Early Nuclear Weapons

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When the Manhattan project started there were two known pathways to developing a nuclear weapon – the plutonium pathway or the enriched uranium pathway. It was hoped that the plutonium pathway would be the best because it was easier to manufacture the plutonium than it was to enrich the uranium.

The other essential technology was the assembly technology. It was well known that the subcritical masses of plutonium or uranium needed to be assembled very quickly to form a supercritical mass. The early estimates for the assembly velocity were based on the spontaneous fission rate for U-235, which resulted in an assembly velocity of about 300 m/s – well within the reach of Naval gun design. The idea was to take a subcritical mass as a projectile and another subcritical mass as a target at the end of the gun, as shown in Figure 1.

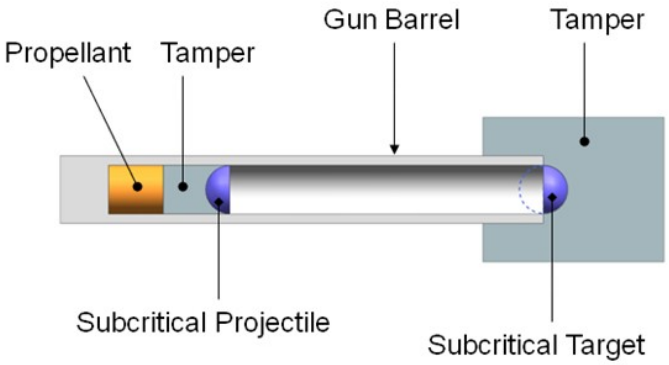

Figure 1 - Diagram of gun-assembled nuclear weapon-
(from https://nuclear-knowledge.com/gun_gadget.php)

In the figure propellant is detonated to drive the subcritical projectile into a subcritical target. Also shown in the figure is a very heavy dense material labeled “Tamper”, which helped contain the explosion to let the chain reaction develop more completely and to help reflect neutrons back into the supercritical mass assembled. Not shown in the figure is the neutron initiator located in front of the subcritical target. This was a very small crenelated cluster of polonium and beryllium foils which when collapsed released a burst of neutrons. This burst comes from the (alpha,n) reaction on beryllium. The polonium is a strong alpha emitter. These alphas have very short range in air, requiring the beryllium and polonium foils to be very close together before the reaction can take place. The incoming subcritical projectile collapses the crenelated cluster of polonium and beryllium foils, bringing them into close contact and promoting the (alpha,n) reaction. This burst of neutrons assures that the chain reaction is initiated at the moment when the two subcritical masses are fully assembled, thus allowing for more efficient burning of the nuclear materials.

It turned out that plutonium has a significantly higher spontaneous fission rate than U-235. This very high spontaneous fission rate required an assembly velocity more than 10 times greater than that available in any Naval gun design.

Both pathways for building a weapon were being followed at Los Alamos – the uranium pathway was time-consuming for the enrichment, and the plutonium pathway needed a very rapid assembly technology.

U-235, the isotope needed for the weapon, has a 0.711% natural abundance which is far below the 80% which is needed for the weapon. During the Manhattan project several enrichment techniques were tried in parallel – the most successful being electromagnetic separation which involved a vacuum chamber in a large magnet which directed the ionized natural uranium into an array of cups that would catch the different isotopes as they orbited differently in the magnetic field. This technique is very time-consuming and required very large amounts of electricity. Hundreds of magnet setups were installed in huge warehouses at Oak Ridge, where electricity was plentifully available.

Pu-239 is the isotope of plutonium that is needed for a weapon. All isotopes of plutonium are made in a reactor as part of the uranium fissioning process. However, if the reactor rods are left in until the economic life of the uranium in the rods is consumed, then many even isotopes of plutonium will be made in addition to Pu-239. These even isotopes can decay through the (alpha,n) reaction neutrons from which makes it difficult to fully assemble the plutonium into an explosive mass. Consequently, during the Manhattan Project, the rods were simply pulled out early thus halting the chain reaction and assuring only Pu-239 would be most abundant. The plutonium can simply be chemically extracted from the rods.

By 1945 there was enough material on hand for only a few nuclear weapons. If more weapons than the Trinity test and the two that were dropped were needed to force Japan to surrender, the US war-planners needed a rapid material production technology that could produce more weapon materials in a short time-thus the plutonium pathway was followed as well as a uranium one.

Very fortunately there were some very clever explosives engineers at work at Los Alamos. These explosive engineers knew a lot about explosive lenses. These devices were used commonly in the mining trade. However, those lenses produced a planar wave shock front. What was needed for the assembly of the sphere of material was a spherical shock front. After a great number of unsuccessful trials, the concept of using both a fast and slow explosive in the lens itself allowed for the creation of a spherical-shaped shock front. The idea is to take a shell or a sphere of Plutonium, surrounded with a soccer ball like tiling of explosive lenses. Each of these lenses would replicate the curvature of the metal that it was in contact with. Naturally each of these lenses had to be detonated at very precisely the same time.

A common illustration of an implosion weapon like the Nagasaki device is shown in Figure 2.

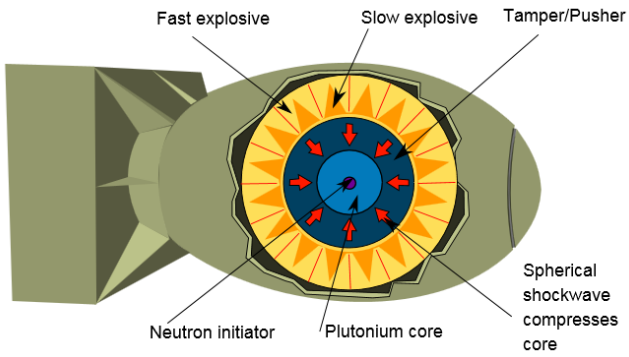

Figure 2 - Illustration of an implosion design nuclear weapon.

In the figure the outer layer of the device is made up of the explosive lenses in yellow and tan and at the very center in light blue is the plutonium core that is to be compressed. The figure illustrates both a slow explosive and the fast explosive as part of the explosive lens. The slow explosive forms the conical center of the lens whereas the fast explosive forms the outer layer. The detonation happens on the outside and at the center of each of the top of the lenses.

The result of the different speeds of the fast and slow explosives allows the outer perimeter of each lens to reach the surface of the metal faster than the center part, which allows for the creation of the spherical shape of the shock front. The shaping and casting of these lenses was a major technical problem at Los Alamos in the 40s.

In the figure the lenses first are compressing a set of tamper/pusher materials that are there to contain the explosion initially and reflect the neutrons back into the plutonium core so that they can be used in the chain reaction. The other utility of these materials is to better match the momentum transfer across the density changes from low-density explosives to higher density metals. At the center of the plutonium core is a neutron initiator which when the core is fully compressed releases an enormous pulse of neutrons that assures that the chain reaction is initiated at the point of maximum compression.

During the Manhattan project the designers were confident in nuclear physics for the plutonium but uncertain as to the design of the explosive lenses. If one of these devices was dropped over Japan it was essential that it detonate. To resolve the uncertainty about the implosion design Los Alamos scientists did a test on July 16, 1945 at the Trinity test site near Alamogordo New Mexico. The yield was about 12 kt. The first nuclear explosion at Trinity is shown in Figure 3.

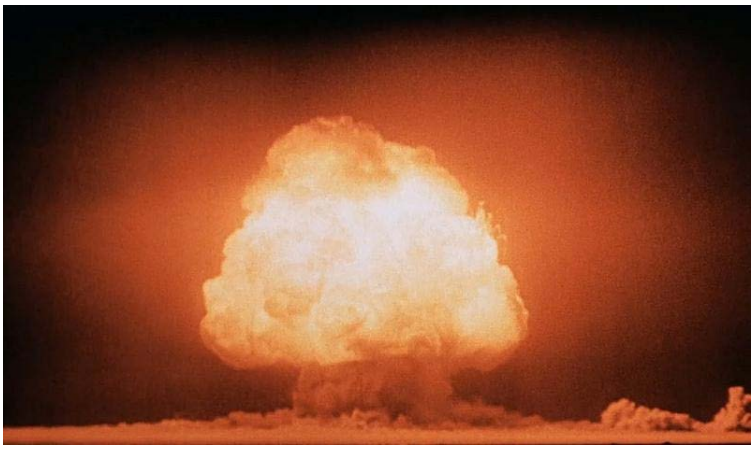

Figure 3 - The Trinity test near Alamogordo New Mexico

On August 9, 1945 the implosion design device was dropped on Nagasaki Japan and yielded about 20 kt.

Plutonium is a metallurgist's delight. Plutonium is stable in a number of phases even at room temperature - these different phases are called allotropes. The Alpha phase, which is most common at room temperature, is like glass whereas the Delta phase is like aluminum. Compressing a sphere of glass is not preferred over compressing a sphere of aluminum. Consequently, the mechanical properties of the Delta phase were preferred. To stabilize the plutonium in the Delta phase required the addition of a trivalent atom like aluminum, cerium, indium, or scandium or in the case of the United States, gallium. The problem is with the 5F electron in the Plutonium metal lattice. This electron cannot make up its mind as to whether it's in the valence band or the conduction band. As a consequence, even at room temperature phases tend to flop around between Alpha, Beta, and Delta causing enormous changes in the material properties of the metal. With the 1% addition of gallium the Delta phase is frozen in the lattice for all temperatures of importance.

The US uses gallium because the other trivalent elements don't offer the same corrosion resistance as gallium does. It is desirable to keep the oxygen content as low as possible and to discourage other high (Alpha,n) cross-section materials as they will give rise to neutrons of significant energy which can possibly pre-trigger the device.

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