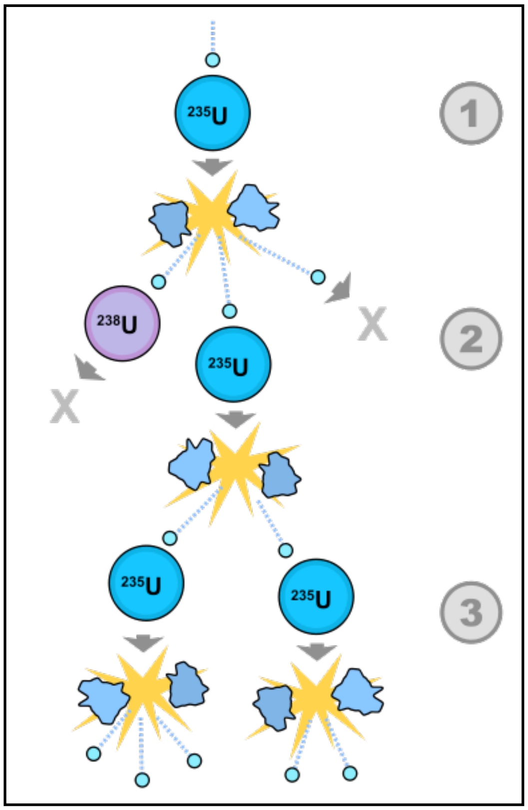
The Physics of Nuclear Weapons

While the technology behind nuclear weapons is of secondary importance to this seminar, some background is helpful when dealing with issues such as nuclear proliferation. For example, the following information will put North Korea's uranium enrichment program in a less threatening context than has been portrayed in the mainstream media, while showing why Iran's program is of greater concern. Those wanting more technical details on nuclear weapons can find them online, with Wikipedia's article being a good place to start.

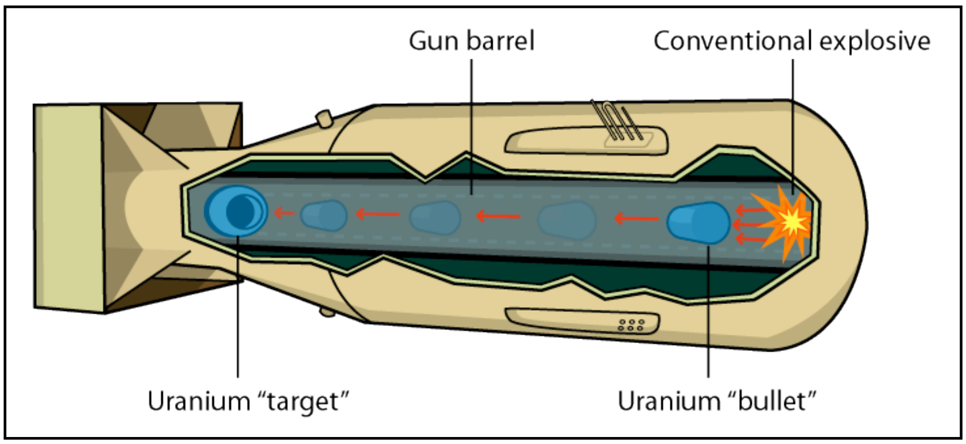
The atomic bombs used on Hiroshima and Nagasaki were *fission weapons*. The nuclei of atoms consist of protons and neutrons, with the number of protons determining the element (e.g., carbon has 6 protons, while uranium has 92) and the number of neutrons determining the isotope of that element. Different isotopes of the same element have the same *chemical* properties, but very different *nuclear* properties. In particular, some isotopes tend to break apart or fission into two lighter elements, with uranium (chemical symbol U) being of particular interest. All uranium atoms have 92 protons. U-238 is the most common isotope of uranium, making up 99.3% of naturally occurring uranium. The 238 refers to the atomic weight of the isotope, which equals the total number of protons plus neutrons in its nucleus. Thus U-238 has 238 – 92 = 146 neutrons, while U-235 has 143 neutrons and makes up almost all the remaining 0.7% of naturally occurring uranium. U-234 is very rare at 0.005%, and other, even rarer isotopes exist.

U-235 is the valuable isotope from a nuclear weapons or nuclear power point of view because it can serve as the primary fuel for a weapon or power plant, while U-238 cannot. As shown in the next diagram (source: Wikimedia Commons), when a U-235 atom absorbs a neutron, it breaks into two smaller atoms plus some number of neutrons. This splitting or fission also releases "atomic energy" that can produce electricity or an explosion. On average, each fission of a U-235 atom produces about 2.5 new neutrons, though of course, in any specific fission the number is an integer. If all of the neutrons released are absorbed by new U-235 atoms, an exponentially growing chain reaction sets in, with the number of atoms involved growing from 1, to 2.5 (on average), to $2.5^2 = 6.25$, etc. After 10 "generations" over 10,000 atoms have fissioned, after 20 generations over 100,000,000 atoms have fissioned, etc. But, as depicted in the diagram, some neutrons escape the bomb or reactor without adding to the chain reaction (the one with an X on the right in step 2) and some are absorbed by U-238 atoms (the one with an X on the left in step 2) and do not produce additional neutrons to add to the chain reaction. (By absorbing an additional neutron, the U-238 atom becomes U-239 which we will deal with later. The important point right now is that it does not produce additional neutrons.) If, on average, each fission leads to more than one additional fission, the chain reaction grows exponentially and releases large amounts of energy.



Atomic forces within the nucleus are much stronger than chemical forces. U-235 in an atom bomb therefore liberates much more energy than exploding the same mass of TNT. The bomb used on Hiroshima contained approximately 50 kg (about 100 pounds) of U-235, yet packed the explosive power of 15,000 tons (30 million pounds) of TNT. If all of the U-235 fuel had fissioned, the yield would have been 500 kilotons. The actual yield was only 3% of that figure because, as the weapon exploded, most of the U-235 was dispersed before it could capture a neutron and contribute to the chain reaction.

The above discussion points out that what is usually called *critical mass* is really a critical mass density. After a bomb based on U-235 explodes, most of the U-235 is still present. It is just too thinly dispersed to maintain a chain reaction. Too few neutrons are captured by other U-235 atoms to maintain the chain reaction. The idea of a critical mass density is at the heart of the "gun assembly" atomic bomb depicted below (source: Wikimedia Commons). Two subcritical masses of uranium are at either end of the gun barrel. One is shaped like a bullet, while the other is a hollow cylinder target that just fits around the



bullet. Conventional explosives shoot the bullet down the gun barrel at high speed, where it mates with the target. The two subcritical masses, when brought together rapidly, form a supercritical mass, resulting in a chain reaction and an atomic explosion. Note that,prior to ignition, the bomb has more than a critical mass worth of uranium, but it is divided into two pieces that are too far apart for neutrons from one to cause fission in the other – there is more than a critical mass, but the density is too low.

As already noted, U-238 is usually not useful as atomic fuel, but constitutes 99.3% of naturally occurring uranium, with most of the remaining 0.7% being U-235. Naturally occurring uranium therefore cannot be used in a weapon or most power plants, and must first be enriched to a higher level of U-235. The most prevalent nuclear power plants today are light water reactors (LWR's), which need uranium enriched to about 3-4% U-235 and known as low-enriched uranium (LEU). Bomb-grade fuel must be enriched much further, preferably to 90% U-235, which is called highly-enriched uranium (HEU).

Unfortunately, the same technology used to make LEU for nuclear power (e.g., the gas centrifuges used in Iran's nuclear program) can be re-plumbed to make HEU for weapons. The Nuclear Nonproliferation Treaty (NPT) requires signatories other than the US, Russia, the UK, France and China to forgo the development of nuclear weapons, but recognizes the "inalienable right" of all nations to develop nuclear technology for peaceful purposes.[1] The close connections between peaceful and military applications of nuclear technology make distinguishing between those aims extremely difficult, and that is a particular problem with uranium enrichment. Mohamed ElBaradei, the former Director General of the International Atomic Energy Agency, has referred to enrichment as the Achilles' heel of nuclear nonproliferation. Iran, for example, can claim – and has – that its enrichment program is needed for its domestic nuclear power program and does not violate its NPT requirements. Yet, its ability to enrich is likely to make it a "latent nuclear power" (a nation that could build a bomb in short order, if it chose to do so) in the near future.

HEU is particularly dangerous from a proliferation point of view because weapons based on it are likely to work without any testing. The HEU weapon used on Hiroshima on August 6, 1945, was never tested before use. The nuclear test explosion on July 16, 1945, at Alamogordo, New

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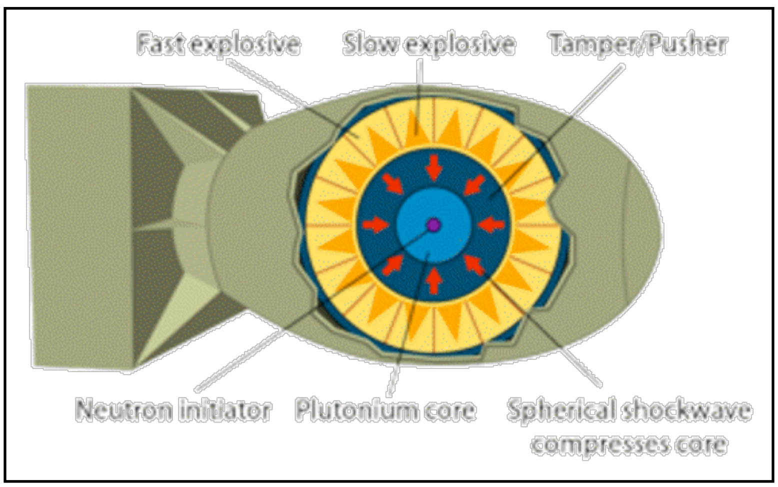
[1] The five nations allowed to maintain nuclear weapons development are called the recognized nuclear weapons states. Article VI of the NPT requires them "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament." The lack of progress on nuclear disarmament since the NPT went into force in 1970 has led to arguments that these five nations, including the US, are in violation of their NPT obligations. The counter-argument is that "good faith" negotiations have in fact taken place, but have not been successful.

Mexico (codenamed the Trinity test) was for the more complex plutonium design described below. The Manhattan Project scientists did not have enough confidence in that design to use it on Nagasaki without first running a full-scale test. North Korea's two atomic tests have been with plutonium weapons, and the low yield of the first test – on the order of 1 kiloton – is evidence of the need to test such weapons before deployment.

Plutonium (chemical symbol Pu, originally suggested as a joke by Glenn Seaborg) has 94 protons, two more than uranium. It also has several isotopes, with Pu-239 being most useful in nuclear weapons. Plutonium occurs only in trace amounts in nature, but is produced in nuclear reactors when U-238 captures a neutron and temporarily becomes U-239. U-239 has a short half-life and decays into neptunium-239 (Np-239), which decays into Pu-239. Pu-239 is much more stable, with a half-life of 24,000 years. The plutonium produced this way is an excellent bomb fuel, but harder to ignite than HEU. Rather than a simple gun assembly, plutonium-based weapons must use the complex implosion technique depicted below (source: Wikimedia Commons).

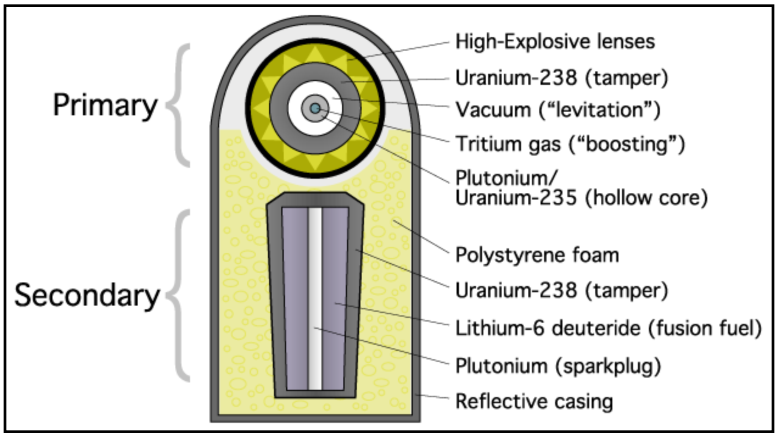


The plutonium is fashioned into a spherical core, known as a plutonium pit (as in a peach pit) that is placed at the center of a hollow shell of conventional high explosives. Known as an explosive lens, these explosives all must detonate at precise times to form a spherical shock wave that compresses the pit, reducing the critical mass. (Even metals such as plutonium will compress under extreme pressure.) In its normal, uncompressed state, the pit has less than critical mass. But once the explosive lens is detonated, the increased density results in a supercritical mass and an atomic explosion. The neutron initiator or trigger shown in the diagram is of critical importance to the functioning of the weapon, but need not concern us at this level of detail.

Although plutonium-based weapons are more complex, once a nation has mastered that design, it tends to be preferred to HEU weapons. One reason is that less than 10 kg of plutonium is needed in a weapon, while several times that amount of HEU is needed. In a guest lecture to this seminar, former Director of Los Alamos and now Stanford Professor Siegfried Hecker, noted that North Korea's uranium enrichment program was of less concern given its demonstrated ability to make the more complex, but more militarily useful plutonium weapons. Iran's enrichment program is of greater concern because it has not yet demonstrated the ability to make plutonium-based weapons.

Natural uranium, with only 0.7% U-235, is not useful as either bomb or power plant primary fuel, with an important exception. That is the Magnox reactor, which is a gas-cooled, graphite-moderated reactor. Magnox reactors can run on natural, unenriched uranium and produce bomb-grade plutonium that is relatively easy to separate out from the uranium due to their different chemical properties. (In contrast, U-235 is much more difficult to separate from the more prevalent U-238 because they have the same chemistry.) North Korea used a small Magnox research reactor to produce all of the plutonium used in its two tests and in its estimated 4-8 remaining weapons. This approach bypassed the need to master the enrichment cycle. Provided that the LEU required by a light water reactor (LWR) is provided by a supplier nation under carefully controlled conditions, LWR's are more proliferation resistant both because the fuel can be carefully monitored and because the plutonium produced by an LWR is less suitable for use in weapons. This helps explain why the 1994 Agreed Framework that sought to limit North Korea's nuclear weapons ambitions called for a trade of that nation's Magnox reactors for two LWR's. We will cover those issues in more detail later, but this explains why our agreeing to provide LWRs to North Korea limited its nuclear weapons program. In contrast, many people mistakenly see providing the LWRs as a stupid move that helped North Korea make weapons.

The fission weapons described above have a theoretical limit to their yield, and the largest such weapon ever developed had a yield of 500 kilotons. Fusion weapons have no such upper limit, and the largest one ever tested yielded 50 megatons – that's 50,000 kilotons, or 100,000,000 pounds of TNT equivalent. Such enormous weapons have little practical value, and today's strategic weapons are in the 100 to 500 kiloton range, still many times more destructive than the roughly 10 kiloton weapons used on Hiroshima and Nagasaki. Tactical or battlefield nuclear weapons have sub-kiloton yields since any bigger blast will annihilate friendly as well as enemy troops.

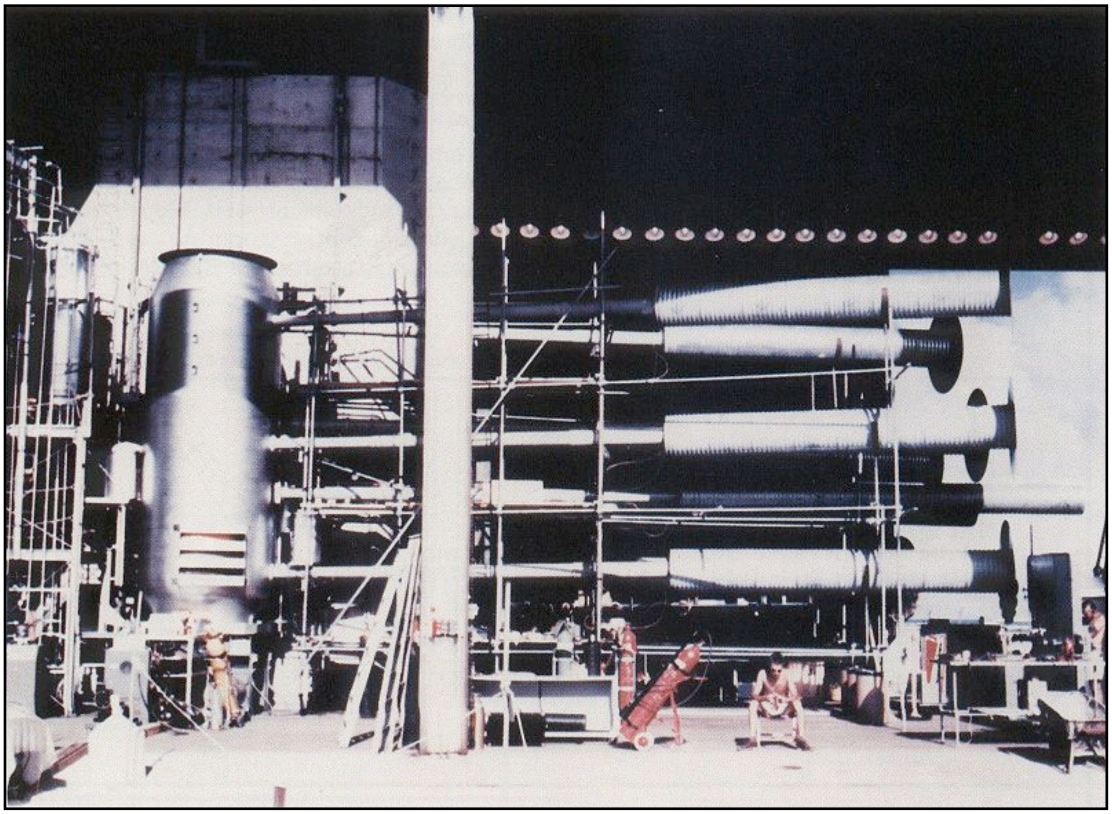


Fission weapons are sometimes called atomic bombs, while fusion weapons are also known as hydrogen bombs or thermonuclear weapons. The basic components of a fusion weapon are shown in this diagram (source: Wikimedia Commons). The "primary" is basically an implosion fission weapon that is used to ignite the secondary, fusion reaction. Hydrogen has three isotopes:

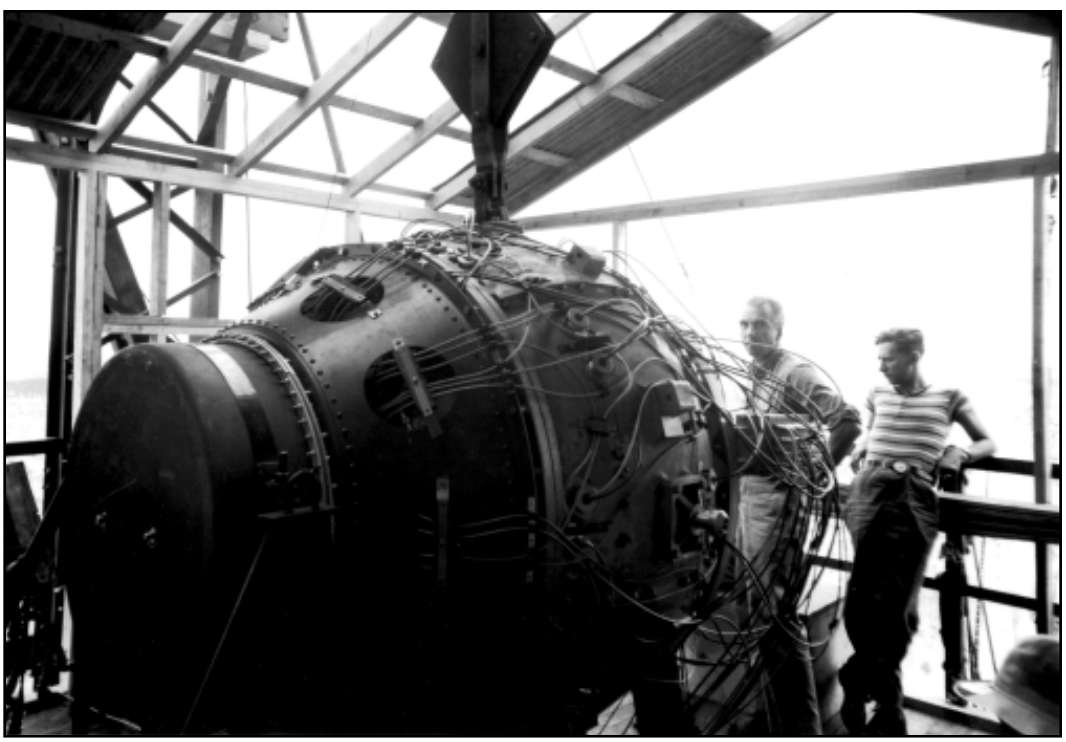
- Normal hydrogen (chemical symbol H) has a single proton in its nucleus and no neutrons. It makes up 99.985% of naturally occurring hydrogen. Light Water Reactors use normal or light water, H_2O.
- Deuterium (chemical symbol D or ^2H) has one proton and one neutron and makes up almost all of the remaining 0.015% of naturally occurring hydrogen. Heavy Water Reactors use heavy water, D_2O, and are more proliferation-prone than Light Water Reactors because, like Magnox reactors, they can use naturally occurring (unenriched) uranium as their fuel.
- Tritium (chemical symbol T or ^3H) has one proton and two neutrons. Unlike hydrogen and deuterium, tritium is radioactive, with a half-life of about 12 years. Only trace amounts occur in nature and the tritium used in nuclear weapons must be man-made.

The most useful fusion reaction in a nuclear weapon is for a deuterium nucleus to fuse with a tritium nucleus. All together those two nuclei have two protons and three neutrons. When they fuse, they produce a helium nucleus with two protons and two neutrons, and an extra neutron that is ejected. (The extra neutron adds to the fission reaction and makes use of the U-238 tamper shown in the diagram. This is an exception to the general rule that U-238 is not useful as bomb fuel. U-238, by itself, cannot be used in a weapon, and requires either HEU or plutonium.) The fusion of the deuterium and tritium nuclei releases a large amount of energy, which is what makes the weapon explode.

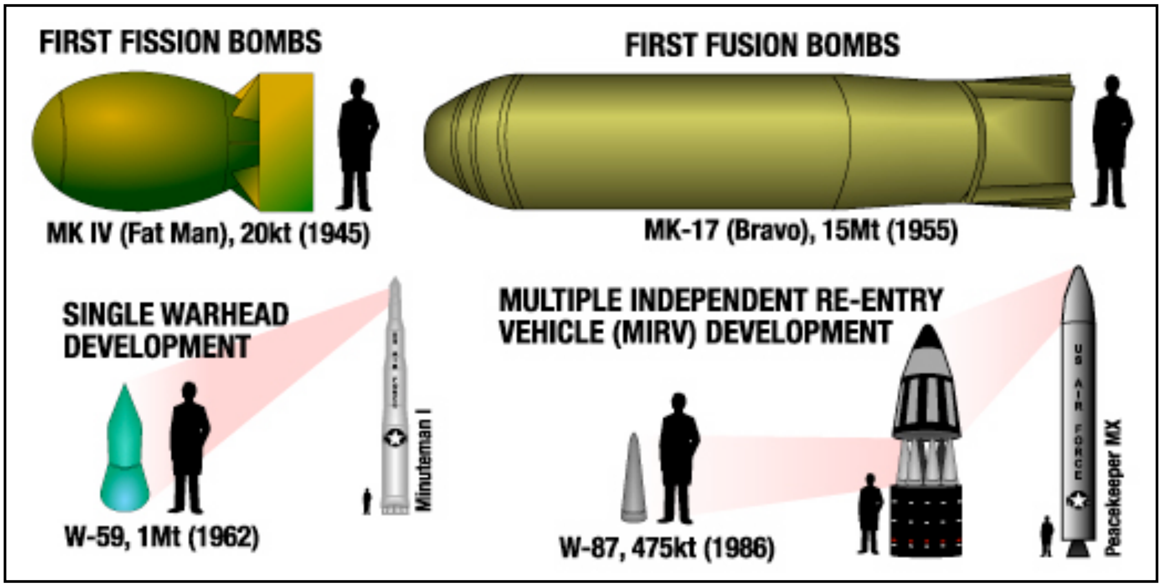
The first "hydrogen bomb," codenamed Ivy Mike, was anything but a bomb as can be seen in the picture below (source: US Department of Energy). To get an idea of the apparatus' size, note the men near the lower right hand corner of the picture. It was intended solely as a proof of concept, which purpose it served well. It had a yield of slightly over 10 megatons.



The first atomic weapon, used in the July 1945 Trinity test, is shown below for comparison purposes (source: US Department of Energy). While large, an airborne version was possible.



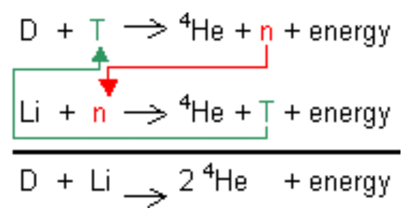
The next figure (source: Wikimedia Commons) depicts the evolution of nuclear weapons over the years, showing how they have been miniaturized. It is hard to comprehend that the 475 kiloton W87 warhead shown in the lower center of the figure is small enough to fit in a backpack, yet can destroy a city. But comprehend it, we must.



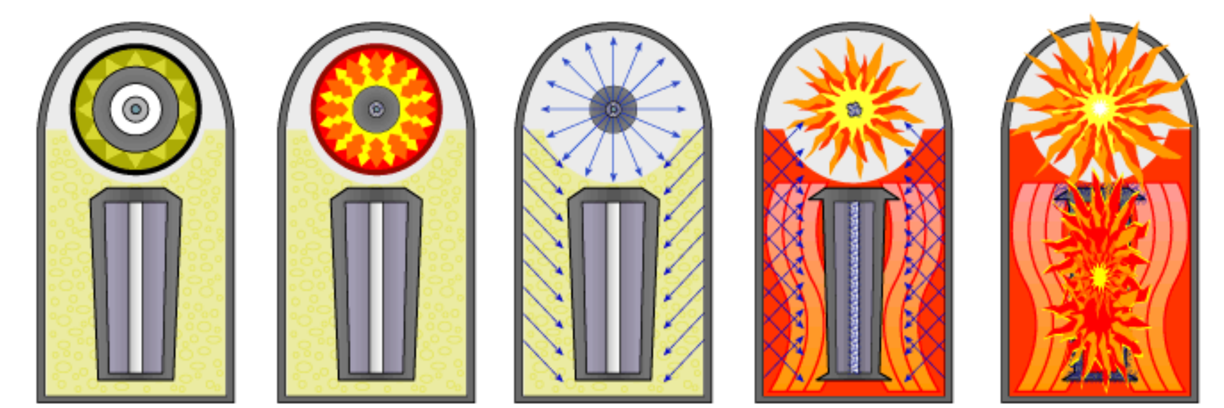
The nose cone of the MX missile (in lower right corner of the figure) can hold up to ten W87 warheads, each independently targeted, a technique is known as a MIRVing the missile. (MIRV stands for Multiple, Independently-targetable Reentry Vehicle.) Initially, highly MIRVed missiles were seen as a cost-effective way to increase an arsenal, but over time they came to be seen as dangerous and destabilizing. That is because MIRVed missiles make an attractive target for a first strike. It only takes one warhead (or several "to play safe") to knock out an enemy missile with a much larger number of warheads. This leads to crisis instability, in which there is an incentive to strike first. In consequence, recent arms control agreements discourage highly MIRVed missiles. For example, the New START Treaty that was recently ratified by the Senate limits both the US and Russia to 700 deployed launchers (missiles and bombers) and 1,550 deployed warheads, allowing only slightly more than 2:1 MIRVing.

There is one more aspect of nuclear weapons that I will cover in this handout, but it is optional reading since this is getting more technical than needed. I noted above that fusion uses deuterium and tritium, two isotopes of hydrogen. At normal temperatures and pressures, all hydrogen isotopes are a gas, and therefore not very dense. Ivy Mike got around this problem by using liquid deuterium and tritium, which helps explain the size of the apparatus – the cryogenic equipment all by itself was quite large. Later, it was realized that the required fuel could be stored in solid form at normal temperatures and pressures by using an innovative approach.

Lithium and hydrogen combine chemically to produce a solid compound or salt LiH, known as lithium hydride, shown in the attached photo. By using deuterium in place of normal hydrogen, the salt becomes lithium deuteride, LiD. The basic fusion equation for a nuclear weapon is the first line of the next figure: Deuterium combines with tritium to produce helium, an extra neutron and energy. The neutron can be captured by a lithium atom, which then fissions to produce helium, tritium and energy. As shown by the green arrow, the tritium thus produced can then fuse with another deuterium nucleus, allowing the reaction to continue. The third line of the figure "adds" the first two equations to show that the overall effect is that lithium and deuterium can be the fuel for the fusion, and that is exactly what composes lithium deuteride! This approach not only solves the low density problem of hydrogen, but also the short half-life problem of tritium. As already noted, tritium has a half life of only 12 years. Hence, if tritium were used as fuel, some of it would have to be replaced every few years. The lithium deuteride is stable for long periods of time and does not require such periodic refueling.



The diagram shown below (source: Wikimedia Commons) traces the steps in the detonation of a thermonuclear weapon based on lithium deuteride, and is also optional reading. In the second step, HE stands for High Explosives.



1. Warhead before firing; primary (fission bomb) at top, secondary (fusion fuel) at bottom, all suspended in polystyrene foam.

2. HE fires in primary, compressing plutonium core into supercriticality and beginning a fission reaction.

3. Fissioning primary emits X-rays which reflect along the inside of the casing, irradiating the polystyrene foam.

4. Polystyrene foam becomes plasma, compressing secondary, and plutonium sparkplug begins to fission.

5. Compressed and heated, lithium-6 deuteride fuel begins fusion reaction, neutron flux causes tamper to fission. A fireball is starting to form...