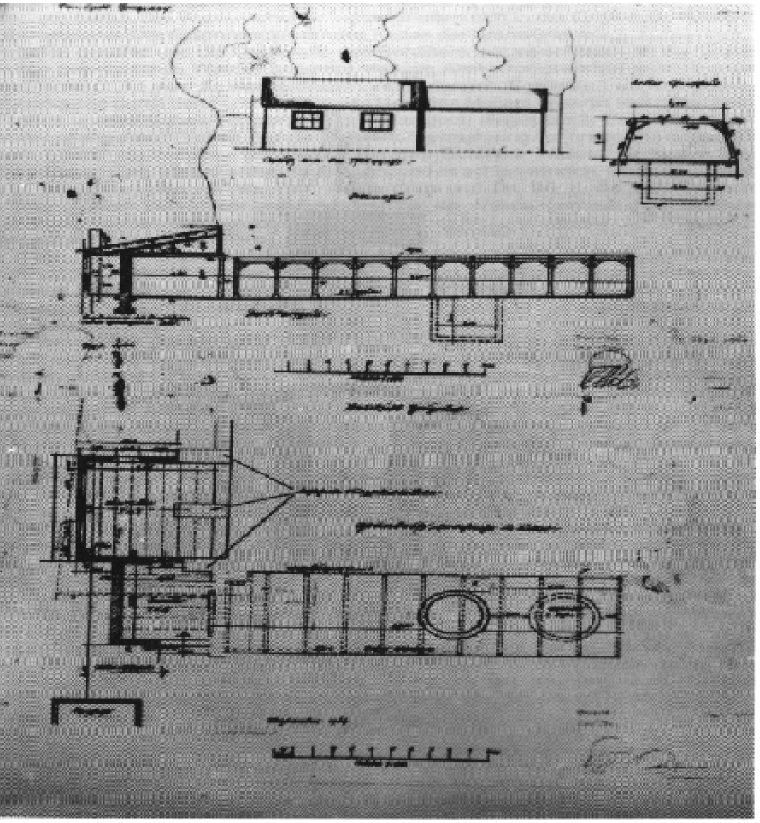
Why didn't he know? Why hadn't pure intellectual curiosity led him to investigate the properties of uranium-235 with fast neutrons? He could have made a small amount using the cyclotrons available in both Paris and Copenhagen. But he never asked that these properties be measured. The best proof of his lack of interest came at the end of the war. Heisenberg and about ten other German nuclear scientists were interned at Farm Hall, a country estate in England. … His first attempt at explanation (*of the Hiroshima bomb*) was totally wrong! He hypothesized something like a nuclear reactor, with the neutrons slowed by many collisions with a moderator.

That he was capable of doing the work was shown about a week later when, in another lecture, he corrected himself and presented a theory similar to that worked out by Rudolf Peierls and Otto Frisch in 1940. He estimated the necessary amount of uranium-235 at about 20 kg, which is nearly correct.

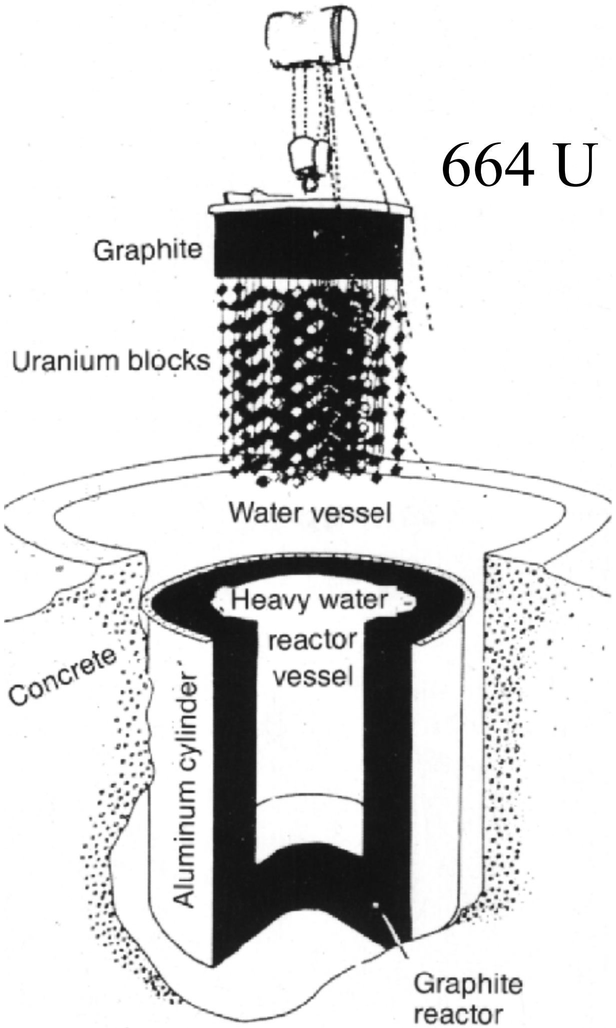
Hans Bethe in Physics Today Vol 53 (2001)

Indications for activity

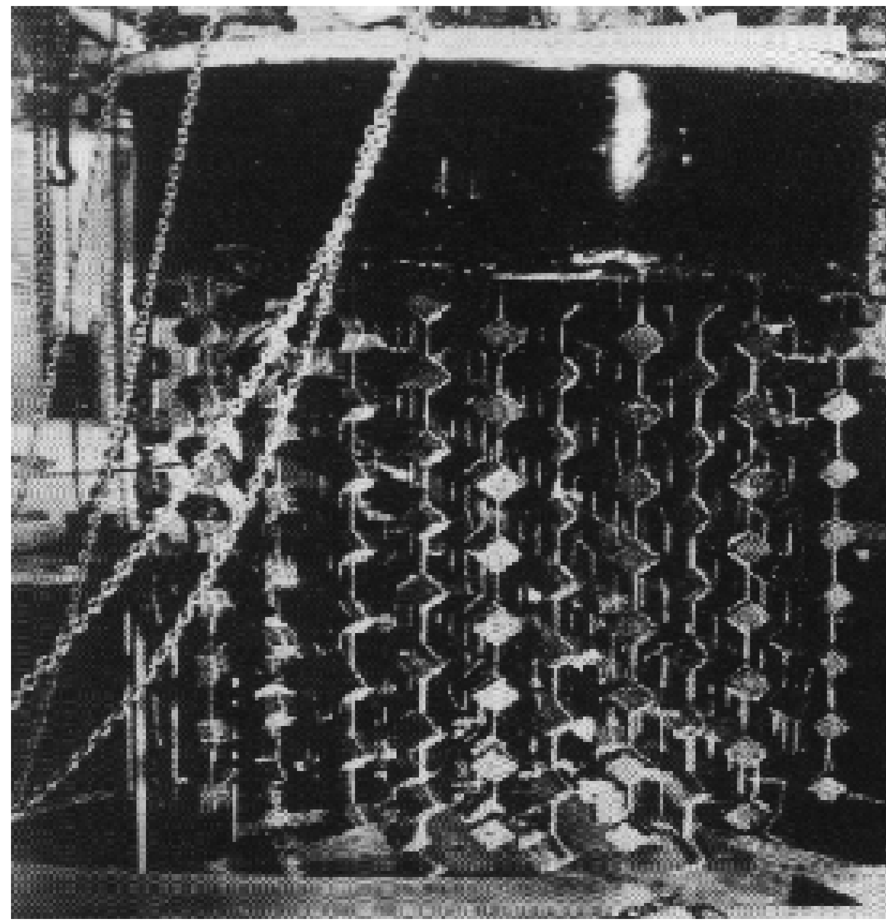
Used French cyclotron accelerator of Joliot-Curie
Maintained studies of moderator systems (Walter Bothe)
Continued reactor research



The German Reactor B8 in Haigerloch



664 U cubes



Uranium blocks immersed in heavy water
Too small on neutron enhancement factor 7

The Alsos Mission in Haigerloch

The end of the German nuclear program

Lucky guys!

German Surrender May 7. 1945


NAZIS GIVE UP!
THE DEPAUW

Was there a nuclear race?

- Did German scientists fail to recognize opportunity?
- Did Bothe stop program by mistake in moderator calculation?
- Did Heisenberg fail (initially) in calculating critical mass?
- Did allied air raids successfully stop German nuclear attempts?
- Did lack of Hitler support stop nuclear weapons program?
- or combination of all these points?