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Fusion reactions, also called thermonuclear reactions, are reactions between the nuclei of certain isotopes of light elements. If the nuclei collide with sufficient energy (provided by heat in a bomb, or by a particle accelerator in the laboratory) then there is a significant chance that they will merge to form one or more new nuclei with the release of energy. Different nuclei combinations have different inherent likelihoods of reacting in a collision at a particular temperature. The rates of all fusion reactions is affected by both temperature and density. The hotter and denser the fusion fuel, the faster the fusion "burn".

The fusion reactions that occur in stars are not the same as the ones that occur in thermonuclear weapons or (laboratory fusion reactors). The somewhat complex catalyzed fusion cycle in stars that converts light hydrogen (protium) into helium is extremely slow, which is why the lifetime of the Sun is measured in billions of years. The fusion reactions used in bombs and prospective powerplant designs are simple, and extremely fast - which is essential since the fuel must be fully consumed within microseconds. These reactions thus are based on the same general principles as stellar fusion, but are completely different in detail.

Candidate Fusion Reactions

The most important fusion reactions for thermonuclear weapons are given below:

1. D + T - He-4 + n + 17.588 MeV
2. D + D - He-3 + n + 3.268 MeV
3. D + D - T + p + 4.03 MeV
4. He-3 + D - He-4 + p + 18.34 MeV
5. Li-6 + n - T + He-4 + 4.78 MeV
6. Li-7 + n - T + He-4 + n - 2.47 MeV

[D and T stand for deuteron or deuterium (H-2), and triton or tritium (H-3) respectively.]

At the temperatures found in fission bombs reaction 1 has a rate 100 times faster than the next fastest candidate (reactions 2 and 3 combined), which are in turn 10 times faster than reaction 4. The rates of reactions 1 - 4 all increase rapidly (exponentially) with temperature, but not in the same proportion. At the higher temperatures achievable by fusion, reaction 4 exceeds the combined rate of reactions 2 and 3. Other reactions also occur between the isotopes listed here, but the reactions rates are too low to be important.

Some additional important facts about these reactions:

The neutron produced in reaction 1 is extremely energetic, it carries away 14.06 MeV of the reaction energy, the alpha particle (He-4 nucleus) only 3.52 MeV.

The neutron produced in reaction 2 has an energy of only 2.45 MeV (similar to the faster fission neutrons), with the He-3 carrying 0.82 MeV. The division of energy in reaction 3 is 1.01 MeV for the triton, and 3.03 MeV for the proton. The two D+D reactions are equally likely and each will occur half the time.

In reaction 4 the alpha particle carries off 3.67 MeV, the proton 14.67 MeV.

Reactions 5 and 6 are not thermonuclear reactions, strictly speaking. They are neutronic reactions, like fission, and do not require heat or pressure, just neutrons in the correct energy range. This distinction is usually ignored in the literature about nuclear weapons however. The Li-6 + n reaction requires neutrons with energies is the low MeV range or below. The Li-7 + n reaction is only significant when the energies are above 4 MeV.

Basic Principles of Fusion Weapon Design

Designs Using the Deuterium+Tritium Reaction

At ordinary material densities (e.g. liquid hydrogen, compressed hydrogen gas, or hydrogen-rich solids) reaction 1, the D+T reaction, is the only reaction that can occur to a significant extent at the temperature of an atomic bomb (50-100 million degrees, the temperature at the center of the Sun is only 14 million degrees!). This reaction can be used by simply allowing the fission explosion to heat up the fuel to fusion temperatures, requiring at most modest compression by the fission reaction itself. The high energy neutrons produced by this reaction are thus used to "boost" fission bombs.

The shortcoming with using the D+T reaction is that tritium is radioactive and decays at a rate of 5.5% year. This means that it does not occur in nature and must be manufactured through the use of reaction 5 in a nuclear reactor. In a weapons program tritium must compete with plutonium production in weapons production reactors, and it costs 80 times as much to produce one gram tritium compared with one gram of plutonium due its low atomic weight. It would be far too expensive to produce enough to make high yield fusion bombs. The decay also means that it must be continually replenished. This reaction, using reactor manufactured tritium, has been used in low-yield neutron bombs where large amounts of tritium are not necessary

The production of tritium through reaction 5 can also be carried out in an atomic bomb, using the neutrons that escape from the critical assembly. This approach was used in the first hydrogen bomb tested by the Soviets. A large bomb cannot be manufactured using this method though because there are insufficient neutrons produced. On average each fission produces roughly one spare neutron, and releases 180 MeV of energy. If the spare neutron is captured by Li-6, producing one atom of tritium, which then fuses, we get a total energy production of 22.4 MeV. We would expect then that the fusion yield would be no more than about 10% of that of the fission trigger. If the fusion energy were the only contribution to the bomb's yield, then there would be no point in using this technique. The 14.1 MeV neutron from the D+T reaction can however cause fission in U-238, which is used in the fission tamper. This extra fission reaction doubles the bombs yield. Due to the low fusion yield inherent to the design this could be considered a type of fusion-boosted fission weapon.

Designs Using Other Fuels

It is militarily desirable to use fuels that are cheaper, and more stable than tritium. Deuterium, the sole fuel in reactions 2 and 3, 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, arguably the first true fusion weapon explosion in history (1 November 1952). Unfortunately deuterium, like all elemental hydrogen, is difficult to store. It must either be highly compressed, or liquified 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.

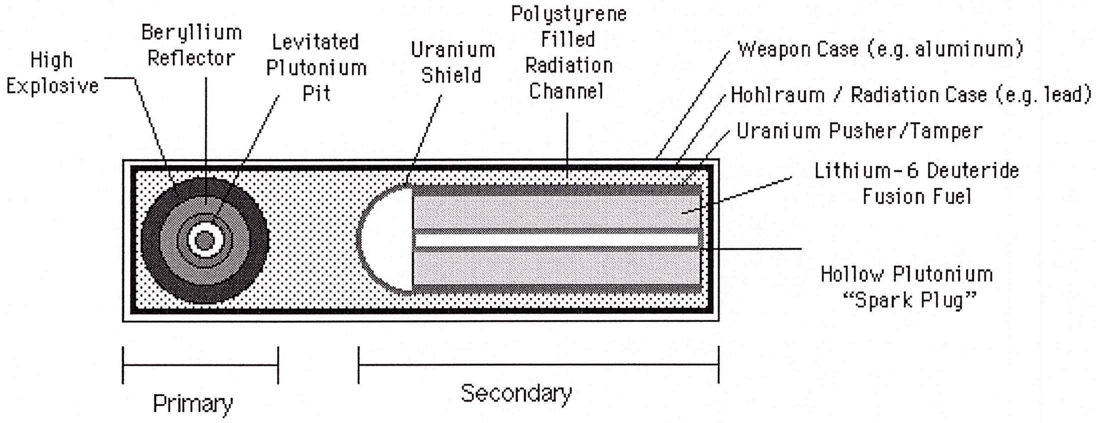
To make use of these fuels, the slower reaction rates must be offset by compressing them to densities hundreds or thousands of times greater than those of normal conditions. At any given temperature the reaction rate goes up with the square of the density, a thousand-fold compression gives a million-fold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



Components of the Teller-Ulam design:

- External Casing (made of structural material: steel, aluminum, plastic, etc.)
- Primary (fission trigger)
- Radiation Shield (high-Z material: uranium or tungsten; this may also contain boron-10 as a neutron absorber)
- Hohlraum or Radiation Case (high-Z material: uranium, lead, or tungsten, etc.)
- Radiation Channel (gap between the casing and the fusion pusher tamper; basically empty, often filled with plastic foam)
- Fusion Pusher/Tamper (high-Z material: natural/depleted uranium, HEU, tungsten, lead, etc.)
- Fusion Fuel (usually Li-6 deuteride; also natural lithium deuteride, liquid

deuerium, etc.)

- Spark Plug (fissionable rod of HEU or plutonium)

When the trigger 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. As the temperature rises the fusion reactions accelerate, enhancing the burn efficiency considerably. The temperatures generated by fusion burning can exceed 300 million K, considerably more than that produced by fission.

The fuel in the fusion capsule consists of lithium deuteride that may be enriched in the Li-6 isotope (which makes up 7.5% of natural lithium). Natural lithium has been used with success in fusion bomb designs, but modern light weight designs seem to use lithium enriched in Li-6.

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 can 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 2.1x10^17 joules, the power produced during the burn was around 5.3x10^24 watts. This is more than one percent of the entire power output of the Sun (4.3x10^26 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.

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