

Based on excerpts from Section 2 of **Nuclear Weapons Frequently Asked Questions** by Carey Sublette.

### **"Teller-Ulam" Summary**

All thermonuclear weapons existing in the world today appear to be based on a scheme usually called the "Teller-Ulam" design (after its inventors Stanislaw Ulam and Edward Teller), or "staged radiation implosion" for a physically descriptive designation. Other designs have been devised that use thermonuclear reactions to enhance weapon yield in various ways, but the term "hydrogen bomb" can be taken to be virtually synonymous with this scheme.

### **Basic Principles of Staged Radiation Implosion**

Using the easy to ignite, but very costly, tritium-deuterium fuel it is possible to ignite a reasonably efficient fusion burn in fuel at normal densities using the heat from a fission explosion (50-100 million degrees K). However, it is militarily desirable to use fuels that are cheaper, and more stable than tritium. Deuterium, the sole fuel in reactions 2 and 3 (see Fusion Principles) is relatively cheap (especially considering its enormous energy content) and is completely stable. Pure deuterium has been used in at least one fusion weapon test - Ivy Mike, the first true fusion weapon explosion in history (1 November 1952). Unfortunately since deuterium is hydrogen it is difficult to store. It must either be highly compressed, or liquefied at extremely low temperatures. This problem can be overcome by combining the deuterium chemically with lithium to form lithium deuteride, a stable solid. An additional benefit is that through reactions 5 and 6, the lithium can itself participate in the fusion reaction.

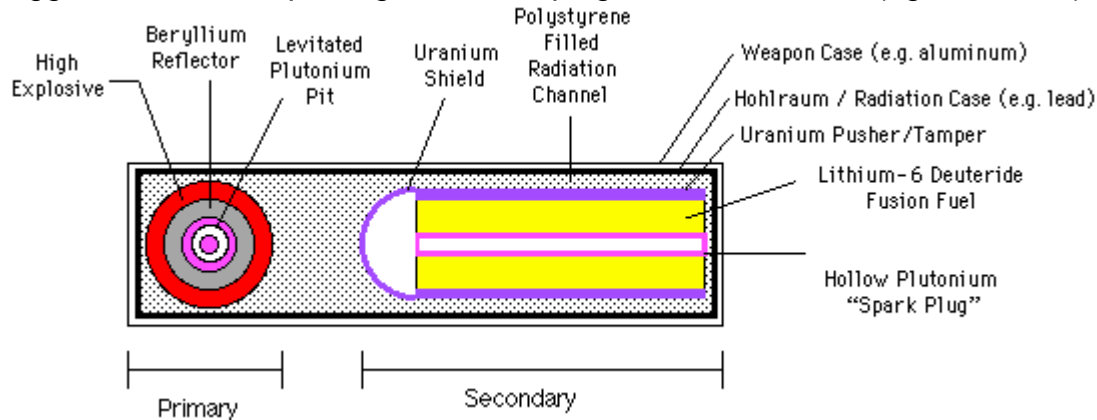
To make use of these fuels, the slower reaction rates must be offset by compressing them to densities hundreds or thousands of times greater than those of normal conditions. At any given temperature the reaction rate goes up with the square of the density, a thousand-fold compression gives a million-fold reaction rate increase.

The work required to compress a gas is proportional to its temperature (at these pressures the physical strength of materials is negligible, and everything can be considered a gas). To minimize the work required for compression, or alternatively to achieve maximum compression for a given amount of work, it is important to keep the fusion fuel from getting hot until after the desired density is reached.

The key to making large fusion bombs is finding a way for using the energy of an atomic bomb trigger to compress a mass of deuterium sufficiently for the D-D reactions to become practical, followed by heating of the mass to ignition temperatures after the proper density has been achieved. The technique for doing this is staged radiation implosion, also called the Teller-Ulam configuration after its original joint inventors, Stanislaw Ulam and Edward Teller (also reinvented independently by Andrei Sakharov and his associates, and by others in Britain, France, and China).

The Teller-Ulam configuration makes use of the fact that at the high temperatures of a fission bomb 80% or more of the energy exists as soft X-rays, not kinetic energy. The transport of energy by radiation from the fission core greatly exceeds the core's expansion rate (a mere 1000 km/sec or so). It is possible then to use this energy to compress, and ignite a physically separate mass of fusion fuel (the second stage) through radiation implosion before the expanding trigger disrupts it.

The principles of the Teller-Ulam configuration are more easily explained with the help of the diagram below. The bomb casing is roughly cylindrical, with the fission Primary (or "trigger") at one end. The fusion fuel (lithium deuteride in the diagram) is a cylinder or ellipsoid wrapped in a pusher/tamper - a layer of very dense material (uranium or tungsten). Running down the axis of the fuel cylinder is a Pu-239 or U-235 rod, 2-3 cm or so in diameter. Lining the casing is a layer of plastic or plastic foam. Separating the trigger from the fuel package is a thick plug of dense material (again U or W).



When the primary explodes, the X-rays escaping from the fission trigger fill the radiation channel, the space between the bomb casing and the fusion capsule, with a photon gas. This space is filled with plastic foam, essentially just carbon and hydrogen, which becomes completely ionized and transparent as the x-rays penetrate. The inner casing and outer capsule surfaces are heated to very high temperatures. The uranium shield between the trigger and the fusion capsule, and capsule pusher/tamper, prevents the fusion fuel from becoming heated prematurely.

Thermal equilibrium is established extremely rapidly, so that the temperature and energy density is uniform throughout the radiation channel. As the surface of the tamper becomes heated, it expands and ablates (blows off the fuel capsule surface). This ablation process, essentially a rocket turned inside out, generates tremendous pressure on the fuel capsule and causes an accelerating implosion. Thermal equilibrium assures that the implosion pressure is very uniformly distributed. The transparent carbon-hydrogen plasma retards the early expansion of the tamper and casing plasmas, keeping the radiation channel from being blocked by these opaque high-Z materials until equilibrium is fully established.

The force that compresses and accelerates the fusion fuel inward is provided solely by the ablation pressure. The other two possible sources of pressure - plasma pressure (pressure generated by the thermal motion of the plasma confined between the casing and the fuel capsule) and radiation pressure (pressure generated by thermal X-ray photons) do not directly influence the process.

The pressure exerted by the plasma causes cylindrical (or spherical) implosion of the fusion capsule, consisting of the pusher/tamper, fuel, and the axial fissionable rod. The capsule is compressed to perhaps 1/30 of its original diameter for cylindrical compression (1/10 for spherical compression), and thus reaches or exceeds 1000 times its original density. It is noteworthy that at this point the explosive force released by the trigger, an amount of energy sufficient to destroy a small city, is being used simply to squeeze several kilograms of fuel!

It is unlikely that the fissionable rod reaches such extreme compression however. Located at the center, it will experience an extremely violent shock wave that will heat it to high temperatures but compress it only modestly, increasing its density by a factor of 4 or so. This is sufficient to make the rod super-critical. Depending on the degree of symmetry and the physics of the particular capsule collapse process higher densities are possible. Thermalized neutrons trapped in the fusion fuel, which are left over from the intense fission neutron flux, initiate a chain reaction as soon as the rod becomes critical. The rod fissions at an accelerating rate as it and the rest of the fuel capsule continue to implode and acts as the fusion "spark plug". Combined with the high temperatures generated by the convergent shock wave, this raises the temperature of the fusion fuel around the rod high enough to initiate the fusion reaction. Self-supporting fusion burning then spreads outward. The fusion tamper prevents the escape of thermal radiation from the fuel, enhancing the burn efficiency considerably. The temperatures generated by fusion burning can considerably exceed that produced by fission (up to 300 million K). As the temperature rises, the fusion reactions accelerate.

The fuel in the fission capsule consists of lithium deuteride that may be enriched in the Li-6 isotope (which makes up 7.5% of natural lithium). There is some tritium generated by the fission neutrons, but as noted above the contribution to bomb yield is insignificant. Far more tritium is produced by the D+D reactions, either directly by reaction 3, or by reaction 5 via the neutrons produced in reaction 2.

Since the D+T reaction rate is so high, and there is large excess of deuterium, the tritium is consumed almost as fast it is produced. The 14.1 MeV neutrons also produce large amounts of tritium from Li-7 through reaction 6.

A large part of the fusion fuel can be burned before expansion quenches the reaction by reducing the density, which takes some 20-40 nanoseconds. The power output of a fusion capsule is noteworthy. The largest bomb ever exploded had a yield of 50 Mt, almost all produced by its final fusion stage. Since 50 Mt is  $2.1 \times 10^{17}$  joules, the power produced during the burn was around  $5.3 \times 10^{24}$  watts. This is more than one percent of the entire power output of the Sun ( $4.3 \times 10^{26}$  watts)!! The peak output was possibly even greater.

The 2.45 MeV and 14.1 MeV neutrons that escape from the fusion fuel can also contribute greatly to bomb yield by inducing fission in the highly compressed fusion tamper. This extra boost can release most of the explosion energy, and commonly accounts for half of the yield of large fission-fusion-fission bombs and can reach at least 85% of the total yield.

The Teller-Ulam fusion bomb described so far is called a "two stage bomb". The fission trigger (the first stage) compresses the fusion capsule (the second stage). As powerful as the trigger is, there is a limit to how large a capsule it can compress in the brief time available. If a still bigger bomb is desired, then the explosion of the fusion secondary can be used to compress and explode a larger third stage. Each stage can be 10-100 times the size of the previous stage. The 50 Mt bomb mentioned above was a three-stage weapon.