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THE COMPONENTS OF NUCLEAR AND THERMONUCLEAR WEAPONS

A country intending to fabricate nuclear weapons must acquire or produce a wide range of components. The major components for a pure fission weapon include: very high quality conventional high explosives; detonators for these explosives; electronic circuits to fire the detonators; a tamper and reflector; a core of fissile nuclear material, mainly weapon-grade plutonium or highly-enriched uranium; a neutron source to initiate a fission chain reaction.

If the explosive yield of a fission weapon is to be ‘boosted’ by some fusion a tritium source will be required. A thermonuclear weapon requires a quantity of lithium deuteride to provide fusion and highly-enriched uranium to ignite the fusion process. The components of nuclear and thermonuclear weapons are now described in some detail.

FISSION WEAPONS

The basic nuclear weapon is the fission weapon (originally called the A-bomb) which relies entirely on a fission chain reaction to produce a very large amount of energy in a very short time—roughly a millionth of a second—and therefore a very powerful explosion. The fission weapons built so far have used the U-235 or Pu-239 as the fissile material. Thorium (Th) could, in theory, also be used. When the nucleus of the isotope Th-232 captures a neutron it becomes Th-233 which undergoes radioactive decay to U-233, which is fissile material like U-235 or Pu-239. Thorium has, however, not been used as the fissile material in nuclear weapons.

Critical mass

The smallest amount of fissile in which a self-sustaining chain reaction is just sustained is called the critical mass. The critical mass is that from which just as many neutrons escape per unit time as are released by fission.

If this mass of material is increased, the number of neutrons produced by fission builds up, and considerably more fissions occur in each successive generation of fission. A ‘super-critical’ mass is created and a nuclear explosion takes place. In a super-critical mass the rate of production of fission neutrons exceeds all neutron losses and a rapid and uncontrollable increase in the number of neutrons within the mass occurs.

The critical mass depends on a number of factors. First, the nuclear properties of the material used for the fission, whether it is U-235 or Pu-239. Second, the shape of the material—a sphere is the optimum shape because for a given mass the surface area is minimized which, in turn, minimizes the number of neutrons escaping through the surface per unit time and thereby lost to the fission process. Third, the density of the material (the higher the density the shorter the average distance travelled by a neutron before causing another fission and therefore the smaller the critical mass). Four, the purity of the material (if materials other than the one used for fission are present, some neutrons may be captured by their nuclei instead of causing fission). Five, the physical surrounding of the material used for fission (if the material is surrounded by a medium like beryllium, which reflects neutrons back into the material, some of the reflected neutrons may be used for fission which would otherwise have been lost, thus reducing the critical mass).

Plutonium metal occurs in six phases, each having a different density (ranging from 19.8 to 15.92 grammes per cubic centimetre) and crystalline form. As normally produced, plutonium metal is brittle and difficult to machine into precise shapes. To make plutonium more machinable, it is alloyed, usually with gallium or indium. A typical alloy for use in nuclear weapons would probably contain 2 per cent by weight (8 per cent by atoms) of gallium.

Alloying plutonium in one phase prevents it changing to another phase. This is important because a phase change, and the associated change in density, will change the volume of the mass of plutonium which may distort it. It would be very undesirable if this occurred in the carefully machined plutonium pieces in a nuclear weapon.

The critical mass of, for example, a sphere of pure Pu-239 metal in the alpha phase, which has a density of 19.8 grammes per cubic centimetre and is the densest form of the metal, is about 10 kilogrammes. The radius of the sphere is about 5 centimetres, about the size of a small grapefruit. If the plutonium sphere is surrounded by a natural uranium neutron reflector, about 10 centimetres thick, the critical mass is reduced to about 4.4 kilogrammes, a sphere of radius of about 3.6 centimetres, about the size of an orange. A 32-centimetre thick beryllium reflector reduces the critical mass of alpha-phase Pu-239 to about 2.5 kilogrammes, a sphere of radius of 3.1 centimetres, about the size of a tennis ball.

Using a cunning technique called implosion, in which conventional chemical explosives are used to produce a shock wave which uniformly compresses the plutonium sphere, the volume of the plutonium sphere can be reduced and its density increased. If the original mass of the plutonium is just less than critical it will, after compression, become super-critical and a nuclear explosion will take place.

In practice, Pu-239 in the delta phase, which has density of 15.92 grammes per cubic centimetre, is used. The delta phase, which has a cubic crystalline form, would be typically stabilized as a gallium alloy. Using implosion the density of the plutonium can be roughly doubled so that a nuclear explosion could, with the best modern design including an effective, but practicable, reflector, be achieved with about 3 kilogrammes of delta-phase Pu-239. The trick is to obtain very uniform compression of the sphere. In such a weapon, the implosion will liquefy the plutonium before the explosion blows it apart.

Nuclear-weapon designers prefer the concentration of Pu-239 to be as high as possible. The larger the concentration, the smaller the critical mass and, hence, the bigger the explosive yield for a given weight of plutonium. Plutonium containing more than 93 per cent of Pu-239 is called weapons-grade. Nominal weapons-grade plutonium contains 0.05 per cent Pu-238; 93 per cent Pu-239; 6.4 per cent Pu-240; 0.5 per cent Pu-241; and 0.05 per cent Pu-242. For the best yield-to-weight ratio, super-grade plutonium is used, containing 98 per cent Pu-239 and 2 per cent Pu-240.

The complete fission of 1 kilogramme of Pu-239 would produce an explosion equivalent to that of 18,000 tonnes (18 kilotonnes, or kt) of TNT. Modern fission bombs have efficiencies approaching 40 per cent, giving yields of 7 kilotonnes or so per kilogramme of plutonium present. It is this high yield-to-weight ratio that makes nuclear weapons so special.

Implosion

In an implosion design, the plutonium would be surrounded by a spherical shell, made from a heavy metal, like natural uranium, which acts both as the tamper and reflector. The conventional explosive used to compress the plutonium sphere is placed outside the tamper.

The tamper has two functions. First, because the tamper is made of heavy metal, its inertia helps hold together the plutonium during the explosion to prevent the premature disintegration of the fissioning material and thereby obtain a greater efficiency. Second, the tamper

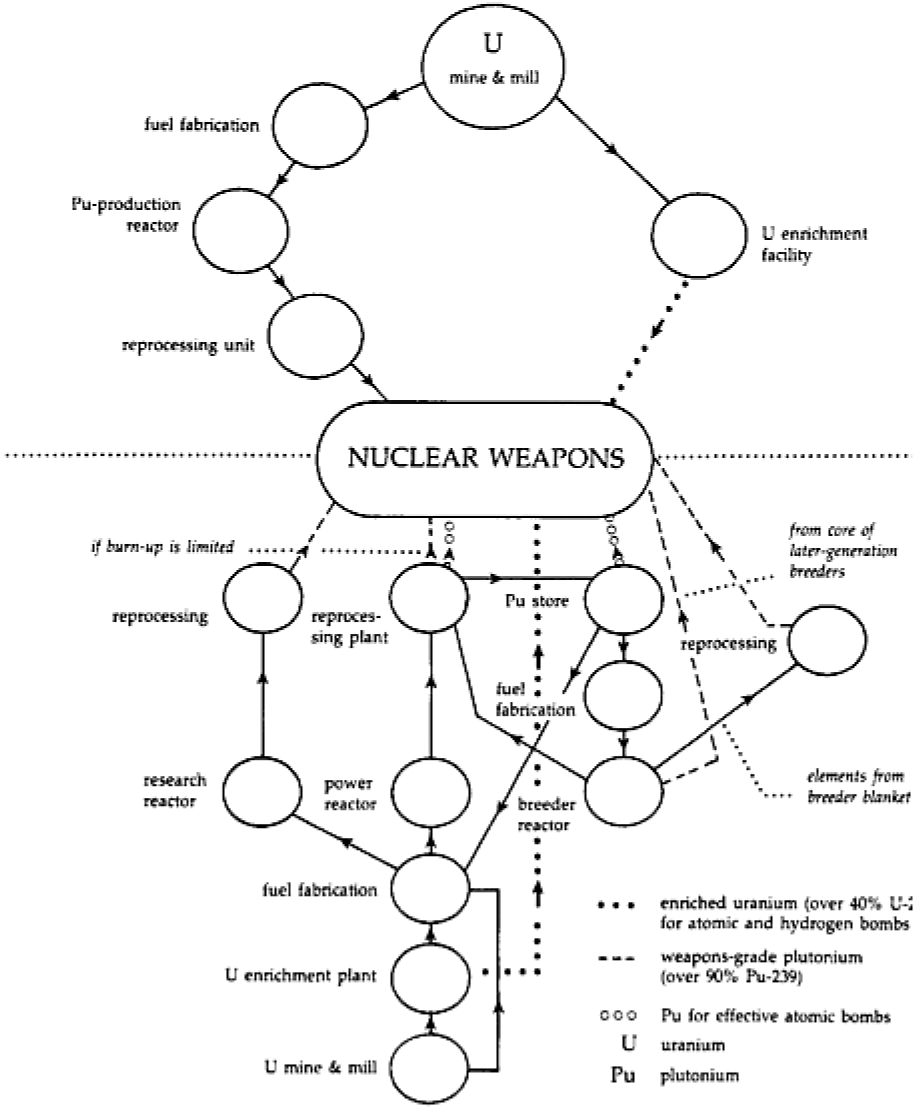

Figure 3 Direct routes to nuclear weapons. All these operations may be done under military control on a small scale and secretly. Nuclear explosives may be produced as by-products of a peaceful nuclear-power programme.

converts the divergent detonation wave into a convergent shock wave to compress the plutonium sphere.

The tamper may also serve to reflect back into the plutonium some of the neutrons which escaped through the surface of the plutonium core to minimize the mass of plutonium needed. In some designs the reflector is of a different material from the tamper, in which case the plutonium sphere is surrounded by another spherical shell, situated between the plutonium and the tamper. Beryllium is a good neutronreflecting material.

An excellent description of a first-generation plutonium fission nuclear weapon is given by Margaret Go wing. Her description of an early British weapon (which she calls ‘the gadget’) follows. The first nuclear weapons developed by a country are likely to be of this type.

> An implosion design has been chosen, in which the mass of high explosive, surrounding a sphere containing both the fissile material and a tamper, was so arranged as to produce a shock wave travelling radially inwards and thus compressing the material. (Author’s note: The high explosive was arranged in a number of shaped charges, called ‘lenses’.) The design had the advantage of high velocities, which reduced the chance of pre-detonation despite the many background neutrons present in plutonium; at the same time the material was compressed to such density that super-critical masses were obtained with comparatively little material. It had been realised at Los Alamos (the Manhattan Project) that performance could be improved by using explosive lens to turn the divergent waves, which started from detonators, into parts of a common spherical wave converging on the centre of the sphere.
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> The main components of the gadget can be listed, working from outside to the centre. First came the detonators, which operated from an impulse from a firing device and involved other auxiliaries like safety switches and arming circuits. The detonation had to be started simultaneously in all the lenses; the lenses themselves were carefully calculated shapes, containing a combination of fast and slow explosive so that transit from the detonator to every point on the inner spherical surface of lens was simultaneous. The detonation from the lenses then reached a spherical shell of homogeneous high explosive called the supercharge. Within the supercharge was the tamper, which converted the divergent detonation wave into a convergent shock wave, reflected some of the neutrons back into the fissile material and generally increased the efficiency of the explosion. Within the tamper was the plutonium and within that the initiator. The last component was necessary because, although the implosion resulted in a powerful compression of the fissile material and the surrounding tamper, the material would stay compressed only for a few microseconds and would then expand again very quickly. It was therefore essential to make sure that the chain started at the right moment. This could be done by creating at the centre of the fissile material an intense neutron source.
>
> (Gowing 1974)

The compression of the plutonium sphere can be improved if the sphere is suspended within the tamper, with an air gap between the sphere and the tamper. This space allows the tamper to gain momentum before hitting the sphere, considerably increasing the compressive shock, a technique called ‘levitation’ (Hansen 1988).

Pre-detonation

In a nuclear explosion exceedingly high temperatures (hundreds of millions of degrees centigrade) and exceedingly high pressures (millions of atmospheres) build up very rapidly (in about one-half of a millionth of a second, the time taken for about 55 generations of fission). The mass of the material used for fission expands at very high speeds—initially at a speed of about 1,000 kilometres a second. In much less than a millionth of a second the size and density of the material have changed so that it becomes less than critical and the chain reaction stops. The designer of a nuclear weapon aims at keeping the fissionable material together, against its tendency to fly apart, long enough to produce an explosion powerful enough for his purpose.

A major problem in designing implosion fission weapons for maximum efficiency is to prevent the chain reaction from being started before the maximum achievable super-criticality is reached—an eventuality called pre-detonation. Pre-detonation is most likely to be caused by a neutron from spontaneous fission—fission that occurs naturally without the stimulation of an external neutron—in the material used for fission. In 6 kilogrammes of Pu-239, for example, the average time between spontaneous fissions is only about three-millionths of a second. To prevent pre-detonation and loss of efficiency, the assembly of a plutonium bomb must be very rapid. Implosion is necessary.

The spontaneous fission rate in the plutonium used to fabricate a fission weapon is clearly important. The fewer spontaneous fissions the better. In super-grade plutonium the rate is about 20 spontaneous fission neutrons per gramme per second whereas it is 66 spontaneous fission neutrons per gramme per second in weapons-grade plutonium.

This rate is very small compared with the huge number of neutrons produced in a fission chain reaction. About 10^{23} nuclei of Pu-239 are fissioned to produce each kilotonne of explosive yield. This number of fissions would produce about 2.5×10^{23} neutrons.

Reactor-grade plutonium

The isotopic composition of the plutonium produced in reactors operated for different purposes varies. The plutonium produced specifically for military purposes is, as we have seen, rich in the isotope Pu-239, typically containing more than 93 per cent of Pu-239. Plutonium produced in nuclear-power reactors operated to produce electricity in the most economical way, known as reactor-grade plutonium, typically contains only about 60 per cent Pu-239. About 25 per cent is Pu-240 (in weapons-grade plutonium the amount is typically about 7 per cent) and about 10 per cent is Pu-241. If the reactor fuel is burnt at a very fast rate, the plutonium will contain about 40 per cent Pu-239, about 30 per cent Pu-240, about 15 per cent Pu-241, and about 15 per cent Pu-242.

Can reactor-grade plutonium be used to produce nuclear explosions? This is an important question because, if it can, countries operating nuclear-power reactors for peaceful purposes have access to plutonium that could be used to produce nuclear weapons. And, as the quantity of reactor-grade plutonium in the world increases, it becomes easier for a country to acquire it illegally and produce nuclear weapons. That reactor-grade plutonium can be used to produce a nuclear weapon has been shown in the USA, where at least two such devices have been built and tested.

The critical mass of typical reactor-grade plutonium in the form of a bare metal sphere surrounded by a natural uranium reflector, about 10 centimetres thick, is about 7 kilogrammes. Reactor-grade plutonium is usually stored, after reprocessing, in the form of plutonium oxide and is, therefore, most likely to be available in this form. The oxide can, however, be easily converted to the metal form.

Amory Lovins (1980) explains that the view that reactor-grade plutonium cannot be used in nuclear weapons is based on the following assumptions:

1. that reactor-grade plutonium is far more hazardous than weapon-grade plutonium to people dealing with it;
2. that a nuclear explosive device made from reactor-grade plutonium is much more likely to explode unintentionally;
3. that such a device, if it explodes at all, will not explode violently enough to do much damage, nor to accomplish the main aims of the makers; and
4. that its explosive yield is too unpredictable to be acceptable to its makers.

Lovins concludes that ‘each of these assumptions contains, in certain circumstances, an element of truth’ but, he adds, ‘each is generally, or can by plausible counter-measures be rendered, false. Their implication that reactor-grade plutonium is not very dangerous is wishful thinking, and causes the proliferation risks of civil nuclear activities to be gravely underestimated.’

The conventional high explosives

The timing of the detonations of the chemical explosives to produce the shock wave to compress the plutonium sphere is crucial for the efficient operation of an implosion atomic bomb. Microsecond (a milli-onth of a second) precision is essential. The shapes of the explosive lenses are rather complex and must be carefully calculated. The high explosive must be chemically extremely pure and of constant constituency throughout its volume.

The conventional high explosives used to compress the spherical fissile core of a nuclear weapon are one of the most crucial components. If the compression is not symmetrical or rapid enough the nuclear explosion will not reach its predicted explosive yield. So important is the constituency of the high explosives that details of the chemicals used, the methods of their preparation, and the size and shape of the charges are closely guarded secrets.

The Nagasaki bomb used high-explosive charges of Composition B, a mixture of cyclotrimethylenetrinitramine (RDX)—$(CH_2)_3N_3$ $(NO_2)_3$—and trinitrotoluene (TNT)—

C_6H_2 $(NO_2)3CH_3$. Composition B is a fastburning explosive more effective than TNT on its own. More modern implosion charges use diaminotrinitrobenzene (DATB)—C_6H_3 $(NO_2)_3NH_2$—or triaminotrinitrobenzine (TATB)—C_6H_3 $(NO_2)_3NH_3$. DATB and TATB are relatively insensitive to shocks.

Pentaerythrtoltetranitrate (PETN)—$C(CH_2O(NO_2)_4$ and cyclotetramethylenetetranitramine (HMX)—$(CH_2)_3N_3$ $(NO_2)_3$—have also been used in nuclear weapons. The Iraqis, for example, were experimenting with HMX for use in their nuclear weapons. The amount of high explosive used in a fission weapon has decreased considerably since 1945—from about 500 kilogrammes to as little as about 45 kilogrammes in modern nuclear weapons (Hansen 1988).

Normally, the more explosive charges there are the more perfect is the spherical symmetry of the shock wave. Forty or so detonations would be typical. Getting the timing of the detonation sequence—milli-microsecond (a thousandth of a millionth of a second) precision is essential—and the chemistry and geometrical shapes of the explosive lenses right are the most difficult problems in designing an efficient implosion-type nuclear fission weapon. The most sophisticated fission weapons use geometries other than the one described above. For example, the high explosive is arranged in an ellipsoid geometry, and only two detonators are used, one at each end of the ellipsoid. This arrangement is used, for example, in nuclear artillery shells.

Firing the detonators

A typical circuit to fire the detonators uses krytrons to generate short, high-current pulses with amplitudes of about 4,000 volts and rise-and-fall times of a few milli-microseconds. The krytron is a cold-cathode, gas-filled switch using an arc discharge to conduct high peak currents for short times.

The energy in the current pulse used to fire the detonators in a nuclear weapon is normally produced by charged capacitors. Because the rate of change of current is very large, the capacitors must have a very low self-inductance. This is why the manufacture of such capacitors, rugged enough for military use, requires special attention.

The neutron source

For maximum efficiency, the chain reaction in an atomic bomb must be initiated at precisely the right moment—the moment of maximum super-criticality. The initiation is achieved by a pulse of neutrons.

In earlier fission weapons, the neutron pulse was produced from a polonium-beryllium source. When alpha-particles from the polonium bombard the beryllium, neutrons are produced. In a fission weapon, the polonium and beryllium are contained in a hollow sphere placed at the centre of the plutonium sphere. The polonium and beryllium are placed on opposite sides of the hollow sphere. When the high-explosive lenses are detonated, the shock wave crushes the hollow sphere and mixes the polonium and beryllium, producing a pulse of neutrons.

In today’s nuclear weapons, the neutron pulse is produced by a small electronic device called a neutron ‘gun’, which is a much more effective neutron generator than a polonium-beryllium source. In a neutron gun a high voltage is used to accelerate

> small amounts of tritium and deuterium. When the tritium and deuterium nuclei collide (and fuse—in this case, a difference in electrical potential is used to give momentum to the nuclei, instead of the high temperature of a fission explosion), neutrons (on the order of several tens of millions) are released. These large numbers of initial neutrons create many fission reactions at the start of the fission chain reaction explosion, thus increasing the efficiency

of the explosion and allowing more of the plutonium to fission before it is blown apart (Hansen 1988).

The neutron gun can be used to vary the explosive yield of a fission nuclear weapon. Variable yields can be obtained either by varying the voltage across the device—which alters the velocity of the tritium and deuterium nuclei and hence the efficiency of the fusion process—or by varying the amount of tritium or deuterium used.

The problem of getting the timing of the shaped-charge detonations and the injection of the neutron pulse right is mainly theoretical, in calculating the timing sequence for optimum efficiency. The practical problems of manufacturing the electronic components and building the circuits to produce the calculated sequence of triggering pulses are much less difficult.

Highly-enriched uranium as fissile material

The alternative to Pu-239 as the fissile material in a nuclear weapon is U-235, although some of the most advanced types of nuclear weapons contain both materials arranged in thin concentric shells, rather than a solid sphere. Plutonium undergoes fission faster than uranium, and placing it inside a shell of enriched uranium makes more efficient use of its fission neutrons. In this way a greater explosive power can be achieved for a given mass of fissile material.

The amount of highly-enriched uranium in, for example, the American nuclear arsenal is about 500 tonnes, five times the amount of plutonium in the arsenal. But the more modern nuclear weapons tend to use relatively more plutonium than earlier models.

In U-235, the average time between spontaneous fissions is much greater than it is in Pu-239 and the so-called ‘gun’ method can be used to assemble a critical mass of U-235 in a nuclear weapon. In the Hiroshima bomb, for example, a less than critical mass of U-235 was fired down a ‘cannon barrel’ (the barrel from a naval gun) into another less than critical mass of U-235 placed in front of the ‘muzzle’. When the two masses came together they formed a super-critical mass which exploded.

About 60 kilogrammes of U-235 were used in the Hiroshima bomb. About 700 grammes were fissioned. The average time between spontaneous fissions was about one-fiftieth of a second—quite adequate for the gun technique. The yield of the Hiroshima bomb was about 12.5 kt.

A fission weapon using U-235 can, however, also be made using the implosion technique. If surrounded by a reflector made from natural uranium 15 centimetres thick, 100 per cent pure U-235 has a critical mass of 15 kilogrammes (compared with 4.4 kilogrammes for Pu-239). With uranium enriched to 40 per cent U-235, the critical mass increases to 75 kilogrammes; with 20 per cent U-235, it is 250 kilogrammes. High concentrations of U-235 are, therefore, highly desirable if the material is to be used to produce nuclear weapons.

Designs based on the Hiroshima and Nagasaki bombs are likely to be used by countries beginning a nuclear-weapon programme. But even the first weapons now produced by a country would probably be more sophisticated than these early, primitive weapons. The Nagasaki bomb, for example, was about 3 metres long, 1.5 metres wide, and weighed about 4.5 tons. A modern fission weapon, even the first produced in a nuclear-weapon programme, should weigh no more than a few hundred kilogrammes.

The difficulty of designing and fabricating a nuclear weapon from either Pu-239 or U-235 is often exaggerated. A competent group of nuclear physicists, and electronic and explosive engineers, given adequate resources and access to the literature, would have little difficulty in designing and constructing such a weapon from scratch. They would not need access to any classified literature.

BOOSTED FISSION WEAPONS

Although very large explosions—equivalent to the explosion of 100 or 200 kt of TNT—can be obtained from nuclear weapons based on pure fission, there is a limit to the explosive power that can be obtained from a *militarily operational* one. The maximum explosive power of a militarily usable fission weapon is 50 kt. Higher explosive power than can be achieved by a pure fission nuclear device can be obtained by ‘boosting’.

In a boosted weapon, some fusion material is placed at the centre of the plutonium sphere in a fission weapon. When the fission weapon explodes, the temperature and pressure at the centre of the core are such that nuclear fusion can take place (see page 38). The neutrons produced during the fusion process produce additional fissions in the plutonium in the weapon before it disintegrates, increasing its efficiency. In an unboosted fission weapon, the rate of production of generations of fissions is about 100 per microsecond, for a boosted weapon it is about 1,000 per microsecond. Boosted weapons are, therefore, about ten times more efficient than unboosted ones.

The fusion in a boosted weapon is used mainly as an additional source of neutrons to help the fission process, rather than as a direct source of energy. Because the efficiency of the weapon is increased, a higher explosive yield is achieved for a given weight of plutonium.

Boosted weapons are essentially sophisticated fission weapons. Using boosting, a much higher explosive power is obtained from a given amount of plutonium. Militarily usable boosted weapons have explosive powers of up to about 500 kt, i.e. about ten times the power of non-boosted operational weapons. The yields of the most powerful boosted weapons are equal to those of low-yield thermonuclear weapons.

In a typical boosted weapon a mixture of deuterium and tritium gases (heavy isotopes of hydrogen) is used as the fusion material. Deuterium is found in natural hydrogen at a concentration of 0.015 per cent. Tritium is normally produced by bombarding lithium-6 with neutrons in a nuclear reactor.

A pressurised deuterium-tritium mixture is injected from a reservoir, placed outside the fission-weapon core, into a space at the centre of the plutonium sphere after the fission process has begun. Because the centre of the sphere is needed for the fusion mixture, a boosted weapon must be initiated by an external neutron gun.

The pressure in the boosting system is typically about 20 million N per m^2 and about 5 grammes of the deuterium-tritium gas mixture are injected into the centre of the plutonium sphere. The timing of the injection is crucial for maximum efficiency.

The explosive yield of a boosted weapon can be varied by varying the amount of tritium and deuterium injected onto the core of the weapon. Alternatively, as described above, the yield can be varied by varying the voltage on the neutron gun.

Because tritium has a relatively short half-life of 12.3 years, the tritium in the reservoir has to be replaced regularly. For ease of replacement the reservoir is fixed on the exterior of the weapon.

THERMONUCLEAR WEAPONS

If explosions in the range of a few thousand kilotonnes are required, extra energy must be obtained from fusion. The fusion process is the opposite of fission. In fission, heavy nuclei are split into lighter ones. In fusion, light nuclei are formed (i.e. fused) into heavier nuclei.

In nuclear weapons, the heavier isotopes of hydrogen—deuterium and tritium—are fused together to form helium. The fusion process, like the fission process, produces energy and is accompanied by the emission of neutrons. There is no critical mass for the fusion process and therefore, in theory, there is no limit to the explosive yield of fusion weapons—or H-bombs (H for hydrogen) as they are often called.

Fission is relatively easy to initiate—one neutron will start a chain reaction going in a critical mass of a fissile material, such as Pu-239 or U-235. But fusion is possible only if the nuclei to be fused together are given a high enough energy to overcome the repulsive electric force between them due to their positive electric charges. In H-bombs, this energy is provided by raising the temperature of the fusion material. Because H-bombs depend on heat they are also called thermonuclear weapons.

In a typical thermonuclear weapon, deuterium and tritium are fused together. But to get this fusion reaction to work, the deuterium-tritium mixture must be raised to a temperature of a hundred million degrees centigrade or so. This can be provided only by a pure fission nuclear weapon (atomic bomb) in which such a temperature occurs at the moment of the explosion. An H-bomb, therefore, consists of a fission stage, which is an atomic bomb acting as a trigger, and a fusion stage, in which hydrogen isotopes (tritium and deuterium) are fused by the heat produced by the trigger.

Normally, the fusion material is in the form of a cylinder. The cylinder is made out of lithium-6 deuteride. When neutrons from the fission explosion bombard lithium-6 nuclei in the lithium deuteride, tritium nuclei are produced. The tritium nuclei fuse with deuterium nuclei in the lithium deuteride to produce fusion energy.

These nuclear processes, employing lithium in a breeding cycle to produce tritium, and deuterium and tritium to produce fusion, can be described as follows:

lithium-6+neutron→tritium+helium-4+4.8 Mev of energy
deuterium+tritium→helium-4+neutron+17.6 Mev of energy
(Mev=million electron volts of energy)

It is very advantageous to use lithium-6 deuteride as the fusion material because it is a solid at normal temperatures whereas tritium and deuterium, the fusion materials used in boosted weapons, are gases at normal temperatures. It is, of course, much easier to construct nuclear weapons from solid materials than gases.

Lithium, the lightest known solid, occurs in nature as the mixture of two isotopes lithium-6 and lithium-7. Most, 92.58 per cent, of natural lithium is lithium-7—only 7.42 per cent is lithium-6. Lithium-6 is separated from lithium-7 in natural lithium by the electrolysis of an amalgam of lithium and mercury. Lithium hydroxide is passed through the lithium-mercury amalgam and the separation of lithium-6 from lithium-7 occurs by chemical exchange by passing the mixture through exchange columns.

Chemical exchange takes place between the amalgam and the aqueous solution of lithium hydroxide. The lithium-7 is concentrated in the amalgam phase and the lithium hydroxide becomes enriched in lithium-6. By repeating the process through each of a number of columns, the proportion of lithium-6 is typically increased from the natural proportion to about 85 per cent.

The energy released from such a thermonuclear weapon comes from the fission trigger and the fusion material. But, if the fusion device is surrounded by a shell of uranium metal, the high-energy neutrons produced in the fusion process will cause additional fissions in the uranium shell. This technique can be used to enhance considerably the explosive power of a thermonuclear weapon. Such a weapon is called a fission-fusion-fission device. On average, about half of the yield from a typical thermonuclear weapon will come from fission and the other half from fusion.

H-bombs are much more difficult to design than fission nuclear weapons. The problem is to prevent the fission trigger from blowing the whole weapon apart before enough fusion material has been ignited to give the required explosive yield. Sufficient energy has to be delivered to the fusion material to start the thermonuclear reaction in a time much shorter than the time it takes for the explosion to occur. This means that the energy must be delivered with a speed approaching the speed of light.

This is achieved using the Teller-Ullman technique, invented by Edward Teller and Stanislaw Ullman. Rotblat has described the technique used:

> The solution to the problem lies in the fact that at the very high temperature of the fission trigger most of the energy is emitted in the form of X-rays. These X-rays, travelling with the speed of light, radiate out from the centre and on reaching the tamper (surrounding the fusion material) are absorbed in it and

> then immediately re-emitted in the form of softer X-rays. By an appropriate configuration of the trigger and the fusion material it is possible to ensure that the X-rays reach the latter almost instantaneously. If the fusion material is subdivided into small portions, each surrounded with a thin absorber made of a heavy metal, the bulk of the fusion material will simultaneously receive enough energy to start the thermonuclear reaction before the explosion disperses the whole assembly.
>
> (Rotblat 1981)

Although essentially weightless, X-rays can exert great pressure. In an H-bomb, the pressure (several million pounds per square inch) is exerted uniformly on the fusion material and long enough for the fusion process to work before the material is blown apart. Because the radiation travels at the speed of light, it arrives at the fusion material about a millionth of a second before the much slower moving shock wave from the trigger explosion. The X-rays also arrive before any particles, including neutrons, produced in the fission explosion. When the shock wave arrives, and blows the assembly apart, the fusion explosion has occurred.

The fusion process in a thermonuclear weapon is initiated by a so-called ‘sparkplug’, a thin sub-critical cylindrical rod of weapons-grade U-235 or Pu-239 placed at the centre of the cylinder of fusion fuel (Hansen 1988). When the fusion fuel has been compressed, by radiation from the explosion of the fission trigger, neutrons from the trigger penetrate into the sparkplug. The sparkplug begins to fission and the fission reaction, in the middle of the highly compressed fusion fuel, initiates the main fusion explosion. A thermonuclear weapon, therefore, uses two fission explosions—one in the trigger and another in the sparkplug.

Very large explosive yields have been obtained with thermonuclear weapons. Typically, each stage of a thermonuclear explosion explodes with a power roughly ten times that of the preceding stage. If the fission trigger explodes with an explosive yield of a few tens of kilotonnes, the first fusion stage would explode with a yield of several hundred kilotonnes, and the second fusion stage, if present, would yield several megatonnes. For example, the Soviet Union exploded an H-bomb in 1962 with a yield equal to that of 58 million tonnes of TNT—equivalent to about 3,000 Nagasaki bombs. This was probably a three-stage device, with a fission trigger which exploded with a power of several hundred kilotonnes, and two fusion stages. Even higher yields could be obtained.

The fusion process in a thermonuclear weapon is probably about 30 per cent efficient so that an explosion equivalent to that of about 25 kt of TNT is produced for each kilogramme of lithium-6 deuteride in the weapon. A 500-kt weapon would, therefore, contain about 20 kilogrammes of lithium-6 deuteride.

Having constructed nuclear or thermonuclear weapons is it necessary to test them before deploying them in the military arsenal?