

## The Bomb

When Chadwick discovered the neutron in 1932, it was realized that there was something that could be used to probe the nucleus. Protons and  $\alpha$  particles (a helium nucleus emitted at high speed from the nucleus) are positively charged. The nucleus is positively charged so there is a repulsive force. A neutron without an electric charge could get into the nucleus without having a large amount of kinetic energy to overcome the electrostatic repulsion.

Irene Curie, the daughter of Marie Curie, and her husband Pierre Joliot had discovered that bombarding an element with neutrons could make the new atom radioactive. Fermi in Italy studied what happens when a neutron strikes a nucleus. He found that slow (**thermal**) neutrons were more easily captured by a nucleus than fast neutrons. How do you slow a neutron down? A neutron will stick to a proton (making a nucleus of 'heavy' hydrogen or deuterium which had been discovered in 1932 by the chemist Harold Urey). However, most of the time it just bounces off the proton. Momentum conservation tells us that the best way for a particle to lose its velocity is for it to collide **elastically** with a stationary equal mass particle. The proton and neutron have almost equal mass so hydrogen is a good '**moderator**' of neutrons. Anything with hydrogen is a good moderator of neutrons. Water works as does do most hydrocarbons (paraffin). (Carbon and Oxygen don't absorb or capture too many neutrons.) Part of the folklore is that when Fermi discovered the benefits of slowing down the neutrons, he took his whole experimental setup outside and put it in the university's fountain!

At the time, uranium was the heaviest known element (atomic number 92). Since an element struck by a neutron often decayed by emitting a  $\beta$  particle and increasing its atomic number by one, Fermi bombarded uranium with neutrons hoping to make a new man-made element. He observed  $\beta$  decays from the neutron irradiated uranium and thought he might have made a new element.

## The Fascist. Politics and the discovery of Fission A very twisted Tale

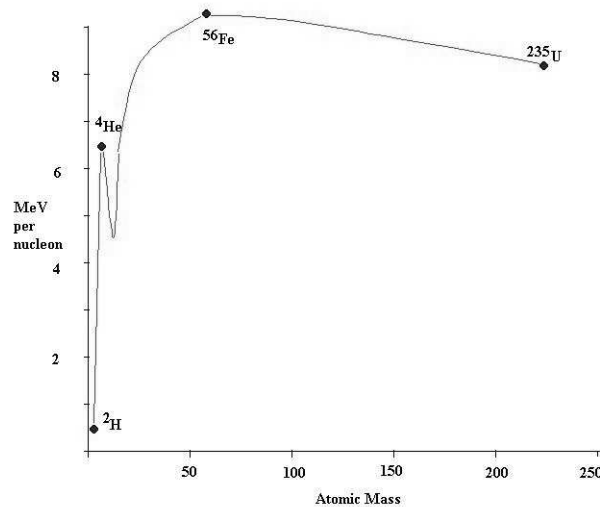
The year was 1939. Fermi had just won the Nobel prize. Fermi thought he might have made the first man-made element. Fermi's wife was a Jew so after picking up his Nobel prize, he accepted an offer from Columbia University and did not return to Italy. During the 1930's many of the great European physicist had left fascist Germany. Many were Jews. Einstein, Bethe, Szilard, Wigner, Born, Teller and others had left Germany for the U.S. or the UK.

One of the best physical chemist in the world was Otto Hahn in Berlin. He had repeated Fermi's experiments with the idea of chemically separating a tiny amount of the new man-made element. He detected tiny amounts of what he called eka-barium because it had the chemical properties of barium. Lise Meitner was a physicist and long time collaborator. Lise Meitner was an Austrian Jew. Fascist Germany had annexed Austria in 1938. Meitner's Austrian passport had protected her from the Nuremberg laws. Since Austria was now part of Germany, she had to flee Germany. She went to the Netherlands and from there to Sweden. At Christmas time in she received a letter from Hahn telling her he had found other elements in his neutron work. All the elements were approximately half the mass of uranium. He also had shown that the element eka-barium **was** barium! Meitner and Otto Frisch, her nephew, discussed the problem and come to the realization that the **uranium atom had split in half!** Frisch ask a biologist what the splitting of a cell was called and was told the process was called '**fission**'.

Frisch worked at Bohr's lab. Bohr was a very respected person in the physics world and was about to leave for an long trip to the U.S. Bohr worked out the theory of fission on the boat trip to the U.S. He was meet at the dock in New Your by the new arrived Fermi. They immediately went to a major physics conference in Washington D.C. where Bohr told the world outside of Germany the news of the discovery in Berlin.

# The Implications of Fission

Why was this so important. Using a mass spectrometer the mass of most of the elements had been carefully determined. From the famous equation  $E = m c^2$  and knowing the mass of the proton and neutron, one can determine the **binding energy** of a nucleon (proton or neutron). This is how much energy it takes to remove a nucleon from the nucleus. It is somewhat like the escape velocity from a gravitational field.

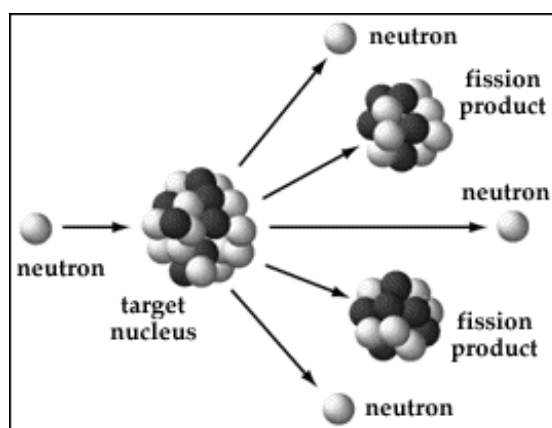


As you can see from the plot,  $\text{Fe}^{56}$  is the most stable nucleus. Below this atomic mass or above the nucleons are less tightly bound. If you can split a heavy atom, enormous energy is released. For fission,  $\approx 200$  MeV of energy is released for each fission. An '**MeV**' is a unit of energy. An electron volt (**eV**) is the energy an electron gains moving through a voltage difference of 1 volt. An MeV is a million eV. One  $\text{eV} = 1.6 \times 10^{-19}$  Joules. One fission is not much energy but if a lot of atoms are split, it would release enormous energy.

Also note in the curve that putting together light elements would also release energy. **Fusion** of light elements such as hydrogen will come up later with the 'hydrogen bomb'.

## Word of Fission Reaches the U.S.

The agenda of the conference was quickly forgotten and all attention turned to fission. Within hours, fission was confirmed in the U.S. Work started at Columbia by Fermi to measure the parameters of the fission process. The big question was: **Does fission of uranium release more neutrons?** The answer was yes. When a uranium atom splits, it releases, on average, 2.5 neutrons.



This was the key. If more neutrons were released during fission, then a **chain reaction** could occur. Under the right conditions vast amounts of energy could be released. With more neutrons being released with each fission, the fission process would sustain itself.

## Uranium Isotopes and Plutonium

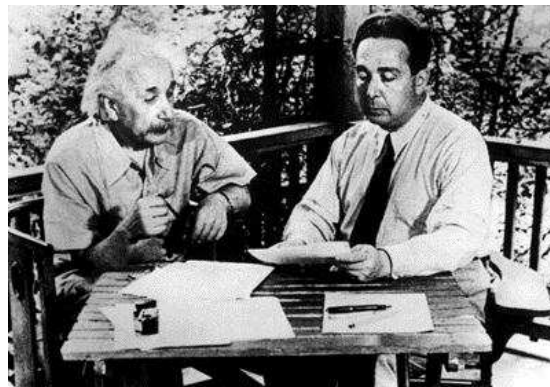
The two main isotopes of uranium are  $U^{235}$  and  $U^{238}$ . Natural uranium is made up of only 0.7%  $U^{235}$ .  $U^{238}$  makes up the rest of natural uranium. Using theory and experiments using the newly invented cyclotron, physicist determined that  $U^{235}$  was the isotope being split by neutrons. For most energies of neutrons,  $U^{238}$  **absorbed** a neutron and  $\beta$  decayed to a new element (neptunium). The new element decayed again by  $\beta$  emission to plutonium.



Using the theory that Bohr worked out on this trip to the U.S. and later with John Wheeler, it was quickly realized that  $\text{Pu}^{239}$  would fission like  $\text{U}^{235}$ .

## The Early Politics of the Bomb

As we have seen, many of the great scientist of Europe had come to the U.S. because of the Fascist in Germany. Many were Jewish and had to leave. When Leo Szilard heard of the discovery of fission, he became concerned that that Germany would develop an atomic bomb. He set about convincing the U.S. government that a program should be started in the U.S. to explore the possibility of a U.S. atomic bomb to counter the threat of Germany developing such a weapon. **Fear of a 'Nazi' atomic bomb was the motivating factor that caused nearly all scientist to work on the atomic bomb during the war.** Remember the U.S. was over two years away from entry into the Second World War. Szilard convinced Einstein of the threat of a Nazi atomic bomb. Probably the best known theoretical nuclear physicists were German. Einstein wrote a famous letter to Roosevelt asking him to look into the problem and provide funds for nuclear research.



In fact, only some small funds were allocated thru the navy. (The navy thought reactors might be used in the future to power ships.) Not much was done until the U.S. entered the war after Pearl Harbor in December 1941. The British had put some effort into the problem. Pierls and Frisch had made estimates of how much fissionable material would be required.

However, the U.K. knew they did not have the money and industrial power during the war to do major isotope separation. When the U.S. entered the war, most of the British effort was transferred to the U.S. atomic project.

## Early Days of the Manhattan Project

When the U.S. entered the war, a major effort was undertaken. It was called the **Manhattan Project** because the early work with the navy money was done at Columbia by Fermi. The project was moved inland for security to the University of Chicago. Fermi had succeeded in showing that very pure carbon could be used in as a moderator at Columbia. He had shown that **natural uranium** with only 0.7%  $U^{235}$  could be used for a self-sustained chain reaction. When enough material (pure carbon - graphite and uranium) was available the Chicago team started building the first reactor. By the way, early reactors were often called 'piles' because they were big piles of moderators and uranium. The reactor also used cadmium rods to control the reaction rate. Cadmium absorbs neutrons so a rod of cadmium with stop the reaction until it is partially removed from the pile of graphite and uranium. On December 2, 1942 the first reactor went '**critical**' in a squash court under the football stadium at the University of Chicago. Critical refers to a critical mass. A critical mass is enough fissionable material to sustain a chain reaction. The first reactor produced  $\approx 1$  watt of power!



## Paths to the Bomb

The Manhattan project now had the knowledge of what it would take to build a bomb. There were two paths:

- Build large reactors to produce plutonium ( $\text{Pu}^{239}$ ).
- Separate  $\text{U}^{235}$  from natural uranium.

It was fairly well understood it would take about 10 kg of  $\text{Pu}^{239}$  or  $\text{U}^{235}$  to make a bomb. Either approach was daunting. Let look at them

Building reactors was a major engineering problem. Before Fermi's reactor had operated, plans were made for several large reactors at Hanford, Washington. Large amounts of cooling water would be required. They would need to be isolated. After the  $\text{U}^{238}$  in the fuel had absorbed enough neutrons, the very radioactive fuel from the reactor would have to be chemically processed to extract the  $\text{Pu}^{239}$ . This would have to be done completely by remote control since the fuel was so radioactive. Many tons of fuel would have to be processed to extract a few kilograms of  $\text{Pu}^{239}$ .

When the reactors were built, the engineers insisted on making them larger than was necessary. It was good they did. When the first reactor was started, it worked as expected for a few days and then stopped. A radioactive isotope of Xenon was found to be the problem. The Xenon isotope being produced by the uranium fission absorbed neutrons and stopped the chain reaction. The extra space for uranium was used to overcome the problem. Extra fuel was inserted into the extra space as the 'Xenon poisoning' occurred. The reacting part of the 'pile' was shifted while the radioactive Xenon decayed in the other part of the reactor.

Isotope separation was a major can of worms. the only isotope separated to that time was heavy hydrogen (deuterium  $\text{H}^2$  in 'heavy water'). The ratio of masses is 2 for this case. With uranium, the ratio is  $235/238 \approx 1$ . Another problem is the chemistry. There is only one gaseous compound of uranium ( $\text{UF}_6$ ) and it is very corrosive. The possible ways to separate uranium are:

- **Electromagnetic** This is basically a big mass spectrometer. It is very slow and only separates small amounts. In the end this is what produced the  $U^{235}$  for the first bomb.
- **Ultra-Centrifuge.** Apply a very large centripetal force (a big 'g' force) and the heavier compound will 'sink' to the outside. The technology for the very high rotation speeds needed was not possible in the 1940's. (It is used today)
- **Gaseous Diffusion.** A lighter gas molecule will diffuse thru a barrier slightly quicker than a heavier molecule. In the end this proved to be the most successful. It was a huge industrial effort.
- **Thermal Diffusion.** A lighter molecule will separate from the heavier molecule because of its slightly greater thermal speed. This method never proved to be successful for large scale isotope separation.

In the end, two major industrial plants were built at Oak Ridge. The electromagnetic method and gaseous diffusion method were used. It took over a year to separate enough  $U^{235}$  with the electromagnetic method for the first bomb. The gaseous diffusion process had many problems, especially with the diffusion barriers. The gaseous diffusion process was a huge project involving thousands of miles of pipe and thousands of pumps. Over 4000 stages were required to produce 95%  $U^{235}$ . The gaseous diffusion method only started producing large amounts of  $U^{235}$  in the Summer of 1945

## Los Alamos

In 1943, work had started on Hanford for plutonium production and extraction. Work was also started at Oak Ridge on the electromagnetic and gaseous diffusion plants for isotope separation. At the start of the war, the Manhattan project had been put under General Leslie Groves. Groves was an engineer who had built the Pentagon building in record time before taking over the Manhattan project.



**Groves did not think much of scientists.** The one scientist he did like was J. Robert Oppenheimer. Oppenheimer (known as 'Oppie' to most people) was a brilliant theorist from Berkeley and Cal Tech. He was one of the U.S. students who had gone to Europe to study physics in the 1920s. He had build a loyal following of graduate students, post-docs and colleague who would go on to become some of the most well know scientist of the century.

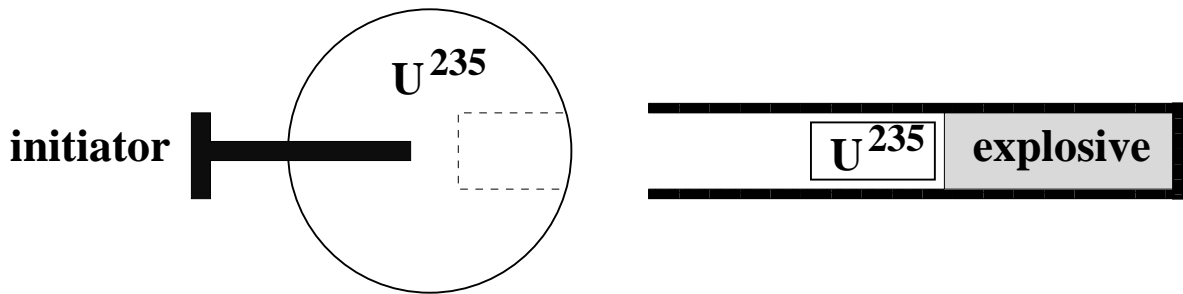
In 1943, Groves appointed Oppenheimer head of the group that would build the 'gadget' as the bomb was known. For security, a new lab was built in the Jemez mountains of northern New Mexico at an old boys school called Los Alamos. The site was on a 7500 ft mesa. A lab was quickly built. The original plan called for about 100 people total. The site grew into a major lab with many hundreds of people by the end of the war.

Originally, Groves had wanted the scientist to be in the military and the work highly compartmentalized for security. It was decided that military discipline for the scientist would be pointless. Oppenheimer and others argued that a compartmentalized effort would be inefficient. In the end Oppenheimer won out. A lab wide seminar concerning the overall progress of the work was started. To this day, this seminar is still held on Friday mornings at Los Alamos.

### “Little Boy”

The purpose of Los Alamos was to design and build the gadget. It looked to be a straight forward project. Ordinance expert 'Deke' Parsons from the navy directed the detailed design of the basic gadget.

In the **gun mechanism**, a plug of  $U^{235}$  is fired by a gun into a sub-critical mass of  $U^{235}$ . The large mass is spherical in shape with a hole the shape of the plug. The plug plus spherical mass forms a critical mass where an uncontrolled chain reaction takes place. The conventional explosive charged fired the plug into the spherical mass at  $\approx 2000$  ft/s. An 'initiator' fired neutrons into the center of the critical mass at the right moment to start the chain reaction.



## The Crisis on 'The Hill'

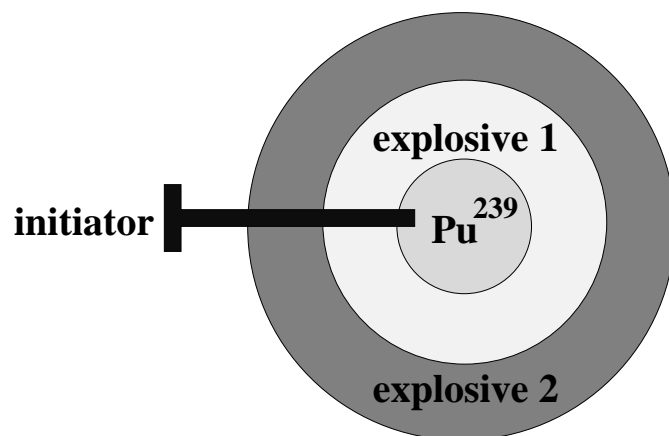
The project to this point had been mainly concerned with engineering details and measurement of physical parameters necessary to design the 'little boy bomb'. When the work had been started a scientist by the name of **Seth Neddermeyer** had proposed a crazy idea. Completely surround a sub-critical spherical mass of fissionable material with high explosives. If the explosives were detonated uniformly, the force would compress the sub-critical mass into a critical mass. This is the **implosion** method. Oppenheimer thought the idea was too technically challenging but had given Neddermeyer permission to work with a small group of people to pursue the idea. It was a limited effort which was not expected to succeed.

When the first samples of plutonium arrived from Hanford and were analyzed in detail, a major problem was discovered. The plutonium contained small amounts of  $Pu^{240}$ . Some of the  $Pu^{239}$ , while still in the reactor, was absorbing a second neutron and becoming  $Pu^{240}$ . This was a major unforeseen problem with plutonium.  $Pu^{240}$  will **spontaneously fission** and release neutrons.

These neutrons will start the chain reaction prematurely. Before the chain reaction has time to propagate thru the entire critical mass, the bomb will 'fizzle' and only release a small fraction of the possible energy. (A 'fizzle' could be equal to tons of dynamite.) The only possible way to assemble the plutonium critical mass in a short enough time so it would not 'fizzle' was the implosion method of Neddermeyer.

The design of the uranium bomb was in hand. They only had to wait until there was enough  $U^{235}$  from Oak Ridge to make the critical mass components. The entire focus of the lab moved to making the implosion method work for plutonium.

The final design used two layers of conventional high explosive to form an **explosive lens** to focus the shock wave of the explosion onto the mass of plutonium so that it was compressed into a critical mass.



The uranium bomb was considered so well understood and the  $U^{235}$  was so precious that a test had not been considered. The uranium bomb would be ready without a test. The plutonium bomb was another story. Plutonium was going to be produced in relatively large quantities so there was enough fissionable material to consider a test. The calculation for the implosion method was poorly understood and a test was considered critical. General Groves had not wanted to do a test since it would compromise security with all those scientist running around out in the open making this incredible explosion. A site in the Southern New Mexico desert near Alamogordo was chosen. The code name for the test was **Trinity**.

## The Scientist Against Using the Bomb

Starting in late 1944, two attempts to impress upon the **highest levels of the of the allied political leadership** the revolutionary implications of the bomb were undertaken. Bohr approached Roosevelt thru Supreme Court Justice Felix Frankfurter. Roosevelt was sympathetic and ask Bohr to talk to Churchill in London. The meeting in London did not go well and with Roosevelt's death in April 1945, Bohr's idea's were ignored.

When the war in Europe was nearly over and the information of the Alos mission were known to the scientist, Leo Szilard and James Franck at the metlab in Chicago approached the new president (Truman). After Szilard's meeting with Truman, the new president refused to meeting again with the concerned scientist.

Both the Bohr and Szilard-Franck approaches emphasized two main points:

- The atomic bomb should be made know or demonstrated to the Japanese in an effort to make Japan surrender before it was used militarily.
- The Soviets should be told of the atomic bomb and the bomb placed under **international controls** to avoid a nuclear arms race.

It was understood by the people responsible for bring the bomb into existence that another major war would mean the end of humanity if nuclear weapons were ever employed on a major scale.

### Hiroshima and Nagasaki

In July the implosion bomb was ready. Truman had delayed his meeting with Churchill and Stalin at Potsdam in order to know if the implosion bomb would work. He intended to use the bomb for leverage with Stalin.

On July 17 at 5:30 at Alamogordo the gadget was exploded successfully.



The result was reported to Truman at Potsdam. He told Stalin of a powerful 'new weapon' but **did not** tell him it was an atomic bomb. He authorized the use of the bomb against Japan as soon as it could be deployed.

At the time of the Trinity test, the  $U^{235}$  bomb ('little boy') was already being shipped to Tinian island where the B-29 bomber 'Enola Gay' was stationed to drop the bomb on Hiroshima Japan. Hiroshima was destroyed at 8:16 on August 6. Approximately 100,000 thousand people died immediately or from injuries due to the bomb. The 'little boy' had an explosive yield of 12,000 tons of TNT.



On August 9 the 'Fat man' plutonium implosion bomb was dropped on Nagasaki. The yield was 19 kilo-tons. 60,000 people were killed at Nagasaki. Kokura had been the primary target but weather had prevented dropping the 'Fat man' device there. The B-29 ('Bock's Car') diverted to the secondary target at Nagasaki.

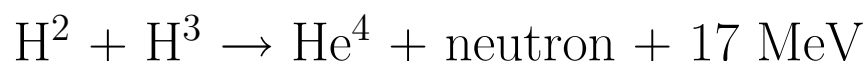


## The Bomb After the WWII

After the War, the U.S. did not place atomic weapons under international control. The Soviet Union developed an atomic bomb by 1949. Szilard and others had warned that the Soviets could develop a bomb in less than five years. Groves and other military leaders had predicted it would take the Soviets 20 or more years to develop atomic bombs. The 'secret' to the atomic bomb is knowing it **can** be built!

## The H-Bomb

A lot of energy is gained by splitting a uranium atom. More energy (by mass) is released if you fuse two light hydrogen atoms together. For example if you fuse deuterium ( $H^2$  - one proton and one neutron) with tritium ( $H^3$  one proton and two neutrons). Tritium is man-made in reactors. The fusion reaction:



releases 17 MeV of energy for each fusion. The energy released is 17 MeV per 5 atomic mass units (3.4). For the uranium bomb the energy released is 200 MeV per 235 atomic mass units (.85)

After the fall of China to the communist in 1949 and the Soviet atomic bomb, the U.S. undertook the development of a hydrogen bomb. Oppenheimer and other opposed the development of the more powerful weapon.

The technical problems were daunting but after a break-thru by Teller and Ulam in the U.S., the H-Bomb was tested in the South Pacific in 1953. Independently Andri Sakharov in the U.S.S.R. developed the same idea and a Soviet H-bomb was exploded in 1954. The explosive yields of this new weapon was **millions** of tons of TNT as opposed to 10s of **thousands** of tons of TNT for the atomic bomb.

## The 'Red Scare' and the H-bomb

The decision by Truman to go ahead with the H-bomb was done against the backdrop of the cold war. China had fallen to the communist, the U.S. was involved in the Korean war and the U.S.S.R had just exploded an atomic bomb. The idea that the U.S. need a 'bigger' or 'better' bomb to stay ahead of the Soviets motivated the politicians. Oppenheimer and several others were opposed to building this weapon.

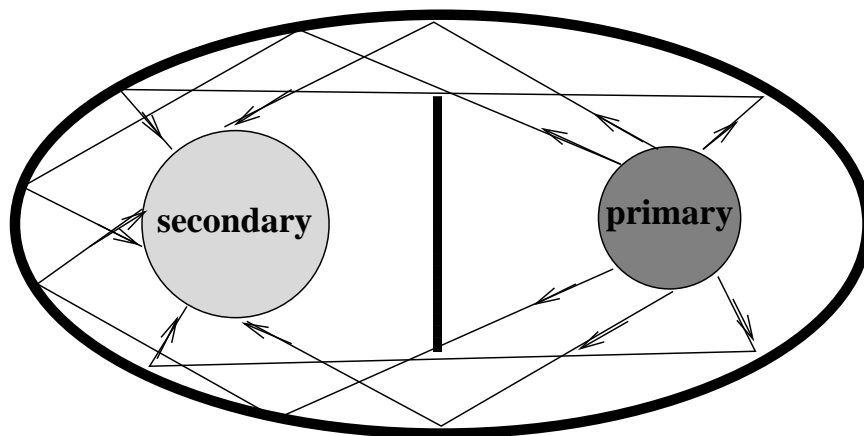
Ed Teller, who had pushed the idea of the **super** even during the early days of the Manhattan project, was the main scientist promoting the H-bomb. Several scientist who opposed the project were investigated as 'un-American'. Oppenheimer's security clearance was revoked.

## Modern Nuclear Weapons

There are two ideas behind modern nuclear weapons which greatly expand the power of these weapons over the bombs used on Hiroshima and Nagasaki.

- Staging. This involves a **primary** atomic bomb with a **secondary** device driven by the primary.
- Boosting. This causes more of the uranium in an atomic bomb to fission.

**Staging** is the so-called secret to the H-bomb discover by Teller and Ulam. A great deal of electromagnetic radiation is released by nuclear explosion. This **extremely intense radiation** creates intense pressure which can be used to compress a secondary. The compression can be an order of magnitude ( $\approx 10$ ) greater than the compression from a conventional explosive lens. If the secondary is made of deuterium and tritium, the two isotopes of hydrogen will fuse and release immense amounts of energy.



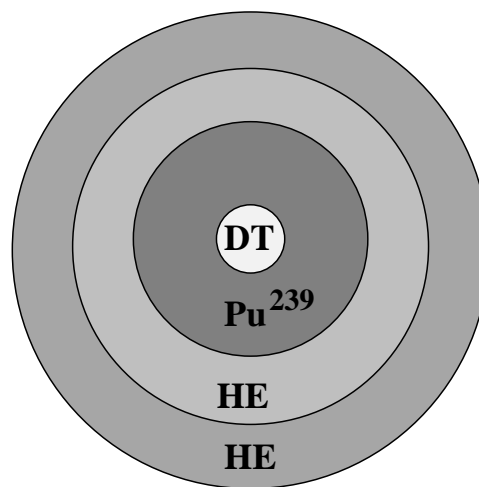
The more you compress a uranium bomb, the better the uranium or plutonium will 'burn'. When the uranium or plutonium is more highly compressed, the neutrons are more likely to strike another uranium atom and not escape from the critical mass. In most modern the weapons, the secondary is another mass of uranium or plutonium which is more completely fissioned. The original WWII bombs only fissioned less than 1% of the fissionable material. In modern nuclear weapons, a few **tens of percent** of the uranium or plutonium is 'burned'.

Why are most modern weapons made with a secondary which is primarily uranium and not deuterium and tritium? Tritium is very expensive to produce and has a 12 year 'half life'. A 'half life' is the time required for  $\frac{1}{2}$  of the material to radioactively decay. Thus is 12 years, 2 grams of tritium will only contain 1 gram of tritium.



Plutonium and even separate  $U^{235}$  are cheaper to produce than tritium. In addition the half lives of Plutonium (24,000 years) and  $U^{235}$  (24 millions years) are long enough that the devices done have to be purified every few years because of contamination from the decay products.

The first attempts to build a H-bomb were to simply place a mass of deuterium and tritium near a fission bomb. That did not work so the deuterium and tritium was placed at the **center** of the fission bomb. This has a 'boosting' effect on the fission weapon.



The the fissionable material begins a chain reaction, the deuterium tritium mixture at the center of the bomb is heated and compressed. The two isotopes fuse and release a large number of neutrons. These neutrons flood thru the fissionable material and cause the a more complete fissioning of the  $Pu^{239}$  or  $U^{235}$ . Much more of the fissionable material is 'burned' in this way.

## Current World Stockpiles

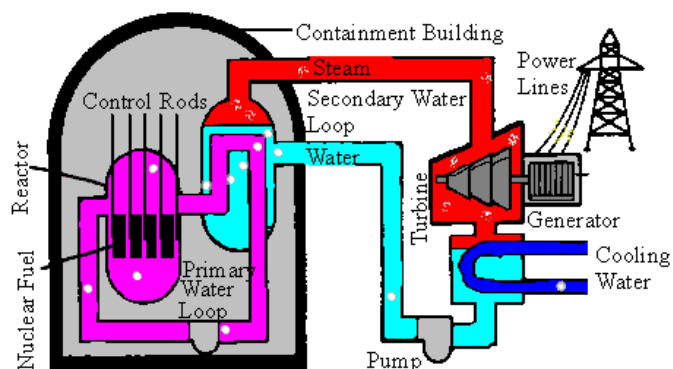
The cold war arms race is well known. However, many people are not aware of how many bombs exist in the world. The vast majority were built by the U.S. and the former Soviet Union. The numbers are staggering.

Country	Strategic	Reserve/Tactical	Total
Russia	2,430	7570	10,000
US	1,950	6550	8,500
France	290	na	300
China	0	240	240
UK	160	65	225

What did all this cost. It is estimated that from 1945 to the 2000, the U.S. spent half of all money spent on defense on nuclear weapons. their delivery systems (missiles, submarines, bombers etc.) and the cost of the infrastructure.

## Fission Reactors

A nuclear power plant simply uses the energy generate in the fission process to generate electrical power. The nuclear reaction is controlled by **control rods** which are made of material which strongly absorb neutrons like cadmium or boron. When the rods are removed, the fission process releases energy from fission. Because the fission process uses slow neutrons, a reactor can not explode like a nuclear weapon. The energy from the fission results in large amounts of heat energy. This heat is then used to create steam which drives a conventional electrical generator.



A typical **base load** nuclear power plants has an output of 500 MW to 1 GW. There are over 400 nuclear power plants in the world. There are 102 in the US. France, Russian and Japan, the UK and South Korea have a significant number of nuclear power plants. Nearly all of these reactors are pressurized water reactors. The fission process heats water to steam at high temperatures (for thermal efficiency) and pressure. While it is relatively easy to 'scam' (stop the fission process) in a reactor but inserting the control rods, the reactor still generates a vast amount of heat from the radioactive fission products. It can take several weeks for enough of the fission products to decay. This means the reactor needs to have cooling water supplied after the fission process stops. Failure to supply the cooling water (from lack of electricity for the pumps or a major break in a pipe) can result in a 'meltdown'. This is what happened at Three Mile Island and Fukushima.

In the US, all of the reactors are different designs. France builds reactors of a standard design which simplifies construction and many safety issues  
Other safety problems with current nuclear power reactors

- Reactor have been sited near population centers and in earth quake areas. Some countries site the reactors together where safety expertise and equipment are centralized.
- The spent fuel is highly radioactive. Spent fuel in the US is stored in large water filled pools on site. A permanent disposal site has been discussed for decades at Yucca Mount Nevada but will probably not be built. Europe reprocess the fuel to separate the long lived isotope which greatly reduces the amount of material that must be stored for centuries until it is safe.

There are several ideas for safer nuclear reactors. Most involve smaller reactors ( $\approx 50$  MW) which could be used individually or together in groups where larger amounts of power are required. They would use a common design and are much safer since the cooling water stored in the reactor is enough to supply the reactor with cooling water for the weeks require for a safe shutdown. A major economic advantage is they are small enough to be built in a factor and transported to the site.

More advanced ideas are for 'sub-critical ' reactors. These use a accelerator to make neutrons to irradiate the fuel. The reactor fuel is a sub-critical amount and only produces energy when neutrons irradiate the fuel. If the electricity goes out then accelerator stops and the fission reaction stops.