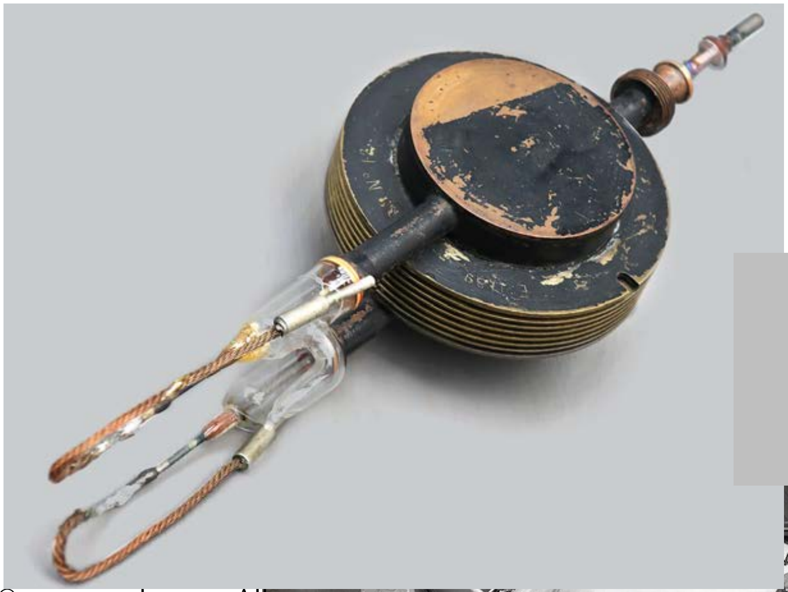
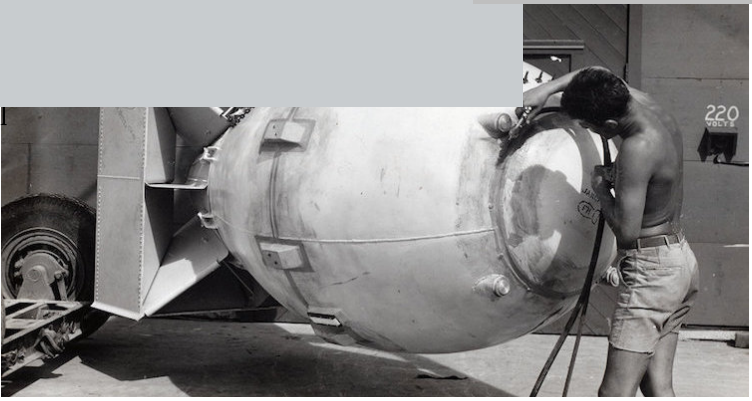


# Radar and the Manhattan Project



8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 21 October 2020

## 1. “Winning the War”: Radar

## 2. Starting the Manhattan Project

## 3. Making Bombs

*Note:* This class session will focus on some conceptual challenges and new institutional arrangements for physicists — mostly within the United States — during the Second World War. There are *many* more aspects of the wartime projects to consider, some of which are introduced in the documentary film *The Day After Trinity*. Students should watch that film on their own. We will have an *optional*, informal discussion of the film via Zoom during our ordinary class time on Monday, October 26, 2020.

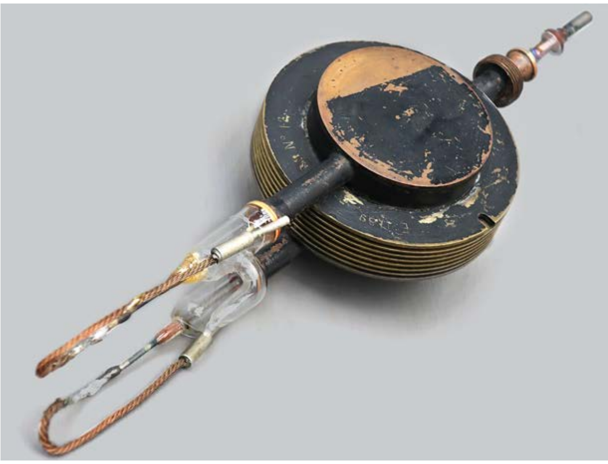
# Radar

Radar systems were first developed in the mid-1930s. The idea was to emit electromagnetic waves, let them reflect off of an object, and detect the "echo." By using the (constant) speed of light $c$ and measuring the time until arrival of the return signal, the devices could determine the *distance* to the object. More sophisticated units measured *Doppler shifts* to also discern the *speed* of the target object.

Both British and American military researchers had developed long-wavelength ( $\lambda \sim$ 1-10 m) systems before the start of the Second World War. Once the war began, intense efforts to improve the technology led to many physicists' first direct involvement with military matters.

One of the earliest challenges: design radar systems that used *shorter wavelength* signals ($\lambda \sim$ 1-10 cm). Remember that the *resolving power* is proportional to *wavelength* ($\delta x \sim \lambda$). Beginning in September 1939, German submarines ("U-boats") became a huge threat to US and UK shipping and naval maneuvers in the Atlantic Ocean. The submarines could only be spotted when their tiny *periscopes* surfaced above the water.

# Radar



British "cavity magnetron," ca. 1940

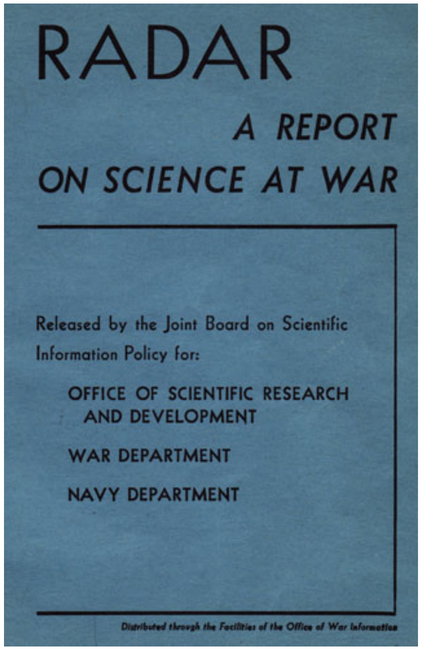
By 1940, British physicists and engineers had developed a new "cavity magnetron": a small device that could emit high-power electromagnetic waves with $\lambda \sim 1$ cm. By then, the UK was under heavy bombardment from German aircraft; it seemed impossible to scale up the research and development of the new short-wavelength radar systems in the UK.

In September 1940 — more than a year before the US entered the war! — a British delegation led by *Sir Henry Tizard* came to Washington, D.C., to ask US colleagues to take over radar development. They handed over a *single cavity magnetron*, so that the US groups could try to reverse engineer it.

MIT's *Vannevar Bush, Karl Compton* and a few other US colleagues met with the small British group to discuss possible collaborations. At one point Compton stepped out to call an assistant at MIT, to see if they could requisition a campus parking lot to convert into temporary research space for the new Allied radar effort. This became the "*Radiation Laboratory*," or "*Rad Lab*."

MIT's Building 20: "The Plywood Palace"

# New Institutions



RADAR

A REPORT ON SCIENCE AT WAR

Released by the Joint Board on Scientific Information Policy for:

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT

WAR DEPARTMENT

NAVY DEPARTMENT

Distributed through the Facilities of the Office of War Information

Image is in the pubic domain.

The radar project became one of the first sponsored by the new *National Defense Research Committee* (NDRC), organized and chaired by Vannevar Bush. The NDRC would operate as the US government's official conduit to research scientists and engineers for the war effort. Military officials would describe what technologies they sought, and the NDRC would arrange contracts with laboratories (both industrial and academic) to conduct the necessary research.

By May 1941 (still before the US had entered the war!), Bush convinced US President Franklin Roosevelt to *expand* these efforts into an even more powerful structure: the *Office of Scientific Research and Development* (OSRD), which could actually oversee production.

Part of Bush's strategy: use *contracts* (rather than gifts or grants) between universities and the federal government, to maintain the *appearance* of two equal partners entering into a business arrangement. In fact, most US universities were *starved* for cash after nearly a decade of the Great Depression. But a "contract" system appeared different than a centralized "bail-out" of higher education by the federal government.

# The Rad Lab

MIT Rad Lab personnel in the rooftop facility of Building 4, 1941.

The MIT Rad Lab quickly began recruiting personnel. It began with 30 physicists (many from other universities), three security guards, two stockroom clerks, and a secretary. It was led by nuclear physicist *Lee DuBridge*, though it quickly brought in experts in many other fields: electrical engineering, meteorology, geology, materials science, even linguists.

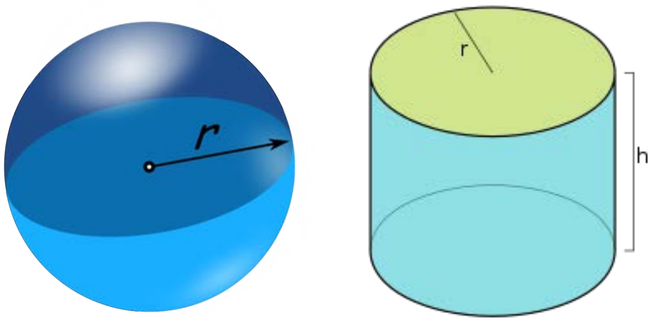
By 1942, the Rad Lab staff numbered 2000; by 1945, it had grown to 4000, including 500 academic physicists. The Lab spent $1m *per month* (~$15m in 2020$). Throughout the war, MIT secured OSRD defense contracts worth $100m (~$1.5b in 2020$), substantially more than any other university and three times more than AT&T, General Electric, RCA, DuPont, and Westinghouse *combined!*

Rad Lab staff designed and produced *dozens* of distinct radar systems (ground-to-air, air-to-sea, etc.) in the λ~1cm range, and conducted tests from MIT rooftops to detect aircraft from nearby airports (now Hansom Air Force Base and Logan Airport). They also trained nearly *10,000* active-duty service members on campus how to use the new radar systems.

# The Rad Lab

Julian Schwinger at the MIT Rad Lab, 1940s

At first, many of the theoretical physicists at the Rad Lab were pretty arrogant; after all, radar was “merely” a problem in classical electromagnetism, not fancy quantum theory or nuclear physics. But as they quickly learned, calculating **E** and **B** field configurations for *realistic* devices, rather than simple toy problems, was “nontrivial.”

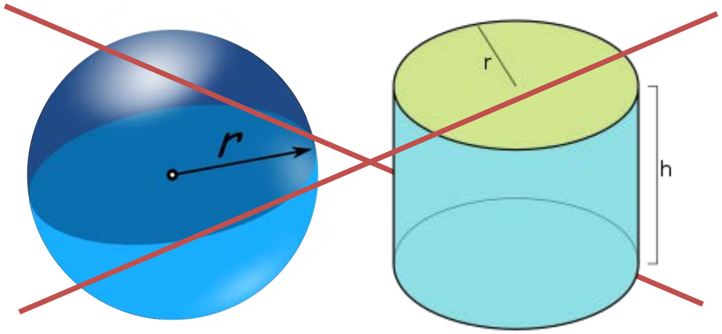


The physicists were very skilled at exploiting *symmetries* to simplify calculations...

# The Rad Lab

At first, many of the theoretical physicists at the Rad Lab were pretty arrogant; after all, radar was "merely" a problem in classical electromagnetism, not fancy quantum theory or nuclear physics. But as they quickly learned, calculating **E** and **B** field configurations for *realistic* devices, rather than simple toy problems, was "nontrivial."

Julian Schwinger at the MIT Rad Lab, 1940s



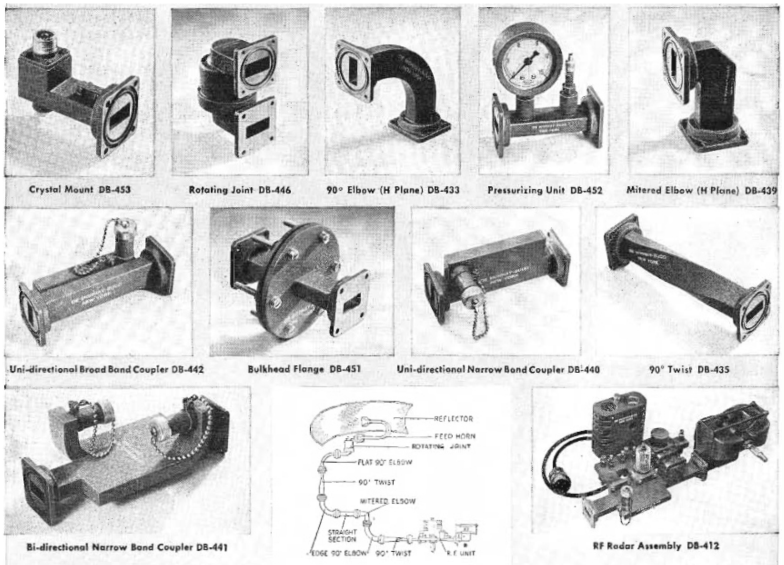


Image is in the public domain.

Some of the waveguide components in regular use by the mid-1940s

A schematic of just one portion of a waveguide antenna feed

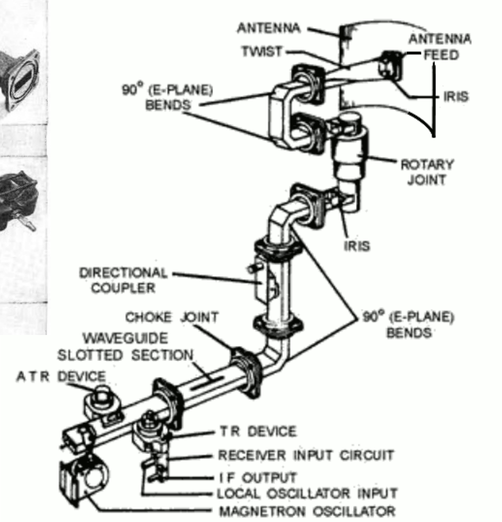


Image is in the public domain.

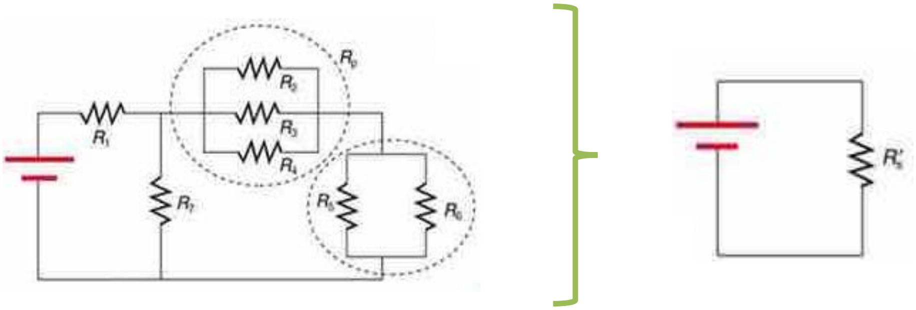
# The Rad Lab

Julian Schwinger at the MIT Rad Lab, 1940s

Complicated circuits could be simplified by constructing *effective circuits*: measure the current flowing in on one side and flowing out of the other, and infer an *overall* resistance.

At first, many of the theoretical physicists at the Rad Lab were pretty arrogant; after all, radar was "merely" a problem in classical electromagnetism, not fancy quantum theory or nuclear physics! But as they quickly learned, calculating **E** and **B** field configurations for *realistic* devices, rather than simple toy problems, was "nontrivial."

The physicists quickly learned from engineers a "black-box" approach to calculating: work in terms of *effective circuits* rather than individual, constituent parts; focus on input-output relationships.



# The Rad Lab

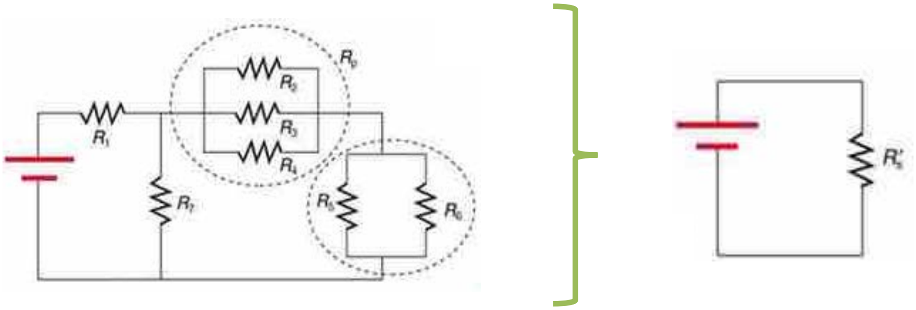
Julian Schwinger at the MIT Rad Lab, 1940s

Complicated circuits could be simplified by constructing *effective circuits*: measure the current flowing in on one side and flowing out of the other, and infer an *overall* resistance.

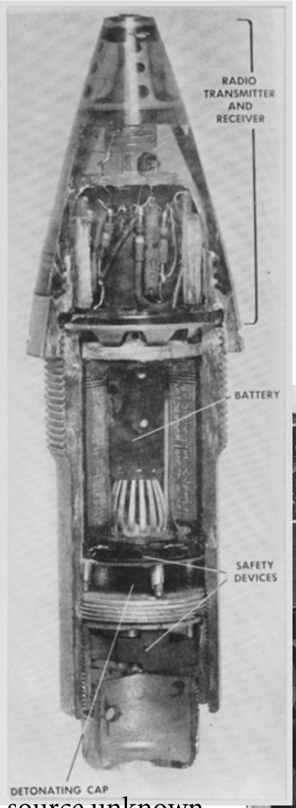
At first, many of the theoretical physicists at the … were
pretty arrogant; after … ssical
… ics! But
… ons for
… toy problems, was "nontrivial."

Several physicists, including Julian Schwinger, later recalled that this new approach to problem-solving — which they learned under *pressure* during the war — shaped how they thought about research questions *after* the war.

The physicists quickly learned from engineers a "black-box" approach to calculating: work in terms of *effective circuits* rather than individual, constituent parts; focus on input-output relationships.



# Radar



© source unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

By 1943, improved microwave-radar units had been developed and installed not just for ground-based scanning stations, but also on-board aircraft and naval vessels. They helped rein in the (previously unchecked) German U-boat campaigns, as well as German air-raids over the UK.

Radar systems were not only deployed defensively. At the OSRD-sponsored *Applied Physics Lab* at Johns Hopkins University, researchers developed the *proximity fuze*, which used tiny radar systems embedded within artillery shells to trigger the explosive once the shell reached a pre-set distance from its target.

Anti-aircraft shells with proximity fuzes during the Battle of Guadalcanal, 1943
Image is in the public domain.

Whereas previous anti-aircraft efforts had required *hundreds* of rounds (on average) to hit a fast-moving aircraft, with proximity fuzes they only needed (on average) *two*.

After the war it became common for veterans of the Rad Lab to say that nuclear weapons might have *ended* the war, but radar *won* the war.

*Questions?*

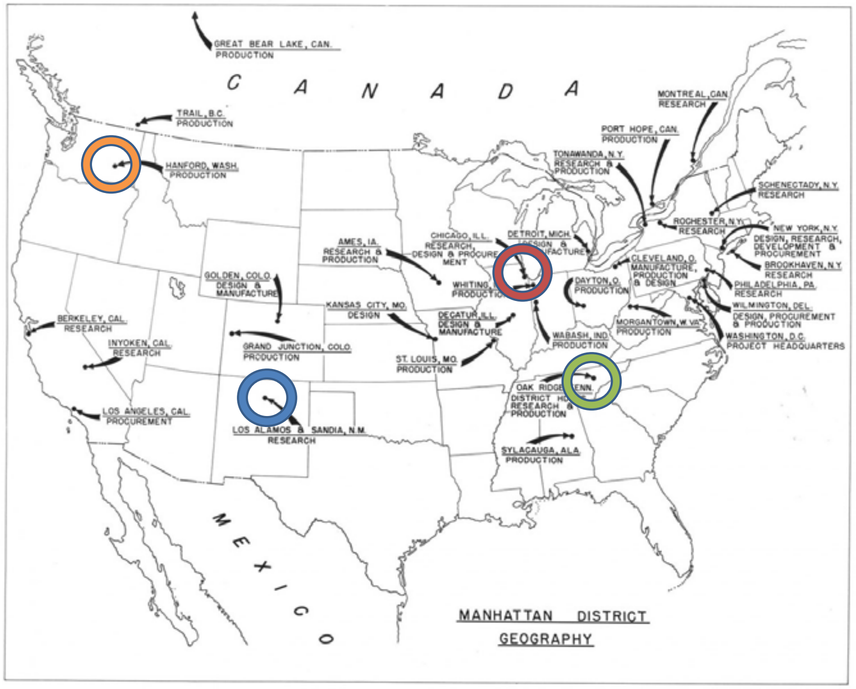
# Starting the Manhattan Project

Some of the earliest MED offices were in the Woolworth Building on Broadway in NYC

The other major OSRD project during the war was the *Manhattan Engineer District* (MED), or *Manhattan Project*, pursued jointly with the US Army Corps of Engineers. Planning began in June 1942 in an NYC office of the Corps, and (at the time) several physicist-members of the preliminary "Advisory Committee on Uranium" (including *Enrico Fermi*) were at nearby Columbia University.

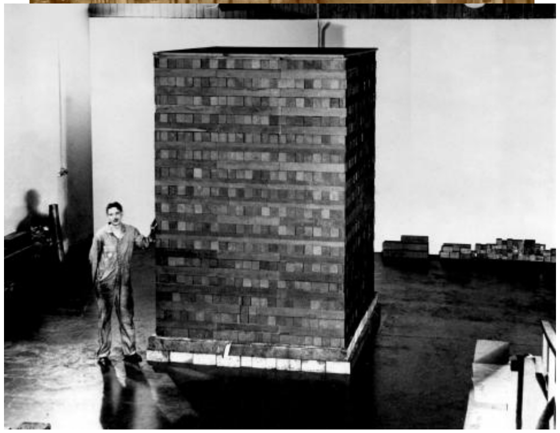
The project expanded to more than *30 sites* across the US and Canada, employing more than 125,000 people — most of whom knew very little about the nature of the top-secret project.

Major sites included **Chicago, IL**; **Oak Ridge, TN**; **Hanford, WA**; and **Los Alamos, NM**.



# Chain Reactions

© University of Chicago.

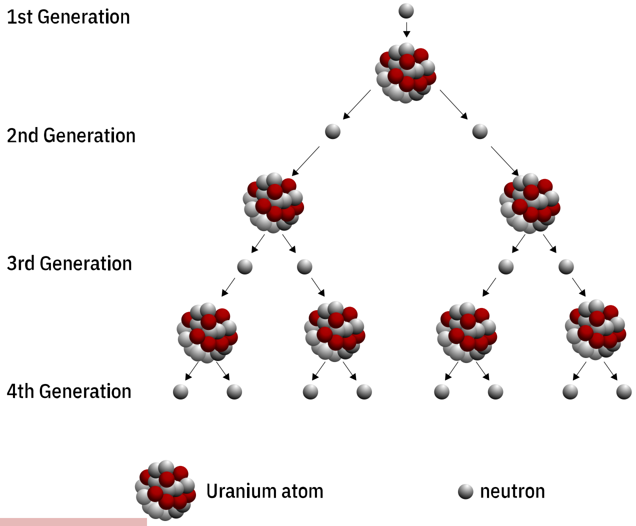


Chicago Pile-1 under construction, 1942
© Argonne National Laboratory.

A team at the Chicago "Metallurgical Laboratory," led by *Enrico Fermi*, studied fission reactions. They built Chicago Pile-1, the first working nuclear reactor, in a squash court under the bleacher seats of the Stagg Field stadium on campus.

Each time a uranium nucleus fissioned, 2-3 additional neutrons were released. Those new neutrons could fission neighboring nuclei, and so on: a *chain reaction*.

The "pile" consisted of 57 layers of closely packed graphite bricks (*moderators* to slow down neutrons), interleaved with small chunks of uranium metal. The pile also included several 14-foot cadmium "control rods" that could be pushed in or out to *absorb* neutrons and prevent a *run-away* chain reaction.



The first *self-sustaining chain reaction* went "critical" on December 2, 1942.

# New Fissile Materials

During 1940-41, Berkeley nuclear chemist *Glenn Seaborg* led a team that successfully produced *genuine* transuranic nuclei. They bombarded uranium with neutrons; sometimes the neutrons were captured and then underwent beta decay. In February 1941, the team first produced *plutonium* via double beta-decay:

$$\mathrm{U}_{92}^{238} + n_0^1 \longrightarrow \mathrm{U}_{92}^{239}$$

neutron capture

$$\mathrm{U}_{92}^{239} \xrightarrow[n\to p+e+\bar{\nu}]{} \mathrm{Np}_{93}^{239} \xrightarrow[n\to p+e+\bar{\nu}]{} \mathrm{Pu}_{94}^{239}$$

double beta-decay

The next month, Seaborg and Fermi's former colleague, *Emilio Segrè*, demonstrated that plutonium could undergo *fission*. Within a few months, Seaborg moved to the Chicago Met Lab to join Fermi and continue his experiments on plutonium, including measurements of its fission rate under various conditions.

# Los Alamos

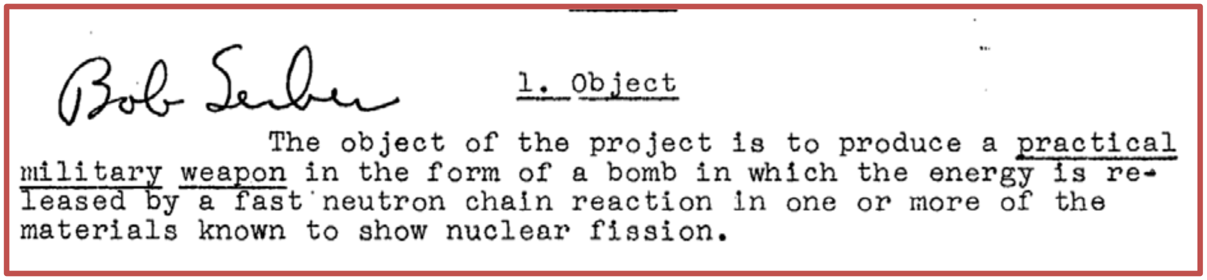
U.S. Brigadier General *Leslie Groves* was put in charge of the MED, over his initial objections. (He was eager to have an active combat role in the war, and did not think that the abstract-sounding weapons project would play much role in the present conflict.) He tapped Berkeley theoretical physicist *J. Robert Oppenheimer* to serve as scientific director of the Los Alamos Laboratory.

Los Alamos began operations in April 1943, taking over a boys' school in rural New Mexico. Oppenheimer recommended the location, based on previous trips to the region.

Oppenheimer (born in 1904) had studied in Cambridge and Göttingen in the mid-1920s, just as the new work on quantum mechanics was emerging. He was hired at Berkeley *and* Caltech in 1929 to teach theoretical physics and to help build up US strength in the field. Before the war, he had virtually *no* experience with either experiments or with large-scale organization.

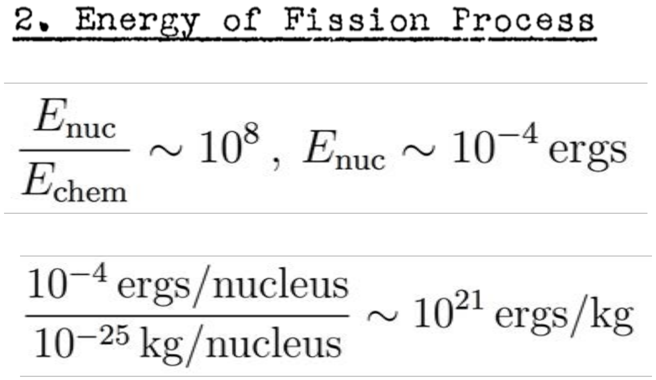
# Los Alamos

As soon as new recruits began to arrive at Los Alamos, Oppenheimer's former postdoc, *Robert Serber*, gave a series of 5 lectures as an "indoctrination course." Another physicist, *Edward Condon*, took notes. The 24-page document became LA-1, the first (top-secret) technical report of the lab. Informally, it became known as the "Los Alamos Primer."


Bob Serber

**1. Object**

The object of the project is to produce a practical military weapon in the form of a bomb in which the energy is released by a fast neutron chain reaction in one or more of the materials known to show nuclear fission.


**2. Energy of Fission Process**

$$\frac{E_{\text{nuc}}}{E_{\text{chem}}} \sim 10^{8}\ ,\ E_{\text{nuc}} \sim 10^{-4}\ \text{ergs}$$

$$\frac{10^{-4}\ \text{ergs/nucleus}}{10^{-25}\ \text{kg/nucleus}} \sim 10^{21}\ \text{ergs/kg}$$

energy release from conventional explosives like TNT:

$$5 \times 10^{16}\ \text{ergs}/\mathit{ton}$$

*code:*

$$U^{235}_{92} = \text{“25”}$$


1 kg of 25 ≈ 20000 tons of

Getting just *one kg* of $U^{235}$ to undergo fission would have the explosive impact of *20,000 tons* of TNT.

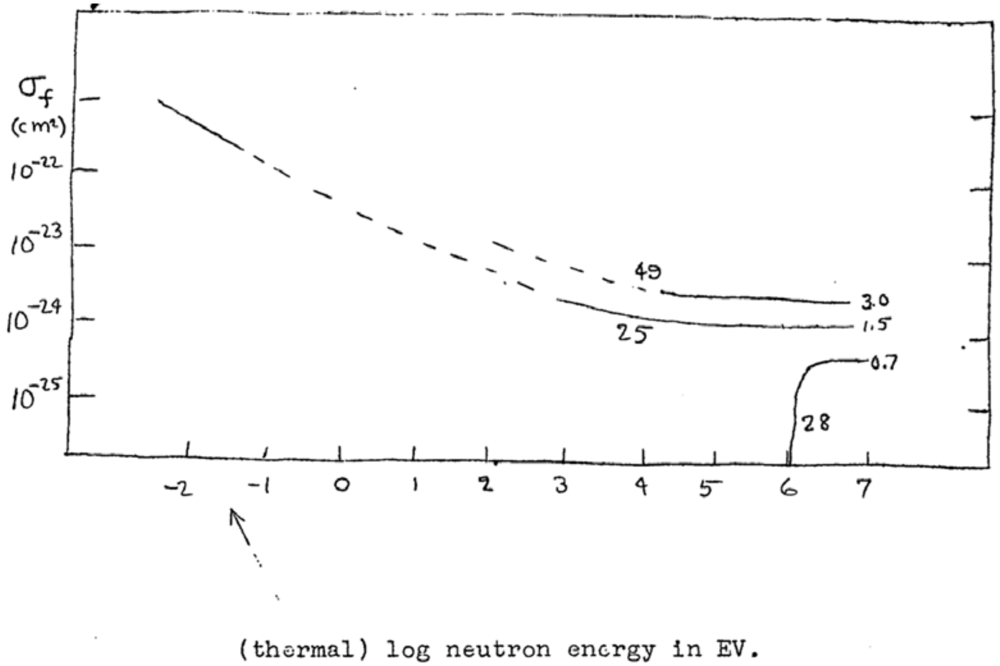
# Which Fuel to Use?

Fissionable materials:

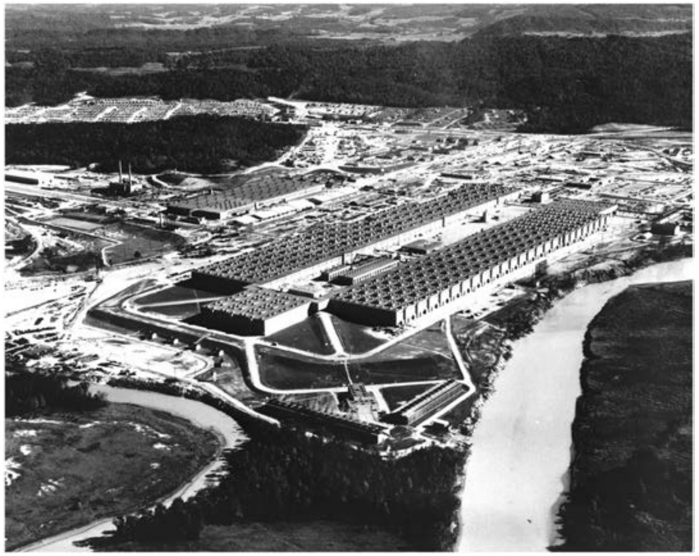
| | |
|---|---|
| $U_{92}^{238}$ | mostly stable |
| $U_{92}^{235}$ | highly fissionable, but only 0.7% of naturally occurring ore |
| $Pu_{94}^{239}$ | highly fissionable, but at the time it only existed in *micrograms* |

The *largest* reaction rates were for $U^{235}$ with *slow* neutrons. But the neutrons *released* from fission were *fast* ($E \sim 1$ MeV). For neutrons at those energies, the largest reaction rate was for *plutonium*.

Challenges: isolate $U^{235}$ from $U^{238}$, and/or scale up production of $Pu^{239}$ a *billionfold*, from μg to kg!

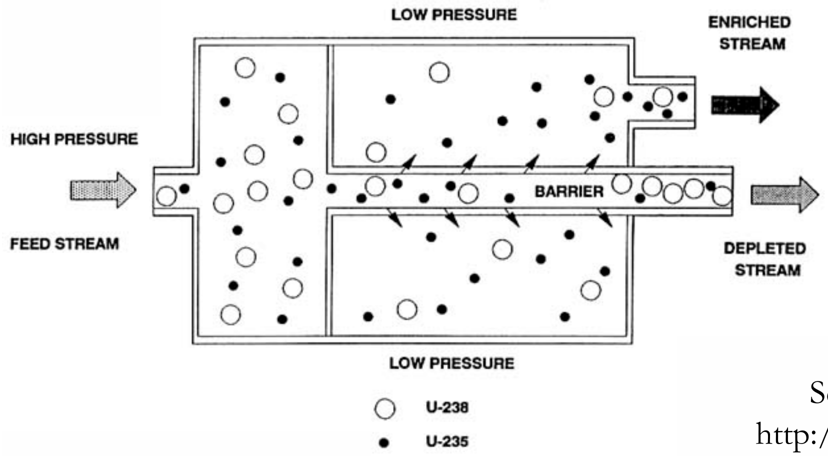


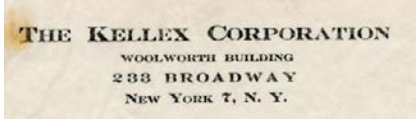
# Oak Ridge: Uranium Isotope Separation



The mile-long U-shaped K-25 gaseous diffusion plant at Oak Ridge: at the time, the *largest factory ever built under one roof*

The Oak Ridge MED facility focused on separating $U^{235}$ from $U^{238}$. Both isotopes behaved identically *chemically*, so they needed to exploit the *tiny* mass difference (~1.3%).





THE KELLEX CORPORATION
WOOLWORTH BUILDING
233 BROADWAY
NEW YORK 7, N. Y.

See *Alex Wellerstein*, "Inside K-25," http://blog.nuclearsecrecy.com/2013/05/24/inside-k-25/

*Gaseous Diffusion*: heat uranium hexaflouride gas ($UF_6$). In equilibrium,

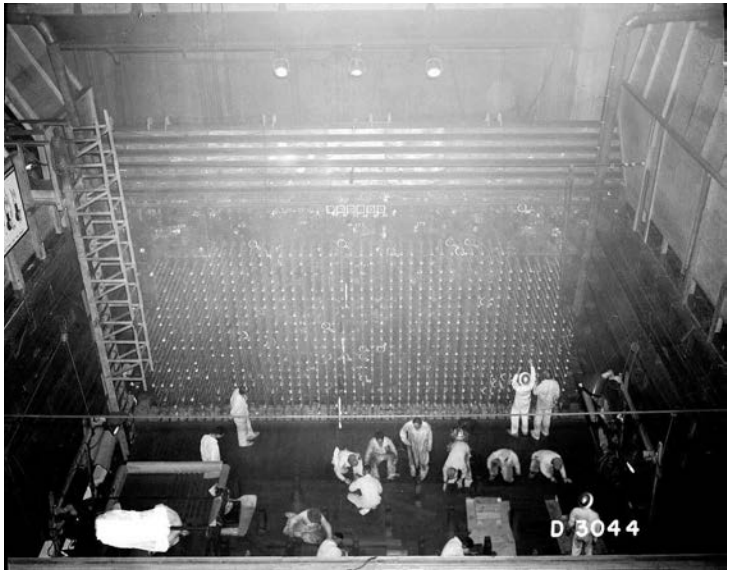
$$\frac{1}{2} m_{235}\, v_{235}^2 = \frac{1}{2} m_{238}\, v_{238}^2$$

so $v_{235} > v_{238}$. Force the gas into a chamber with permeable membranes. The faster-moving molecules with $U^{235}$ will diffuse more quickly. Enrichment from one cycle: **1.0043** ! So repeat... *a thousand times.*

# Hanford: Plutonium From Reactors

F Reactor complex at Hanford under construction, ca. 1944.
Image is in the public domain.

At the Hanford MED site, staff focused on scaling up Fermi's Chicago Pile-1 reactor to industrial scale. Their job was to produce kilograms of *plutonium* by neutron bombardment of $U^{238}$.



Inside Hanford's B reactor
Image is in the public domain.

The reactor complexes at Hanford required more than *one billion cubic meters of concrete*.

*Questions?*

# Critical Mass

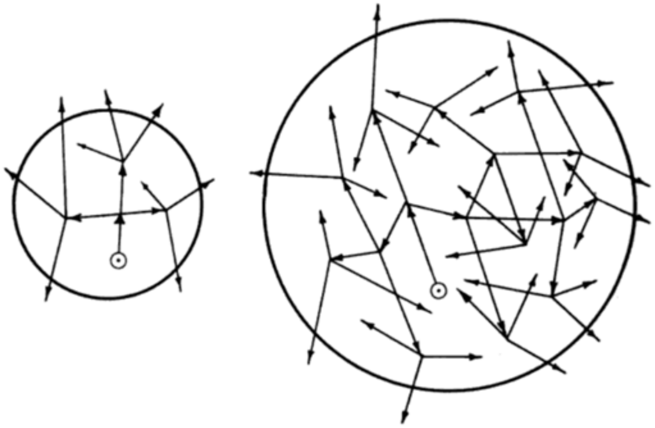


**Figure 1.40.** Effect of increased size of fissionable material in reducing the proportion of neutrons lost by escape.

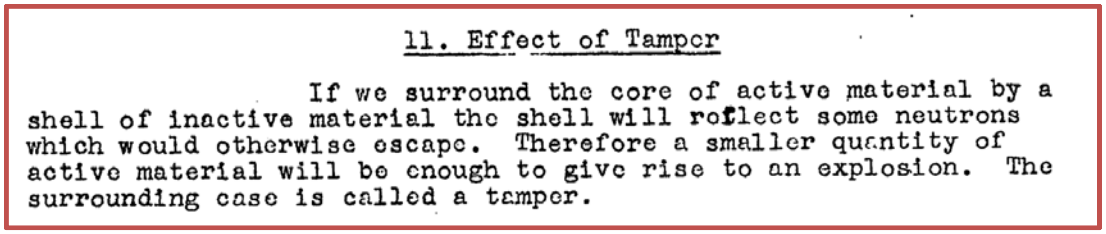
Samuel Glasstone, *Effects of Nuclear Weapons* (1957)

Each time a nucleus fissioned, 2-3 additional neutrons were released. If the volume of fissionable material were *too small*, too many neutrons (on average) would *escape* the material before causing additional fissions: *fizzle*.

With teams of (mostly) women "computers" using mechanical Marchant calculators, researchers at Los Alamos calculated the *critical size* of $U^{235}$: $R_c \sim 9$cm, so

$$M_c = \frac{4\pi}{3}\rho R_c^3 \sim 50\,\mathrm{kg}$$

Images are in the public domain.

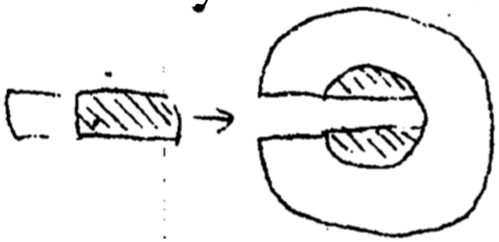


11. Effect of Tamper

If we surround the core of active material by a shell of inactive material the shell will reflect some neutrons which would otherwise escape. Therefore a smaller quantity of active material will be enough to give rise to an explosion. The surrounding case is called a tamper.

With an effective tamper, could expect $R_c \sim 3$cm, so $M_c \sim 2$ kg, not 50 kg.

# Gun Assembly



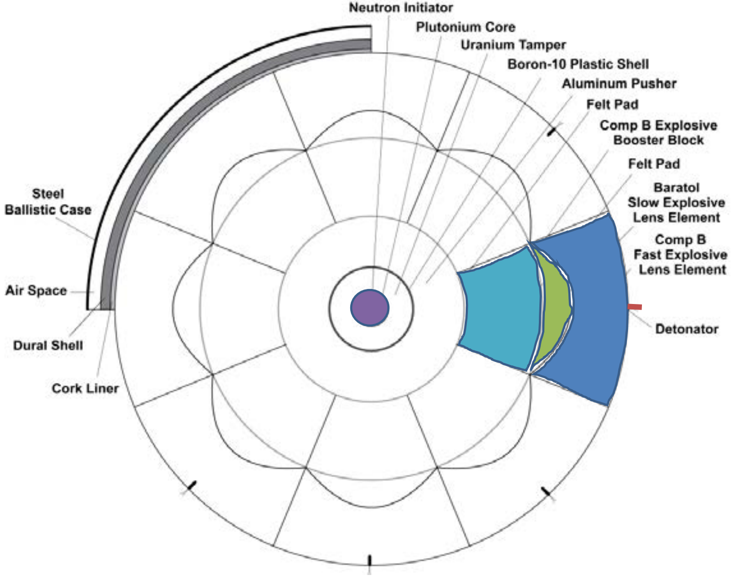
How to initiate a chain reaction? Serber explained one method: prepare two *subcritical* pieces of U$^{235}$ and shoot them together within about 10$^{-5}$ seconds; such speeds were consistent with muzzle speeds from US Army guns.

There would also need to be a *neutron source* to initiate the chain reaction. Serber suggested attaching an α-emitter (like radium or polonium) to one subcritical piece and beryllium to the other, so that when the two pieces came together they would (in effect) reproduce Chadwick's 1932 experiment and produce neutrons.

The group was so confident of this method that the *very first detonation* of this type of bomb was over the Japanese city of Hiroshima on August 6, 1945.

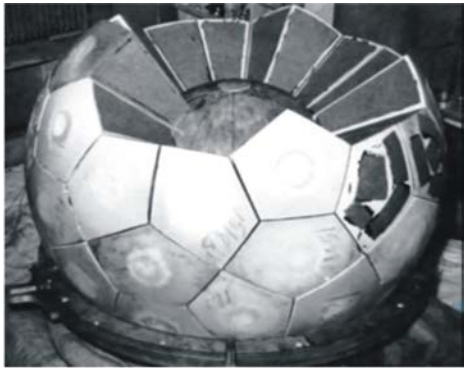
Ruins near the Hiroshima Prefectural Industrial Promotion Hall.

# Implosion



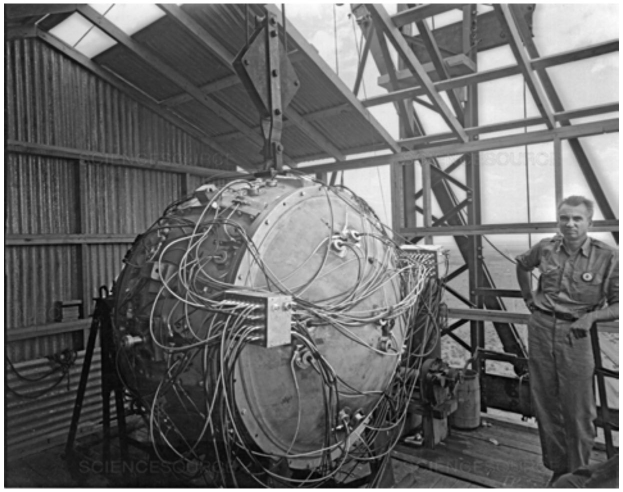
Major challenge at Los Alamos, August 1944: The gun assembly method did not work for *plutonium* bombs, because the *spontaneous fission rate* was too high; each subcritical mass tended to fall apart before a critical mass could be assembled.

Alternate method: *implosion*. Set up a spherically symmetric arrangement of sub-critical Pu pieces. Surround them with *shaped charges* of conventional explosives. Given their shapes and distinct burn-rates, they would create a synchronized, *in-going* pressure wave to rapidly compress the Pu pieces into a critical mass.



This created major challenges, both theoretical and experimental: how to shape the conventional-explosive charges into a kind of *lens*; how to produce conventional charges with the requisite purity; how to coordinate the electronics so the resulting shock wave retained spherical symmetry, ...

# Trinity Test



Norris Bradbury was responsible for the final assembly of the "gadget" before the Trinity test on July 16, 1945

Project leaders were *much* less confident about the complicated implosion design than the gun-assembly method. They arranged for a test in the desert outside Albuquerque, NM, which Oppenheimer dubbed the "Trinity" test.

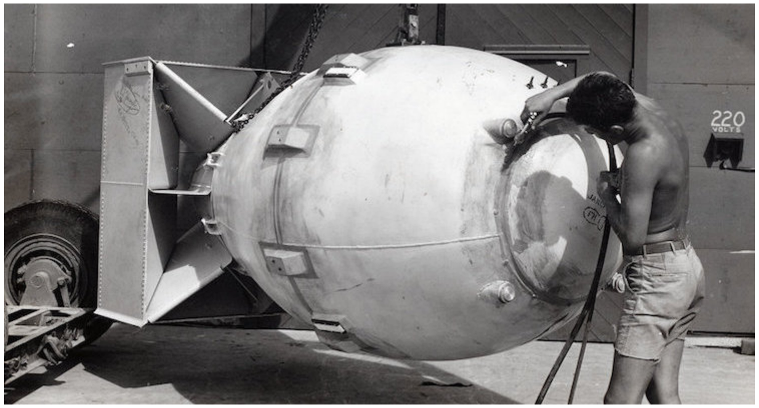
Plutonium remained so rare that leaders first planned to encase the bomb in a huge steel container: if the bomb were a dud, they could scrape off the plutonium from the inside of "Jumbo." In the end, they feared that "Jumbo" would interfere with instrumentation, so they didn't use it.

The "Jumbo" container arriving in NM

The blast was so intense that it fused sand into glass: radioactive "trinitite."

# “Fat Man”

Three weeks after the Trinity test — and just three days after the bombing of Hiroshima — a plutonium implosion bomb was dropped on the city of Nagasaki, on August 9, 1945.



The “Fat Man” Pu-implosion bomb being prepared on the island of Tinian, near Japan, August 1945

Mushroom cloud rising over Nagasaki

Survivors re-enter the city after the bombing

# *The Day After Trinity*

*Many* more questions to think about.

Watch the film on your own. We will then have an *optional*, informal discussion during class time on Monday, 26 October. Some questions to think about:

- What motivated scientists and engineers to work on the Manhattan Project? Did their motivations change over time?
- How was the decision made to use the bombs?
- What impact did they have on the course of the war?
- What reactions did scientists and others have to the use of the new weapons?

STS.042J / 8.225J Einstein, Oppenheimer, Feynman: Physics in the 20th Century
Fall 2020