Chapter 2
Nuclear Weapons

Our world faces a crisis as yet unperceived by those possessing power to make great decisions for good or evil. The unleashed power of the atom has changed everything, save our modes of thinking, and we thus drift toward unparalleled catastrophe.

[Albert Einstein 1946]

2.1 The Nuclear Age

The fission age began in 1932 when James Chadwick discovered neutrons by observing knock-out proton tracks in a cloud chamber.

Observe neutrons with no electric charge and no tracks? An alpha particle (helium-4 nucleus from radioactive decay) combines with a beryllium-9 nucleus to make carbon-12 and a neutron. The super-script number on the isotope is the mass number, the sum of the neutrons and protons in the nucleus.

$$^{4}\mathrm{He} + {}^{9}\mathrm{Be} \Rightarrow {}^{13}\mathrm{C} \Rightarrow {}^{12}\mathrm{C} + {}^{1}\mathrm{n}.$$

The neutron without an electric charge doesn't leave a track, but it hits and propels a proton with electric charge, which does leave a track.

Fluke of nature with a rare isotope: Nuclear weapons are, essentially, a fluke of nature. Fission of uranium in nuclear weapons and nucleaer reactors is caused by a rare isotope, ^{235}U, of a moderately rare element, uranium. There are no easy replacements for ^{235}U, until mankind made plutonium from uranium. Uranium is, essentially, the only economic path to start-up reactors and nuclear weapons. One could use expensive particle accelerators or other isotopes produced in reactors, but that came later.

D. Hafemeister, *Nuclear Proliferation and Terrorism in the Post-9/11 World*,
DOI 10.1007/978-3-319-25367-1_2

Leo Szilard, the first to consider nuclear bombs, had this recollection in September 1933:

> As I was waiting for the light to change and as the light changed to green and I crossed the street, it suddenly occurred to me that if we could find an element which is split by neutrons and which would emit two neutrons when it absorbed one neutron, such an element, if assembled in sufficiently large mass, could sustain a nuclear chain reaction. I didn't see at the moment just how one would go about finding such an element.

Chain Reaction and Neutron Multiplication

Szilard thought that neutron multiplication might take place with this reaction:

$$^{1}\mathrm{n} + {}^{9}\mathrm{Be} \Rightarrow 2\,^{4}\mathrm{He} + 2\,^{1}\mathrm{n}.$$

If this worked, the initial neutron would make 2n, and these 2n would make 4n, to make 8n, finally to some 10^{24} neutrons. This idea is correct for uranium fission, since an average of 2.5 neutrons are released for each fission event.

Szilard's beryllium nuclear weapon can't be built, since beryllium-fission neutrons lack sufficient energy to fission ^{9}Be nucleui. Still, Szilard realized the military importance of chain reactions to the British military, even though uranium fission was not discovered for another 6 years. After Joliot submitted an article on the number of neutrons given off in a fission event to *Nature* on March 8, 1939, Szilard and Fermi published in the 1939 *Physical Review* that uranium fission produced "about two neutrons." Thus, physicists who read the *Physical Review* and *Nature* deduced that nuclear weapons could become a reality.

Scientific details of nuclear weapons are classified "top secret" and "restricted data," but the basic science of nuclear weapons was declassified in Robert Serber's *The Los Alamos Primer*, which presents basic equations and concepts, which was considered worrisome when it became publicized. In the 1970s the *Primer* was considered unclassified but don't talk about it. In the 1990s the *Primer* was considered basic science that is widely known, but without secret technical details. Lastly, *The Effects of Nuclear Weapons* by S. Glasstone and P. Dolan is considered a classic on describing the many–parameter results of nuclear explosions (Fig. 2.1).

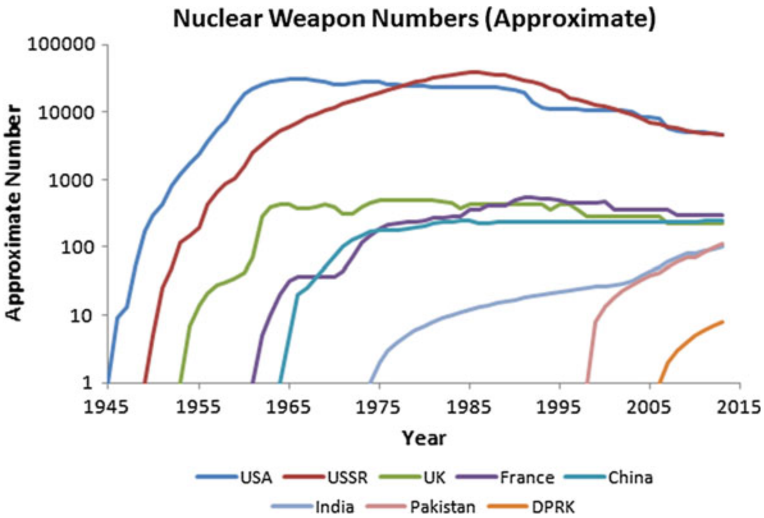

Fig. 2.1 Numbers of nuclear weapons from 1945 to 2012 for eight nations. We define a weapon as either deployed or in reserve, giving the total stockpile. The 8 curves are plotted in the following order, left to right, keyed to the date of the first nuclear test for the state: US (2015 totals; 4650 stockpile, 2150 operational), Russia (5000 stockpile, 1800 operational), UK (225), France (300), China (250), India (90–110), Pakistan (100–120) and N. Korea (5–10). The logarithm of the number of nuclear warheads is used in order to display the large differences in numbers between states. The US curve peaked in 1965 and the Soviet/Russian curve peaked in 1985. The US and Soviet/Russian curves show the drop in numbers over time (P. Corden and D. Hafemeister, *Physics Today*, April 2014. Pierce Corden and Derek Updegraff (AAAS), adapted for graphics from the warhead numbers from Hans Kristensen (FAS) 2013)

2.2 Nuclear Proliferation

At least 25 nations have attempted to develop nuclear weapons, beginning with Germany and the five nuclear weapon states (NWSs), the "big five" of World War II (the United States, United Kingdom, Russia, France and China). Nuclear tests by India in 1974 and 1998, Pakistan in 1998 and North Korea in 2006, 2009, 2013 and 2016 increased the list to eight. South Africa built six uranium weapons, but dismantled them in 1992. Israel is generally reported and believed to have nuclear weapons. During the Gulf War of 1991, the UN and the IAEA (International Atomic Energy Agency) discovered Iraq's large nuclear program. North Korea produced enough plutonium for a half-dozen weapons, encouraging South Korea, Japan, and the United States to give North Korea two commercial reactors in exchange for ending its program and allowing inspections. This 1994 agreement collapsed in 2002 with the announcement that North Korea restarted its weapons program in the late 1990s and ejected IAEA inspectors. Iran moves towards nuclear prowess with its enrichment program, but is now in "negotiations" with the *P5 + 1*. In the past, Argentina, Brazil, Germany, Japan, Libya, South

Korea, Sweden, Switzerland, Syria, Taiwan took steps to obtain nuclear weapons, but they stopped. The news is not all dark, as four weapons-owning states (South Africa, Ukraine, Belarus, and Kazakhstan) have given them up. This totals 23, but we know that doesn't end the list of nuclear-coveting states.

The 1970 Non-Proliferation of Nuclear Weapons Treaty (NPT) anchors a global regime that bans nuclear weapon technologies in non-nuclear weapons states (NNWS). The NPT regime relies on declarations by states-parties on their nuclear materials, which are monitored by IAEA inspections to determine their validity. In return for this loss of sovereignty, NNWSs expect NWSs to greatly reduce their reliance on nuclear weapons and to negotiate toward their ultimate elimination. The total elimination of nuclear weapons is hopeful, but unlikely, but substantial reduction is wise. As part of the bargain, NNWSs believe NWSs must stop testing nuclear weapons to conform to their obligation to stop the nuclear arms race. The NPT states agreed in 1995 to extend the NPT indefinitely, but only after the five NWSs stated that they would stop testing and join a Comprehensive Test Ban Treaty (CTBT). In addition, NWSs are expected to assist NNWSs with their peaceful nuclear power programs. Beyond these incentives, NNWSs prefer to live next to non-nuclear neighbors, which has led to the creation of nuclear-weapon-free zones in Latin America (Tlateloco), Africa (Pelindaba), Pacific (Rarotonga), SE Asia (Bangkok), Central Asia, Antarctic, Sea-Bed, and Outer Space.

The NPT regime was severely undercut when the US Senate rejected the CTBT by 51 to 48 in 1999 and the George W. Bush administration stated it would not seek CTBT ratification. The G.W. Bush Administration called for the development a 5-kton earth-penetrating weapon to attack underground bunkers. CTBT ratification has floundered since then, President Obama couldn't get enough Senate support for it.

2.3 Fission Energy

A 1-Mton weapon destroys houses at a distance of 5–10 km, gives third-degree burns at 10 km and releases lethal radioactive plumes beyond 100 km. The size of 1-Mton of conventional explosive could be likened to a train made up of 100 rail cars, each carrying 100 tons of coal. The length of this 1-Mton train is 200 km. However, the mass of a 1-Mton nuclear weapon is less than one-millionth of this trainload, making it far easier to deliver nuclear weapons over long distances with missiles and planes, as compared to conventional explosives of the same yield.

Fission of uranium and plutonium. Slow neutrons in reactors fission (split) ^{235}U nuclei, but do not have sufficient energy to fission ^{238}U. Fast neutrons from compact nuclear bombs that are not slowed (moderated) will fission ^{238}U. This is useful for nuclear weapons. Thermal (slow) neutrons produce these fission reactions:

$$n + {}^{235}U \Rightarrow FF_1 + FF_2 + 2.43n + 207\ \text{MeV}$$

$$n + {}^{239}Pu \Rightarrow FF_1 + FF_2 + 2.87n + 214\ \text{MeV}$$

where FF_1 and FF_2 are newly-created, binary-fission fragments. The total number of neutrons and protons is constant in these reactions. Fast neutrons produce an extra 0.1 neutron. The number of neutrons released in fission varies between zero and six, with energy between 1 and 10 MeV. Weapon neutrons remain very energetic since the explosion takes place in less than a microsecond.

After a ^{235}U or ^{239}Pu nucleus captures a neutron, the resultant ^{236}U or ^{240}Pu nucleus oscillates like a liquid drop, with repulsive forces from charged protons in the nucleus and attractive nuclear forces from the close-by neighbors. Oscillations split the nucleus into two fission fragments. Because target nuclei have an odd number of neutrons, the binding energy of the absorbed neutron includes pairing energy from combining spin-up and spin-down neutrons. On the other hand, ^{238}U with an even number of neutrons has a smaller neutron binding energy since the pairing energy is not available. Because less energy is available from neutron capture by ^{238}U nuclei, only fast neutrons over 1 MeV can fission ^{238}U. Thus ^{238}U cannot be used, by itself, to make a fission weapon. However, energetic 14-MeV neutrons from fusion can fission all isotopes of uranium. Thus ^{238}U and ^{235}U can be used in the secondary of a hydrogen bomb to gain fission energy along with fusion energy. Fission weapons can also be made with ^{233}U, but the energetic gamma rays from ^{233}U make it difficult to turn into a weapon. The U.S. produced 1500 kg of ^{233}U, and made a few weapons from it. Because it has no mission, it is being buried in Nevada in 2012. The IAEA is placing ^{237}Np and two americium isotopes under safeguards, since they also can, in principle, be made into weapons.

2.4 Critical Mass

The largest deliverable conventional bomb, made with conventional explosives, was the 6-ton (0.006 kton) BLU-82 bomb the United States used in Vietnam and Afghanistan. Nuclear weapon yields vary from the 0.01 kton backpack weapons, to destroy bridges and dams, to the huge Soviet 100–150 Mton weapon, that was tested at the 58-Mton level in 1962. The yield ratio between these two weapons is 10 million! To explain the concept of critical masses, we use scaling laws to consider the effects of simply changing the size of an object.

Scaling laws answer pragmatic questions, such as, "Why do cows eat grass and mice eat grains?" Consider animals as simple spherical shapes whose *heat loss* through skin is proportional to skin surface *area* (radius squared). The *amount of*

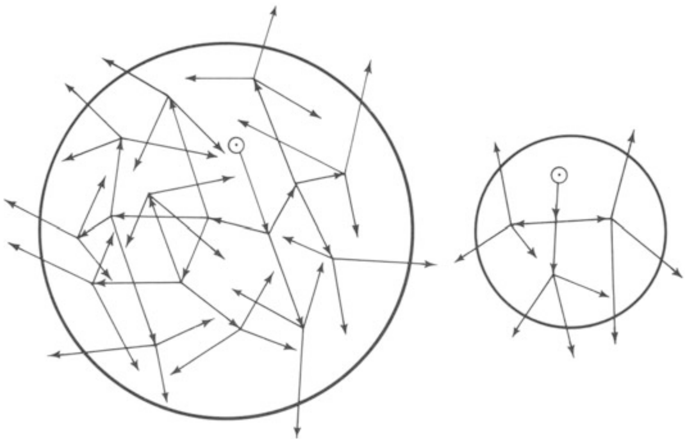

Fig. 2.2 Critical Mass. A larger mass of fissile material contains relatively more neutrons for future fission events, while a smaller sample loses more neutrons through its surface, halting the growth of future neutrons. The critical mass is the minimum amount of fissile material needed to sustain exponential growth of the neutron population, which depends on the isotope composition, its density and geometrical shape and situation (Atomic Heritage Foundation)

stored food energy is approximately proportional to the animal's *volume* (radius cubed) and the type of food it eats and stores. If an animal has thick skin fur, it can be smaller and still gain sufficient energy from eating grass. On the other hand, mice must eat high quality grains since their area/volume ratio (loss/storage) is large. Scaling shows that small animals (mice and humming birds) eat often and they must eat energetic grains to overcome their large ratio of area to stomach volume, and their thin fur. For the opposite reason, large animals eat less often and eat less energetic foods, such as grass. Scaling arguments also show that big animals must have relatively large diameter bones. Similarly scaling arguments show that you need three sticks to start a fire, by making a protective cavity for the fire (Fig. 2.2).

Scaling to obtain a critical mass. Simple geometry is a powerful tool to understand how much nuclear material is needed to "just" make a nuclear weapon. Neutrons are lost from a spherical bomb through its surface area, $4\pi r^2$. Thus the neutron loss rate is proportional to the square of the radius. At the same time neutrons are produced in a volume at rate proportional to the volume of a sphere, $4\pi r^3/3$. The production rate is proportional to the radius cubed. The rate of production divided by the rate of loss is r cubed over r squared, or it is proportional to the radius. More material gives you a better chance of having enough for a critical mass. Less material will make it harder to make a critical mass.

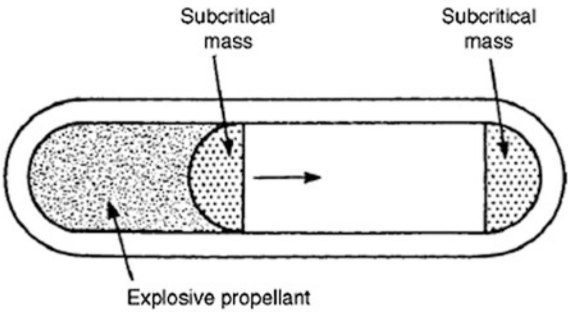

Fig. 2.3 Hiroshima weapon, ^{235}U gun-assembly nuclear device. *Little Boy* was long and thin because it used a 2 m long cannon that projected the smaller mass into the larger spherical mass with a velocity of 900 m/s to avoid pre-detonation. There was some certainty that the *Little Boy* would work as planned and there was little ^{235}U to spare, so it was not pre-tested (Glasstone and Dolan 1977)

Table 2.1 Critical mass

SNM	Bare sphere	U tamper
^{235}U (kg)	47.9	15
^{239}Pu (kg)	10.2	5

The ^{235}U and ^{239}Pu critical masses are at normal densities for the case of bare spheres and for the case of a natural uranium tamper surrounding the bare sphere. The thorium cycle makes ^{233}U, with a tampered critical mass of 2 kg, but it is harder to deal with because of its high radiation level. (*TOPS Task Force*, Nuclear Energy Research Advisory Committee, Department of Energy 2000)

Robert Serber in the *Los Alamos Primer* estimated a bare-sphere uranium critical mass with a 9-cm radius and a mass of 55 kg (too large by a factor of two). Reflectors made of beryllium (giving two neutrons) or uranium reduce the critical mass from the "bare-sphere" values. Implosion increases the density of ^{239}Pu or ^{235}U, reducing the critical mass (Figs. 2.2 and 2.3) (Table 2.1).

2.5 Neutron Generations and Bomb Yield

One kilogram of fissile material contains a total possible energy of 17 kton. The Hiroshima uranium gun-weapon released 13 kton of energy, consuming 0.8 kg of ^{235}U. *Little Boy* consumed only 1.3 % of its 60 kg of ^{235}U. The 22-kton Nagasaki implosion weapon obtained a much higher efficiency of 20 %, consuming 1.3 kg of 6 kg of ^{239}Pu. The higher efficiency of *fat man* was obtained because it was imploded, increasing the density of ^{239}Pu.

The growth of neutrons in a warhead is analogous to folding a piece of paper, as each folding doubles the thickness. Folding a sheet of paper 51 times gives a folded thickness of 2×10^{15} sheets of paper, which is 170 million km, the distance to the sun. A paper folded eighty times (corresponding to a 15-kton warhead) has a thickness of 10^{24} sheets of paper, or 1000 light years, 200 times the distance to the nearest star, Alpha Centuri.

2.6 Plutonium–Implosion Weapons

Advances in plutonium weapons have been dramatic. The 1945 *Fat Man* was a 22-kton bomb with a diameter of 1.5 m, while the Peacekeeper's (W-87) 300-kton warhead has a diameter of only 0.6 m, volume reduction of about ten, with a gain in yield of 15. Nuclear artillery shells are only 0.16 m in diameter. Plutonium is produced when ^{238}U absorbs a neutron to become ^{239}U, which beta-decays in minutes to neptunium (^{239}Np), which in turn beta-decays in days to plutonium (^{239}Pu), with a half-life of 24,000 years.

Prior to the atomic age, plutonium was produced naturally just below the surface of the earth. Strangely, the uranium at Oklo, Gabon, in Africa, contains only 0.4 % ^{235}U, rather than the usual 0.7 %. This apparent anomaly is explained because the ^{235}U content has been changed for two reasons:

1. ***Decay***: ^{235}U naturally decays during the 1.8 billion years, when ^{235}U was 4 % of all uranium. Today ^{235}U is 0.7 % of all uranium, when correcting for ^{235}U's half-life of 700 million years. The original 4 % level is similar to today's power-reactor fuel.
2. ***Natural Fission***: ^{235}U content was also depleted from that distant time by fission-consumption in a natural nuclear reactor. The natural reactor operated for several hundred thousand years. The rich uranium deposit was in a damp place with enough water to moderate neutrons, creating a natural reactor without human effort. The natural reactor was about 5–10 m thick and 600–900 m wide. It operated at an average power of 100 kW over 150,000 years. In practice the power cycled on and off as the water moderator evaporated with the seasons and power production and then was replenished. Nature managed to make plutonium without much effort long before mankind, but the plutonium direct-evidence has decayed.

2.6.1 *Pu Preferable to HEU for Weapons*

Plutonium is favored over *highly enriched uranium* (HEU with 90 % ^{235}U) for weapons since it emits more neutrons per fast fission ($v = 2.94$ versus 2.53), more neutrons per neutron capture ($\eta = 2.35$ versus 1.93), has a higher fast fission cross-section (1.7 barns versus 1.2 barns) and releases slightly more energy (214 MeV versus 207 MeV). For these reasons, plutonium makes smaller primaries, which are essential for multiple–independently–targetable reentry–vehicles (MIRV) on inter-continental ballistic–missiles (ICBM) and submarine–launched ballistic–missiles.

However, plutonium is more difficult to make into nuclear explosives because of the high rate of spontaneously-emitted neutrons that are emitted by ^{240}Pu. these precursor neutrons can begin a chain reaction before plutonium reaches its most compact form. We call this *preinitiation*, which is similar to preignition in automobiles, when the spark ignites the gasoline before maximum compression. Severe preignition prevents cars from operating; the technical fix is to delay the spark. In a similar fashion, slow-moving, plutonium gun-type weapons would preinitiate and lose considerable yield. This problem can be overcome by explosive implosion using multipoint detonation on a 32-sided soccer–ball sphere. Hollow pits of plutonium enhance efficiency and allow volume for deuterium–tritium gas to give a fusion boost. The hydrogen secondary is located near the primary and, in some cases, a *dial-a-yield* feature is used to tailor the yield to the mission.

2.6.2 Plutonium Spontaneous Neutron Emission

During a long reactor residency, a considerable fraction of ^{239}Pu captures a second neutron to become ^{240}Pu. The length of stay in a reactor determines whether the plutonium is *weapons-grade* Pu (6 % ^{240}Pu, made in months) or *reactorgrade* Pu (>20 % ^{240}Pu, made in years). The isotopic contents of the five most common types of plutonium are listed in Table 2.2. Plutonium metallurgy is complicated by the fact that it exists in six different phases, but it is stable in the delta phase with 2 % gallium. Note that plutonium from breeder-reactor blankets is excellent weapons-grade plutonium, while mixed-oxide (MOX) fuel, used in thermal reactors, is not. Reactor grade plutonium can be made into viable nuclear weapons by mature nuclear nations. Difficulties can arise because of the extra dose rate of spontaneous neutrons and the excess heat that can damage high explosives.

The rate of spontaneous neutrons from ^{240}Pu is 100,000 times higher than it is for ^{239}Pu. (The spontaneous neutron rate of ^{235}U is about 1 % of the ^{239}Pu rate.) The spontaneous neutrons from 5 kg of weapons-grade plutonium come primarily from ^{240}Pu, not ^{239}Pu.

Table 2.2 Isotopic composition of various grades of plutonium

Pu grade	(% Pu isotope)				
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Super-grade	–	98	2	–	–
Weapons-grade	0.01	93.8	5.8	0.4	0.02
Reactor-grade	1.3	60	24	9	5
MOX-grade	2	40	32	18	8
Breeder blanket	–	96	4	–	–

(Mark 1993)

Neutron multiplication and (*α,* n) reactions on light impurities (oxygen and nitrogen) marginally increase the neutron rate in metallic plutonium. The spontaneous neutron rate is 4 times larger in reactor-grade plutonium (24 % ^{240}Pu), which itself would be doubled if it were in plutonium oxide form from the (*α,* n)-reaction. Clearly it is more difficult to make a warhead with reactor-grade plutonium, but it can be done.

Assembly Time in Implosion. The assembly time of an implosion bomb is reduced by a factor of 100 compared to the gun-barrel design; this is due to two things:

- The critical implosion sizes are less than 10 % the length of the gun barrel.
- The implosion velocity is a factor of 10 higher than the projectile velocity of a *Little Boy* gun-type weapon. During the implosion time, about 0.5 neutrons are generated. This can be reduced by a factor of three by using super-grade 2 % ^{240}Pu.

2.6.3 Summary of ^{239}Pu versus ^{235}U for Weapons

Plutonium gives an extra one-half neutron on average from each fission event, reducing the number of fission generations needed, allowing for more complete fission of the bomb material and a smaller critical mass of 4 kg, compared to 20 kg for uranium This reduces the amount of fissile material needed, assisting miniaturization, which is useful for smaller primaries and for multi-warhead ICBMs and SLBMs. Pu is made in reactors and chemically reprocessed, which is easier to detect than uranium enrichment. Pu passively emits many more intense gamma rays than U, thus it is easier to detect. Pu needs implosion to make a viable bomb, this is more difficult to accomplish than a uranium gun-type weapon. Uranium-weapons (both implosion and gun-barrel) are easier to make than for Pu warheads, since pre-initiation is much less of an issue for U. Plutonium mixed-oxide fuel is not as a good as enriched uranium fuel. Pu MOX has a net negative economic value because its radioactivity, which complicates mixed oxide fuel production.

Uranium used to be more difficult to enrich in the past, as compared to the production of Pu in reactors. The advent of better centrifuges makes this no longer true. U production is harder to locate since U emits much less radiation and U does not need reactors for production. There is a shift in preference for wannabe nuclear states to use U for weapons as compared to Pu. U gun-barrel or implosion weapons are easier to make and HEU is less radioactive so easier to work with. There is more weapons grade uranium as compared to plutonium. The extra weight of U weapons is only relevant for missile delivery. HEU has a valuable market, when diluted for reactor fuel. After the break-up of the Soviet Union, prompt action was needed, more for HEU protection than Pu since HEU can be made more easily into a weapon, and it is harder to detect (Table 2.3).

Table 2.3 Weapon problems and solutions

• Neutron initiation: From ^{210}Po-Be radioactivity to DT initiator tubes
• Extra neutron multiplication: Add beryllium reflector (n to 2n)
• Reduce mass: Bare sphere to heavy tamper and implosion
• Reduce mass: Levitated hollow pit
• Reduce mass: Boost with DT to fission more efficiently
• Fission increase: ^{238}U tamper and casing (FFF for H bomb)
• H bomb: Radiation compression (not mechanical), U in secondary
• Deliverable H bomb: ^{6}Li^{2}H instead of Big Mike cryostat
• Safety: Two-point triggering, ENDS, fire-resistant pits, insensitive high explosives
• Theft: Permissive Action Links (PAL)

2.7 Boosted Primaries and H–Bombs

Basic Physics. Fusion of 4 hydrogen nuclei into helium sustains the Sun and its planet Earth. Shortly after physicists began on fission bombs, they realized that much more explosive energy could be available from fusion, which combines hydrogen isotopes into helium. The sun fuses four hydrogen isotopes into helium, releasing 27 MeV in a three-step, *proton-burning* process. (The carbon-nitrogen fusion process is more likely, but it gives the same result.) The mass loss going from four ^{1}H nuclei (4 × 1.008 atomic mass units = 4.032 amu) to one ^{4}He (4.003 amu) is 0.029 amu, This converts 0.7 % of the original mass to energy, an amount that is much less than 100 % conversion from antimatter conversion, but much more than that from chemical explosives (50 eV). The sun's gravity confines the energetic hydrogen/helium plasma to high pressures and temperatures. Since the sun has a life span of 10 billion years, it slowly uses a three-step process for *gravitational confinement* fusion. *In this 3 step process*, hydrogen atoms 1 and 2 combine, say a billion years ago. Another billion years goes by and #3 proton combines (1–2 to obtain 1–2–3). Another billion years goes by and #4 combines (1–2–3 to get 1–2–3–4), with great patience.

DT Burning. The little time available for nuclear weapons requires a *one-step process* to obtain ^{4}He from deuterium and tritium, or "d plus t gives He plus n,"

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \Rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{n} + 17.6\mathrm{MeV}.$$

DT fusion develops 5 times more energy/mass than fission. DT is not limited in its storage size, it doesn't have a self-sustaining critical mass. The neutron carries 14.4 MeV, enough to fission all the isotopes of U and Pu, as well as ^{6}Li to produce tritium for further fusion,

$$^{1}n + {}^{6}Li \Rightarrow {}^{3}H + {}^{4}He.$$

Hydrogen bombs do not have large gravitational or magnetic fields to confine hot plasmas. They use *inertial confinement* since all the neutron generations take place in a microsecond before the weapon blows apart. For fusion to take place, d and t must have sufficient kinetic energy of motion to overcome coulomb repulsion between the two nuclei.

A boosted primary contains $d + t$ gas (heavy hydrogen and heavy-heavy hydrogen) to magnify its yield. The extra energy from *dt* "burning or fusing" is small, but the extra neutrons, released early in the cycle, allow the fission cycle to skip many generations, increasing the fraction of nuclei that fission. This increases the efficiency of burning *dt*. The energy released per warhead is small at one-third a kton, which is not significant. But a pulse of a mole of neutrons (6×10^{23}) rapidly advances the number of neutron generations, increasing fission yield and lowers the amount of fissile material. Without tritium, modern nuclear weapons would not function since *dt* reactions are needed to raise the yield to ignite the secondary stage.

Since tritium decays with a half-life of $T_{1/2}$ = 12.3 year. Tritium must be manufactured periodically to maintain nuclear arsenals. Tritium is produced by the absorption of neutrons by ^{6}Li in thermal reactors. The United States has not produced tritium since 1988. After considering proposals to make tritium in dedicated accelerators or reactors, the Department of Energy (DOE) opted to make tritium at an existing Tennessee nuclear power plant operated by the Tennessee Valley Authority (TVA). As the stockpile has dropped from 30,000 to 5000 warheads, the need for tritium was reduced greatly, balancing losses from decay. Under the *New START* treaty, we estimate tritium production will be needed in 2030, assuming a supply of 10 kg of tritium in 2005 for 2000 warheads.

Plutonium pit lifetime. The natural decay of plutonium propels alpha particles into the surroundings, which dislodges the plutonium atoms from their spots in the lattice. Will this jeopardize the quality of the plutonium pits? Experiments have been conducted with faster decaying ^{238}Pu, to speed up the decay cycle. The Department of Energy and the JASON group determined that pit lifetime is in excess of 150 years in 2012. The Los Alamos Pit Production Facility has a capability to make 6–10 pits per year. This can be increased to 40 per year with reuse capacity and investments. The New START Treaty might require a total inventory of 2000 warheads. This could be maintained with a capacity of about (2000 warheads)/(150 year lifetime) = 15 pits/year, much less than the original planned capacity of about 200/year.

2.7.1 Radiation Compression

From the beginning of the Manhattan Project, Edward Teller wanted to develop the hydrogen bomb so much so that he refused to work on pure fission bombs. The initial idea was to compress the secondary with mechanical shock waves. This would not work because the primary explosion destroys the secondary before sufficient mechanical compression of the secondary takes place. However, Stanislaus Ulam and Teller solved the problem when they deduced that x-rays from the primary would reflect (re-emit) from the casing on to the secondary. The absorbed x-rays heat the casing and other materials to such high temperatures that they produce black-body emission, x-rays as well as reflected x-rays. Since x-rays travel with the speed of light, they are absorbed by the secondary before the mechanical shock arrives. The high temperature rise at the surface of the secondary creates radiation pressure as the hot surface of the secondary evaporates. Since evaporating ions travel outward, perpendicular to the surface, this compresses the surface since the emission of x-rays carries away momentum, which equally is applied to the surface. When you push on the swimming pool wall to the North, you travel to the South! This compression of the hydrogen secondary heats the secondary. The bath of neutrons at high temperatures ignites both U for fission and $^{6}Li^{2}H$ to start fusion. In the late 1970s, Howard Moreland published rough drawings of the hydrogen bomb. The government's case to prevent publication was greatly weakened when it was discovered that it had already declassified these facts and they were publicly available at the Los Alamos laboratory library.

Radiation Compression. Mechanical compression was unsuccessful in its attempt to produce nuclear fusion, which was obtained with radiation compression. A primary generates some 10 kton in 100 ns, producing thermal power of 4×10^{20} W, considerably greater than the US electrical grid of 10^{12} W. This tremendous of amount of heat in a small volume is radiated away, proportional to the fourth power of the temperature, T^4. The temperature at the surface of the primary is about 15 million K, similar to the sun's core temperature, and a thousand times greater than sun's surface temperature. The energy of the x-rays is about 6 keV, similar to some medical x-rays. The x-rays are absorbed by the secondary to reradiate new x-rays, which vaporize outward and implode inward. The casing and other materials also absorb x-rays which re-radiate inwardly to further compress the secondary.

2.7.2 Lithium Deuteride for Large Hydrogen Bombs

The first hydrogen device, "Big Mike," was detonated on 31 October 1952. Mike was a large thermos bottle containing liquid deuterium, giving a yield of 10 Mton.

Mike could not be delivered with bombers or ICBMs because of the extreme size of its cryogenics. A deliverable H bomb was soon developed with deuterium in the LiD salt in the form of $^6Li^2H$. Since salt is a solid, there is no need for a cryostat. A neutron interacting with ^6Li gives an instant tritium to interact with deuterium ($^6Li + ^1n \Rightarrow ^3H + ^4He$). Note that the tritium supplies from ^6Li are not dependent on tritium's 12.3 year half-life as it is used within microseconds of production. ^6Li is relatively cheap to separate since its mass is 15 % smaller than ^7Li. Thus, $^6Li^2H$ gives

$$d + t \Rightarrow He + n \quad \text{or} \quad ^2H + ^3H \Rightarrow ^4He + ^1n.$$

There is no problem with storing too much $^6Li^2H$. There will be no dangerous, unintended criticalities from $^6Li^2H$ stockpiles as there can be with ^{235}U and ^{239}Pu, which sets upper limits on sizes of unboosted fission weapons. The largest Soviet explosion of 58 Mton took place on 31 October 1961. This explosion was only one-third or one-half of the design size of 100–150 Mton. The 58 Mton explosion used an incomplete secondary with less nuclear fuel to reduce the yield.

Of what purpose are large US bombs of 20 Mton and those of that 100–150 Mton? There are four possible uses for large yield weapons, none of which is needed:

1. *Hard Target warheads* to attack ICBM silos and command posts with first-strike warheads. In Chap. 4 we address this issue, but for now we can state that the accuracy of the warhead and the hardness of the target dictates the choice of yield. As accuracy has gotten better, the yield of hard-target warheads decreased.
2. *Area destruction*. At some point it is inefficient to attack area (people) with large weapons. Since the blast pressure falls as the cube of the distance, the kill radius from large bombs is less effective per unit of yield. If the yield is reduced by a factor of 8, the kill radius is reduced by a factor 2, and the kill area is reduced by a factor of "only" 4.
3. *Electromagnetic pulses* can disrupt command and control and military communications and shut down the electrical grid.
4. Anti-ballistic-missile weapons (Chap. 5).

2.8 Neutron Bombs

The western nations were greatly concerned about the possibility of a Soviet invasion from the East. It is true that the Warsaw Pack had a substantial numerical advantage in conventional arms, but the threat was not as great as stated because the Soviets kept older, inferior equipment in place, and the risk of invasion to the attacker was very large. The tactical battlefield weapons were delivered with artillery pieces, or howitzers. At one time the US had some 7000 tactical weapons

Fig. 2.4 Tactical nuclear weapons. The first live nuclear artillery test of 15 kton on 25 May 1953 at the Nevada Test Site. The W33, 8 inch, howitzer projectile had a yield of either sub-kton or 5–10 kton, with a range of 18 km. The US and seven European nations (Belgium, Italy, Greece, Netherlands, Turkey United Kingdom and West Germany) controlled 1800 W33's. The smaller 6 inch W48 had a range of 14 km with 3000 deployed in Europe and S. Korea. The W82 enhanced radiation projectile was scheduled to replace the W48, but Congress did not agree (Atomic Heritage Foundation)

and the Soviets had far more, some 20,000. The neutron bomb was the follow-up weapon to these tactical weapons (Fig. 2.4).

Neutron bombs produces smaller blast yields, reducing collateral damage. At the same time, neutron bombs enhance neutron emissions to more effectively kill troops and tank drivers, producing prompt death in 5 min with fast neutron doses of 80 Sv (8000 rem). The introduction of the neutron bomb was a shift from pure fission tactical weapons to weapons that were approximately equally divided between fission and fusion at 1 kton. This was accomplished by replacing the uranium tamper with chromium, to let 50 % of the neutrons escape. In addition, extra *dt* boosting gas was used to produce fusion to produce more neutrons per energy released. Fusion neutrons are much more energetic at 14 MeV, as compared to fission neutrons at 1–2 MeV.

The political debate on deploying neutron bombs was sharply contested in the United States and Europe in the late 1970s. Those who wanted to deploy neutron bombs were concerned that tactical weapons would not be used in Europe because their yields would be too damaging, particularly in Germany. They wanted 1-kton weapons that would incapacitate tank crews at a distance of 850 m, compared to 375 m for a pure fission 1-kton weapon. Proponents believed deployment of the neutron bomb would increase Soviet perception that the US would actually use it, a result that would deter a Soviet invasion. On the other hand, it could be envisioned that the deployment of neutron bomb lowered the psychological and bureaucratic threshold for first-use of nuclear weapons. Such a deployment would increase the probability of its first-use by local commanders, thus starting a more general nuclear war. Lastly, there already was considerable deterrence to discourage an invasion because the United States had other nuclear weapons in Europe. The view of the opponents carried the day as Congress blocked its deployment. Those who lost the debate commented that a different name for the weapon, such as the *reduced-blast and—yield bomb*, would have helped their case.

Radiation dose and reduced blast. Neutron bombs produce only one-half as much radioactivity as pure fission bombs, but they give a much larger radiation dose to close-in troops. The radiation dose from a neutron bomb is considerably greater because it produces 6 times more neutrons *and* fusion neutrons are 7 times more energetic than fission neutrons. These effects are multiplicative, and considerable. Most fission energy appears as fission-fragment kinetic energy, which heats bomb debris to produce a blast wave. Pure fusion contributes less blast energy since escaping neutrons carry considerable energy away from the weapon. The neutron bomb is about 9 times (per unit area destroyed) more effective at killing tank drivers as compared to tactical nuclear weapons.

2.9 Exotic Weapons

Isomer EMP warhead. A nuclear isomer is a nuclear excited state of a nucleus with a long half-life. It appears stable in spite of it not being in the ground state, awaiting decay. If an isotope can be found that has a high-energy excited-state with a long half-life, it might be used as a weapon. Such a metastable state might be induced to discharge with an x-ray machine, releasing massive gamma rays in a short time. The isomer usually suggested is hafnium-178 m, ^{178m}Hf, with a 31 year half-life at 2.4 MeV. The isomer bomb obtained funding, but was canceled as nonsensical. See *Imaginary Weapons* by Sharon Weinberger (Nation Books 2006) for the history of the isomer bomb through the bureaucracy and the laboratory, where x-rays did not readily discharge ^{178m}Hf.

Trans-actinide warhead. The nuclear shell model shows that there are potential regions of stability for massive nuclei, considerably heavier than the actinides. These isotopes could be stable, similar to the lead region of the nuclear chart. This is *analogous* to the full shells of atomic rare gas elements, which are stable and reluctant to make chemical bonds. If proton/neutron closed-shell nuclei are made, it would be possible to have critical masses of *grams, rather than kilograms*. Such nuclei would emit many more than 3 neutrons per fissile event. Not to worry, such nuclei have not been discovered.

Robust nuclear earth–penetrating warhead. The bunker buster was devised by the Los Alamos National Laboratory in 1991. RNEP research was banned by Congress in 1994, but it reappeared in Congress in 2002, until it was terminated in 2005. RNEP warheads were to penetrate 10 m of rock, or 30 m in dirt, then explode, *increasing blast pressure by 30 times* since rock is hard to compress and air is not. There are disadvantages: (1) Considerable radioactive aerosols are produced when neutrons interact with rock and soil. There is much more radioactivity from a bunker buster than from an air-burst. A 10-kton warhead would have to penetrate 250 m to avoid spewing radioactivity, which is not possible. (2) A buried warhead can crush rock at a distance. A 10-kton crush–radius is 100 m, which is the accuracy of a good ICBM. But RNEP would be delivered as a bomb, guided with a laser to be more accurate, but not as much penetration as if it were from a missile. RNEP was intended to attack underground chem/bio stockpiles (or leadership), but it would have to be close to the CW/BW stockpiles for combustion. RNEP was finally terminated in 2006 (See reference by Rob Nelson).

Reliable replacement warhead. The Comprehensive Nuclear–Test–Ban Treaty bans nuclear warhead tests. Using more cautious designs, warheads can be built that are more robust, further from the reliability margins, and without the use of Be and BeO as neutron reflectors. In March 2007, NNSA chose Livermore's W-89 design since it already had been tested and did not need testing to be certified. It had a mass of 150 kg and a yield of 200 kton. The RRW was originally intended to be used in 2000 warheads, but this was scaled back. The stockpile stewardship program was designed to learn more than testing could ever provide, and RRW was terminated.

^{233}U warhead. About 1500 kg of ^{233}U was produced in reactors for nuclear weapons, at a cost of \$6–11 billion. Since ^{233}U is less useable for warheads, compared to ^{239}Pu and ^{235}U, it will be disposed of as waste. "DOE is to waive its own acceptance criteria to allow the direct, shallow-land disposal" in near-surface burial by 2014.

Suitcase bomb. In 1997, Russian General Alexander Lebed claimed that 50 RA-115 suitcase bombs "are not under the control of the armed forces of Russia." He was famous for allowing the 1991 military rebellion in Moscow to proceed. The US has made very small nuclear weapons. The smallest was 45 kg, 13 cm diameter and 62 cm long. The W-54 was backpack-carried for munitions demolition and on Davy Crockett short-range missiles.

X-Ray–Laser Pumped with a Nuclear Explosion (Chap. 5).

2.10 Nuclear Weapon Effects

Nuclear weapon energy appears as blast pressure waves, thermal radiation, and prompt/delayed radiation. The division of the total energy into these quantities depends on weapon yield, ratio of fusion to fission energies, and height of burst. Typically, 40–60 % of the yield appears as blast energy, 30–50 % appears as thermal radiation, 5 % as ionizing radiation and 5–10 % as residual radiation. This section discusses blast, thermal, and radiation effects, as well *nuclear winter* and electromagnetic pulses, while Chap. 3 discusses low-dose radiation effects. Nuclear weapons can destroy opponent's weapons, but it is far easier to devastate cities and people. The 13 and 22 kton weapons used on Hiroshima and Nagasaki killed

180,000 people, about 40 % of the inhabitants. Those that died from radiation, also died because they were within the lethal blast radius. Outside the lethal blast areas about 400 Japanese died from delayed, low-dose cancer. Citizens at 3-km distance had their eye-sight severely damaged. However, the 15-Mton Castle Bravo hydrogen bomb created a gigantic radioactive plume, killing a Japanese fisherman on the *Lucky Dragon*. The destructive effects of Mton-size weapons would be immense and it is possible with US and Russia forces operating under some launch-on-warning scenarios. We hope that the Launch–on–Warning scenarios have been abandoned. In the 1960s, Secretary of Defense Robert McNamara *defined mutual assured destruction* as the assured second strike that would kill 25 % of a nation's population and 50 % of its industry, as shown in Tables 2.4 and 2.5.

Some radiation rules-of-thumb effects are as follows:

- lethality from neutrons predominates up to a few kton;
- lethality from blast pressure waves predominates from 5–100 kton;
- lethality from thermal radiation predominates above 100 kton, but lethal radiation plumes can extend considerably beyond 100 miles.

Fusion makes much less radioactivity than fission since it does not produce fission fragments. Fusion neutrons are very harmful to people within 1 km of the blast, but this effect is much less significant than close-in blast effects and fission radioactivity. The yield of a secondary stage is about 50 % fusion and 50 % uranium–fission. Thus, a 1-Mton, 50–50 weapon has about 500 kton of fission, while a

Table 2.4 Assured destruction

	1999 population (M)	W88 warheads
China	1281	368
Iran	64	10
Iraq	21	4
North Korea	22	4
Russia	152	51
US	259	124

The number of hard-target warheads to kill 25 % of population and destroy 50 % of industry (Matt McKenzie, NRDC).

Table 2.5 LD-50 radii

1 Mton	Blast (5 psi)	Thermal (7 cal/cm^2)	Radiation (4.5 Sv, 450 rem)
Surface (km)	4.6	11	2.7
Air burst (km)	6.7	17	2.7

The distances from the explosion where 50 % of the affected population would die from blast, thermal radiation, and nuclear radiation from 1-Mton surface and air explosions. (Glasstone and Dolan 1977)

10-kton primary is 100 % fission if unboosted. Blast height is extremely important in determining the amount of radioactive fallout. If an explosion takes place at low altitudes, excess neutrons produce large amounts of radioactivity in the soil, which disperses in a plume. High altitude bursts make much less radioactivity since nitrogen and oxygen absorb neutrons, which decay quickly, but ^{14}C lingers. In addition, a high altitude burst directly disperses and dilutes the radioactivity. A particularly nasty target would be a nuclear reactor. One estimate for a 1-Mton bomb hitting a 1-GW_e reactor predicts an area of 34,000 km^2, which would give a lifetime dose of over 1 Sv (100 rem) to the affected population.

Overpressure of 5 psi (30 kPa) destroys wood and brick houses beyond repair. One might think that blast pressure would diminish as the inverse square of the distance, but it falls off faster, proportional the inverse cube on the distance (Fig. 2.5).

Fallout. The radioactive plume from a nuclear weapon depends on yield, height of blast, and wind conditions. A 1-Mton weapon can produce a plume that deposits radiation of 5 Sv (500 rem) over an area 30 miles wide and 1000 miles long. A prompt dose of 4.5 Sv (450 rem) is lethal to about 50 %, and essentially no one survives 1000 rem. If citizens stay inside buildings, the dose is reduced by a factor of three. Terrorist *dirty-bombs* are discussed in Chap. 13. Radioactive plumes from nuclear accidents are discussed in Chap. 3 (Figs. 2.6, 2.7 and 2.8).

Cratering. The radius of a crater in hard rock is about 150 m for 1 Mton and 75 m for 100 kton (OTA). The Russian 1908—asteroid of 30 to 50 m in diameter broke apart in the atmosphere, destroying 2000 km^2 of Siberian forest. Another example of danger from asteroids is the Barringer Crater of 1.2 km diameter and 0.2 km deep, created by a 50-m asteroid, 50,000 years ago near Winslow, Arizona. If astroids are discovered very early and very far away, one might use very large nuclear weapons to get a small deflection angle from (1) x-rays, (2) explosive push, (3) fragmentation. This is difficult to do.

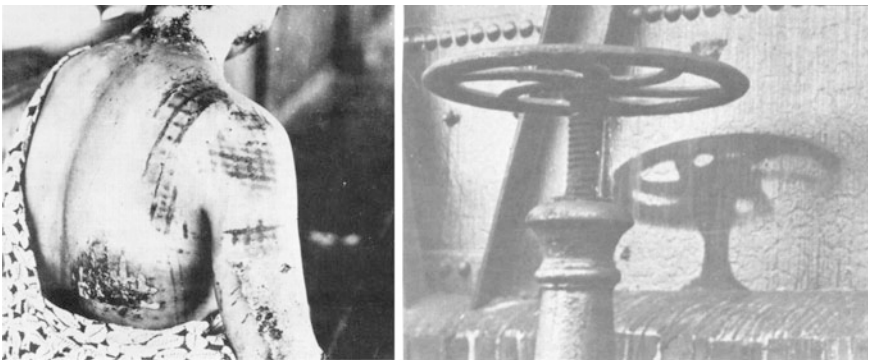

Fig. 2.5 Thermal radiation of Hiroshima victim and valve shadow (AHF)

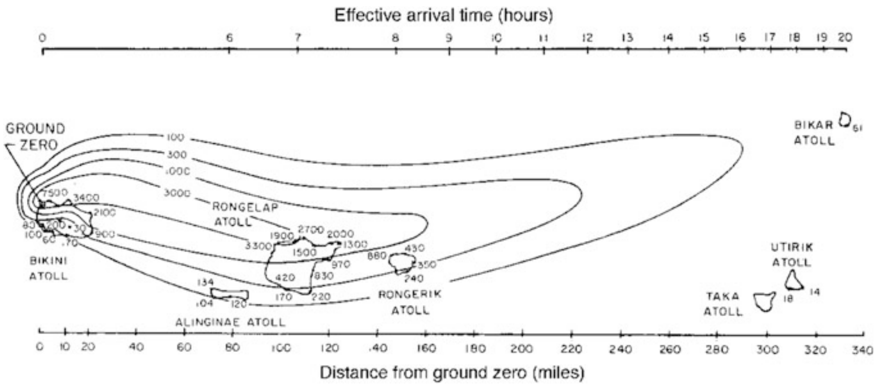

Fig. 2.6 Bikini fallout. Total accumulated dose contours in rads, 4 days after the BRAVO test explosion (Glasstone and Dolan, 1977)

Nuclear Winter. The volcanic eruption of 10 April 1815, on Tambora led to global cooling and June frost in 1816, the "year without a summer." Atmospheric physicists realized in 1982 that large nuclear attacks on cities would create massive amounts of micron-sized soot and raise them to the stratosphere, with effects similar to very large volcanic eruptions. It was projected that 10,000 0.5-Mton warheads could reduce light levels to a few percent of ambient levels and temperatures could *drop* by 30 °C for a month, warming to 0 °C for another 2 months. Hence, the name *nuclear winter*.

A key factor is *lofting of soot* to the upper troposphere. Weapons over 300 kton raise soot high enough to absorb sunlight and heat the upper atmosphere by 80 °C, which raises (lofts) the soot higher. A major effect of such weapon blasts would be destruction of much of the world's food supply by low temperatures. The US government carried out burning and chemical explosions to test some of these ideas, but it is difficult to test larger scenarios peacefully. The 1980s debate became that of a *matter of degrees* between a *nuclear winter* and a *nuclear autumn*.

After 3 decades, there is less concern about possible large-scale exchanges with the Russia, but dire predictions are still relevant for the case of accidental wars and regional wars involving 100 Hiroshima-sized weapons. Such a war between India and Pakistan, each with fifty 15-kton weapons could lead to about 44 million casualties and 6.6 trillion grams (Tg) of soot. A war using 4400 warheads, each with a yield of 100 kton, could cause 770 million casualties and 180 Tg of soot, enough to create ice-age conditions. Toon, Robock and Turco "estimate that most of the world's population, including that of the Southern Hemisphere, would be threatened by the indirect effects on global climate." Thus, nuclear winter scenarios are possible.

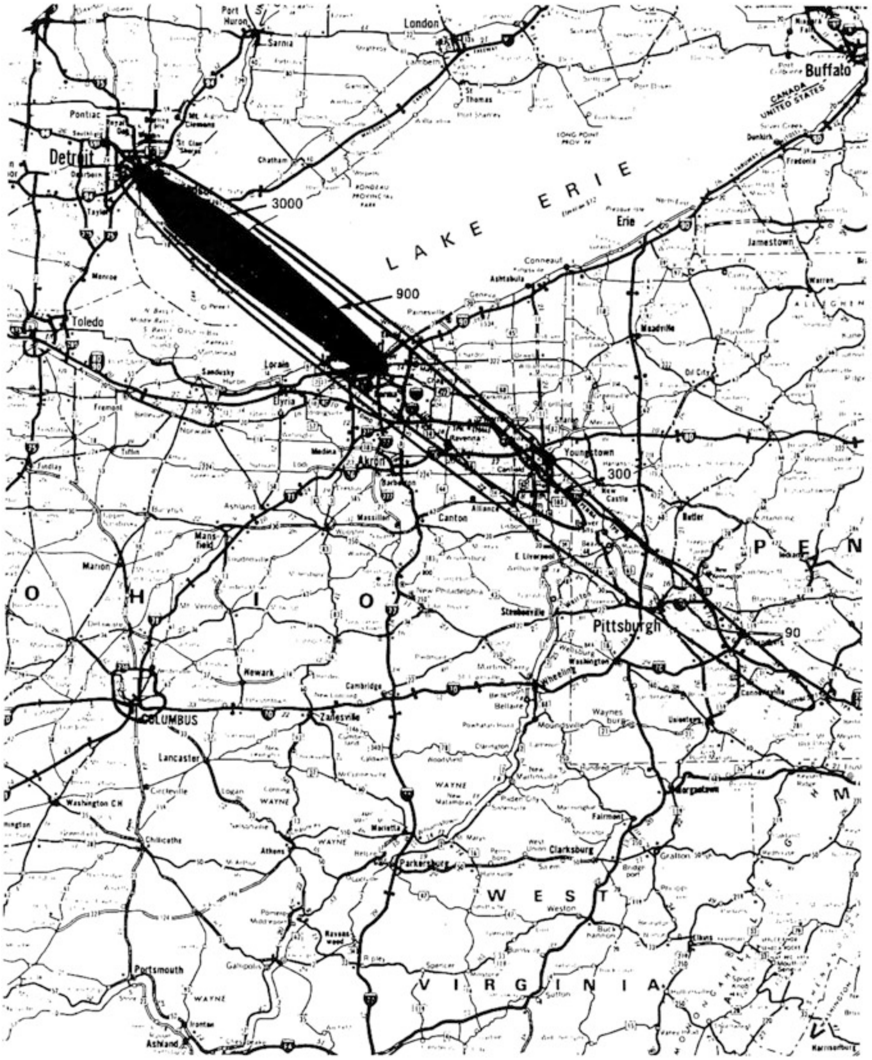

Fig. 2.7 Detroit fallout. Main fallout pattern after a 1-Mton surface explosion in Detroit, with a uniform, steady 15-mile/h wind from the Northwest. The 7-days accumulated dose contours (without shielding) are for 3000, 900, 300, and 90 rem. The constant wind would give lethal fallout in Cleveland and 100 rem in Pittsburgh (Office of Technology Assessment, 1979)

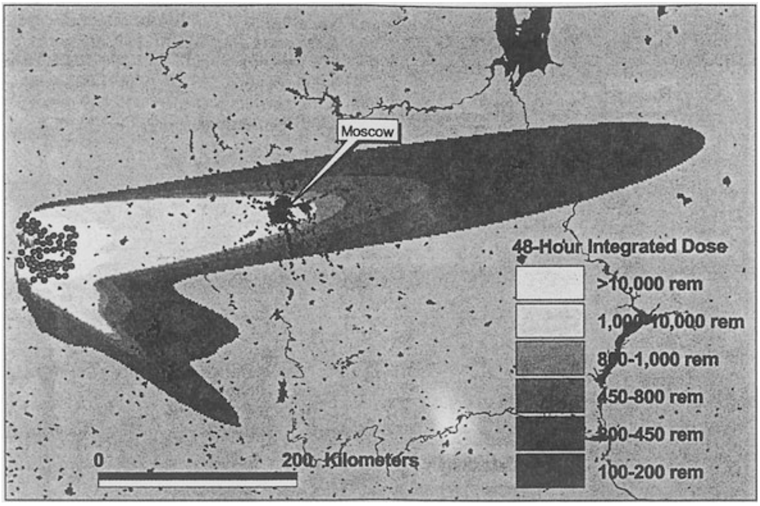

Fig. 2.8 Attack on SS-19's at Kozelsk. Under this scenario 13 million die from radiation received in the first two days (McKinzie et.al., NRDC, 2001)

2.11 Electromagnetic Pulse Attack on Power Grids

The electric power grid and the command, control, and communications (C^3) systems that control US strategic forces are vulnerable to large electromagnetic pulses (25,000 V/m), created by high-altitude (100–500 km) and low-altitude bursts of nuclear weapons. These effects were observed with our first nuclear tests, but they were formally tested on 9 July 1962 with the *Starfish Prime* explosion above Johnston Island. The 1.4-Mton weapon exploded at an altitude of 400 km on a Thor ballistic missile. The nighttime sky above Hawaii, 1300 km away, momentarily lit up with a white flash as if at noontime. This was followed by the sky turning green for about a second. The Hawaiian streetlights suddenly went out. Radio stations and telephone lines failed for a time. The US, Russia and China are probably not going to do such attacks these days, but EMP high altitude tasks might be used to attack sensors in orbit. Satellites are soft targets for EMP. It is difficult to shield sensitive detectors and soft silicon logic.

This vulnerability creates a possible instability in nuclear arms. If a country perceives its strategic forces could be negated by EMP, it might be tempted to adopt a "launch on warning" policy to use them rather than lose them to a preemptive first strike. The situation is not as unstable as I have characterized because these systems are hardened to partially withstand EMP and missiles based on submarines are not vulnerable to a first strike. However, perception of vulnerability in the land-based leg of the strategic triad creates pressure for a *launch on warning response*. Some of the C^3 facilities, such as the Air Force's Looking Glass Command Post in the sky, are more vulnerable than the strategic weapons.

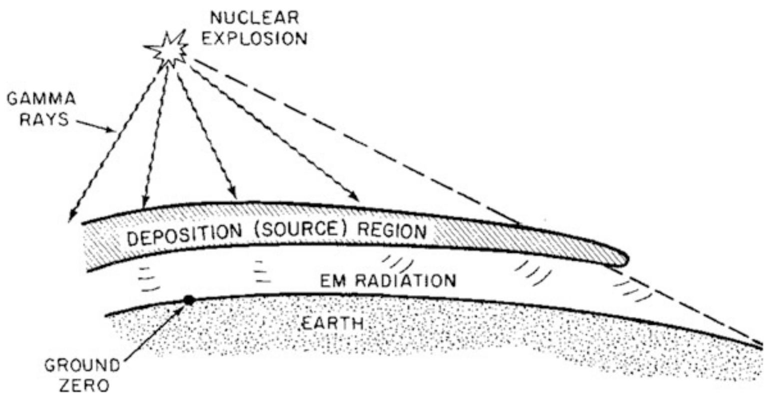

Fig. 2.9 Electromagnetic pulse. Schematic representation of an electromagnetic pulse (EMP) from a high-altitude burst. Fission fragments release prompt MeV gamma rays, which interact with the thin upper atmosphere creating Compton electrons. The electrons spiral with reasonable coherence in the Earth's magnetic field at about 1 MHz because they begin at essentially the same phase in the orbit. The October 1962 test at Johnston Island shut down the power grid in Hawaii and blocked radio and TV for several hours on the West Coast and throughout the Pacific region. See problems 1.17 and 1.18 (Glasstone and Dolan, 1977)

These issues have not ended with the end of the Cold War. EMP can be used by nations with few nuclear weapons against a nation with many nuclear weapons in an asymmetrical attack. "An EMP attack may degrade 70 % of the Nation's electrical service, in one instant." Extra-high-voltage transformers that are used for long-distance lines are vulnerable. These are not made domestically and might take 2 years to replace at considerable cost.

The adoption of variable power sources of wind and solar encourages upgrading of power grids. The smart grid, with digital sensors and control devices, could become targets for hackers and saboteurs. Incorporating shielding to protect against EMP might increase costs by 2–10 %. Installing resistors on the neutral–to–ground connections could reduce currents by 60 %. In recent years, non-nuclear EMP weapons have been down-scaled for delivery by planes and land vehicles. It is planned to use mini-EMP weapons to shut-down vehicles and boats (Fig. 2.9).

2.12 Stockpile Stewardship

The Comprehensive Nuclear–Test–Ban Treaty (CTBT) was open for signature in 1996. Since then there have been a half-dozen tests by India and Pakistan in 1998, which were easily detected. Four North Korean (DPRK) nuclear tests (2006, 2009, 2013 and 2016) were easily detected by the International Monitoring System (IMS) seismic stations. Nuclear radiation from the 2006 and 2013 tests was also detected by the IMS radionuclide network. Chap. 11 discusses CTBT monitoring

Table 2.6 DOE complex

	Employees	$B/year
Kansas City Plant	2700	0.6
Los Alamos National Laboratory	7300	1.6
Lawrence–Livermore National Lab.	5200	1.1
Nevada National Security Site	2400	0.3
Pantex Plant, Amarillo, TX	3100	0.6
Sandia National Lab., NM & CA	9800	1.7
Savannah River Site	5600	0.55
Y-12, Oak Ridge, TN	4700	1.2

Managing the DOE weapons complex involves over 40,000 employees with an annual budget of over $8 billion. The number of employees and budget are listed for the eight largest facilities.

and the connection between the Non-Proliferation Treaty and CTBT. In this section, we discuss the Stockpile Stewardship Program, which maintains nuclear weapon reliability and safety, without using nuclear testing for diagnostics.

Between 1958 and 1961, there was a moratorium on nuclear tests by the US and USSR, as Eisenhower/Kennedy and Khrushchev negotiated a test ban treaty. A few problems developed in untested US weapon types with major design innovations. This is not the situation today, as the US stockpile consists of 7 well-tested legacy warheads. When the US was conducting 20 tests per year, only one test per year was used to determine confidence in reliability, thus reliability was determined with very low accuracy. Statistics show that the weapon primary is much more vulnerable to change than the secondary (Table 2.6).

A major concern is that aging might reduce primary yields, preventing the triggering of the secondary. Aging effects could be caused by alpha decay of ^{239}Pu, causing thousands of lattice displacements for every Pu-decay.[1] Since 1997, NNSA and the JASONS studied Pu pits by combining short-lived ^{238}Pu with ^{239}Pu, 24,000-years lifetime, to speed up the aging process. By combining 8 % ^{238}Pu with 92 % ^{239}Pu the aging rate is increased by a factor of 16. An 11-years old Pu sample has an effective age of 170 years. The samples are examined for size changes with an accuracy of 0.1 microns out of 2 cm. The tests showed changes of only 0.25 % in volume in a 100-years period. The NNSA 2006 panel concluded that Pu pits have a minimum life of 85 years, "indicating that lattice damage and helium in-growth are not leading to catastrophic aging effects such as void swelling." In 2012, the DOE weapons labs reported more information after doing more experiments, concluding that the primaries (pits) "will function as designed up to 150 years after they were manufactured." Longer-lived pits imply that remanufacturing capabilities for

[1]A. Heller, Plutonium at 150 years: Going strong and aging gracefully, *Science and Technology Review* (LLNL), December 2012, 11–14.

Table 2.7 US enduring stockpile weapons

Weapon	System	Yield (kton)	Number Built	Laboratory
B61	Bombs	170	1,200	LANL
B61/11	Earth Penetrator	400	47	LANL
W76	SLBM Trident	100	3,200	LANL
W78	ICBM Minuteman-3	335	1,000	LANL
W80/1	ALCM (SLCM = 0)	150	1750	LANL
B83	Bomber	325	625	LLNL
W87	ICBM Minuteman-3	300	560	LLNL
W88	SLBM Trident	455	400	LANL

The US dismantled 11,751 warheads between 1990 and 1999. The US and Russia both had about 5000 operable warheads in 2015.
US (strategic deployed 1700, tactical 500, non-deployed 2800)
Russia (strategic deployed 1500, tactical 2000, non-deployed 2000)
(Kristensen and Norris 2014, 2015)

making pits can be reduced. Originally the plan was to make 125 to 450 pits per year (2004). Congress cancelled that plan in 2006. This was replaced with a Los Alamos facility, to make 50 to 80 pits per year, then lowered to 20 to 30 per year. Since Los Alamos can now make 10 to 20 per year, the new facility will not be needed. The Obama administration has suggested a five-year waiting period to determine actual needs. For a 1000-warhead stockpile, lasting 100 years each, a production rate of 15 per year would be sufficient.

Each of the enduring warheads in Table 2.7 is being refurbished under the individualized life-extension program (LEP). Their goal is not to make changes in the basic physics package design. Mostly these programs appear to be successful, with the exception of the B61 bomb, which is costing additional funds, but is progressing to be refurbished by 2022.

The Stockpile Stewardship Program is determining an improved equation of state for solid-state plutonium, used to calculate the properties of imploding primaries. The Joint Actinide Shock Physics Experiment Research (JASPER) Facility at the Nevada Test Site projects high–velocity plutonium samples into plutonium targets with a two-stage gas gun, 20-m long. JASPER achieves millions of atmospheres of pressure and temperatures of thousands of Kelvins, resulting from an initial velocity of 8 km/s.

Strategic nuclear bombers have had a number of major accidents, obtaining a much poorer safety record than that of ICBMs and SLBMs. This is no longer relevant since heavy bombers have been de-alerted, no longer carrying nuclear weapons, except for times of nuclear threat. In addition, the vulnerable US liquid-fueled, Titan ICBMs have been decommissioned, further reducing safety concerns.

In 2002 and 2012, the National Research Council released CTBT oversight reports by a panel of experts. They examined the US Stockpile Stewardship

Program (SSP), which is dedicated to making US warheads reliable and safe without nuclear testing.[2] The NRC committee concluded the following in 2012:

> Constraints placed on nuclear-explosion testing by the monitoring capabilities of the IMS, and the better capabilities of the US National Technical Means, will reduce the likelihood of successful clandestine nuclear-explosion testing, and inhibit the development of new types of strategic nuclear weapons. The development of weapons with lower capabilities, such as those that might pose a local or regional threat, or that might be used in local battlefield scenarios, is possible with or without the CTBT for countries of different levels of nuclear sophistication. However, such developments would not require the United States to return to testing in order to respond because it already has—or could produce—weapons of equal or greater capability based on its own nuclear explosion test history. Thus, while such threats are of great concern, the United States would be able to respond to them as effectively whether or not the CTBT were in force.
>
> A technical need for a return to nuclear-explosion testing would be most plausible if the United States were to determine that adversarial nuclear activities required the development of weapon types not previously tested. In such a situation, the United States could invoke the supreme national interest clause and withdraw from the CTBT.
>
> As long as the United States sustains its technical competency, and actively engages its nuclear scientists and other expert analysts in monitoring, assessing, and projecting possible adversarial activities, it will retain effective protection against technical surprises. This conclusion holds whether or not the United States accepts the formal constraints of the CTBT.
>
> Finding 1.1: The technical capabilities for maintaining the U.S. stockpile absent nuclear-explosion testing are better now than anticipated by the 2002 report.
>
> Finding 1.2: Future assessments of aging effects and other issues will require quantities and types of data that have not been provided by the surveillance program in recent years.
>
> Finding 1.3: The committee judges that Life-Extension Programs (LEPs) have been, and continue to be, satisfactorily carried out to extend the lifetime of existing warheads without the need for nuclear-explosion tests. In addition to the original LEP approach of refurbishment, sufficient technical progress has been made since the *2002 Report* that *re-use or replacement* of nuclear components can be considered as options for improving safety and security of the warheads.
>
> Finding 1.4: Provided that sufficient resources and a national commitment to stockpile stewardship are in place, the committee judges that the United States has the technical capabilities to maintain a safe, secure, and reliable stockpile of nuclear weapons into the foreseeable future without nuclear-explosion testing. [The three weapon laboratory directors indicated they agreed with this conclusion.] Sustaining these technical capabilities require at least the following:
>
> – *A **Strong Scientific and Engineering Base***. Maintaining both a strategic computing capability and modern non-nuclear-explosion testing facilities (for hydrodynamic testing, radiography, material equation-of-state measurements, high-explosives testing, and fusion testing) is essential for this purpose.
> – *A **Vigorous Surveillance Program***. An intensive surveillance program aimed at discovering warhead problems is crucial to the health of the stockpile.
> – ***Adequate Ratio of Margin to Uncertainty***. Performance margins that are sufficiently high, relative to uncertainties, are key ingredients of confidence in weapons performance.

[2]National Research Council, *The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States*, (National Academy Press, Washington, D.C., 2012).

- ***Modernized Production Facilities***.
- ***A Competent and Capable Workforce***.

Hydronuclear testing refers to a test in which criticality is achieved but the nuclear yield is less than the energy released by the high explosive. In this report the committee distinguishes hydronuclear tests as a subset of nuclear-explosion tests, most of which have nuclear yield far greater than the energy released by the high explosive but all of which are banned under the CTBT.

Finding 4.2: Hydronuclear tests would be of limited value in maintaining the United States nuclear weapon program in comparison with the advanced tools of the stockpile stewardship program.

Finding 4.3: Based on Russia's extensive history of hydronuclear testing, such tests could be of some benefit to Russia in maintaining or modernizing its nuclear stockpile. However, it is unlikely that hydronuclear tests would enable Russia to develop new strategic capabilities outside of its nuclear-explosion test experience. Given China's apparent lack of experience with hydronuclear testing, it is not clear how China might utilize such testing in its strategic modernization.

Problems

2.1 **Neutron detection**. How did Chadwick detect this neutral-charged particle?
2.2 **Kennedy's 25 NWp states**. Name 25 that started nuclear weapons research.
2.3 **Fission energy**. Why is fission energy primarily electrostatic energy.
2.4 **235 versus 238**. Why does 235 work in atom bombs and 238 does not?
2.5 **Cow/Mice diets**. Why can cows live on grass, but mice cannot?
2.6 **Critical mass**. How is critical mass affected by neutrons/fission, geometry, isotope ratios, reflectors, compression, etc.?
2.7 **Tritium. How is tritium produced**?
2.8 **d + t = He + n**. What three ways is this reaction used in nuclear weapons?
2.9 **Radiation compression**. How does this squeeze and heat the secondary?
2.10 **Tritium supplies**. Because of tritium's 12.4–year half life, it needs replenishing. Why did our tritium resource become larger at the end of the Cold War?
2.11 **HEU versus Pu**. What are the relative difficulties to obtain Pu and HEU?
2.12 **Weaponization**. Is HEU or Pu easier to make into a weapon? Why?
2.13 **Ease of detection**. Is HEU or Pu easier to hide? Why?
2.14 **H-bomb**. Why is lithium-6 deuteride ($^{6}Li^{2}H$) useful for hydrogen weapons?
2.15 **H-bomb size**. Is there an upper limit on yield for a hydrogen secondary?
2.16 **Boosted primaries**. Why do they work, extra energy vs. extra neutrons?
2.17 **Neutron bomb**. Why were these lethal to enemy tank-drivers? Why dangerous?
2.18 **Anti-Matter bomb**. Why are anti-matter bombs unlikely? How efficient if exist?

2.19 **Nuclear winter**. What conditions might cause a temperature drop of 30 °C?
2.20 **Stockpile stewardship**. What are the legacy weapons? What is the Pu-pit lifetime? What tools is the SSP using to make weapons reliable?

Seminar: Nuclear Weapon Issues
artificial radioactivity, Ban the Bomb, Bikini Tests, Baruch Plan, Big Mike explosion, big vs. small nuclear weapons, boosted nuclear weapons, Castle Bravo Test, critical mass, Cuban Missile Crisis, Earth penetrating warhead, electronic initiator, electromagnetic pulse, Franck report, heavy water in Norwegian Vermok, Jewish physics, lithium deuteride, lost nuclear weapons, Manhattan Project, neutron bomb, peaceful nuclear explosions (PNE), permissive action link (PAL), polonium-210, Project Orion, Pugwash Conferences, safety features on nuclear weapons, tamper, thorium, uranium resources, uranium-233 stocks and use, Y-12 enrichment.

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http://www.springer.com/978-3-319-25365-7

Nuclear Proliferation and Terrorism in the Post-9/11
World
Hafemeister, D.
2016, XXIV, 434 p. 52 illus., 35 illus. in color., Hardcover
ISBN: 978-3-319-25365-7