The Manhattan Project

8.S271
Class 2
Nuclear Weapons – History and Future Prospects

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Outline

Physics

Prelude to the Manhattan Project

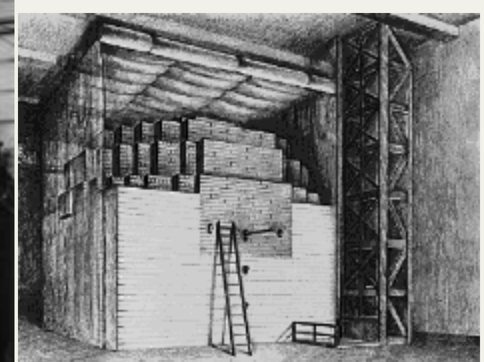
Nuclear weapon materials

Gun assembled weapons

Implosion weapons

Creation of the Manhattan Engineering District

- Decision to go forward with production of Plutonium and enriched Uranium led to the involvement of the Army Corps of Engineers
- Bush transferred process development, materials acquisition, engineering design, and site selection to the Army while retaining control of the university research for the OSRD.
  - Delicate negotiations for university control of research
  - Army officer in overall charge of project
- Summer-Fall of 1942
  - Initial Army organization based in New York City from which the new organization got its name
  - After several organizational collisions, Leslie Groves promoted to Brigadier General and made head of the Manhattan Project on September 17, 1942
  - In October Groves accepted the Oppenheimer suggestion of an isolated site for the laboratory
- Groves acted quickly to redirect the efforts even in ambiguity
  - By November 1942 Plutonium seemed the most promising approach but Uranium not abandoned
  - Centrifuge project canceled in favor of electromagnetic and gaseous diffusion enrichment
  - Oppenheimer selected to be the head of the bomb research and development laboratory to be built in Los Alamos, New Mexico and the production site at Clinton, Tennessee.



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Two Pathways to the Bomb Uranium and Plutonium

Physics

The Uranium Pathway – Major obstacle was U-235 Enrichment

Winter – Spring of 1942

- Urey worked on gaseous diffusion and centrifuge enrichment
- Lawrence concentrated on electromagnetic separation
- Abelson worked on liquid thermal diffusion
- Murphee worked on methods to industrialize the approaches
- Uranium ore needed for research
  - 1200 tons in storage on Staten Island
  - Uranium hexafluoride also needed for centrifuge and diffusion processes
  - Murphee arranged for DuPont and Harshaw to provide the industrial production
- Lawrence very successful at electromagnetic separation
- Bush reports to Roosevelt 3/9/1942 that Lawrence's work may make the bomb possible on a short time scale – by 1944
  - Also aided by new and smaller estimates of the critical mass
- Roosevelt told Bush – "The whole effort should be pushed – this is very much of the essence"

The Plutonium Pathway – Major obstacle was Reactor Prodcution

Winter – Spring of 1942

- No one knew about the spontaneous fission and neutron problem yet
- Compton consolidated fission research at the new Metallurgical Laboratory at the University of Chicago (MET Lab)
- Fermi still working at Columbia with plans to relocate to Chicago
- Theoretical work continued at Princeton and Berkeley
- Under the west grandstand at Stagg Field Allison began building the first reactor – graphite moderated Uranium
- Recent US calculations had cast doubt on MAUD report negative findings on Plutonium

May 23 1942

- Committee decides to go forward with all enrichment approaches for U-235 and the reactor production of Pu-239
- No clear path for selection at the time
- Too critical to war effort to down-select prematurely

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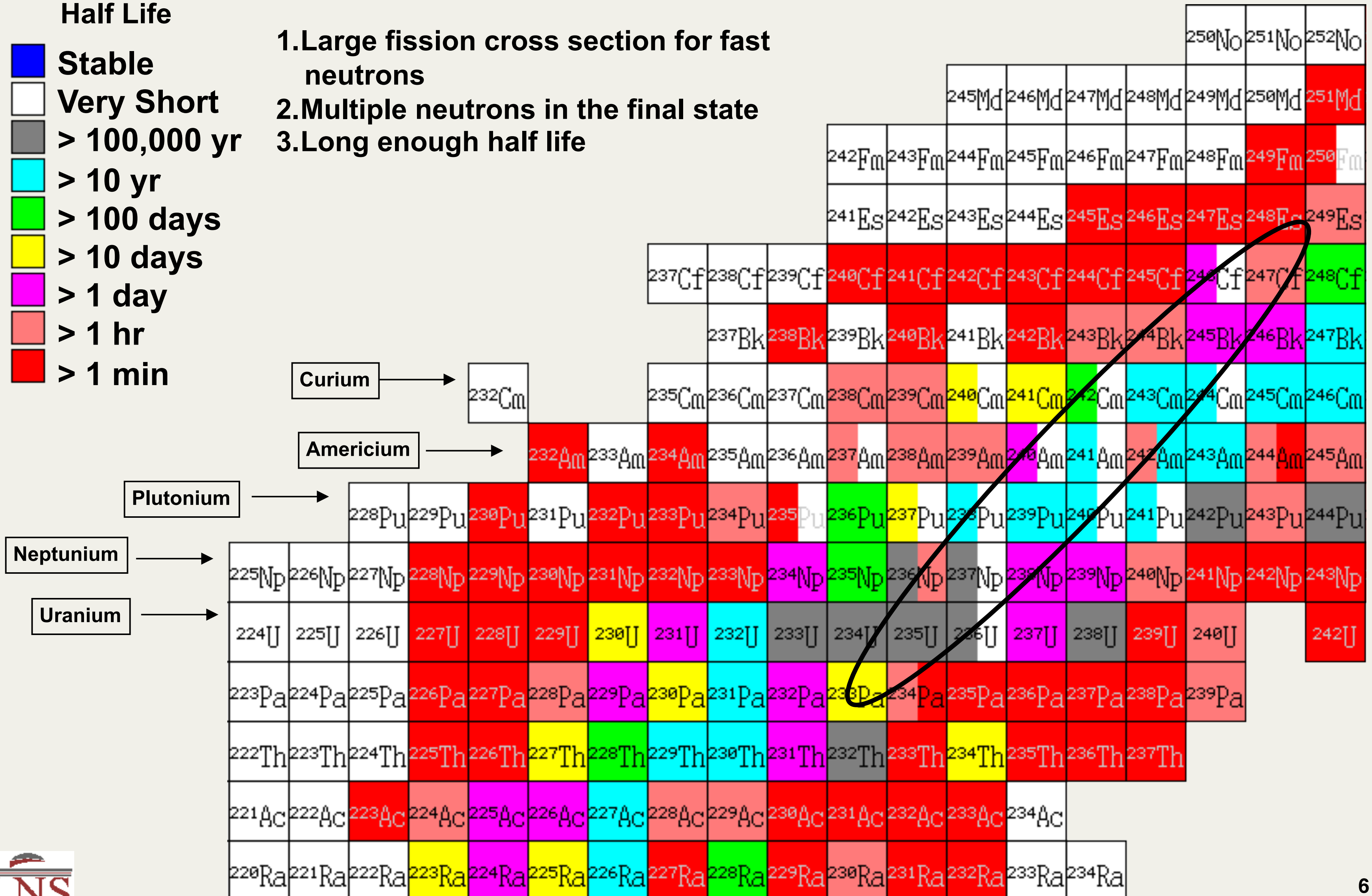
Corridor of Weaponizable Isotopes

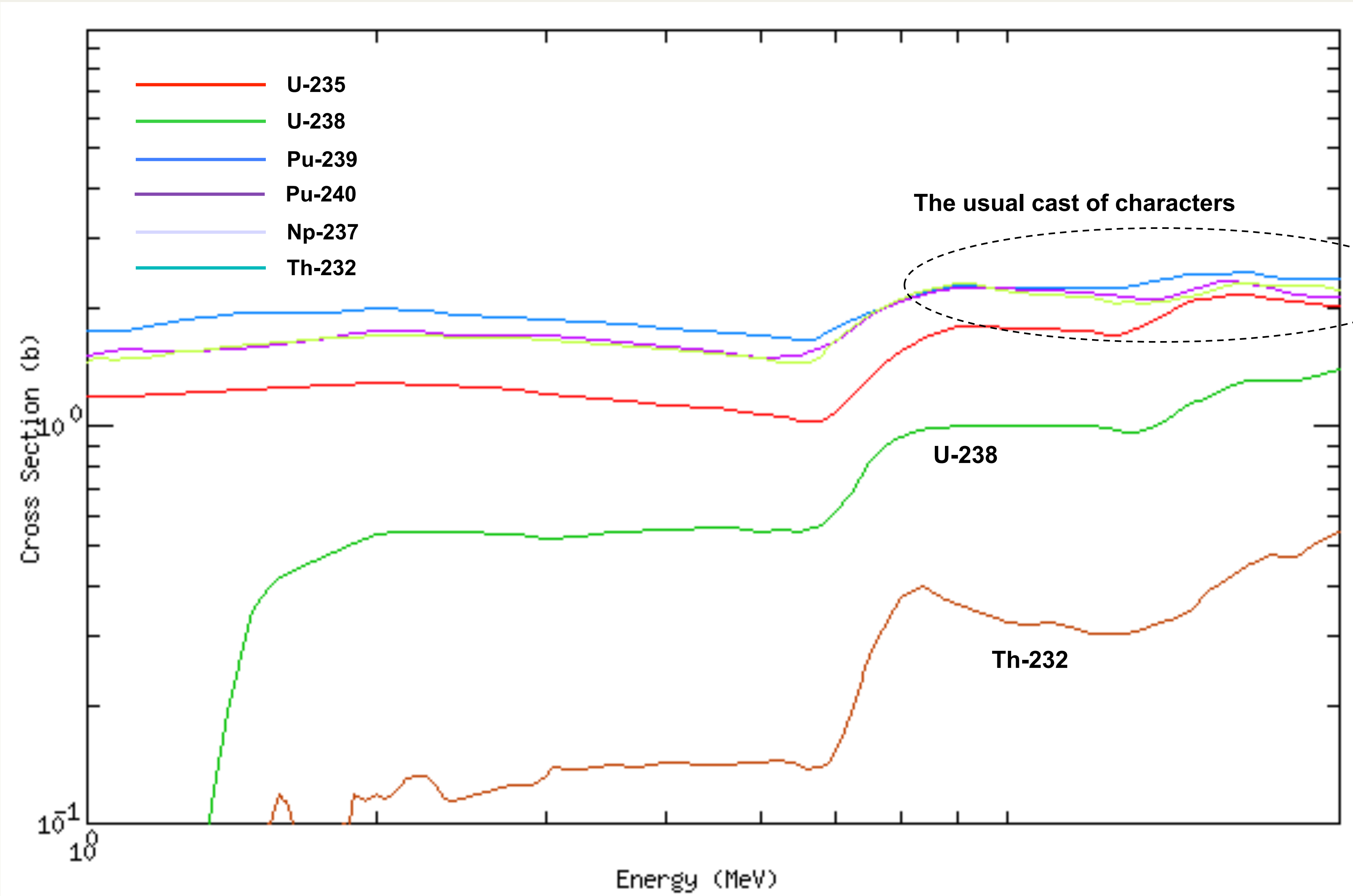
Half Life

- Stable
- Very Short
- > 100,000 yr
- > 10 yr
- > 100 days
- > 10 days
- > 1 day
- > 1 hr
- > 1 min

1. **Large fission cross section for fast neutrons**
2. **Multiple neutrons in the final state**
3. **Long enough half life**



Fission Cross Section Comparison



Multiple High Energy Neutrons After Fission

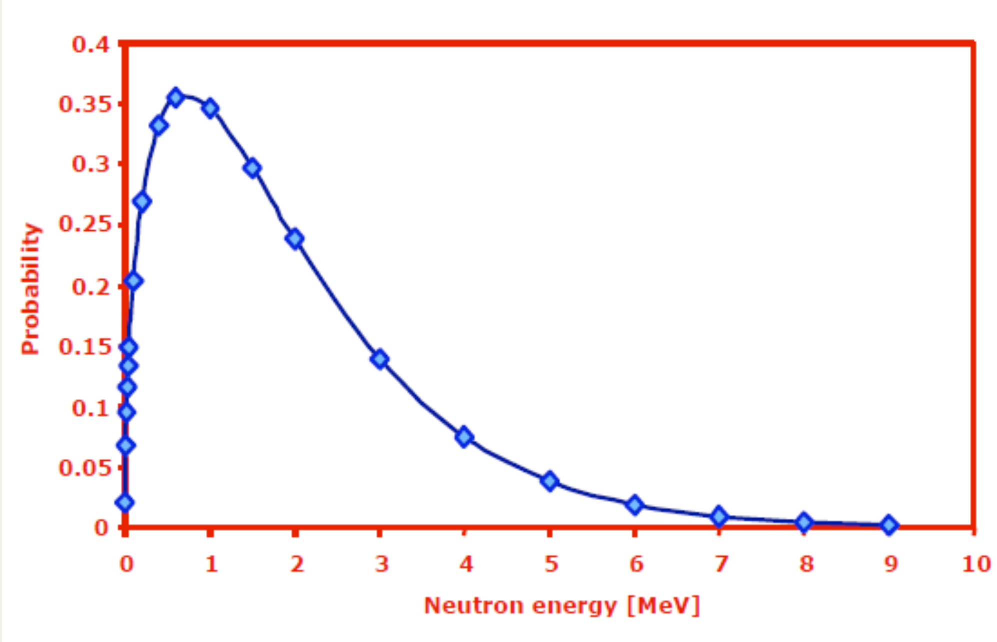
Physics

The Watt Spectrum

$$P(E) = 0.4865 \sinh\left(\sqrt{2E}\right) e^{-E} \text{ MeV}^{-1}$$

This is an *empirical* formula – it is just a convenient way of expressing the experimental distribution.

- The probability of a neutron from fission having an energy between *E and E+dE is the* function P(E)dE.
- In modern parlance the Watt Spectrum
- The distribution in the figure is for neutrons from the fission of 235U with a slow neutron
- *This was unknown in the 1930s or 1940s.*



From J. Watterson, CERN 2007

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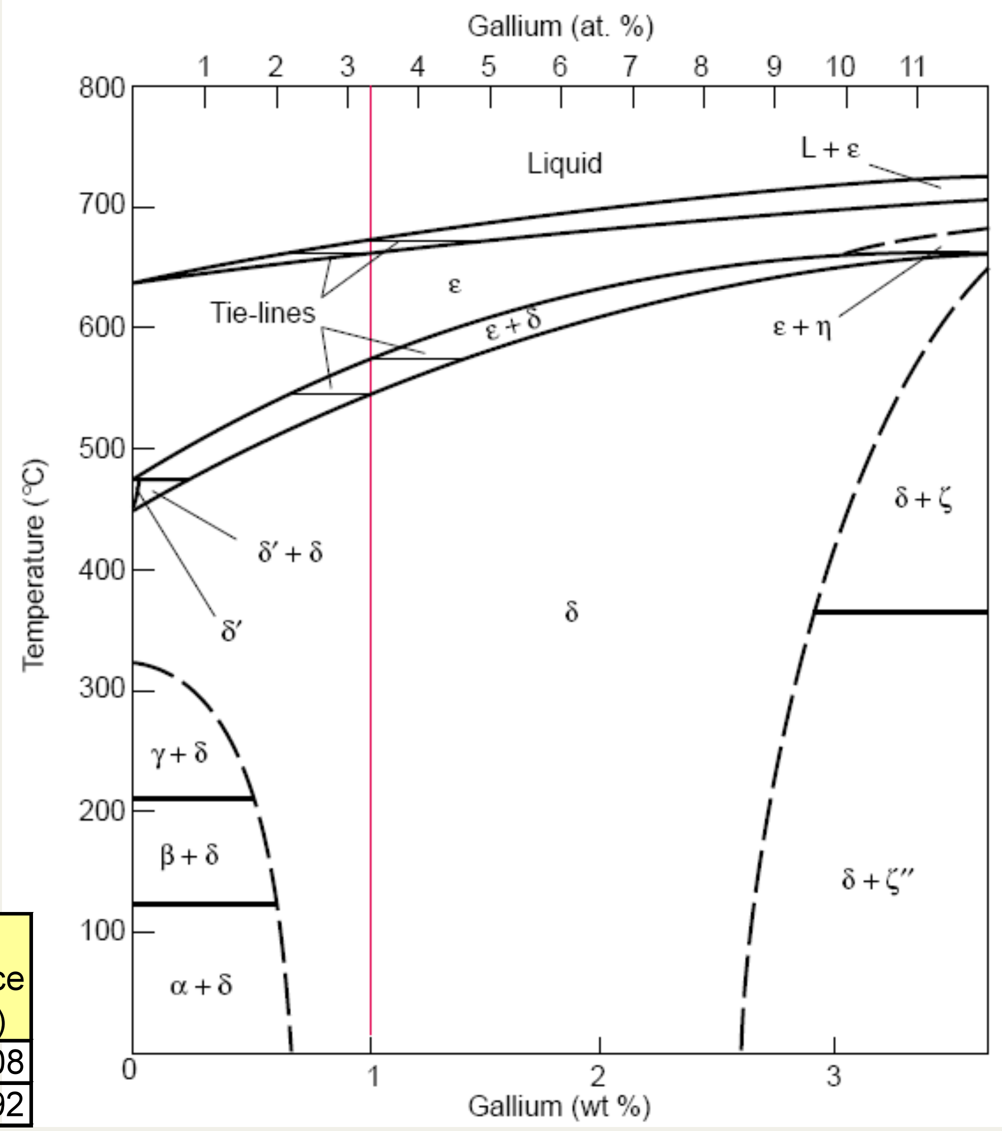
Stabilizing Plutonium in the Delta Phase

- **Plutonium pits are always stabilized in the delta-phase by alloying with Gallium.**
- **The delta phase is metallurgically like Aluminum whereas the alpha phase is like glass.**
- **Other trivalent atoms, like Aluminum, Cerium, Indium, or Scandium, but these other materials have either large (alpha,n) cross sections or do not make the alloy corrosion resistant.**
- **About 1% Gallium by weight is used in modern weapons.**
- **Gallium has 2 stable isotopes**

Isotope	Percent of Total Weight
Pu-238	0.005
Pu-239	92.367
Pu-240	5.940
Pu-241	0.436
Pu-242	0.015
Oxygen	0.238
Gallium	1.000

Isotope	Natural Abundance (percent)
Ga-69	60.108
Ga-71	39.892

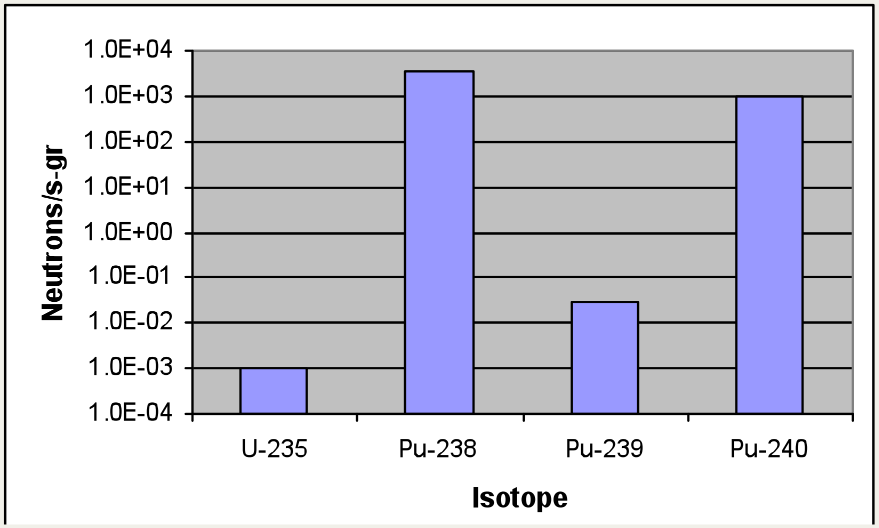


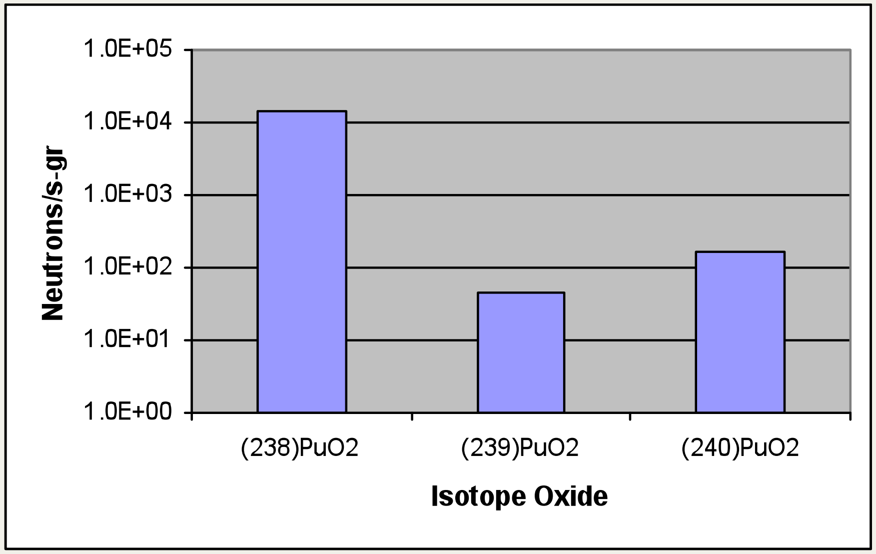
FOUO

Background Neutrons are a Problem Because of Predetonation Probability

Physics

- **Predetonation happens when the chain reaction is triggered before the device is fully assembled**
  - **Due to spontaneous fission neutrons**
  - **Due to (alpha,n) reactions with Oxygen**
  - **This is called a fizzle**
- **The rate of neutron emissions is plotted in adjoining graphs for various isotopes (top) and oxides (bottom)**
- **For U-235 this rate is very small**
- **For Pu-240 and Pu-238 the rate is very high**
- **Keeping the Plutonium metal free of oxides suppresses the (alpha,n) reactions**





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Basic Requirements Fulfilled

Physics

1. Large fission cross section for fast neutrons
   - Check
2. Multiple high energy neutrons in the final state
   - Check
3. Long enough half life
   - Check

Materials available in significant enough quantities?

With some effort

→ ***Nuclear Weapons Possible***

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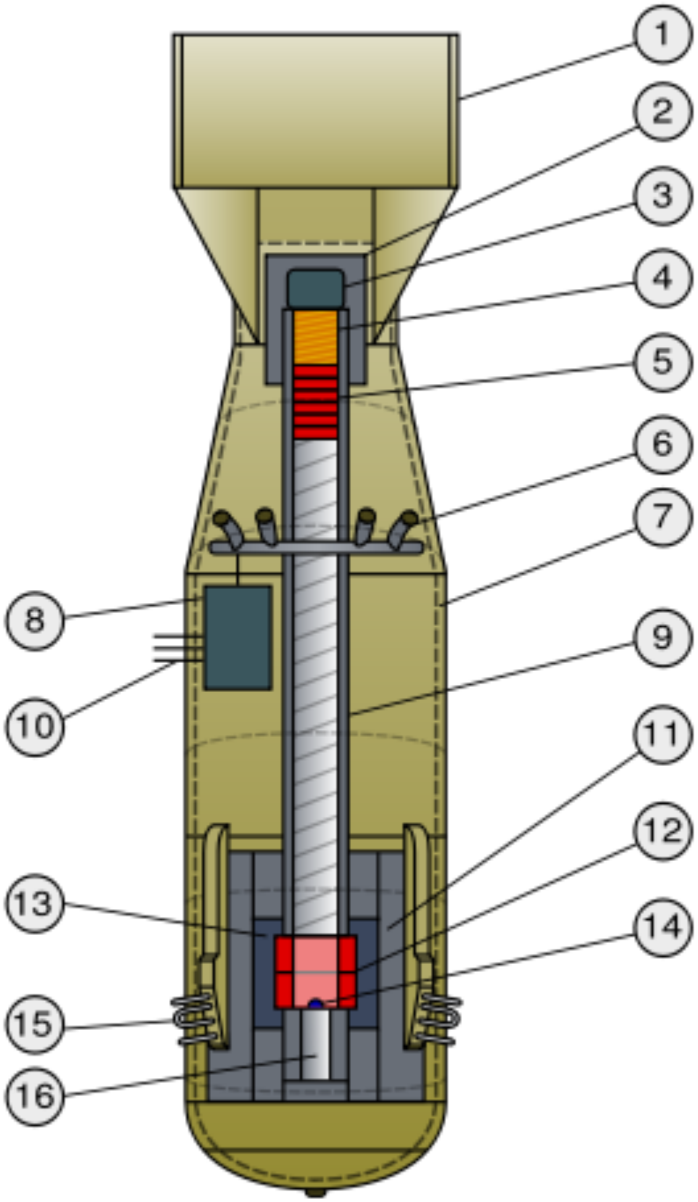
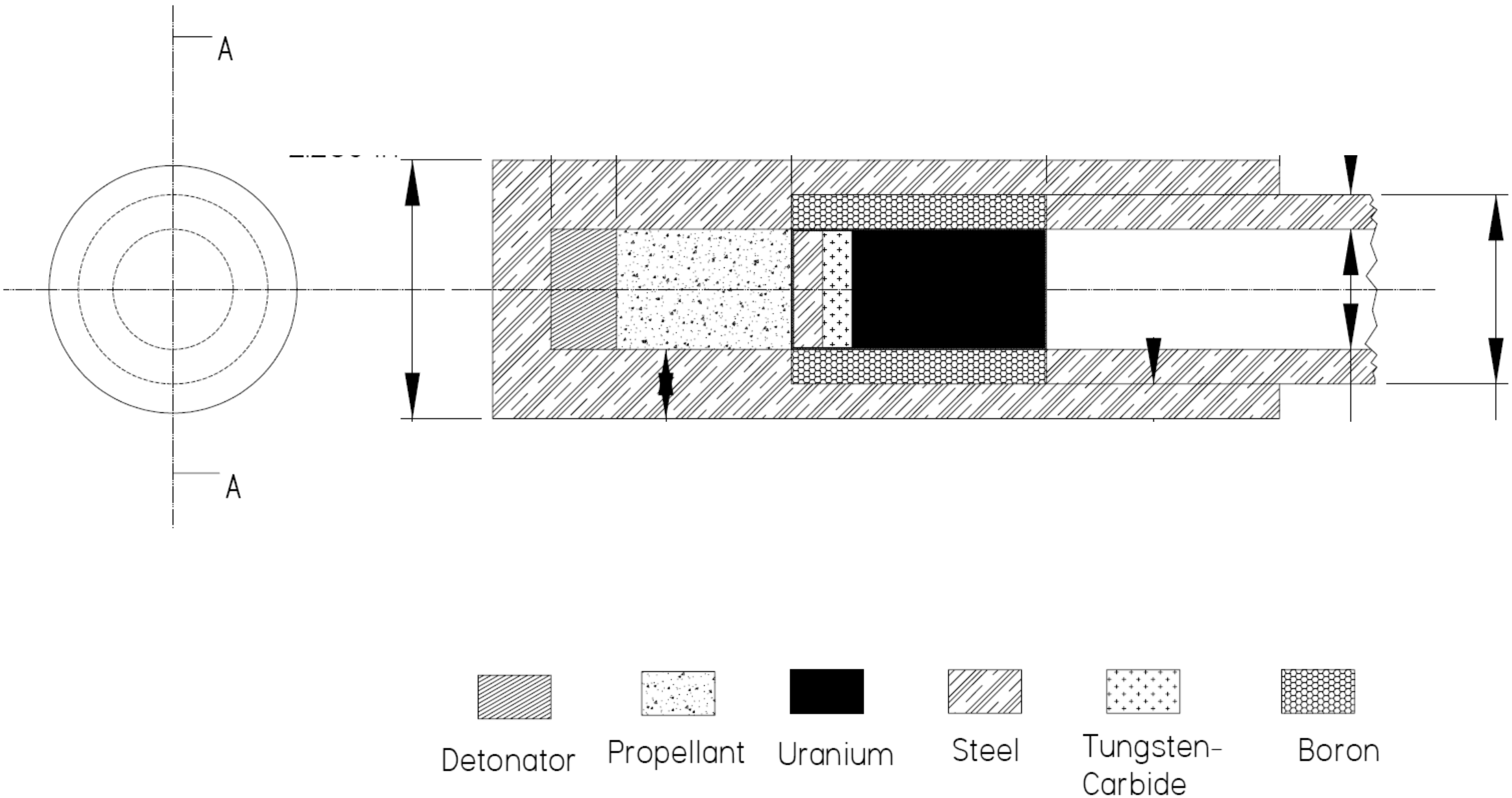
Common illustration of Hiroshima Weapon

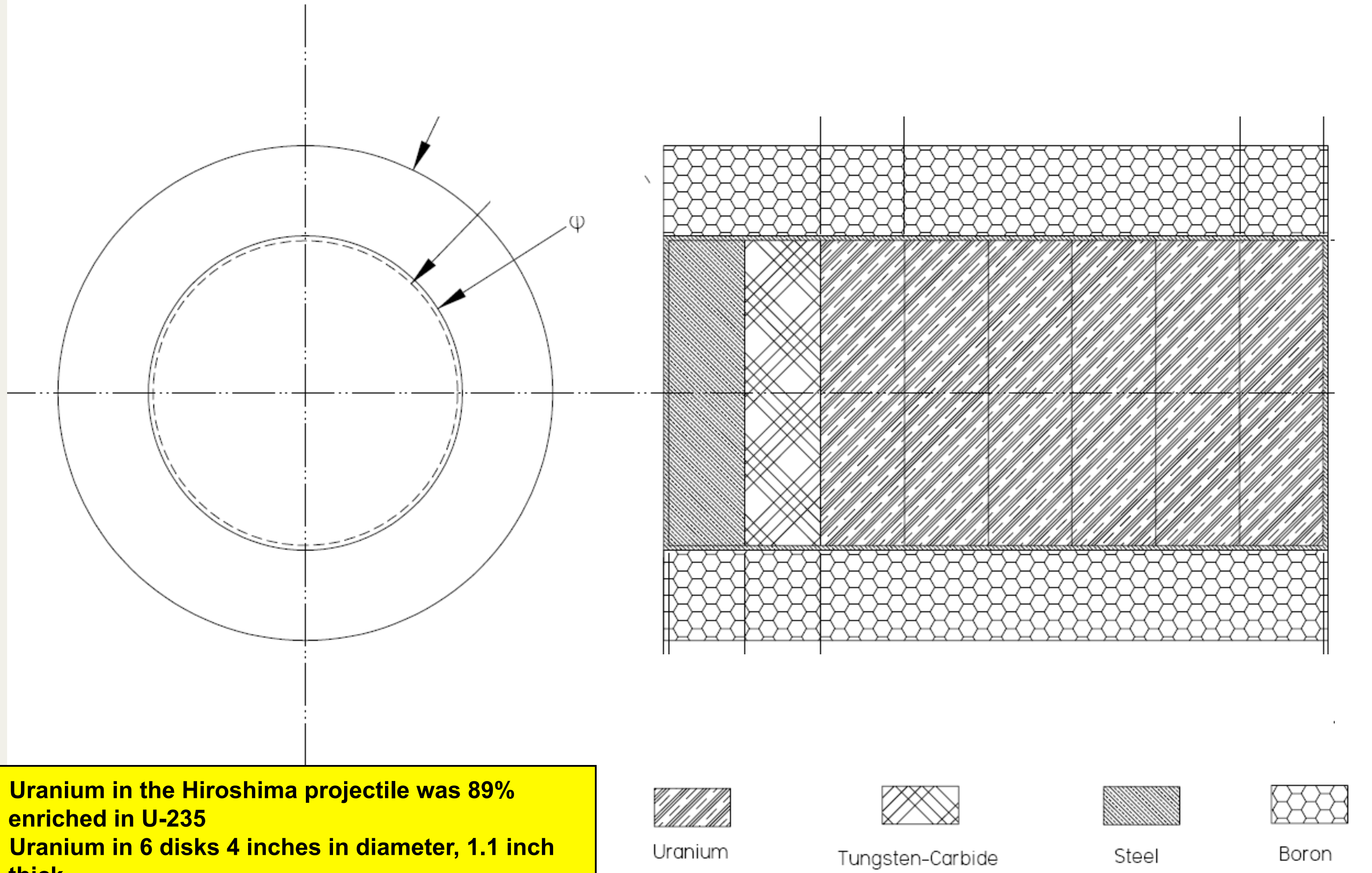


1. Box tail fins
2. Steel gun breech assembly
3. Detonator
4. Cordite (conventional) explosives
5. Uranium-235 "projectile", six rings (26 kg) in a thin can of steel
6. Baro sensing ports and manifold
7. Bomb casing wall
8. Arming and fusing equipment
9. Gun barrel, steel, around 10 cm diameter, 200 cm length
10. Arming wires
11. Tamper assembly, steel
12. Uranium-235 "target", two rings (38 kg)
13. Tamper/reflector assembly, tungsten carbide
14. Neutron initiator
15. *Archie* fuzing radar antennas
16. Recess for the boron safety plug (not shown) to be ejected into

Breech Assembly for Hiroshima-Style Gun-Assembled Weapon



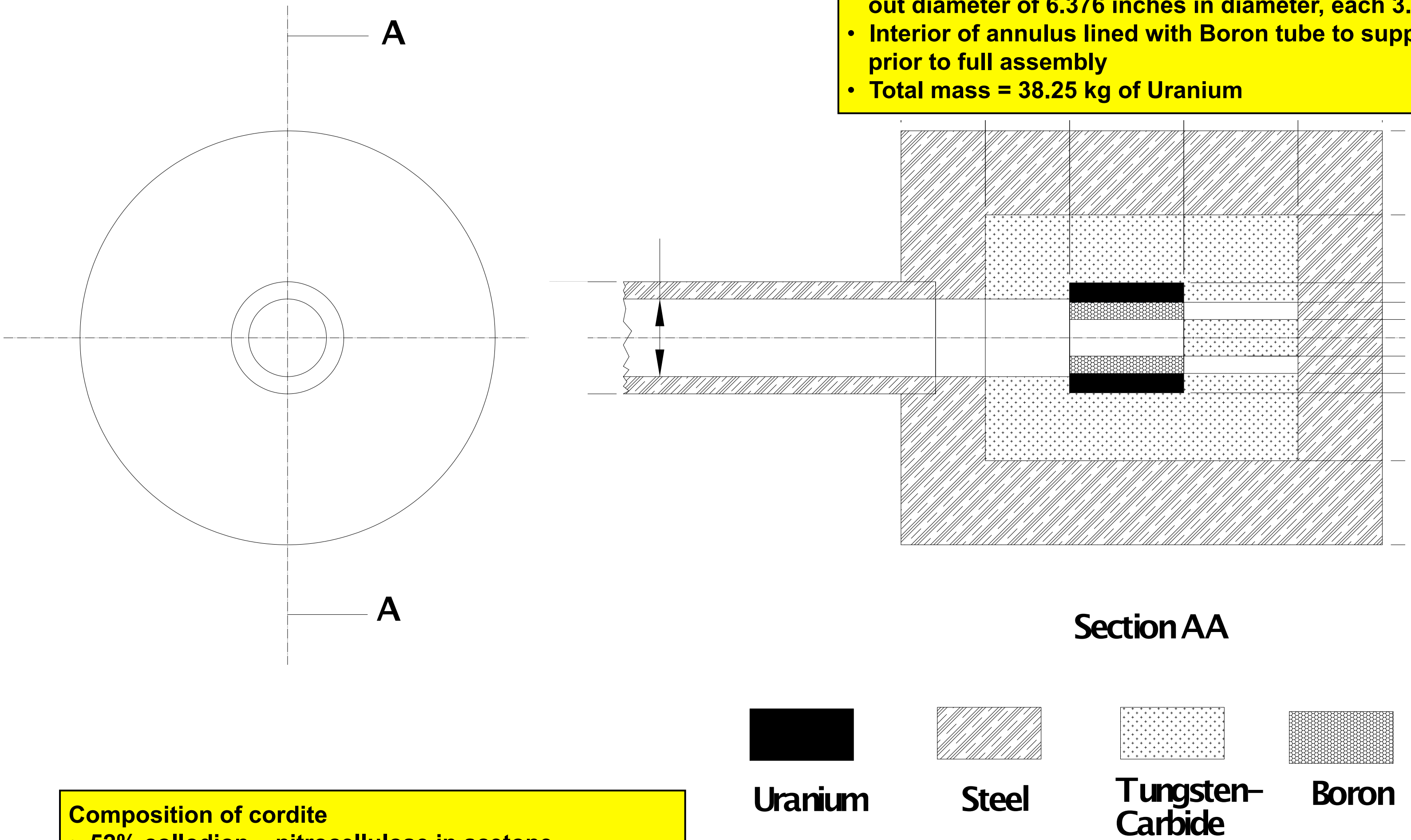
Projectile for Hiroshima-Style Gun-Assembled Weapon



- Uranium in the Hiroshima projectile was 89% enriched in U-235
- Uranium in 6 disks 4 inches in diameter, 1.1 inch thick
- Outside of projectile sheathed with Boron to suppress neutrons prior to assembly
- Total mass = 25.9 kg of Uranium

Target-Tamper Assembly for Hiroshima-Style Gun-Assembled Weapon

- Uranium in the Hiroshima Target was 75% enriched in U-235
- Uranium in 2 annuli with an inner diameter of 4.125 inch and an out diameter of 6.376 inches in diameter, each 3.3 inch thick
- Interior of annulus lined with Boron tube to suppress neutrons prior to full assembly
- Total mass = 38.25 kg of Uranium



Composition of cordite
- 52% collodion – nitrocellulose in acetone
- 42% nitroglycernine
- 6% petroleum jelly
- Often includes nitroguanadine in equal proportions

Little Boy

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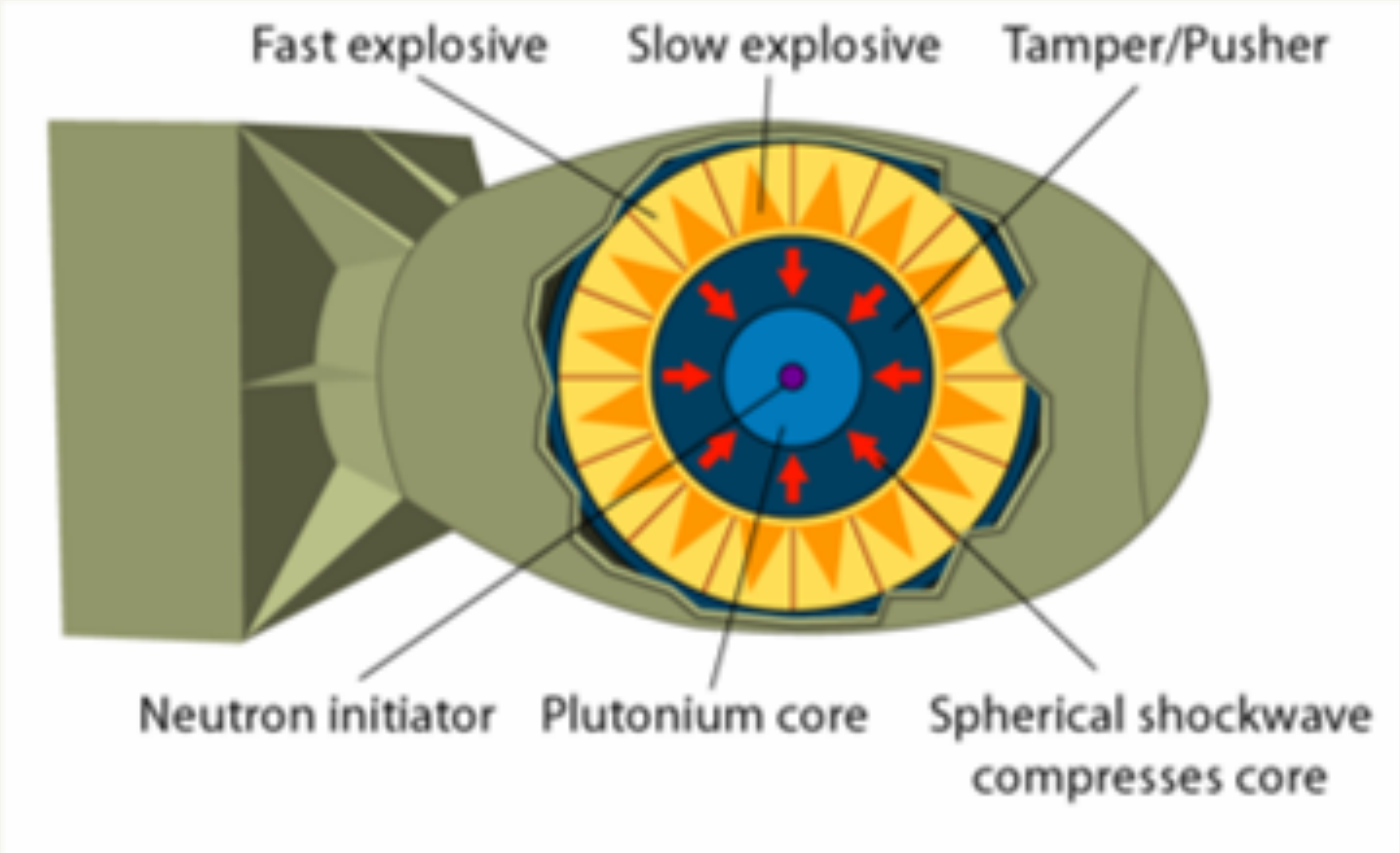
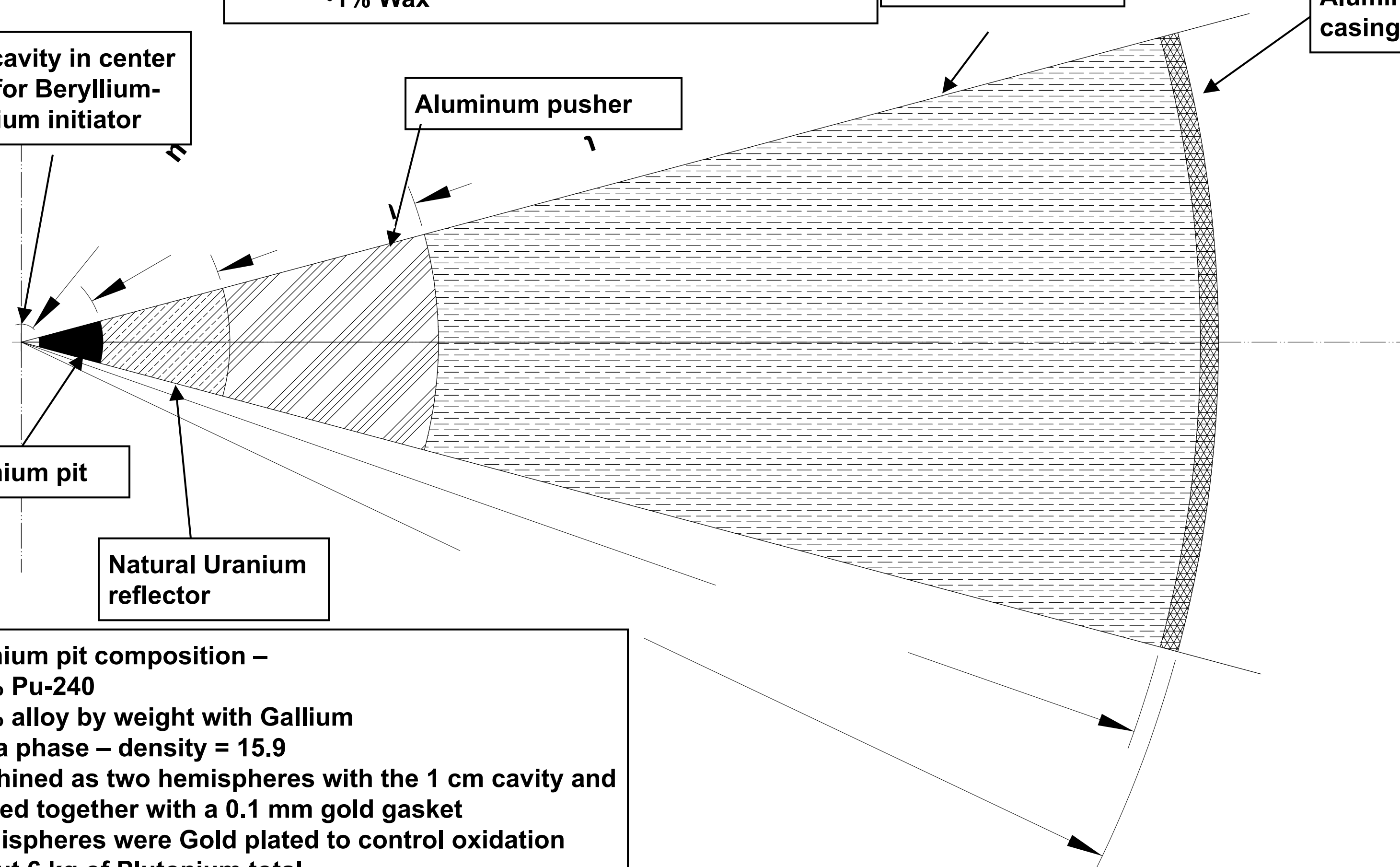
Common Illustration of an Implosion Weapon



Cross Section of Nagasaki-Style Implosion Weapon

Composition of explosive lens system –
- **Fast explosive**
  - **60% RDX**
  - **39% TNT**
  - **1% Wax**
- **Slow explosive**
  - **60% Barium nitrate**
  - **39% TNT**
  - **1% Wax**



Plutonium pit composition –
- **0.9% Pu-240**
- **0.8% alloy by weight with Gallium**
- **Delta phase – density = 15.9**
- **Machined as two hemispheres with the 1 cm cavity and brazed together with a 0.1 mm gold gasket**
- **Hemispheres were Gold plated to control oxidation**
- **About 6 kg of Plutonium total**

Fat Man

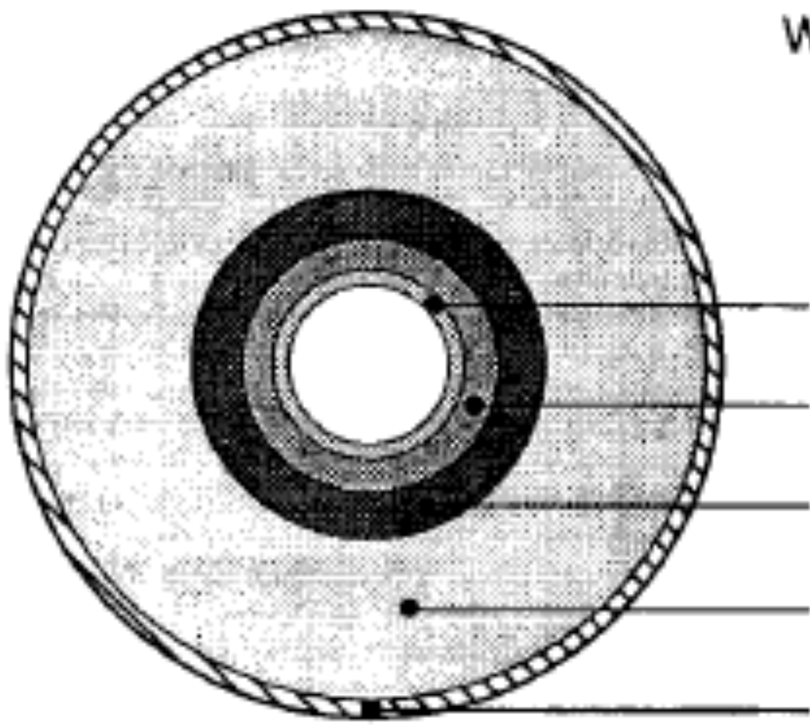
Note that modern weapons are designed differently than these early ones

Typical Modern Implosion Weapon Design

Core

WgU: 12 kilograms
1.23 centimeters thick
7 centimeters outside radius

WgPu: 4 kilograms
5 centimeters outside radius
0.75 centimeters thick



Early Thoughts on Fusion

- Fusion reactions well known to nuclear community by the 1920s
  - Very high energy-temperatures needed for reaction to proceed
- Work on Hydrogen fusion as the source of the Sun's energy
  - Culminated in Hans Bethe publication in Physical Review in 1939
  - Bethe was head of the Theory Division at Los Alamos during the Manhattan program
  - Nobel Prize in Physics in 1967
- With discovery of nuclear fission explosions the idea of igniting a fusion reaction may be possible
  - In September of 1941 Fermi suggested to Teller this possibility
  - Teller concluded at this point it was not possible but started his obsession with fusion weapons
- During Manhattan project there was a "Super" explosion effort
  - Many twists and turns as fission reactions became better understood
- By May of 1944 Teller removed from Theory Division and set in small group to concentrate on fusion weapons
  - Too much interference with fission work

- At end of WWII Los Alamos scientific experts departed – for the most part
- April 1946 Teller has a conference on the status of the Super
  - Resulted that idea could be sound but more detailed calculations needed
  - Klaus Fuchs attended this conference

Los Alamos ID badge photo

Questions

がひくしこふへやし
Схеуфйпоу?
Questions?
美友天迎由喜行新迎会
QUESTIONS?
QUESTIONS?
Θυεστιονσ?
QUESTIONS?
QUESTIONS?
Questions?

Class Discussion

- What did you learn from the Los Alamos Primer?
- What is a Gadget?
- What do the numbers 25, 28, and 49 mean?
- What does the word fish signify?

- Why were code words used?

- Did you read The Making of the Atomic Bomb, by Richard Rhodes?
  - What did you learn?

Reading Assignment for Next Class

Physics

•Racing for the Bomb: General Leslie R. Groves, the Manhattan Project's Indispensable Man - Robert S. Norris (Author)

•The Manhattan Project: A Documentary Introduction to the Atomic Age ---- Michael B. Stoff , Jonathan F. Fanton --- R. Hal Williams (Editor)

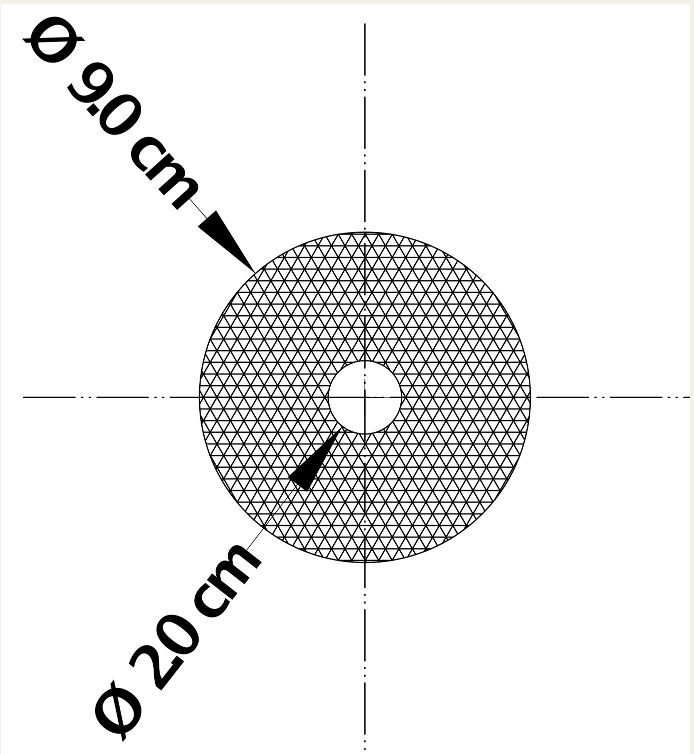
First Writing Assignment

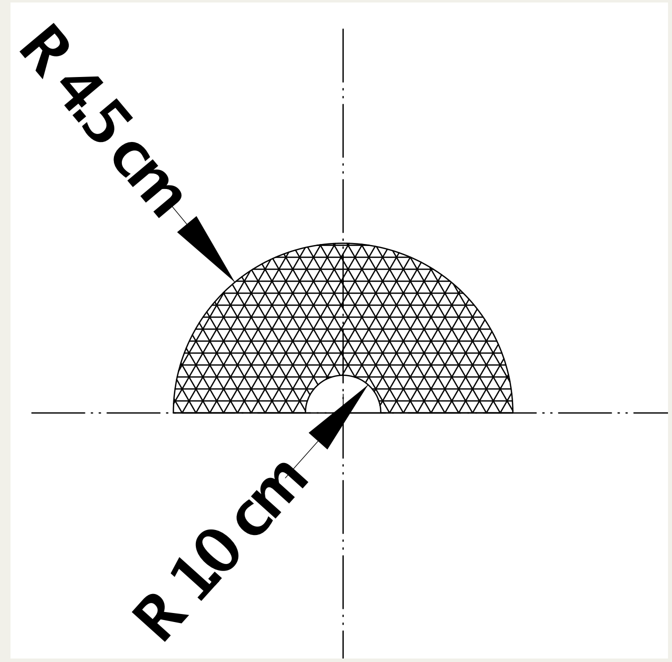
- How much did the development and testing program cost?
- Was it worth it?

- Aim for roughly 5-10 pages
- Due after 3rd Class -- February 18

BACKUP SLIDES

Cross Section of the Plutonium Pit of a Nagasaki-Style Implosion Weapon





Plutonium pit composition –

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- **0.8% alloy by weight with Gallium**
- **Delta phase – density = 15.9**
- **Machined as two hemispheres with the 1 cm cavity and brazed together with a 0.1 mm gold gasket**
- **Hemispheres were Gold plated to control oxidation**
- **About 6 kg of Plutonium total**

Modern Day Definition of WGPu

Physics

Weapon Grade Plutonium

Isotope	Percent of Total Weight
Pu-238	0.005
Pu-239	93.300
Pu-240	6.000
Pu-241	0.440
Pu-242	0.015
Oxygen	0.240

The Oxygen content is adjusted to give the measured (alpha,n) spectra.

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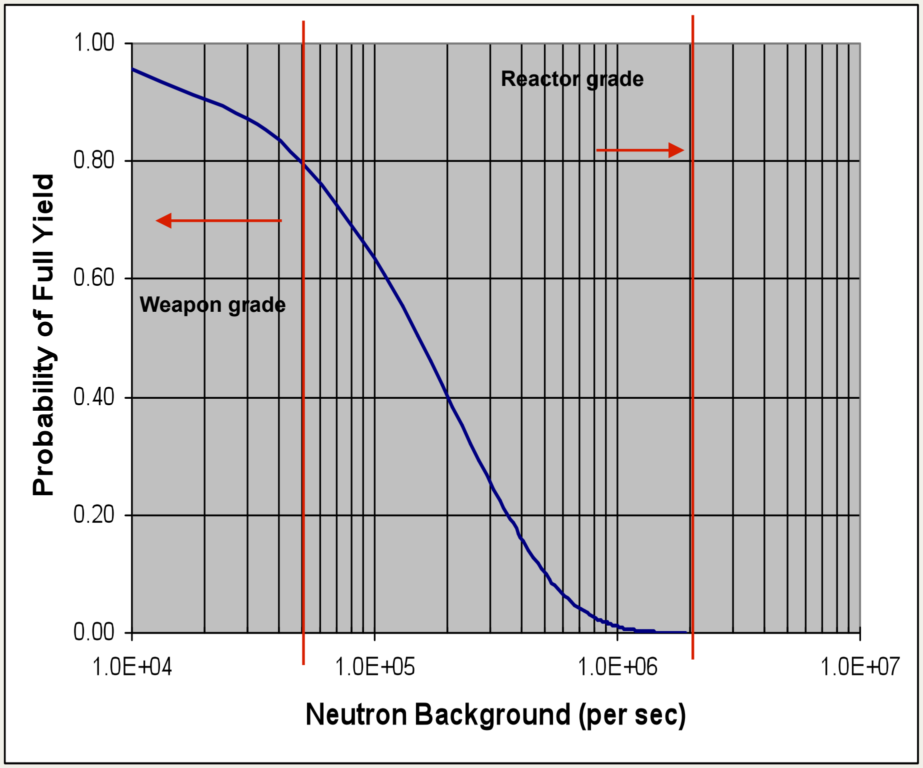
Fizzle Yields can be Substantial

Physics

- **Fizzles happen when the neutron background triggers the chain reaction before the assembly is complete**
  - **Only a problem for Plutonium**
  - **All Pu weapons have a chance for a Fizzle**

- **For a Plutonium implosion weapon can use LANL model to estimate probabilities and yields**
  - **45 generations of neutrons, time for supercriticality, and time between generations are assumed values**
  - **Graph shows probability of full yield versus background**



- **Every Pu implosion weapon has a minimum yield regardless of Pu grade.**
  - **What changes with grade is the likelihood it will perform at the minimum yield**
  - **In LANL model $Y_{min} = 0.027Y_0$ where Y_0 is the design yield**
  - **For a 20Kt design Y_{min} = 540 tons**
  - **This is 54 times bigger than a MOAB**

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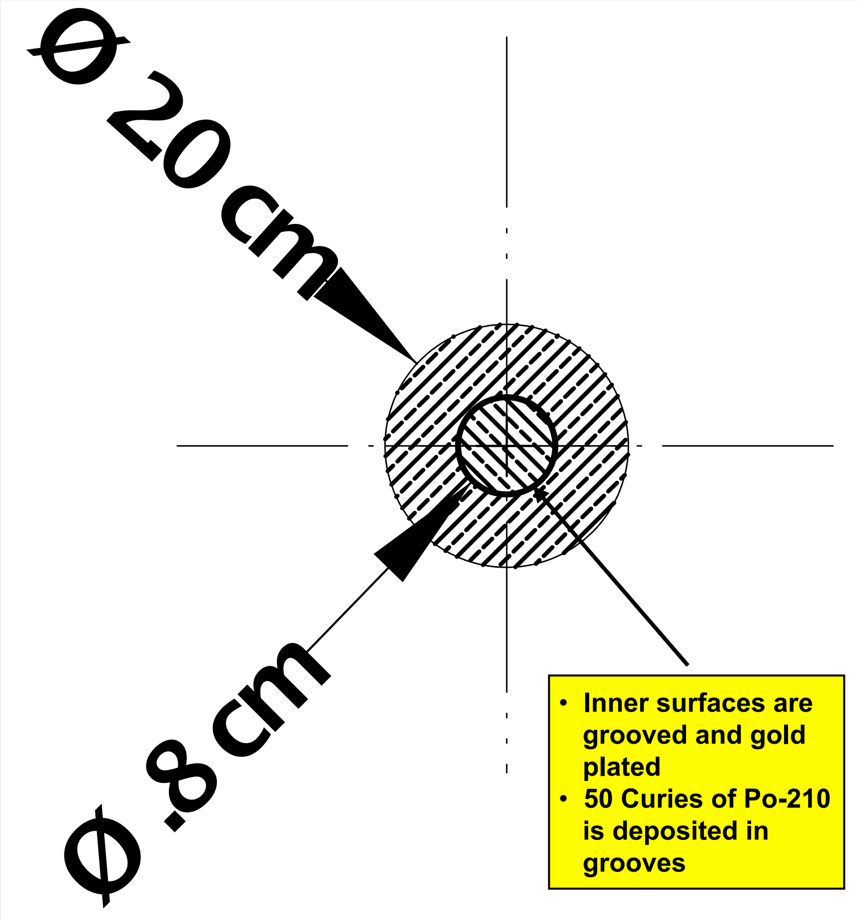
Cross Section of the Neutron Initiator of a Nagasaki-Style Implosion Weapon

- About 7.5 grams of Beryllium
- An outer shell of Beryllium 2 cm in diameter with a wall thickness of 0.6 cm
- An inner sold sphere of Beryllium 0.8 cm in diameter
- Hemispheres are cast and machined to these dimensions
- The inner surface of the shell is grooved
- The inner surfaces of the shell and the outer surface of the sphere is gold plated to about 0.1mm thickness
- About 50 Curies of Po-210 is deposited on the inner grooved surfaces of the shell
- The assembly is brazed together.



The First Soviet Nuclear Test

- Stalin informed of US and British work on fission
- April 1942 – letter from G. Flerov pointing out no publication by western scientists on fission research since discovery in 1939
- Initial head of project was V. Molotov replaced soon by I. Kurchatov
  - Other physicists involved – Khariton, Zeldovich, and Sakharov
- Program benefited strongly from espionage
  - Klaus Fuchs
  - Basic knowledge of critical masses
  - Choice of Pu weapon over U weapon due to ease of separation technology.
  - Shortened development time enormously
- August 29, 1949 – first Soviet test
  - “First Lightning” – 7:00 local time
  - Semipalatinsk, Kazakhstan
  - 22 kT
- Nickname by US – Joe 1 – after Stalin
- Similar design to Fat Man –
  - Tiled implosion weapon
  - Plutonium fueled
  - After Joe-1 Soviets more interested in arms control agreements
- February 3, 1950 – Klaus Fuchs arrested in Britain
  - Harry Gold, David Greenglass arrested in US
  - Julius and Ethel Rosenberg Arrested

Andrei Sakharov and Igor Kurchatov

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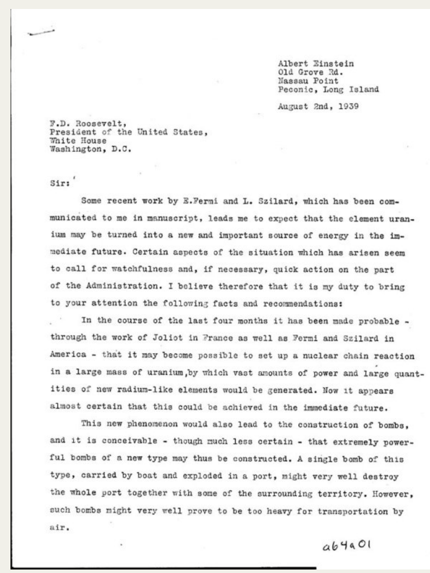
Einstein's Letter 8/2/1939

- **Leo Szilard meets with Einstein and helps draft a letter to Roosevelt urging rapid work into Uranium chain reaction research as it was probable these reactions could release very large amounts of energy**
- **Einstein believed the German government was pursuing this line of research and the US should too**
- **Alexander Sachs meets with Roosevelt 10/11/1939 to discuss –**
  - **Two months after receiving letter**
  - **Preoccupied with events in Europe**
  - **Initially at meeting Roosevelt noncommittal**
  - **The next day discussions launched Roosevelt into action**
- **Roosevelt writes back to Einstein that he has set up a committee to study the issue10/19/1939**
  - **Roosevelt now convinced the US could not take the risk that Nazi Germany would have such a weapon**



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

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 quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

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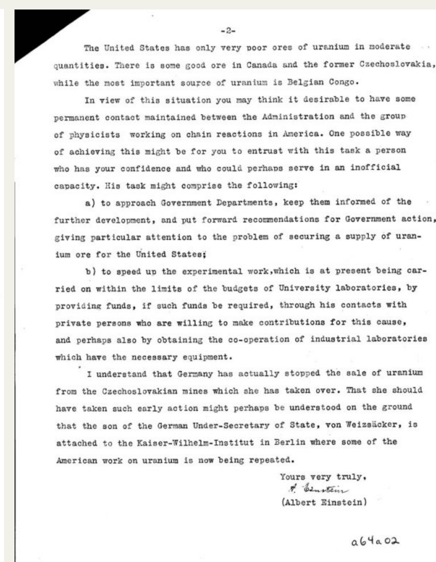

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The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

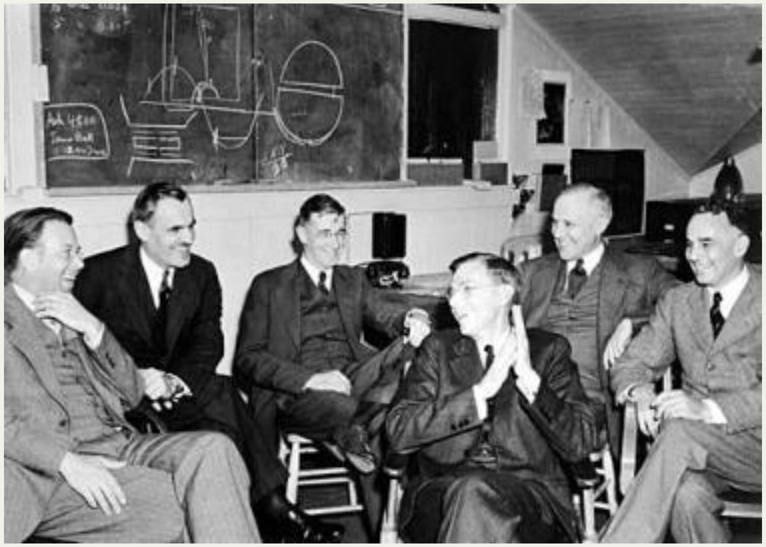
I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,
A. Einstein
(Albert Einstein)

a64a02

The Organization of Science

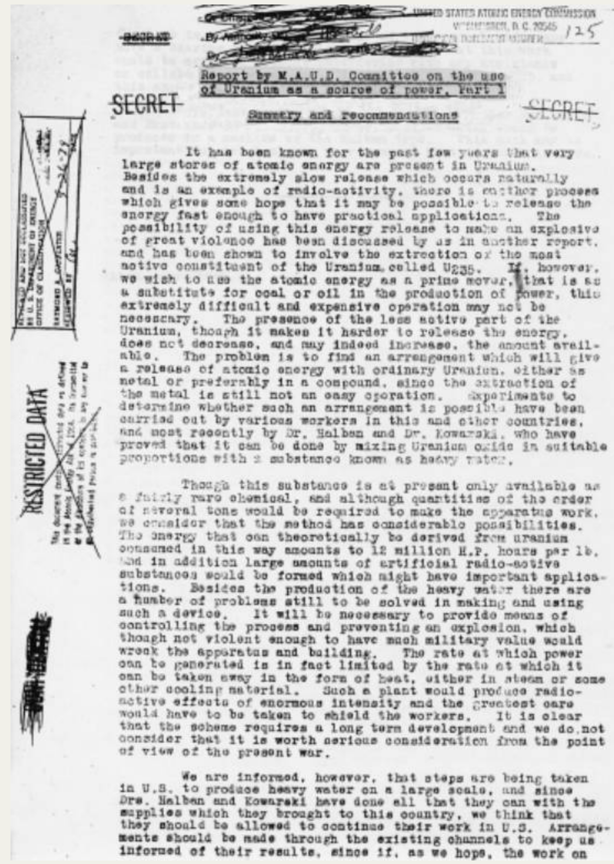
- Restriction of publications
  - Radical step for US scientists
  - Effort led by Szilard, Wigner, Teller, Weisskopf, Fermi
  - Voluntary agreement – NRC G. Breit proposes "Censorship committee"
- Roosevelt appoints Lyman Briggs, head of NBS, to chair the Uranium Committee
  - Uranium committee meets for first time, 10/21/1939
  - Civilian and military representatives
  - First report discusses nuclear power and bombs and first request for funds - $6,000
  - Second report eclipsed by events – U-235 is the primary fissioning isotope after finding a large effort at Kaiser Wilhelm Institute
  - Columbia results on Carbon as a moderator
- Too many small efforts
  - Better organization and broader scope of effort needed
- Roosevelt approves formation of National Defense Research Council in June of 1940 at urging of Vannevar Bush
- Roosevelt transfers Uranium Committee to NDRC under Vannevar Bush in fall of 1940
  - Bush reorganizes without military direct membership
  - Enrichment was main focus
- All reports very skeptical of development of a bomb before 1946 or later
- Recognized a bomb needed fissioning from fast neutrons not thermal ones.
- Suggested that a Plutonium bomb may be quicker pathway to a weapon



Meeting in the Radiation Laboratory at the University of California, Berkeley (UCB) in March 1940 to discuss the 184-inch cyclotron. Left to right: Ernest O. Lawrence, Arthur H. Compton, Vannevar Bush, James B. Conant, Karl T. Compton, and Alfred Loomis.

The MAUD Report - Good News from the Brits

- July 1941 – Bush receives MAUD report from Brits
- Reported that a sufficiently purified mass of U-235 could support a chain reaction by fast neutrons
    - Critical mass estimated to be 10 kilograms
    - Bomb is possible with this amount of material
- Report had plans for a bomb drawn up by the Brits
- Report also dismissed
    - Plutonium weapon option
    - Enrichment by thermal diffusion, electromagnetic, and centrifuge
    - Supported enrichment by gaseous diffusion
- MAUD also reported progress by Nazi Germany in this area
- MAUD also was the vehicle alerting Soviet intelligence to Anglo-American discussions on this topic
- Bush and Conant began redirection of the efforts
    - Enrico Fermi added as head of theory efforts
    - Harold Urey added as head of isotope separation and heavy water research



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Report by M.A.U.D. Committee on the use of Uranium as a source of power, Part I

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Summary and recommendations

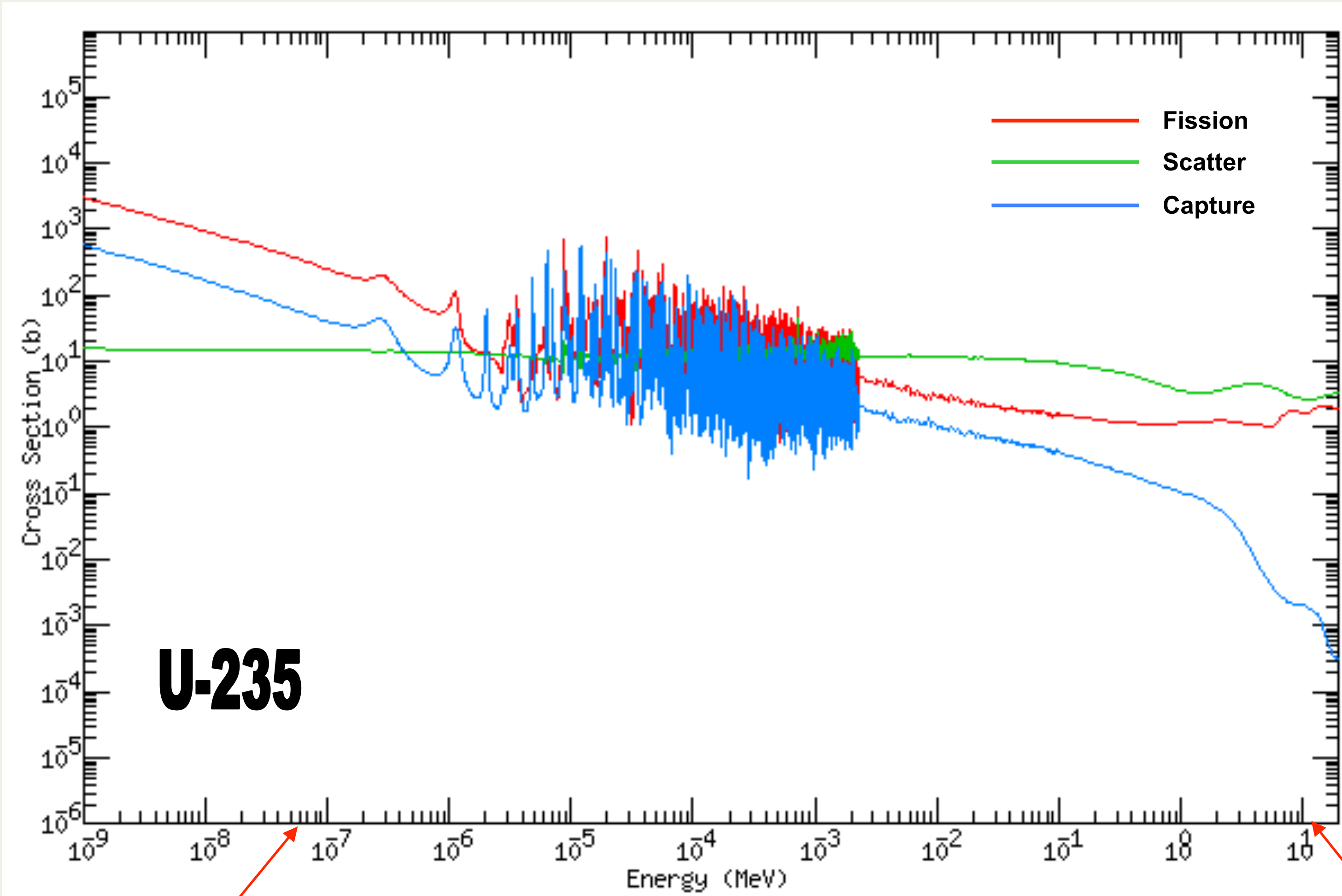
It has been known for the past few years that very large stores of atomic energy are present in Uranium. Besides the extremely slow release which occurs naturally and is an example of radio-activity, there is another process which gives some hope that it may be possible to release the energy fast enough to have practical applications. The possibility of using this energy release to make an explosive of great violence has been discussed by us in another report, and has been shown to involve the extraction of the most active constituent of the Uranium, called U_{235}. If, however, we wish to use the atomic energy as a prime mover, that is as a substitute for coal or oil in the production of power, this extremely difficult and expensive operation may not be necessary. The presence of the less active part of the Uranium, though it makes it harder to release the energy, does not decrease, and may indeed increase, the amount available. The problem is to find an arrangement which will give a release of atomic energy with ordinary Uranium, either as metal or preferably in a compound, since the extraction of the metal is still not an easy operation. Experiments to determine whether such an arrangement is possible have been carried out by various workers in this and other countries, and most recently by Dr. Halban and Dr. Kowarski, who have proved that it can be done by mixing Uranium oxide in suitable proportions with a substance known as heavy water.

Though this substance is at present only available as a fairly rare chemical, and although quantities of the order of several tons would be required to make the apparatus work, we consider that the method has considerable possibilities. The energy that can theoretically be derived from uranium consumed in this way amounts to 12 million H.P. hours per lb. and in addition large amounts of artificial radio-active substances would be formed which might have important applications. Besides the production of the heavy water there are a number of problems still to be solved in making and using such a device. It will be necessary to provide means of controlling the process and preventing an explosion, which though not violent enough to have much military value would wreck the apparatus and building. The rate at which power can be generated is in fact limited by the rate at which it can be taken away in the form of heat, either in steam or some other cooling material. Such a plant would produce radio-active effects of enormous intensity and the greatest care would have to be taken to shield the workers. It is clear that the scheme requires a long term development and we do not consider that it is worth serious consideration from the point of view of the present war.

We are informed, however, that steps are being taken in U.S. to produce heavy water on a large scale, and since Drs. Halban and Kowarski have done all that they can with the supplies which they brought to this country, we think that they should be allowed to continue their work in U.S. Arrangements should be made through the existing channels to keep us informed of their results, since if, as we hope, the work on

MAUD is a code name not a acronym – turns out to be the governess for Bohr's children

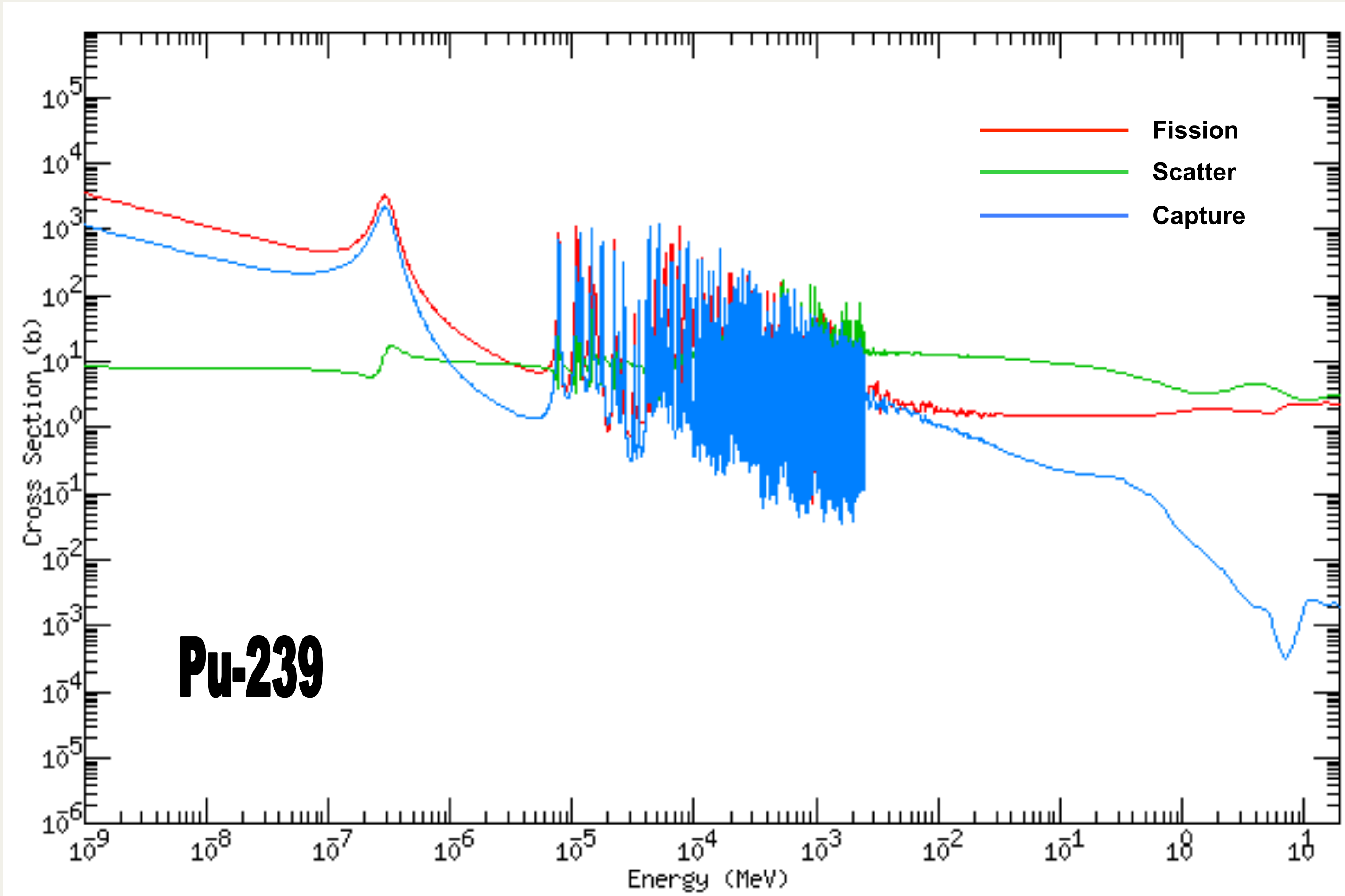
U-235 Cross Sections



Speed of sound in Uranium

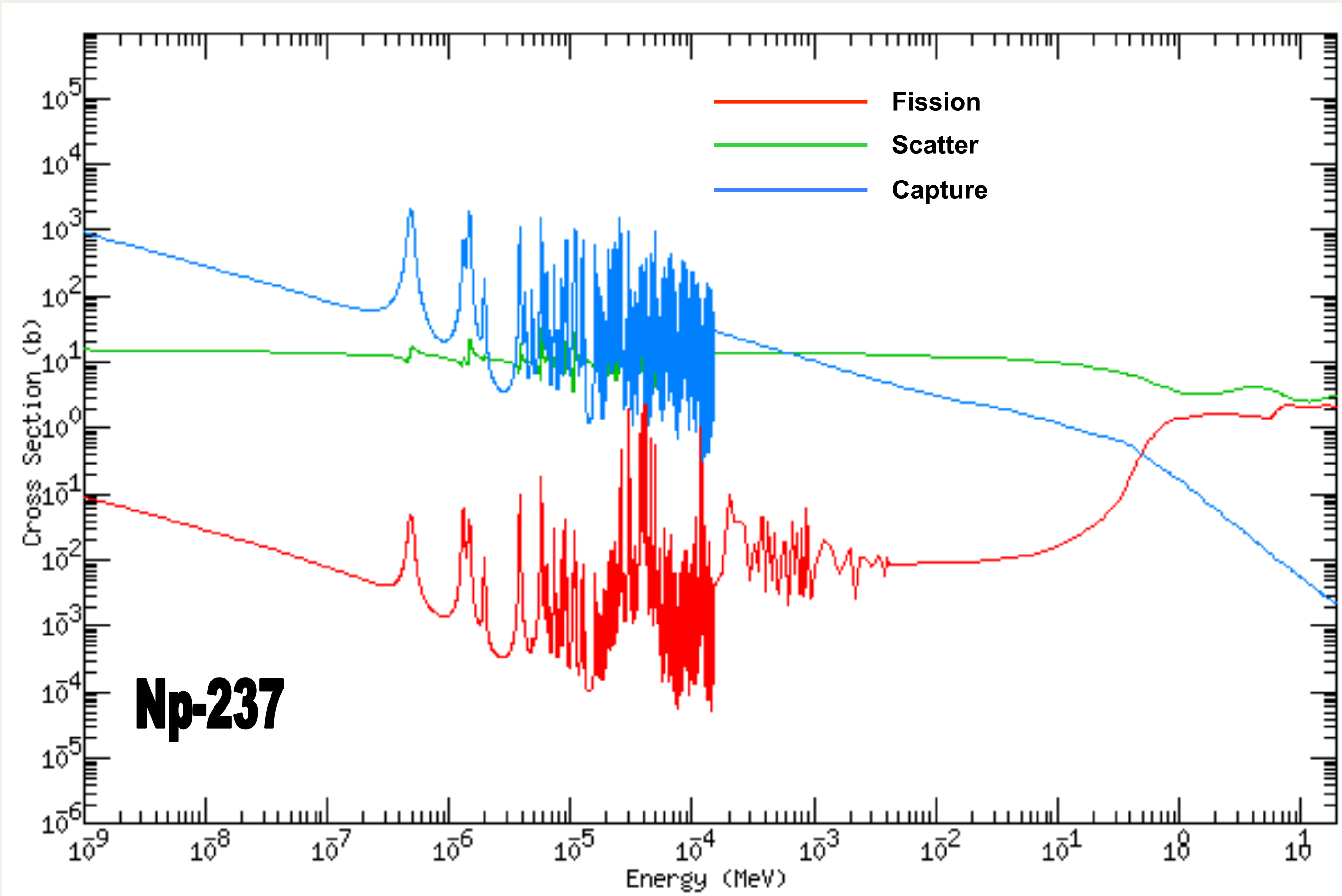
15% Speed of Light

Pu-239 Cross Sections



Half life: 24,110 years

Np-237 Cross Sections



Half life: 2,144,000 years

Fuels for Nuclear Explosives

Uranium

- Naturally occurring in Earth crust at 0.7% U-235 isotopic abundance
- Weapons grade Uranium (WGU) considered to be 90% or more U-235
- Any enrichment above 20% (HEU) is considered weapons usable
- Cost to produce LEU (3-5% U-235) very substantial fraction of cost to produce HEU or even WGU
  - Given LEU or HEU not that much investment in physical plant and equipment to enrich to get to WGU
- Metallic or oxide forms can be turned into weapons
- LEU available for power reactors, HEU available research reactors, WGU in stockpiles in nuclear weapon states.

Plutonium

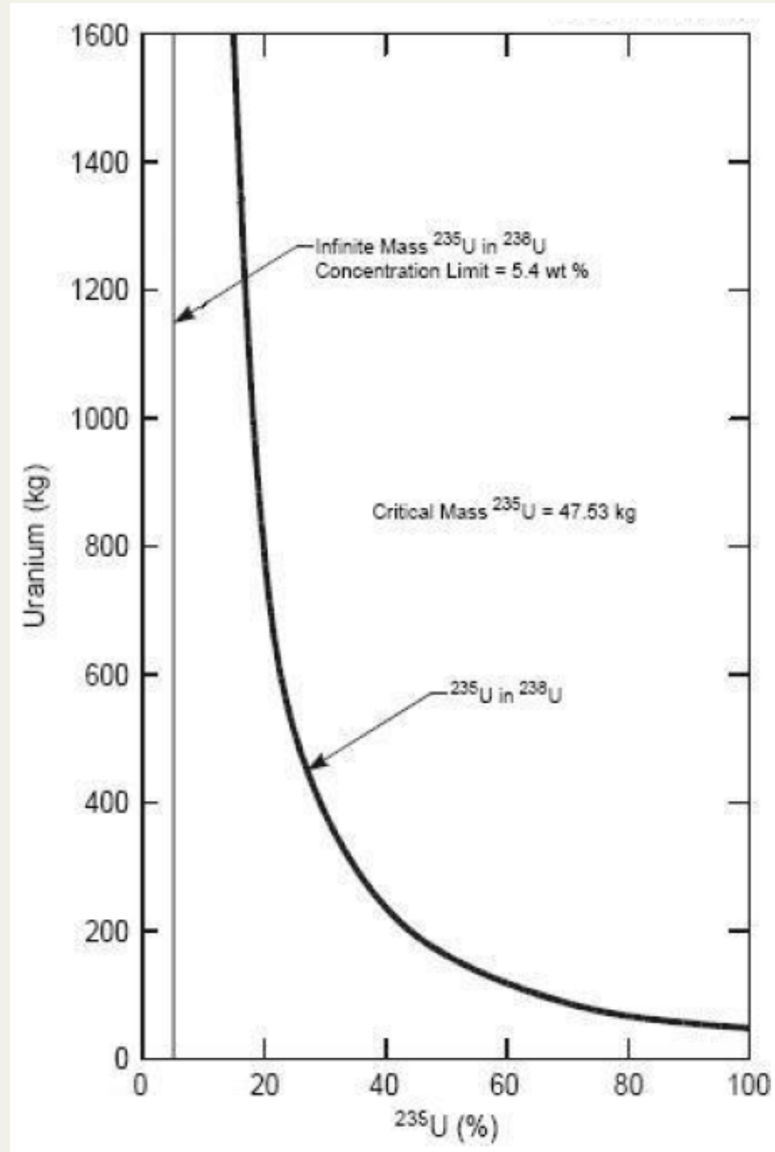
- Made only in nuclear reactors
- Weapons grade Plutonium (WGP) considered to be 94% or more Pu-239 and less than 6% Pu-240.
- Reactor grade Plutonium at 60% 239 and 24% 240 and MOX grade Plutonium at 40% 239 and 32% 240 considered to weapons usable but predetonation is very likely yielding a fizzle which will still yield at about 0.5 – 1.0 KT (for a Nagasaki-like device). No neutron generator needed.
- Metallic or oxide forms can be turned into weapons
- Reactor and MOX grade Plutonium available for power reactor or at rod-storage facilities, WGP in stockpiles in nuclear weapon states.

Neptunium

- Made only in nuclear reactors
- Only Np-237 stable for long times (2e6 years) and made in quantity in reactors
  - No enrichment needed
  - Chemically separated from other elements in waste stream
- About 50-80 metric tons available world wide from reactor rod reprocessing
- Unregulated as a special nuclear material by IAEA

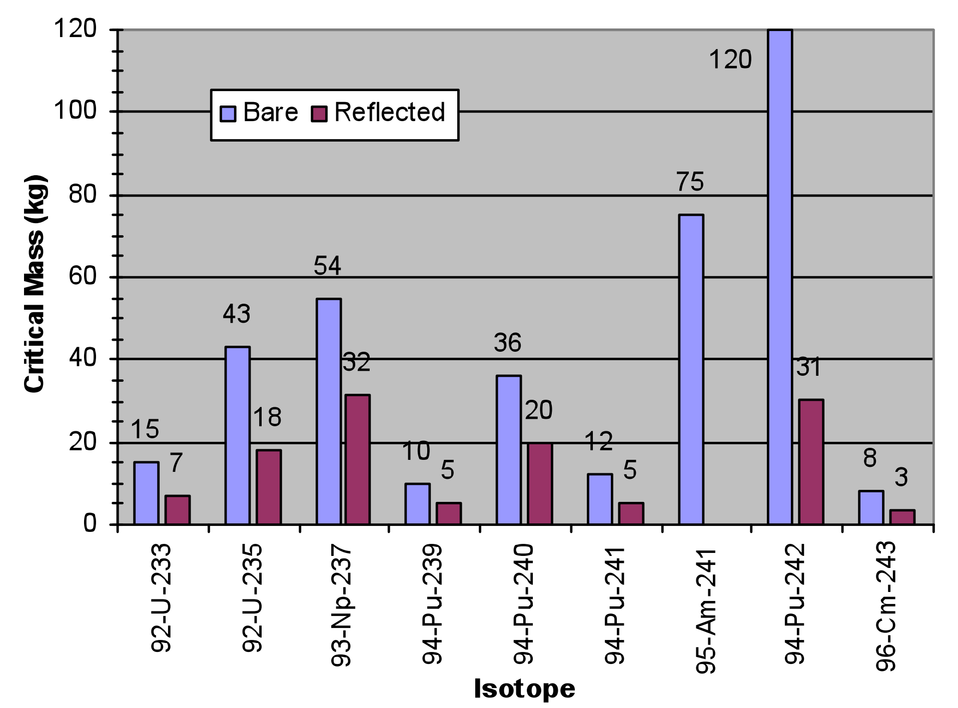
Critical Mass and U-235 Enrichment

- Critical mass of U-235 depends on enrichment level.
- HEU is formally any enrichment above 20%
- WGU is formally any enrichment above 80%
- Any enrichment above about 20% can be weaponized
- Smaller masses are preferred because it is a lot of metal to move around with a propellant



Small quantities of Fissile Material are Involved

- Nuclear weapons need only about 1-2 critical masses of weaponizable material
- Critical assembly must be supercritical to explode
- Chart shows the critical masses for some weapon isotopes
- Bare refers to the critical mass of a sphere of material without anything surrounding it
- Reflected refers to the critical mass when surrounded by a neutron reflector such as Iron or Tungsten
- Using a neutron reflector always reduces the critical mass
- Generally a few tens of kilograms or less of material will be involved.

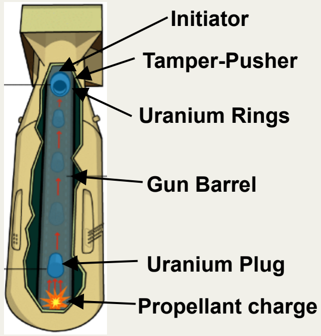
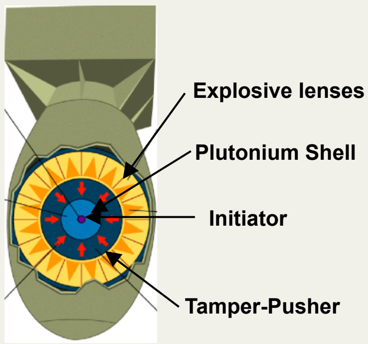


What a Detonation Really Looks Like

Grable – 25-May-1953 – Frenchman Flat, NV – 15kT

Fizeau – 14-Sept-1957 – Yucca Flat, NV - 500 kT

Weapons and Technologies

	Gun Assembly	Implosion Assembly
Schematic		
Overview	A sub critical plug of fissile material is fired into a subcritical ring of material to make a supercritical assembly	A subcritical shell of material is uniformly collapsed into a supercritical assembly
Assembly Technologies	A plug is driven down the inside of metal tube into a series of rings. The propellant in WWII was a cordite derivative, basically very easy technology.	An explosive shell of lenses is uniformly detonated surrounding the shell of fissile material, basically rather difficult technology.
Separation Technologies	Electromagnetic, gas diffusion, or centrifuge technologies required for HEU – basically very difficult technologies.	Chemical separation required for Plutonium and Neptunium – basically very easy technologies