Appendix B: A Primer on Fissile Materials and Nuclear Weapon Design
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What are fissile materials? How are they made? What quantities of these materials are necessary to produce a bomb? How do different designs affect a weapon's size, yield, and fissile material requirements? What are the differences between advanced thermonuclear weapons, advanced fission weapons, and crude fission weapons? When does testing become necessary? Given an understanding of these basic concepts, what can we assume about the bombs that might be designed by nuclear terrorists given a supply of fissile material? This appendix provides answers to these questions and shows why nuclear leakage from Russia is so dangerous.

Simple nuclear weapons are easy to design, make, and deliver, assuming an adequate supply of fissile material. It is the difficulty of obtaining fissile material that provides one of the major defenses protecting the international community from a major surge in nuclear proliferation. Fissile materials and their means of production will continue to be difficult to obtain if excess fissile materials do not leak from Russia. If, on the other hand, fissile materials do leak from Russia, then the supply of nuclear weapons in the world will soon equal the demand.

This appendix is organized as follows: First, I outline briefly the physics involved in a nuclear detonation and discuss the fissile materials required. Then I describe the design of an advanced thermonuclear weapon; almost all simpler weapons, which I next describe, are a special case of an advanced design.

Having demonstrated that design is not a major obstacle, I turn to what is the major obstacle: production of fissile materials. To summarize: since a simple weapon is not difficult to design, since expertise is available, and since testing is not necessary, all that stands between proliferants and nuclear weaponry is the difficulty of obtaining fissile materials.

FISSION AND FUSION

The simplest and lightest element - hydrogen - consists of a nucleus with one positively charged particle, the proton, and a negatively charged particle, the electron, in orbit around that nucleus. Elements are distinguished from each other by the number of protons in their nuclei.

This number is their atomic number, and hydrogen's is one. Almost all nuclei also contain a second kind of particle, the neutron, which has nearly the same mass as the proton, but no electrical charge. Together, protons and neutrons are known as nucleons, and the total number of nucleons in a nucleus is known as the atomic weight or mass. Hydrogen, with one proton and no neutrons, has a mass of one.

A given element generally occurs in several forms, called isotopes. Different isotopes of an element are distinguished by the number of neutrons in their nuclei. Hydrogen has three isotopes: hydrogen, with one proton and no neutrons; deuterium, with a proton and a neutron; and tritium, with a proton and two neutrons. Isotopes can be referred to symbolically by element and mass. For example, the three hydrogen isotopes can be represented as H-1, H-2, and H-3.

Uranium and plutonium have atomic numbers of 92 and 94 respectively. Uranium isotopes range from U-232 to U-238. Plutonium isotopes range from Pu-238 to Pu-242. The isotopes of most concern to this discussion are U-235 and Pu-239. They have an odd number of neutrons in their nuclei.

When nuclei of the isotopes U-235 and Pu-239 are struck by neutrons, they sometimes split, or fission. They fission into two lighter elements, or fission fragments. The sum of the atomic masses of the two fission fragments is always less than the total atomic mass of the original U or Pu nucleus. The size of the difference determines the amount of energy released in the form of neutrons, light, and other forms of radiation as a result of the fission.

Under certain conditions of high density and intense heat, the nuclei of hydrogen isotopes can come close enough to fuse despite the repulsive force of their like-charged nuclei. The atomic mass of the new element, always an isotope of helium, is always less than the sum of the two hydrogen isotopes that fused to form it. Again, this mass difference determines the amount of energy released in neutrons and other forms of radiation.

A fissioned uranium or plutonium nucleus releases roughly ten times the energy created by the most energetic of the various fusion reactions between different hydrogen isotopes. On the other hand, a single fission reaction requires on the order of 236 to 240 nucleons (protons and neutrons), while a single fusion reaction requires as few as four or five. Thus, per nucleon, fusion produces five to six times more energy than fission.

FISSILE MATERIALS

Fissile materials consist of isotopes whose nuclei fission after capturing a neutron of any energy. Fissionable isotopes fission only after the capture of neutrons with energies above some threshold value. Many heavy isotopes are fissionable, but many fewer of them are also fissile, and almost all of these are isotopes of uranium or plutonium. All fissile materials and some fissionable materials are usable in weapons. It is the odd-numbered isotopes of uranium and plutonium that are fissile: U-233,235 and Pu-239,241. U-235 and Pu-239 are the most common and are the best weapon materials.

The probability that a nucleus will fission when struck by a neutron of a given energy is expressed in terms of its fission cross-section. Cross sections, expressed as an area, are measures of the probability that a given neutron will fission a given nucleus. Isotopes with large fission cross sections are more likely to fission than isotopes with lower cross-sections. Pu-239 has a higher fission cross-section than U-235 at all neutron energies.

Neutrons cause nuclei to fission, and neutrons are also released when nuclei fission. The average number of neutrons released per fissioning nucleus varies, depending on the isotope. Pu-239 releases 3 and U-235 2.5 neutrons per fission, on average. Because Pu-239 has a higher fission cross-section, and because it emits more neutrons per fission, it takes less Pu-239 than U-235 to sustain a fission chain reaction.

A chain reaction occurs when every nucleus that fissions causes, on average, at least one other nucleus to fission. When this occurs in a mass of fissile material, we describe it as a critical mass, i.e., one that is just capable of sustaining a chain reaction. Nuclear reactors cause sustained chain reactions by assembling a mass of fissile material whose criticality is dependent on the presence of a moderator like graphite or water that slows neutrons down, thereby exploiting the high fission cross-sections of fissile materials in the presence of low energy, or thermal, neutrons.

An explosive chain reaction occurs when every nucleus that fissions causes, on average, more than one other nucleus to fission. A supercritical mass of fissile material is necessary for an explosive chain reaction. Nuclear weapons generally assemble supercritical masses by uniting or compressing subcritical masses of fissile materials, and by reflecting neutrons back into those masses that would otherwise have escaped into free space. The better the compression and the better the neutron reflection, the fewer neutrons escape, the more fissions are caused per fission, and the greater the rate at which the chain reaction multiplies. For these reasons, the critical mass of Pu-239 is about three times smaller than that of U-235 at normal densities, because of its higher fission cross-section and average neutron production rate per fission. Thus, less Pu-239 than U-235 is needed to make a fission weapon.

CRITICAL MASSES

All by itself, apart from any neutron reflection and at normal densities, a bare, solid sphere of plutonium with greater than 90 percent PU-239 is critical when its weight exceeds 22 pounds. This amount is called the "bare crit." Under the same circumstances, uranium enriched to more than 90 percent U-235 will go critical when it weighs 114.5 pounds. As the percentage of Pu-239 in plutonium is reduced, the bare crit goes up slowly. High burn up (or recycled) reactor plutonium with 60 percent Pu-239 has a bare crit only 25-35 percent higher than plutonium with 90 percent Pu-239. The rise in critical mass is much greater as U-235 enrichment levels are lowered. Uranium enriched to 50 percent in U-235 would have a bare crit three times as high as uranium with 90 percent U-235.(1)

Critical mass requirements drop steeply in the presence of neutron reflection. Reflectors made of heavy metals can reduce the bare crit to half, while reflectors made from the lightest metals can cause a threefold reduction. High explosive compression to twice normal density can reduce bare crits by half again. Thus, a highly conservative implosion weapon might use a fissile core that was large enough to be barely sub-critical at normal density when surrounded by a reflector. The detonation of the high-explosive shell and the compression of the barely sub-critical core could hardly avoid producing some nuclear yield. Once a supercritical mass has been assembled by whatever means, the yield of the resulting explosion will be increased if the explosion can be contained or tamped for several microseconds before it disassembles. Tampers can be made from any heavy metal. Therefore, in some weapons, the tamper and the reflector are the same component.

The Fat Man design tested at Alamogordo and used over Nagasaki was a simple weapon that used all these techniques. It was an implosion weapon that used a massive quantity of high explosive to implode a very heavy, spherical uranium/tungsten reflector/tamper enclosing a solid sphere containing 12 pounds of plutonium. The resulting explosion had a yield equivalent to 20,000 tons (20 kilotons) of high explosive. The same assembly mechanism would have required 30 pounds of highly enriched uranium (HEU) to produce the same yield. (2)

More sophisticated designs use even less fissile material. Current U.S. weapons use advanced fission weapons to begin a thermonuclear detonation. These use 9 pounds or less of plutonium. Fractional crit fission weapons producing low kiloton yields can be made with as little as 2.5 pounds of plutonium or 5.5 pounds of HEU. (3) On the other hand, as we will see below, advanced thermonuclear weapons use fissile materials in significant quantities in more than one place.

From Advanced Thermonuclear to Simple Fission Weapons Designs

In this section I discuss weapons design, beginning with a description of the configuration and detonation of an advanced thermonuclear weapon. (4) Almost all other simpler designs, discussed below, are a special case of an advanced design.

First, there is the trigger, or primary stage. Imagine a sphere consisting of a series of concentric shells of different materials nested together. The core of the sphere is hollow, and there is an air gap that separates the outer shells of the sphere from the inner ones. Along the outside of the sphere is a thin metal casing. Then, moving inward, one finds a high-explosive jacket, a heavy metal tamper, and a light metal reflector. These parts comprise the assembly mechanism.

Next is the air gap that separates the assembly mechanism from the fissile shell, or pit. The pit rests on a pedestal inside the air gap and is itself a hollow sphere of plutonium clad with a metal plating. The pedestal supporting the plutonium pit also serves as a tunnel connecting the outside of the assembly mechanism to the pit's hollow core. At the other end of this tunnel are two containers of tritium and deuterium gas, one much smaller than the other. The whole assembly is called a primary, as in primary stage.

Physically separate from the primary is another component, the secondary.

A cylindrical shape, rather than a sphere, it too consists of layers of different materials, but it is solid and has no air gaps. The outside layer in this notional design is natural uranium, but it could be any number of fissile, fissionable, or other heavy metals. This outer layer, or pusher, encloses a layer of lithium deuteride, a very light compound comprising isotopes of lithium and hydrogen. The lithium deuteride, in turn, encloses an innermost layer of fissile HEU, also known as the sparkplug.

Finally, a heavy casing shaped like a large watermelon contains the primary at one end and the secondary at the other. Assume that all the batteries, cables, capacitators, detonators, safety devices, fuses, radiation shields, and so on are in place, and that the fusing and firing systems work as intended, and the weapon detonates.

The detonation begins in the high-explosive layer surrounding the primary. It explodes, imploding the tamper/reflector shell. The tamper/reflector is driven inward through the air gap, picking up momentum while facing no resistance. It slams into the plutonium pit, crushing it. The pit is compressed to two or three times its normal density, driving its nuclei closer together, while remaining enclosed by the imploding tamper/reflector. Through compression and neutron reflection, a supercritical mass of plutonium is formed in the pit. This is the primary assembly phase.

As the pit approaches its maximum compression, the smaller of the two external tritium-deuterium gas containers, the initiator, uses an electric charge to compress its contents; the tritium and deuterium nuclei fuse, and emit high-energy neutrons through the tube leading into the hollow core of the imploding pit. Some of these neutrons strike plutonium nuclei and fission them. This initiates a larger number of parallel chain reactions in the pit. This is the primary ignition phase. After ignition, a race develops between the fission chain reaction propagating through the fissile pit, and the rate at which the pit blows apart by disassembly The more generations of the chain reaction before disassembly, the more material is fissioned, and the larger the yield.

Therefore, at this point, the chain reaction receives a boost. The much greater quantity of tritium-deuterium gas in the larger of the two external containers - the booster - is now injected at high pressure into the fissioning pit. There, the intense pressures and temperatures cause the hydrogen isotopes to fuse and a much larger burst of high energy neutrons is released than during the initiation phase. These high-energy neutrons boost the fission chain reaction, by greatly increasing the number of fissions in each succeeding generation of the reaction. The primary boost phase increases the energy release prior to the explosive disassembly of the plutonium pit.

The primary stage has now detonated. It first emits a burst of intense X-ray radiation. The X-rays travel at the speed of light, some thirty times faster than the nuclear particles released by the exploding primary. They are absorbed by the interior of the weapon casing and re-radiated onto the outer shell of the secondary. Thus, X-ray radiation transports, or couples, the energy of the primary to the secondary.

The secondary shell is turned into a dense plasma. As this plasma ablates, or burns off, it exerts an implosive force inward on the rest of the secondary that is a thousand or so times greater than the pressure created by high explosives. The shell pushes inward and compresses the secondary.

As the secondary is compressed, the innermost layer of fissile material at its core begins to fission. The lithium deuteride between the imploding shell and the exploding core is now being compressed even further. Neutrons from the fissioning core bombard the lithium deuteride; lithium nuclei capture neutrons, emit an alpha particle (a helium nucleus), and become tritium.

At this stage, the secondary has been compressed, its fissile core has fissioned, and tritium has been bred in the lithium.

Now the two hydrogen isotopes most prone to fusion reactions - deuterium and tritium - are present in the fusion fuel capsule of the secondary They have been compressed by the imploding shell and heated by the exploding core. They fuse under the intense pressure and temperature. The heat produced increases the temperature of the secondary further, causing more fusions of the hydrogen isotopes, and the hydrogen fuel burns, releasing thermonuclear energy in a manner analogous to the sun.

As part of this tremendous energy release, the fusing hydrogen isotopes are also producing highly energetic neutrons. These cause the imploding shell of fissionable U-238 (or fissile U-235) to fission. The fissioning of the secondary shell, in turn, simultaneously boosts and tamps the energy released in the burning fusion fuel capsule. This completes the detonation of the secondary.

Thus, the detonation of a modem two-stage thermonuclear weapon actually involves many more than two distinct stages: high-explosive detonation, primary assembly, primary ignition and fissioning, primary boosting, primary detonation, radiation coupling from the primary to the secondary, secondary implosion, secondary core ignition and fissioning, tritium breeding, thermonuclear burn, and secondary shell fissioning. It is more accurate to think of the detonation of a thermonuclear weapon as a series of mutually reinforcing fission-fusion-fission reactions, begun with chemical high explosives in a primary, and continued in secondary and, in some cases, tertiary stages via radiation coupling.

Thus one can think of the primary stage of a thermonuclear weapon as simply an advanced fission (atomic) weapon. Even though some of its explosive yield results from fusion reactions due to tritium-deuterium gas boosting, none of it depends on X-ray radiation coupling between physically separate stages.

Let us now take this advanced thermonuclear weapon, whose design we have already described, and progressively simplify it.

SIMPLE WEAPONS

The most advanced designs emerged out of the ballistic missile era that began in the United States in the 1950s. Ballistic missiles created a demand for weapons with high yield-to-weight and yield-to-volume ratios. Before the ballistic missile era, thermonuclear weapons were designed to maximize yield-to-fissile material ratios. These criteria influenced both the primary and secondary stages.

Modern primaries use as little high explosive and fissile material as possible, and rely heavily on tritium boosting to produce yields sufficient to compress and ignite secondaries. This minimizes volume and weight. Modem secondaries often use considerably greater amounts of fissile material for the same reason. For example, using fissile rather than fissionable material in the shell of a secondary substantially increases yield without increasing weight or volume. Expanding the diameter of the heavy, cylindrical fissile or fissionable components of a secondary at the expense of the diameter of the much lighter lithium deuteride component within a given overall volume increases yield, but also increases weight.

Before the advent of ballistic missiles, weapons were delivered primarily by aircraft capable of lifting large, heavy payloads. U.S. fissile material stockpiles were also smaller then, and designers built large weapons which maximized yield for a given amount of fissile material. Primaries were much larger and heavier even when they used boosting, because high-explosive jackets were larger and heavier: with more high explosive, the same pit will be compressed more and produce more yield. Secondaries were larger, but contained less fissile material. Most of their volume, and therefore more of their yield, derived from fusion. During this first phase of thermonuclear design, very large weapons were deployed with ternaries, or third stages that brought yields into the tenmegaton range.

Prior to the development of multi-stage thermonuclear weapons, U.S. designers experimented with high-yield single-stage fission weapons. They used very large quantities of HEU in an implosion design. Plutonium could not be used because in large quantities its high spontaneous neutron emission rate made pre-detonation likely even in an implosion device. Even without boosting, such high-yield HEU implosion designs approached half a megaton in yield. With boosting they could approach a megaton. On the other hand, they were very heavy, they used enormous amounts of HEU, and they were very hard to make safe from accidental detonation due to shock or fire.

Concerns about accidental detonation were a major issue for weapon designers early in the Cold War because U.S. Strategic Air Command aircraft flew peacetime training and alert missions with weapons aboard. Prior to the widespread adoption of tritium boosting, single-stage implosion weapons or primaries of a multi-stage weapon were designed with two-piece cores, one piece of which was stored separately and inserted just prior to use. In the event of an accident causing detonation of the high-explosive assembly mechanism, core detonation would be impossible due to the missing piece of the pit. With boosting, sealed pit weapons were developed with less fissile material in the core. These weapons depended on a tritium-deuterium gas injection to produce an appreciable yield even if the assembly mechanism worked perfectly. In an accident, when the high explosive would detonate unevenly, and without gas boosting, such a device would produce no appreciable nuclear yield.

As we have seen, boosting was also used to maximize yield while preserving scarce fissile material. Two other innovations designed to achieve the same objective preceded boosting. One involved "levitated pits," or the separation of the pit from the tamper by an air gap. Levitated pit designs increased the efficiency of assembly mechanisms by allowing them to develop more kinetic energy before they struck the pit.

The other involved "composite pits," or pits that consisted of a mix of both plutonium and HEU. Composite cores were developed by the United States during a period immediately after World War II when it was producing eight times as much HEU as plutonium per ton of natural uranium feed. HEU could be used much more efficiently in an implosion weapon than in a gun weapon. Furthermore, as long as plutonium was scarce, a given quantity of HEU and plutonium could be used more efficiently if combined in individual weapon pits than if the two fissile materials were used separately in different weapons.

Levitated pits and composite cores, used together or separately, greatly increased the efficiency of the first postwar generation of fission weapons in the United States. Prior to the introduction of these advances in the late 1940s and early 1950s, fission weapon design had not advanced much beyond the first generation of fission weapons developed in wartime at Los Alamos.

Another early postwar innovation involved a change in the means of initiating the fissi ' le chain reaction. Prior to the development of external deuterium-tritium initiators, internal initiators were used. Located at the core of the fissile pit, these used polonium, which is a strong alpha emitter, and beryllium, which emits neutrons in the presence of an alpha source.(5) Normally separated by a thin screen in a small, bimetallic, golf ball-sized container, these elements, when crushed together by the imploding pit, became a strong neutron source. The drawbacks to this early practice were twofold. Polonium has a very short half life of 138 days and therefore early weapons had very short shelf lives. They could not be deployed in the field for long. In addition, internal initiators tended to detonate weapons too early, causing less-than-optimal pit compression.

This simplification takes us essentially to the Trinity-Nagasaki "Fat Man" implosion design. Fat Man used a lot of plutonium packed solidly inside a massive assembly mechanism of high explosive and a very heavy tamper. The advanced neutron reflecting properties of beryllium were not exploited to reduce critical mass requirements, and the polonium/beryllium initiator needed to be inserted into the core shortly before use. Fat Man was a very conservative design, and it remains the simplest implosion weapon design available. It worked on the first try both at Alamagordo and at Semipalatinsk.

Implosion was itself a wartime Los Alamos innovation that solved the first major nuclear weapon design challenge. To explain this challenge, it is useful to consider some history. The first fissile material to be discovered was the isotope Uranium 235. Since U-235 is rare in nature (.72 percent of natural uranium), it must be enriched (concentrated). This requires that it be separated from other non-fissile uranium isotopes, primarily U-238. Isotope separation remains today a very sophisticated technology. In the late 1930s, it seemed impossible on the scale needed for a weapon.

At first, therefore, the discovery of plutonium seemed to get around this problem. Plutonium could be produced in the nuclear reactor when U-235 fissioned and emitted neutrons that were captured by U-238, producing Plutonium 239. After removal from the reactor, the Pu-239 could be chemically separated from the uranium because it was a different element. Chemical separation was much simpler than isotope separation, and plutonium production reactors using natural uranium fuel could be designed as soon as a moderating material of sufficient purity was found to slow fission-induced neutrons enough to sustain a thermal neutron chain reaction. Very pure graphite solved this problem for the United States, and it appeared that weapons would now be easier to produce, especially since an even simpler design than Fat Man had already been developed by Los Alamos.

This initial fission weapon design was not an implosion device. Rather, it was really just a glorified cannon. In such a "gun type" design, a shell of fissile material is fired down a gun barrel into a hollow fissile target fastened to the other end of the barrel. Once united, the two sub-critical pieces form a supercritical mass and detonate. Since no compression of the fissile material occurs in such a design, it requires a lot of fissile material, and what it uses, it uses inefficiently. Nevertheless, it was clear in 1943 that a gun-type weapon would work.

Shortly after the first plutonium emerged from the pilot scale X-10 reactor at Oak Ridge in the summer of 1944, the existence of another plutonium isotope, Pu-240, was confirmed. It was formed in the reactor when Pu-239 captured a neutron but did not immediately fission. Pu-240 spontaneously fissioned at a rate much greater than Pu-239. Thus, Pu-240 proved to be a potent neutron source, as some had anticipated.(6) More importantly, the supercritical mass in a gun weapon is assembled at a rate which turned out to be too slow to allow a gun weapon to be made with plutonium, because it spontaneously emits neutrons at a rate likely to cause predetonation. Implosion solved this design challenge at the cost of some increase in complexity. Implosion assembly of a supercritical mass occurs much more quickly than gun assembly, allowing the use of plutonium.

Thus the first design challenge of the nuclear age involved a choice between a very simple gun weapon using HEU which was very expensive to produce, and a more complicated implosion weapon using plutonium which was somewhat less difficult to obtain. In the event, the Manhattan Project pursued both options. Alongside the Fat Man plutonium weapon, Los Alamos also designed an HEU gun bomb called Little Boy. Its designers were confident enough of success on the first try that Little Boy was "tested" over Hiroshima. Gun-type weapons using HEU remain the simplest of fission weapons. Early postwar, air-delivered, earth penetration bombs used gun designs because their simple assembly mechanism could function even after the shock of a high velocity impact. Later, certain nuclear artillery shells used a gun firing the shell, and because such weapons could be made with small diameters.

However, the main attraction of a gun weapon remains its simplicity. The likelihood of success without testing, combined with an indigenous source of HEU, made a gun design the weapon of choice for the South Africans some thirty years after Little Boy.

Thus we see that there are very simple nuclear weapon designs available to a potential proliferator. Weapons based on these designs would bear little resemblance to the more advanced weapons deployed by today's nuclear powers, but that is beside the point, since even simple weapons could reliably produce an explosion equal to hundreds or thousands of tons of TNT. That is a much easier task than most people think; the main obstacle has been the difficulty of securing an adequate supply of fissile material. Producing fissile materials is, however, more difficult than most people think, and it is to that subject I now turn.

Producing Fissile Materials

HEU is produced at enrichment plants using one of several isotope separation technologies.(7) All of these technologies exploit the small differences in atomic mass to separate different isotopes of the same element from each other. The most widely used isotope separation technique today uses centrifuges. Uranium hexafluoride gas is fed into a connected "cascade" of centrifuges. The centrifuges are spun at verv high rates. The heavier U-238 gravitates toward the rotating outer wall of the centrifuge, while the U-235 remains closer to the axis. At each stage of the cascade, uranium depleted in U-235 is collected and separated.

After many repetitions, what is left is run consisting primarily of U-235, or enriched uranium.

Before centrifuges, most industrial scale enrichment plants used a gas diffusion process. In a gaseous diffusion plant, uranium gas is pumped at high pressure through a series of cylinders with porous walls, or diffusion barriers. Lighter isotopes pass through the barriers at slightly greater rates. Again, after passing through a cascade of many barriers, the U-235 content is enriched and the U-238 reduced. A gas diffusion cascade is much larger than a centrifuge cascade, and consumes more electrical power by an order of magnitude. Diffusion plants are larger because gas barriers give less enrichment, or separative work, per stage than centrifuges, and they consume more power because the gas pumps that fill the cascade need to be much more powerful than the small motors that spin centrifuges. Large gas diffusion plants still operate in the United States, France, and China. Most of the rest of the world's enrichment capacity uses the more modern centrifuge technology.

There are other enrichment technologies. The South Africans, probably with German assistance, developed an aerodynamic enrichment technology that exploits the different paths followed by different isotopes in gaseous form as they flow at high speeds around a curved nozzle. The United States developed and later abandoned an enrichment technology that used high-current cyclotrons (calutrons). Calutrons ionize uranium gas and pass the positively charged ions through an intense magnetic field that acts more strongly on the lighter isotopes. The Iraqis later adapted this inefficient method as a part of their enrichment enterprise. Laser isotopic enrichment technologies have been developed and may be used in the future, but they are probably too sophisticated for any but the most advanced nations. They also exploit the behavior of positively charged, ionized isotopes, but do so selectively and with much greater efficiency than do calutrons.

Plutonium is produced in nuclear reactors.(8) The energy produced in a reactor results from the chain reaction that begins when a critical configuration of U-235 is created in its core. As we have seen, such chain reactions are carried by neutrons. When a nucleus fissions, it produces several neutrons in addition to the fission fragments. Only one of these, on average, needs to fission another nucleus for the chain reaction to be sustained. Of the other neutrons, some are captured by "fertile," as opposed to fissile, materials in the reactor's fuel elements. A fertile isotope (U-238) is one that, upon capturing a neutron, becomes a fissile isotope (Pu-239).

Most reactors use uranium fuel with U-235 enrichment levels ranging from 0.72 percent (natural uranium) to 5 percent (low-enriched uranium, or LEU). In other words, reactor fuel usually consists mostly of fertile U-238. When U-238 nuclei capture neutrons, they decay rapidly through a two-stage process to become Pu-239. Pu-239 is both fissile and fertile. When Pu-239 captures a neutron, instead of fissioning, it can become Pu-240. When Pu-240 captures a neutron, it can become Pu-241, and Pu-241 can, in turn, become Pu-242. In fourteen years, half the Pu-241 decays into the element Americium, but the other isotopes last for thousands of years. All of these plutonium isotopes, and Americium as well, are fissile or fissionable as well. Therefore, as plutonium is produced in a reactor, some of it also fissions. Thus, over time, the total amount of plutonium produced in the reactor fuel elements ceases to increase. On the other hand, the higher-number plutonium isotopes become a larger and larger percentage of the total plutonium produced. When reactor fuel is used in a reactor for a long time, it is called "high burn up" fuel, and the plutonium produced from it will be less concentrated or enriched in the isotope Pu-239 than if it were "low burn up" fuel that was in a reactor for a comparatively shorter period.

When fuel elements are removed from a reactor, the plutonium and uranium still present can be separated chemically in what is usually called a "reprocessing" facility. Reprocessing separates elements from each other, but not different isotopes of the same element. Thus, the plutonium is separated from the other elements, but its isotopic composition remains the same. In principle, plutonium isotopes could be separated from each other in enrichment facilities, but this is not done, at least on anything more than a laboratory scale, for several reasons.

First, the main reason to enrich plutonium would be to separate Pu-239 from Pu-240. Pu-240 is a strong neutron emitter. Its presence in all plutonium is the reason why plutonium cannot be used in simple guntype weapons; it might cause pre-initiation. The atomic weights of these two isotopes differ by only one neutron. It would take much more enrichment capacity, using existing methods, to separate Pu-240 from Pu239 than it takes to separate U-235 from U-238. Second, enrichment cascades used to process plutonium would be permanently contaminated with it. Third, it has generally been simpler for the weapon states to simply produce low burn up plutonium in dedicated reactors, and to treat the plutonium in higher burn up power reactor fuel as material to be recycled, or as waste.

WEAPONS GRADE VERSUS WEAPONS USABLE MATERIAL

Many confuse the concept of weapons-grade plutonium with the much more inclusive concept of weapons-usable plutonium. From a weapon designer's point of view, it is best to use plutonium and uranium that are as pure in the isotopes Pu-239 and U-235 as possible. This reduces critical mass requirements to their minima, and reduces the difficulty of making reliable plutonium weapons that remain easy to handle throughout a long stockpile life. The nuclear weapon states have established tacit standards defining weapons grade materials. In the United States, HEU for weapons is generally at least 93 percent U-235, and weapons grade plutonium is at least 94 percent Pu-239. These standards do not in any way constitute the dividing line between what is and is not usable in weapons; they simply reflect what is optimal. It is possible to form a supercritical configuration using uranium enriched to as little as 20 percent, though such a device would require a massive assembly mechanisms. (9) Likewise, plutonium of any isotopic content (burn up level) is usable in a weapon.(10) High burn up plutonium simply changes the probability distribution between the "fizzle" yield and the "nominal" yield, making yields closer to the former value more likely than yields closer to the latter. The fizzle yield for the Fat Man design was about one kiloton, and the nominal yield was 20 kilotons. Thus, Fat Man's fizzle yield would have been four thousand times more powerful than the 500-pound general purpose bombs in use both then and today. Such plutonium will also produce more heat and radioactivity, but heat sinks and shielding can be included in a design, if necessary, as compensation.

DEVELOPING OR OBTAINING TECHNOLOGY TO PRODUCE WEAPONS-USABLE MATERIALS

The United States, the Soviet Union, Great Britain, France, China, Israel, India, South Africa, Pakistan, Brazil, Argentina, Iraq, and North Korea have all developed or obtained the means of producing fissile material in programs designed at least to provide a nuclear weapons option, if not in an explicit weapons program. (11) Some of these countries successfully pursued plutonium and HEU simultaneously (the United States, Soviet Union), some developed or obtained one first and the other later (Great Britain, France, China), while the rest have, for the time being, achieved only one.

Since the early days of the Manhattan Project, the plutonium route has been perceived as the simpler technology. All other things being equal, it is technically simpler to develop and build a reactor/reprocessing facility than it is to develop and build a uranium enrichment facility. In fact, the discovery of plutonium was the event that made nuclear weapons a practical rather than merely theoretical prospect in the eyes of many physicists in the early 1940s. (12) Great Britain and France began their weapon programs with plutonium forty or more years ago largely because they were more confident in their ability to quickly, and at a reasonable expense, develop an indigenous reactor/reprocessing enterpnse than an enrichment enterprise. Today, North Korea pursues plutonium presumably for the same reason.

Of course, all other things are never equal. For many states, neither route lies within the abilities of their domestic industrial base. This was China's situation in the late 1950s, but the Soviet Union planned to simply give China both a plutonium and an HEU production capability. When cooperation between these two states abruptly ended in 1960, the enrichment plant was much further along than the reactor facility and so HEU initially became the basis for the early Chinese weapon program. Most less-developed aspiring nuclear states are not offered plutonium or HEU production capabilities as a gift. The question for them becomes which technology is easiest to purchase.

Until the 1970s, for states like India, Israel, and Iraq, reactors were easier to purchase. Over time, though, these calculations have changed as the non-proliferation regime has grown in strength. Since the late 1970s, the question for less-developed states concerns the comparative ease of covert purchase. Pakistan and Iraq, and perhaps South Africa, found it easier to covertly purchase or gain assistance in developing uranium enrichment technology Ironically, in the case of Pakistan and Iraq, it proved easier to covertly purchase components of the most advanced uranium enrichment technology, the gas centrifuge. This is because centrifuges are now in wide use in Europe where the nuclear industry has historically had more freedom than the U.S. or Soviet nuclear industry to sell its wares to all buyers.

The North Korean program is, in many ways, the antithesis of the Pakistani and Iraqi programs. It is almost completely indigenous. There has been no covert North Korean purchasing campaign of dual-use technologies, and there has been no flood of North Korean graduate students in the physics departments of western universities. It uses the oldest and simplest of fissile material production technologies, the natural uranium-fueled, graphite-moderated plutonium production reactor, pioneered by Enrico Fermi and Leo Szilard in 1939 and utilized in one form or another by the Soviets, the British, the French, and the Israelis. One can speculate that the North Koreans chose the plutonium route for several reasons, and despite a major drawback. It is the simplest way to a completely indigenous program, and North Korea's isolation made foreign assistance or foreign purchases of other technology unlikely. On the other hand, the plutonium route is difficult to hide, even when it is completely indigenous, because the "signature" associated with reactor construction is significant, especially in a country like North Korea which is already under close observation.

More advanced states have more choices, and a larger set of political and institutional factors to consider. Whether with German assistance or not, South Africa was the first country to develop aerodynamic nozzle technology on a commercial scale when it began enriching uranium at Valandiba in 1978, so this was an indigenous program to a considerable extent. South Africa also chose the HEU route for reasons of energy self-sufficiency and to add value to its already large uranium ore exports.

Somewhat later than South Africa, Argentina and Brazil also began relatively autonomous uranium enrichment programs. The Brazilian Navy already had an interest in developing naval reactor designs that required HEU fuel, and this provided both an organizational home and a rationale for HEU production. Argentina had a more inchoate set of motivations, and initially sought both HEU and plutonium production capabilities simply to match anticipated developments in Brazil's civilian nuclear sector. Though Argentina's nuclear power reactors use natural uranium fuel, its research reactors use HEU fuel, and these supplies were cut off by the United States in the late 1970s. This provided a rationale for continuing the HEU program.

Argentina and Brazil announced their uranium enrichment programs in 1983 and 1987 respectively, well before they were capable of producing HEU in significant quantities. Before these announcements, the enrichment facilities in question do not seem to have been detected by the rest of the world, although this was less certainly the case with the Argentine gaseous diffusion plant at Pilcaniyeu than it was for the pilot Brazilian centrifuge facility at Sao Paulo University. Thus, these two programs were more covert than the South African program, which was announced at its outset in 1970. On the other hand, both Argentina and Brazil announced these programs before they became operational, unlike the Pakistani and Iraqi programs, which sought to maintain a veil of secrecy to the end.

For the future, one can imagine a causal relationship of sorts, with the dependent variable being the choice between plutonium and HEU, and the independent variable being the level of development of a state's industrial base. To simplify the analysis, assume that the non-proliferation regime remains intact, that the nuclear aspirant has no civilian nuclear power industry as a base and desires at least a weapons option, but that it is not a state that could simply buy a reactor from a western supplier within the confines of the Nuclear Non-proliferation Treaty (NPT) without setting off some alarm from the non-proliferation community.

Up to a fairly advanced point of industrial development, such a state is likely to face a tradeoff created by the technology denial regime which is a part of the non-proliferation regime. HEU production technology is hard to develop indigenously, but centrifuge components can be bought covertly in dual-use pieces from many different western component suppliers, albeit over a considerable period of time, at great expense, and with considerable probability of eventual detection. Plutonium production technology is easier, but still difficult, to develop indigenously, and it is more difficult to purchase. Further, in neither case can these plutonium production capabilities be hidden as they take shape.

Rich but relatively undeveloped states like Iran and Iraq can continue to attempt to buy centrifuge enrichment technologies covertly, much as Pakistan first developed its nuclear capability. Such programs cannot be completely covert, but their scope and rate of progress may be masked until it is too late for the international community to respond effectively. The same countries can attempt to buy reactors, as Iran is doing now, but such purchases cannot be hidden, take years to unfold, and provide plenty of time for the international community to apply pressure or supply inducements designed to stop the purchase. Even if such purchases go through, countries like Iran must still prevent suppliers from demanding that the spent fuel be returned, as Russia may in the proposed Russian-Iranian reactor deal.

The denial regime had little direct effect on North Korea, which indigenously developed gas-cooled, graphite-moderated reactors. For isolated, but somewhat more developed states like North Korea, plutonium may be the material of choice because the reactors are marginally easier to develop, and because plutonium requires less natural uranium feed. On the other hand, this has always mandated an essentially overt program, since reactors are vulnerable to overhead observation and identification as they are built. It remains to be seen whether the overtness of North Korea's program ultimately prevents its fruition due to the response it has provoked from the international community. Beyond a certain point, the industrial development of a state allows a range of choices based on a variety of financial, institutional, and military factors. South Africa, Argentina, and Brazil all had the technical and industrial skills to produce either plutonium or HEU. They chose HEU for reasons other than its comparative ease of development.

South Africa chose HEU production because it also had a civilian power industry that required low enriched uranium (LEUI), because LEU could be sold on world markets, and because it may have had assistance in developing its specific aerodynamic nozzle enrichment technology from German companies. South Africa made no serious attempt to keep its enrichment program covert, but it did go to great and largely successful lengths to keep its HEU production secret.

Once Argentina decided to pursue HEU, it chose the older and less efficient gaseous diffusion method of enrichment because it could not indigenously develop the more modern centrifuge enrichment technology, and because it believed that an effort to purchase centrifuges or their components abroad would be detected. Argentina sought to maintain a covert development program, with apparent success between 1978 and 1983. It chose to make the program public in 1983, five years before it succeeded in producing its first HEU, enriched only to 20 percent U-235, late in 1988.

Unlike Argentina, Brazil was confident enough of its technical abilities to launch an indigenous centrifuge program. However, Brazil also followed the same path as Argentina of initial secrecy, followed by public revelation prior to completion, although the lag between announcement and first HEU production was only from 1987 to 1988.

If both countries had sought to preserve secrecy for their HEU production capabilities, Brazil would have had a better chance of success because its capability was based on modem centrifuge technology. Centrifuge facilities are not especially large and they consume very little power. A largely indigenous centrifuge program like Brazil's is therefore very hard to detect. The South African nozzle technology, along with the gaseous diffusion technology chosen by Argentina, is much harder to hide because of its size and prodigious energy consumption. Furthermore, the energy requirements of these older technologies can be used to determine whether an overt program like the one in South Africa, and now in Argentina, is secretly being used to produce HEU rather than LEU.

To summarize, the traditional non-proliferation regime seeks to control the spread of unsafeguarded facilities to produce fissile materials. This denial regime operates in several ways. It either forces states that seek nuclear weapons capability into covert, costly, and lengthy purchasing programs of dual-use technologies useful for uranium enrichment (centrifuges); or it forces them into the indigenous development of technologies that are difficult or impossible to hide (reactors, gas diffusion plants). (13) Only when a state's science and industrial base can support the indigenous development of a modern, energy-efficient uranium enrichment technology like the gas centrifuge has it crossed the threshold beyond which nuclear capability can be indigenously developed without interference from the international community. This means that even countries as advanced as Argentina and South Africa in the late 1970s and 1980s were far from immune to the direct and indirect constraints of the traditional non-proliferation regime.

Summary: Building a Simple Nuclear Weapon

The first nuclear weapon used in anger was Little Boy. Untested, it was detonated over Hiroshima with a yield equivalent to 15,000 tons of TNT, or 15 kilotons. Little Boy used 132.8 pounds of HEU enriched to a little over 80 percent in the fissile isotope U-235. It was 10 feet long, 28 inches wide, and weighed 9000 pounds. (14) During the 1980s, South Africa developed a very similar gun weapon using essentially the same technology. This design used 121 pounds of HEU enriched to over 90 percent U-235 and had an expected yield of 10-18 kilotons. It was 6 feet long, 26 inches wide, and weighed 2200 pounds.(15) Gun weapons of quite simple design were used in eight-inch artillery shells by the United States beginning in the early 1950s. These designs were made smaller while retaining yields in the ten-kiloton range by reducing barrel length and tamper bulk, and adding beryllium reflectors and more energetic high-explosive charges. One such design, the W-33, used about 1140 pounds of HEU enriched to 93 percent U-

235.(16) It fit inside an artillery shell 3 feet long, 8 inches wide, and, when fully armed, weighing 250 pounds.(17)

The reduction in fissile material requirements and the possibility of plutonium use that an implosion design allows comes at a small price in design complexity. The implosion must be symmetrical; the high-explosive jacket must therefore be uniform in its effects when it explodes, which means that the firing system must detonate the jacket simultaneously at 50-100 points spaced uniformly about its exterior. Though complicated, such a firing system can be perfected through a series of instrumented non-nuclear implosion tests using non-fissile heavy metal cores. The increase in complexity does not put a crude implosion design beyond the reach of a terrorist or organized crime group. In addition, the benefits of an implosion design allow designers to use much less fissile material, and to use fissile material that would not be usable in a gun design, such as plutonium of any isotopic composition and uranium of less than the highest level of enrichment in U-235.(18)

Fat Man was about the same length and weight as Little Boy, but was 5 feet wide. Like Little Boy, Fat Man had an extremely heavy, bullet-proof aerodynamic casing that constituted a large portion of its weight. It was also highly conservative in its use of high explosive to ensure optimal assembly of a supercritical mass. High explosives constituted almost half its weight and most of its internal volume. Dramatic reductions in size and weight with no loss in yield and reliability or increase in design complexity could be achieved simply by taking Fat Man's design, adding several pounds of plutonium to the core and a beryllium reflector, and cutting the size and weight of the implosion assembly mechanism in half. Further, dramatic reductions in the size of the assembly mechanism (high explosives, tamper, etc.) could be achieved if the pit were levitated; a levitated pit design could be validated using non-nuclear proof tests of the assembly mechanism.

Thus we have seen that weapons can be designed very simply. They need be no more complicated than the first designs tested by Great Britain, France, China, and India; those designs all worked perfectly the first time. (Russia's first test in 1949 used a copy of the U.S. Fat Man implosion design.) Furthermore, much has changed since the summer of 1945, when the designs for Little Boy and Fat Man were frozen. Science has progressed, secrets have been declassified, and military technologies have developed commercial uses. College professors write textbooks that would have won Nobel prizes fifty years ago, governments publish primers on simple nuclear weapon design, and tritium-deuterium neutron sources are sold for commercial purposes.(19)

The recipe, as shown above, is no secret, and has not changed appreciably in many decades. Nor are the ingredients, other than plutonium or HEU, hard to obtain. For a gun weapon, the gun barrel could be ordered from any machine shop, as could a tungsten tamper machined to any specifications the customer desired. The high-explosive charge for firing the bullet could also be fashioned by anyone with access to and some experience handling TNT, or other conventional, chemical explosives. Other than the initial supply of HEU, the only possible complications are development of a neutron initiator and, if desired, a supply of beryllium for the reflector. All the information necessary to solve these problems, as well as any others that might crop up, are available in the open literature, and have been for some time. Designers of U.S. weapons have been repeating this basic truth over and over again since the early 1970s when John Foster, a former director of the Lawrence Livermore nuclear weapons laboratory, stated that "the only difficult thing about making a fission bomb of some sort is the preparation of a supply of fissile material of adequate purity; the design of the bomb itself is relatively easy." (20)

Thus, given a sufficient quantity of fissile material, virtually any state and many terrorist or organized crime groups could build a simple, reliable nuclear weapon. There is an overwhelming consensus that fissile material constitutes the major obstacle to a simple nuclear weapons capability. (21) There is also a more narrowly specified consensus among U.S. weapons designers that almost any state, and many terrorist groups, could build a simple nuclear weapon given an adequate supply of fissile material. (22) If would-be proliferants want professional help, history suggests that they will probably get it. Nearly every successful national nuclear weapons program has benefited greatly from "brain drain," and weapon designers from any of today's declared or threshold nuclear states, but especially from Russia, could accelerate the pace of an existing program or hasten the creation of a new weapons program. (23)

Those who believe that knowledge and technology are so widely disseminated as to make advanced or unconventional nuclear weapon designs beyond denial to potential proliferants occasionally demonstrate, albeit inadvertently, the opposite point. For example, Tom Clancy and Russell Seitz argued that such denial regimes would become impossible or irrelevant. One of their points involved an exaggeration of the utility for weapons of certain kinds of nuclear waste not normally considered to be weapons-usable material. Such a mistake could take a small, autonomous weapons program down a several-years-long blind alley, which a professional weapons designer from Arzamas or Chelyabinsk would know to avoid. This mistake makes the point that it is not easy to use modern sources of unclassified information to get the details of unusual or advanced nuclear weapons design exactly right; however, simple weapons using proven designs and standard materials are another matter. (24)

Some argue that inability to test weapons would hamper proliferation. Testing is indeed a big issue: the declared weapon states are in the midst of a debate on whether or not there is a need for continued testing at full or partial yield. (25) However, this debate has little relationship to the question of whether testing is necessary to confirm the design of a simple fission weapon.

In the declared weapon states, the need for testing grew out of the desire to get more and more bang for the buck out of a given supply of very expensive fissile material, using smaller and easier-to-deliver weapons. After small high-yield weapons were developed, testing was required to make them as safe as possible under the conditions they might encounter, including shock, fire, and radiation. Then, testing was required to make weapons reliable in the absence of testing. This involved confirming the performance of new, more conservative designs containing larger margins of error. Then, testing was required because the standards for safety and reliability rose, and the new standards had to be applied to the existing stockpile.

Testing would be of much less concern to the designer who is happy to settle for simple gun-type or implosion weapons like Little Boy or Fat Man. Both designs could be considerably reduced in size and weight from their original 1945 configurations without nuclear testing. Such a step would risk only a small decrease in the size and predictability of their nominal yields. More significant design advances could be accomplished without testing using computerized simulation techniques and extensive non-nuclear testing. Thus, a levitated pit implosion weapon might be developed in this fashion by a small, sophisticated design group without nuclear testing. Such weapons were initially deployed in the U.S. stockpile in the late 1940s without testing. (26)

At some point during the climb up the ladder of sophistication, the simulation techniques become sophisticated enough to require the intellectual and financial resources one would normally associate only with a state, rather than a terrorist or organized-crime group. Some would place this point where one adds tritium-deuterium boosting to the design. Further demands might exhaust the simulation techniques available to even the most advanced industrial states; few would argue, for example, that even the United States would have confidence in any untested multistage weapon design without at least a full-yield test of the primary. (This, incidentally, was part of the rationale for the threshold test ban treaty, which allowed underground detonations of up to 150 kilotons.)

However, very simple weapons can be designed and used with high reliability without testing, as the United States did with the Little Boy design over Hiroshima. South Africa also developed and deployed nuclear weapons without testing. Israel and Pakistan are believed to be nuclear weapon states, and this status was achieved in both cases without testing. (India, with one test, is also believed to be a weapon state.) Even a relatively undeveloped state like North Korea, with no tests but with a small cache of plutonium, could be credited, and already is in some circles, with nuclear weapons capability. The same status would apply to Iraq, test or no test, if it ever succeeds in amassing thirty or more pounds of HEU.

States or criminal and terrorist groups desirous of nuclear capability designed to extort money or terrorize cities will not need to be concerned with testing. They will use the simplest designs possible given the nature and quantity of their supply of fissile material. Therefore, the necessary absence of testing in a covert weapons program is no defense against that program. With a modicum of preparation, but without any nuclear testing, reliable weapons with kiloton yields can be quickly produced as soon as a sufficient quantity of fissile material becomes available.

Thus, the recipe for a simple nuclear weapon is not beyond the reach of most states and many groups. It is only by keeping a lid on the supply of fissile material that non-proliferation can succeed.

FOOTNOTES:

1. Paul Leventhal and Yonah Alexander, eds., *Preventing Nuclear Terrorism: The Report and Papers of the International Task Force on Prevention of Nuclear Terrorism* (Lexington, Mass.: Lexington Books, 1987), pp. 56-57.

2. Thomas Cochran and Christopher Paine, *The Amount of Plutonium and Highly Enriched Uranium Needed for Pure Fission Weapons: Nuclear Weapons Databook* (Washington DC: The Natural Resources Defense Council, April, 1995), p. 5 and Figures I and 2.

3. Ibid., Figs. 1 and 2.

4. The following discussion depends heavily on Chuck Hansen, *U.S. Nuclear Weapons:The Secret History* (Arlington, Tex.: Aerofax, 1988), especially pp. 11-41. See also Charles S. Grace, *Nuclear Weapons: Principles, Effects and Survivability* (London: Brassey's, 1994), pp. 3-24; Hans A. Bethe, "Comments on the History of the H-Bomb," *Los Alamos Science,* Vol. 3, No. 3 (Fall 1982), pp. 43-53; and "Appendix E: Physics of Nuclear Weapon Design," in Committee to Provide Oversight of the DOE Nuclear Complex and Commission on Physical Sciences, Mathematics, and Resources, *The Nuclear Weapons Complex: Management for Health, Safety, and the Environment* (Washington, D.C.: National Academy Press, 1989), pp. 123-128.

5. On various neutron sources, see Robert Mozley, "Particle Sources and Radiography," *Science and Global Security,* Vol. 1, Nos. 3-4 (1990), pp. 291-293.

6. See Richard Rhodes, *The Making of the Atomic Bomb* (London: Penguin, 1980), Pp-548-549.

7. See Alan Krass, Peter Boskma, Boelie Elzen, and Wim A. Smit, *Uranium Enrichment and Nuclear Weapons Proliferation* (London: Taylor & Francis, 1983); and Robert F. Mozley, *Uranium Enrichment and Other Technical Problems Relating to Nuclear Weapons Proliferation*, Center for International Security and Arms Control, Stanford University, July 1994.

8. On reactors, see Anthony V. Nero, Jr., *A Guidebook to Nuclear Reactors* (Berkeley, Calif.: University of California Press, 1979).

9. Mason Willrich and Theodore Taylor, *Nuclear Theft: Risks and Safeguards (Cam*bridge, Mass.: Ballinger, 1974) pp. 16-17.

10. The definitive statement on this point is J. Carson Mark, "Explosive Properties of Reactor Grade Plutonium," *Science and Global Security,* Vol. 4, No. 1 (1993), pp. 111-124.

11. The following discussion uses: Joel Ullom,"Enriched Uranium versus Plutonium: Proliferant Preferences in the Choice of Fissile Material,"

The Nonproliferation Review, Vol. 2, No. 1 (Fall 1994), pp. 1-15; David Albright, "A Proliferation Primer," *Bulletin of the Atomic Scientists,* Vol. 49, No. 5 (June 1993), pp. 14-23; David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium* (New York: Oxford University Press, 1993), especially pp. 153-194; and Leonard Spector and Jaqueline Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons 1989-1990* (Boulder, Colo.: Westview, 1990).

12. Rhodes, *The Making of the Atomic Bomb,* p. 352.

13. Calutrons of the type used recently in Iraq and earlier bv the United States during the Manhattan Project are also very energy intensive, but they are easier to hide than gaseous diffusion plants because they do not have to be formed into massive cascades. On the other hand, calutrons by themselves are a very inefficient means of enriching natural uranium to levels

necessary for use in a weapon. The Iraqis intended to use calutrons as part of a two-stage enrichment process in which centrifuges were used to bring calutron-enriched uranium from levels of a few percent U-235 to over 90 percent. See David Albright and Mark Hibbs, "Iraq's Nuclear Hide-and-Seek," *Bulletin of the Atomic Scientists,* September 1991, pp. 14-23.

14. Thomas Cochran and Christopher Paine, *The Role of Hydronuclear Tests and other Low-Yield Nuclear Explosions and Their Status Under A Comprehensive Test Ban*, Nuclear Weapons Databook (Washington DC: Natural Resources Defense Council, March 1995) p. 4.

15. David Albright, "South Africa and the Affordable Bomb," *Bulletin of the Atomic Scientists,* Vol. 50, No. 4 (July/August 1994), pp. 44-45.

16. "Nuclear Notebook," *Bulletin of Atomic Scientists,* Vol. 49, No. I (January/ February 1993), p. 56.

17. Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook, Vol.* 1: *U.S. Nuclear Forces and Capabilities* (Cambridge, Mass.: Ballinger, 1984), pp. 47-48.

18. J. Carson Mark, Theodore Taylor, Eugene Eyster, William Maraman, and Jacob Wechsler, "Can Terrorists Build Nuclear Weapons?" in Leventhal and Alexander, eds., *Preventing Nuclear Terrorism: The Report and Papers of the International Task Force on Preventing Nuclear Terrorism*, p. 61. Advocates of plutonium use for civilian power generation often argue that only plutonium enriched to more than 90 percent in the isotope Pu-239 can be used in a weapon. See, for example, Ryukichi Imai, "Can University Students Make an Atomic Bomb?" *Plutonium* (Tokyo: @ouncil for Nuclear Fuel Cycle, Winter 1995), pp. 2-8. This contention has now been decisively rebutted in Mark, "Explosive Properties of Reactor-Grade Plutonium," pp. 111-124. Others make the same claim about HEU, i.e., that it is useful for weapons only if it is enriched above 90 percent in U-235. See, for example, Jane Perlez, "Radioactive Material Seized In Slovakia; 9 Under Arrest," *Boston Globe,* April 22, 1995, p. 4. Others, however, correctly note that while HEU enriched to more than 90 percent is desirable for weapons, it is not necessary. See Reuters, "Nuclear Contraband Intercepted," *NewYork Times,* April 22,1995, p. 13.

19. On some of these points see Tom Clancy and Russell Seitz, "Welcome to the Age of Proliferation," The National Interest, No. 26 (Winter 1991-92), pp. 3-12. See also Robert Serber, *The Los Alamos Primer: The First Lectures on How to Build an Atomic Bomb* (Berkeley, Calif.: University of Cahfomia Press, 1992). Tritium-deuterium neutron sources are used in oil wells to bombard materials surrounding the bore hoie and induce various identifiable reactions, thereby providing a diagnostic tool for the well drillers.

20. John Foster, "Nuclear Weapons," *Encyclopedia Americana,* Vol. 20 (New York:Americana, 1973) pp. 520-522; see also Chapter 2, "Nuclear Weapons" in Willrich and Taylor, *Nuclear Theft,* pp. 5-28, esp. P. 6: "If the essential nuclear materials are at hand, it is possible to make an atomic bomb using information that is available in the open literature."

21. Michael May, "Nuclear Weapons Supply and Demand," *American Scientist,* Vol. 82 (November-December 1994), pp. 527, 530; Committee on International Security and Arms

Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium* (Washington DC: National Academy Press, 1994), P. 26; U.S. Congress, Office of Technology Assessment, *Technologies Underlying Weapons of Mass Destruction* OTA-BP-ISC-115 (Washington DC: U.S. GPO, December 1993), p.3; and Peter Zimmerman, "Technical Barriers to Nuclear Proliferation," in Zachary Davis and Benjamin Frankel, eds., "The Proliferation Puzzle: Why Nuclear Nations Spread (and What Results)," *Security Studies*, Vol. 2, Nos. 3-4 (Spring/Summer 1993), pp. 345-356, esp. "Note Added In Proof" on p.356: "Should a nation determined to build a nuclear weapon quickly be able to purchase the fissfle material, the costs for its project would probably plummet, and the time needed to construct its first weapon might decrease from years to months or weeks."

22. Mark, et al., "Can Terrorists Build Nuclear Weapons?" pp. 55-65.

23. Of course, the most dramatic example of brain drain occurred in the Manhattan Project where individual European emigr6s and the British government both played key roles. The Soviet program benefited from the efforts of captured German scientists and also the espionage of Klaus Fuchs. The British received significant assistance from the United States and the Chinese from the Soviet Union. Of the declared nuclear states, only France seems to have had a largely indigenous weapon design and production program at the outset.

24. Clancy and Seitz claimed that Neptunium, a trans-uranic element contained in spent reactor fuel, would be an effective fissile material for weapons purposes. Clancy and Seitz, "Welcome to the Age of Proliferation," p. 9. For their retraction on this point in the face of comments by Leonard Spector and Peter Zimmerman, see "Nuclear Proliferation," *The National Interest*, No. 27 (Spring 1992), pp. 110-112.

25. Testing - the experimental detonation of weapons in the atmosphere and underground - has been an integral part of the nuclear weapon programs of the five declared nuclear weapon states: the United States, the Soviet Union, Great Britain, France, and China. Tests provide experimental data used to design weapons, they confirm the design of new weapons, and they confirm the reliability of old weapons, or weapons that have had to be redesigned because of some flaw discovered after their initial deployment.

26. Hansen, *U.S. Nuclear Weapons,* p. 33.

Chapter excerpt from **Avoiding Nuclear Anarchy: Containing the Threat of Loose Russian Nuclear Weapons and Fissile Material** by Graham T. Allison, Owen Cote, Jr., Richard A. Falkenrath, and Steven E. Miller

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The Atomic Bomb and Its Consequences

Pulitzer Prize – winning author Richard Rhodes gave an enlightening lecture at the Hanford site for the 70th anniversary of the Manhattan Project. The lecture cuts through our modern rose-colored glasses to delineate what led to the bomb. Photo credit: Nancy Warner

Nuclear fission was discovered accidentally in Nazi Germany on December 21st, 1938, nine months before the beginning of the Second World War. It was a discovery that in the long run would sharply limit national sovereignty and change forever the relationship between nation-states, and it came as a complete surprise.

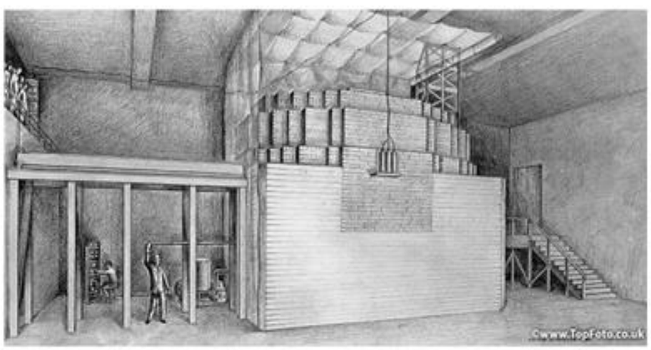
The German radiochemists Otto Hahn and Fritz Strassmann, working at the Kaiser Wilhelm Institute for Physical Chemistry in Dahlem, a suburb of Berlin, were bombarding a solution of uranium nitrate with lukewarm neutrons, transmuting microscopic quantities of the uranium into a brew of substances of differing characteristic radioactivities which the two chemists believed might include new manmade elements heavier than uranium as well as familiar elements like radium, one of uranium's natural "daughters." Instead of radium, however, Hahn and Strassmann found barium in their irradiated solutions, an element only about half as heavy as uranium that they had not expected to find there and that had not been there before. When they had consulted with their Jewish physicist colleague Lisa Meitner, who had escaped Nazi Germany to exile in Sweden, and when Meitner had consulted with her physicist nephew Otto Frisch, who came over from Denmark to visit her, it became clear that the unexpected barium was a marker for a new species of nuclear reaction—that in fact Hahn and Strassmann's neutrons had split uranium nuclei, atomic number 92, into two nearly equal pieces, one of barium, atomic number 56, and one of krypton, atomic number 36: 56 plus 36 equals 92. The new reaction, converting a small amount of matter into energy, was fiercely exothermic, ten million times as much energy coming out as the neutrons carried in. Physicists had known for forty years, ever since the discovery of radioactivity, that enormous energy was locked up in the atom. Here at last was a way to release it. Otto Hahn, a veteran of the First World War, said later that he brooded on the probable military applications of his discovery and seriously considered suicide.Word spread quickly across the small world community of physicists. Hahn and Strassmann published their results in the German science journal Naturwissenschaften, as scientists do. Frisch and Meitner told Niels Bohr, the great Danish physicist, and followed up with confirming physical experiments published in the British journal Nature. From biology, from the process whereby cells divide, binary fission, they borrowed a name for the new reaction—nuclear fission. Bohr carried the news to America early in 1939 in the course of attending a physics conference in Washington. Soviet physicists working in Leningrad under young Igor Kurchatov, British physicists, German physicists, the French team at the Radium Institute in Paris, American experimenters from coast to coast rushed to demonstrate nuclear fission in their laboratories with off-the-shelf equipment: the discovery, as the physicist Philip Morrison would say later, was "overripe" (1). A Japanese Army lieutenant general who was an electrical engineer, reading the report in Nature, assigned a member of his staff to track it. If Hahn and Strassmann hadn't discovered nuclear fission in Germany, others would soon have discovered it in some other laboratory somewhere else. Here was no Faustian bargain, as some even all these years later find it comforting to imagine. Here was no evil machinery one or another noble scientist might have hidden from the politicians and the generals. To the contrary, here was a new insight into how the world worked, an energetic reaction older than the earth that science had finally devised the instruments and arrangements to coax forth. As the American theoretical physicist Robert Oppenheimer would say, "It is a profound and necessary truth that the deep things in science are not found because they are useful; they were found because it was possible to find them."The physicists saw immediately what might be done with the new reaction. Hungarian emigré physicist Leo Szilard told his American patron Lewis Strauss on January 25, 1939, that nuclear energy might be a means of producing power, and mentioned "atomic bombs" (2). The young Berkeley graduate student Philip Morrison remembered that "when fission was discovered, within perhaps a week there was on the blackboard in Robert Oppenheimer's office [at Berkeley] a drawing—a very bad, an execrable drawing—of a bomb" (3). "These possibilities," commented American theoretician Robert Serber, "were immediately obvious to any good physicist" (4). Within months of the German discovery, the Italian Nobel laureate Enrico Fermi would stand at his panoramic office window high in the physics tower at Columbia University, look down the gray winter length of Manhattan Island alive with vendors and taxis and crowds, cup his hands as if he were holding a ball and say simply, "A little bomb like that, and it would all disappear" (5).

Lise Meitner (right), standing here with Arthur Compton and Katherine Cornell, was in exile in Sweden when Hahn asked her advice on what he had discovered with atomic fission (Photo credit: Wikipedia)

Why would these men of good will, who believed themselves to be members of a peaceful international community of scientists, want to build a weapon of mass destruction? Always and everywhere in that first round of nuclear proliferation the same reason repeats: because possession of such a weapon appeared to be the only defense against an enemy similarly armed. Deterrence had already been debated publicly and at length during the 1930s in the context of aerial bombardment. It found its first documented expression in the context of nuclear weapons in a secret report prepared early in 1940 as a warning to the British government by two emigré physicists, Otto Frisch (again) and Rudolf Peierls, a report that also first laid out on paper the basic design and operation of an atomic bomb. "If one works on the assumption," the two physicists wrote, "that Germany is, or will be, in the possession of this weapon, it must be realized that no shelters are available that would be effective and could be used on a large scale. The most effective reply would be a counter-threat with a similar bomb. Therefore it seems to us important to start production as soon and as rapidly as possible, even if it is not intended to use the bomb as a means of attack" (6).

The world was at war. The new tool of nuclear energy, like all tools, might also serve as a weapon. In the course of the Second World War, every major industrial nation began a program to build atomic bombs: the Germans, the British, the French before their surrender, the Soviets, the Americans, the Japanese. But nuclear-weapons development required a massive commitment of government funds, funds that would have to be diverted from the conventional prosecution of the war. If atomic bombs could be built, they would be decisive, in which case no belligerent could afford not to pursue them. But making that judgment depended on two corollary assessments: the first, whether or not such weapons were inventible—whether nature would allow such an explosion to proceed; the second, whether or not the enemy was capable of producing them in time to affect the outcome of the war. Both assessments depended critically on how much scientists trusted their governments and how much governments trusted their scientists.

Chicago Pile Scientists



Chicago Pile – 1 December 2, 1942
3:20 pm operated for 33 minutes
25 ft wide and 20 ft high

The first sustained nuclear chain reaction, called the Chicago Pile went critical on December 2, 1942. Top: The Chicago Pile Scientists. Back row, left to right, Norman Hilberry, Samuel Allison, Thomas Brill, Robert G. Nobles, Warren Nyer, and Marvin Wilkening. Middle row, Harold Agnew, William Sturm, Harold Lichtenberger, Leona W. Marshall, and Leo Szilard. Front row, Enrico Fermi, Walter H. Zinn, Albert Wattenberg, and Herbert L. Anderson. Source: DOE

Trust would not be a defining issue later, after the secret, the one and only secret—that the weapon worked—became known. This first time around, however, it was crucial, as the Russian physicist Victor Adamsky, who worked on the Soviet bomb, has pointed out:

The tension [between the scientists and their governments, Adamsky writes,] stemmed from the fact that there existed no a priori certainty of the possibility of creating an atomic bomb, and merely for clarification of the matter it was necessary to get through an interim stage: to create a device (the nuclear reactor) in order to perform a controlled chain reaction instead of the explosive kind. But the implementation of this stage requires tremendous expenses, incomparable to any of those previously spared for the benefit of scientific research. And it was necessary to tell this straight to your government, making it clear that the expenses may turn out to be in vain—an atomic bomb may not come out….The American nuclear scientists…addressed the President…directly and described that complicated situation to him…. After a number of procrastinations which are inevitable even in a democratic society, a decision was taken in the USA to make the research as comprehensive as required by logic, disregarding the [un]certainty of the final result.

…There was [no such confidence and mutual understanding] in Germany (7).

In the United States the trust was there, and President Franklin D. Roosevelt duly authorized a full-scale Anglo-American nuclear weapons program on October 9th, 1941. In Germany the trust was not there on either side, and the German program fragmented and stalled. After 1942, Werner Heisenberg, Otto Hahn, Richard von Weizsächer turned their attention to building a nuclear reactor and the bomb went by the board. Nor did the German scientists believe the Allies could do what they themselves had not judged feasible (8).

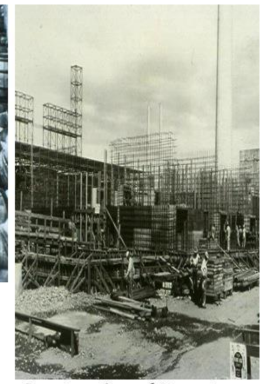
The French program was stillborn. The Soviets, fighting for their lives against an almost overwhelming German invasion, put their early work on hold, not entirely convinced of its importance, and revived it in 1943 after the Red Army pushed back the Wehrmacht outside Moscow and espionage revealed the extent of the developing programs in Britain and the United States. The Japanese saw that a bomb program was beyond their resources, estimated incorrectly that it was also beyond American resources, and scaled down their efforts to laboratory studies of uranium isotope separation.

The Anglo-Americans knew very little of these developments. Until 1944, they raced against an imaginary German clock, calculating that from the discovery of fission forward, the Germans might have at least a two-year lead. Then another and more terrible clock ticked off the project's hours: the clock of the war itself, of the young men dying on the battlefields of Europe and Russia and the bloody Pacific beaches. The Germans, the British, the French had used poison gas in the last Great War, as they all said, to shorten the war and save lives; Robert Oppenheimer, recruiting scientists for a secret laboratory in New Mexico where the first bombs would be designed and built, whispered that he couldn't tell them what they would be doing, but he could tell them that their work would end the war and save lives.

Before Oppenheimer began recruiting, Szilard, Fermi and their colleagues at Columbia and then at the University of Chicago had to accomplish the intermediate step Adamsky mentions: they had to build an experimental nuclear reactor to prove that it was possible to achieve a controlled chain reaction in uranium. This would be a slow-neutron chain reaction, multiplying in thousandths of a second and relatively easy to control, not the microsecond fast-neutron chain reaction that would proceed in a bomb, but fission was the source of the energy in both arrangements. The reactor design Szilard and Fermi worked out and jointly patented was a spherical assembly large as a two-car garage of graphite blocks drilled with blind holes into which would be inserted pucks or slugs of uranium oxide or metal. They needed 700,000 pounds of highly purified graphite; all the uranium metal they could get, which turned out to be 12,400 pounds; and some 80,000 pounds of oxide. None of these materials could be bought off the shelf; their manufacture had to be developed and subsidized.

The "secret" of the bomb would turn out to be industrial production on an enormous scale—2.2 billion-dollars-worth by the end of the war in 1945 dollars, about the same as it cost twenty years later to go to the moon. What began as a table-top experiment on a laboratory bench in Germany in 1938 became, in the United States, an industry comparable in scale to the United States automobile industry of the day (9). Niels Bohr had gone back to Denmark in 1939 secure in the conviction that no nation could afford to build such an industry in time of war. The United States not only did so; it did so redundantly, pursuing three different and expensive paths to accumulating the necessary quantities of fissionable materials. The Manhattan Project, as the program to build atomic bombs was named, commanded a higher priority for materials and staff than any other program of the war—not because anyone thought the atomic bomb would win the war, but because its sole possession by an enemy might turn Allied victory abruptly into defeat.

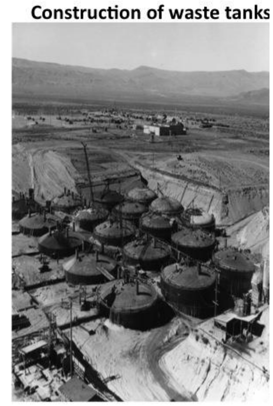
Camp Hanford meal service



Construction of B reactor

Reprocessing and separation plants

Construction of waste tanks



The size and intensity of the bomb effort was fantastic. Hanford was constructed between March 1943 to July 1945, including fuel fabrication facilities, three full-scale reactors, three full-size radiochemical separation plants, a plutonium isolation facility, the first single-shell tanks for waste storage, 800 barracks, 600 Quonset huts, a trailer camp for 4,300 people, 8 cafeterias for 51,000 workers (meals cost 67 cents each and were all you could eat – 50 tons of food was served at each meal). Source: DOE

Fermi called his construction a “pile” because it was made that way, by piling up layers of uranium-slugged graphite bricks crosswise one on top the other to achieve a critical mass. The pile would not only prove the chain reaction; it would also be a model cauldron for transmuting from uranium the first manmade element, plutonium, Berkeley radiochemist Glenn Seaborg’s discovery, several times more fissionable than uranium itself. Fermi’s pile went critical in a doubles squash court under the stands of Stagg Field at the University of Chicago on December 2, 1942, one year almost to the day after the Japanese attack on Pearl Harbor.

Scientists at the Metallurgical Laboratory of the University of Chicago determined the parameters of the site where plutonium would be produced for the first atomic bombs. Thirty-three-year-old Army Corps of Engineers Colonel Franklin T. Matthias, known to his friends as “Fritz,” wrote the requirements into his diary after a meeting at DuPont’s home offices in Wilmington, Delaware, on December 14, 1942: The site needed to be spacious enough to accommodate a manufacturing area of approximately 12 by 16 miles, with no public highway or railroad nearer than 10 miles, no town of greater than 1,000 population nearer than 20 miles, an available water supply of at least 25,000 gallons per minute and an electrical supply of at least 100,000 kilowatts. Matthias looked in the Grand Coulee area of Washington and at several sites in Tennessee before flying over Hanford in an Army observation plane. “I came back over [the] Horse Heaven [Hills],” he remembered many years later— "in the area northeasterly from Plymouth—and over Rattlesnake Mountain to the Hanford site from the west, and I got over that mountain, and I had looked at everything else, and I knew that was it, right then." His boss, Brigadier General Leslie Richard Groves, agreed, and the Corps of Engineers began land appraisals at the Hanford site in January 1943.

The first great question was what kind of cooling system to use in the production reactors that would be built and operated at Hanford to make plutonium. Graphite would serve as moderator, uranium metal as fuel. The fission chain reaction would release tens and hundreds of thousands of kilowatts of energy, and since these reactors were being built to breed plutonium, that energy would not be used to make steam to generate electricity but would have to be transferred away. The first chain reaction in the natural-uranium squash court pile at the University of Chicago had operated with a barely positive reactivity of 1.006, so conserving neutrons was an important consideration. Helium, which absorbed no neutrons at all, was the coolant of choice at first, but Hungarian theoretical physicist Eugene [Vegner] Wigner, trained as an engineer, held out for water despite its neutron-scavenging propensities because it would be simpler and thus faster to engineer. Wigner judged that they would improve reactivity in the big production reactors with purer materials. He was convinced that Nazi Germany was ahead of the United States in bomb development. Wigner even moved his family out of Chicago in December 1943, when he estimated the German head start might have given them atomic bombs by then—which he thought Germany would, logically, drop first on the Met Lab.

B Reactor, the first full-sized nuclear reactor, built in only 11 months, operated from 1944 to 1968 to produce Pu. Several others followed in the next decade. Source: DOE

Eventually Enrico Fermi, General Groves and DuPont's Crawford Greenewalt came round to once-through water cooling. Wigner designed an elegant reactor: a three-story assembly of graphite blocks drilled through with a cylindrical lattice of channels into which could be inserted slugs of uranium metal clad with aluminum. Water from the Columbia River would flow through the channels around the slugs for cooling, and when the slugs had been sufficiently exposed to the pile's neutron flux to breed about a dime's weight of neptunium, element 93, per ton of uranium, they could be pushed out the back into a cooling pool, where the neptunium would quickly decay to plutonium, element 94.

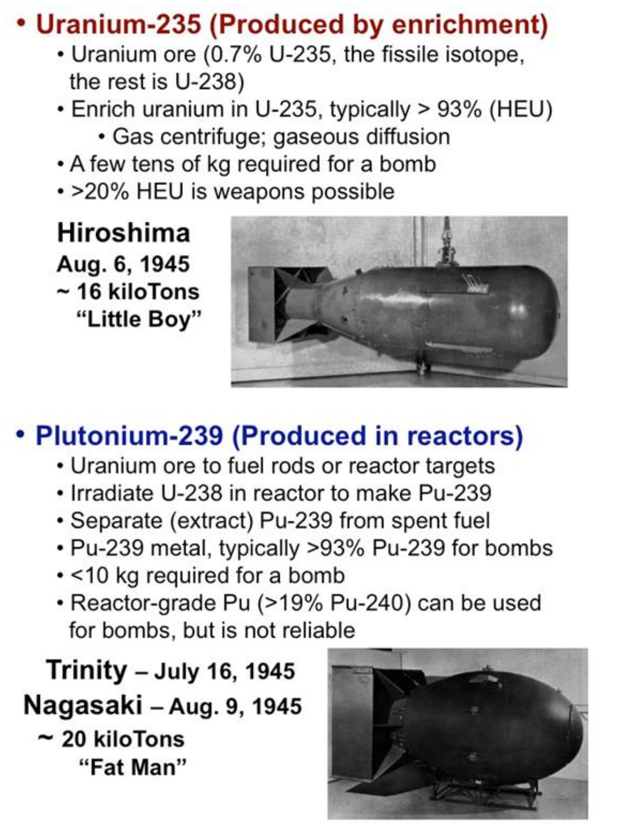
Which brings up one of the mysteries I mentioned. The B Reactor at Hanford was the first to go critical, late in the evening on September 26th, 1944. Early the next morning the power was increased to 9 megawatts and held there. Then, to everyone's surprise and consternation, the reactivity began slowly to decrease, at a rate that would drop the reaction below criticality at about six in the afternoon. To slow any possible water leak they reduced the pressure, which dropped the power to 200 kilowatts, but the reactivity continued to decline, at which point they decided to shut the reactor down and hunt for leaks.

When Crawford Greenewalt returned with Fermi the next morning, September 28th, he wrote later, he "found that the pile had died according to prediction, but had mysteriously come to life starting at about 1 a.m. today. The reactivity had increased steadily," Greenewalt continues, "and at 7 a.m. they started controlling the power at 0.2 MW. From this time on the activity kept increasing….During the night an attempt had been made to find leaks but neither conclusively or successfully." They continued trying to check for leaks, but by now they had come to believe that something was poisoning the reaction, and that evening, to test their suspicion, they raised the power to 9 MW, Greenewalt wrote in his diary, "and the earlier phenomenon repeated itself almost exactly: the reactivity first flattened off, then decreased…. At midnight we dropped the power again to 0.2 MW and when I left at 2:30 a.m. the loss of reactivity was decreasing and looked definitely as though it was going to turn up."

Since the reactivity seemed to be cycling with the increase and then decrease of the poison, they thought of two possible explanations: either the reactor's radiation was causing some substance to deposit on the slugs and tubes—which the cooling water then dissolved off when the pile power was reduced—or some short-lived fission product was decaying to a longer-lived radioactive daughter with a large appetite for neutrons. From the data on the changes in the pile reactivity Greenewalt plotted the half-life of the daughter at 11.7 hours, but, he wrote, they "couldn't think of any reasonable radioactive process which would produce the results."

By the morning of Friday, September 29, however, physicist John Wheeler had solved the mystery. The offender was a fission chain after all. The most likely, Wheeler thought, was 6.6-hour iodine 134 decaying to 9.1-hour xenon 135. The loss of reactivity the xenon had caused meant it had thirty times the appetite for neutrons of any isotope previously known. Wheeler calculated that they could override the poisoning by increasing the pile's reactivity by 1.3 percent, which they could do by loading more channels with slugs—up to 1,500 channels and, if necessary, 2,000.

Why was the reactor built with extra, unused channels? The accepted explanation, which I think may have come from postwar reminiscences by Fritz Matthias, is that DuPont engineers were conservative and wanted to leave a margin of safety in case a problem cropped up. In contrast, [Vegner] Wigner, trusting his calculations and wanting to move ahead as fast as possible to beat the Germans, had designed a lattice—the horizontal cylindrical arrangement I mentioned—that made optimum use of the minimum necessary number of channels. But it wasn't simply DuPont conservatism that led Crawford Greenewalt to order extra channels drilled through the corners of the cubical graphite structure. John Wheeler had assured Greenewalt that there were no unknown decay products that would poison the chain reaction, and Greenewalt seems to have accepted Wheeler's assurances. (Wheeler's overconfidence may explain why he hustled so quickly to identify the isotopes that DID cause the poisoning.)



The final products – two paths to the bomb. Little Boy was an enriched uranium device like Iran was attempting to make and Fat Man was a separated plutonium device similar to what North Korea has developed

Greenewalt was in fact concerned with a different problem: water corrosion of the cladding around the uranium slugs, which could lead to leakage of the highly radioactive fission products into the cooling water and thus into the environment. It was possible, he realized, that the uranium slugs might have to be double-canned to prevent them from corroding, in which case the extra aluminum might scavenge enough neutrons to quench the chain reaction. To prepare for that possibility, Greenewalt ordered the corners of the reactor blocks drilled with extra channels where more uranium might be inserted to increase the reactor's flux and override the aluminum can problem if it emerged—and fortuitously, the channels were then available to override the xenon poisoning no one had expected. Greenewalt's decision was crucial, and he made it despite contrary advice from the Met Lab leadership. Had DuPont followed the Met Lab's overconfident advice, the entire Hanford plutonium production program would have been stalled until new production piles could be designed and built, and the United States would have produced only one atomic bomb, the uranium bomb, Little Boy, in time to affect the outcome of the war.

The new channels were quickly lined, piped and loaded, and on November 24th, 1944, the B Reactor's first irradiated slugs were pushed into the cooling pool.

The D reactor went critical on December 17th, 1944, at 11:11 in the morning, and on December 26th, the first charge of B reactor metal was dissolved in separation building 200-N.

By then, the Hanford Engineer Works was the third largest city in the state of Washington, a thriving society that Fritz Matthias oversaw. The baseball season had opened the previous summer when six crafts had fielded teams. Where orchards and dusty scablands had been, a community of almost 50,000 people had sprung to life a safe distance south of the futuristic piles and canyons and was finding its identity. "At the game Sunday," Matthias noted proudly, "there were probably 5000 people watching. The plan is that three games will be played every Sunday until the end of the season." There were churches now in the Hanford residential areas as well as schools, barber shops, beauty salons—and bars. Native Americans still pulled salmon from the river in season at a camp that dated back to the days of Lewis and Clark; and since the camp was within the secure area, Matthias had agreed to supply the tribe with trucks to haul its salmon out for smoking.

Six plutonium extraction runs were processed during January 1945, resulting in a “charge” of plutonium of 97 percent purity. “The charge,” the DuPont History reports, “was loaded into a ‘sample can’…on February 1st, 1945. Because the closure on the sample cans had been shown to have a high probability of leakage,” the History explains, “it was decided to evaporate the product solution nearly to dryness after loading. This was done on the first and all subsequent shipments.” According to Matthias, the quantity involved was “72,000 units,” which probably means 720 grams—three-quarters of a kilogram—painstakingly extracted from tens of tons of dissolved uranium. Matthias himself made that first delivery, on February 5th, 1945: “I drove from Hanford to Portland,” he remembered. “I had a guy with me and we had a locked space on the train from Portland to Los Angeles. [The container with the plutonium was] about a two-foot cube, wrapped up in wrapping paper and ropes, and inside was a test-tube thing suspended and secured—all surrounded by lead and rigged so it stayed right in the middle of that box. It was quite a heavy thing, and I carried it just like a box any traveler might have with him.”

F Reactor went critical on February 25th, 1945, and another shipment of product left Hanford on March 1st. The F Reactor was soon running smoothly, one of three now that were breeding plutonium around the clock. Matthias was able to inform Groves early in March that 10 kilograms of plutonium—enough for two bombs—would be ready for shipping between April 18th and July 12th. The first 5 kilograms would be used to test the implosion system Los Alamos had invented; the second 5 kilograms would be destined for Japan. In a memorandum Groves prepared for President Truman on April 23rd, 1945, shortly after the death of Franklin Roosevelt, he resolves another mystery—whether we would have used the bomb on Germany had it been ready before the German surrender in May. “The target,” Groves says he told the President, “is and was always expected to be Japan.”

By May 3rd, Matthias calculated that 20 cans of plutonium—about 3 kilograms—had left Hanford for Los Alamos. After the initial deliveries, Matthias had begun delivering the cans by army ambulance to Salt Lake City, where they were transferred to another ambulance driven up from New Mexico. The shipments took only two days, start to finish, to reach Los Alamos, Matthias noted proudly in his diary, “far better than could be done by train.” He noted VE Day—Victory in Europe, the defeat of Nazi Germany—on May 8th, prompting himself to make sure the War Department film “Two Down and One to Go” was shown to remind Hanford workers that the Allies had defeated Fascist Italy and Nazi Germany but were still fighting a war in the Pacific against the Japanese. He was happy with plutonium production results, which he attributed to “the reduction of initial cooling periods” which permitted “processing of pushed material at an earlier date than scheduled.” Colonel Kenneth Nichols, Groves’ deputy, was able to write Los Alamos director Robert Oppenheimer on June 1st promising cumulated production and delivery of 7 kilograms of plutonium by June 1st, 13 kg by July 1st, 20 kg by August 1st, 26 kg by September 1st, 40 kg by October 1st and 54 kg by October 31st. At 5 kilograms per bomb, that would be enough for 10 bombs, with a little left over.

As there were two kinds of nuclear materials, uranium and plutonium, so there were two kinds of bombs. The more conservative design, nicknamed Little Boy, was a six-foot cannon with a cylinder of U235 fitted inside the muzzle and an assembly of stacked rings of the same material to be fired up the barrel at the appropriate time like an artillery shell. When the rings slammed into place around the target cylinder they formed a supercritical mass and chain-reacted. The gun-type bomb was grossly inefficient, but experiments with diluted uranium confirmed that it was reliable, so much so that it was certified for use without proof testing. In any case there wasn't enough highly-enriched uranium for a test; the first Little Boy built was the one that was used.

Los Alamos, Oppenheimer's secret laboratory on an extension of the vast Valle Grande caldera northwest of Santa Fe, had discovered to its horror in the spring of 1944 that an admixture of plutonium 240 and higher isotopes in Hanford reactor-bred plutonium made that material so unstable that a stack fired up a gun barrel even at 3,000 feet per second would melt down before it had time to mate and explode at full yield. Oppenheimer ordered a massive shift of laboratory priorities that summer to develop an alternative method of assembling a critical mass, a method the physicists named implosion: using a lensed sphere of high explosives to squeeze a subcritical sphere of plutonium to critical density.

The laboratory worked night and day for the rest of 1944 and the first half of 1945 to develop implosion; the technology was sufficiently unreliable even then to require a full-scale test. The test, in the New Mexican desert northwest of Alamogordo, counted down to zero just before dawn on July 16th, 1945, the first full-scale, manmade fast-neutron chain reaction, exploding with a force equivalent to that of 18,000 [tons] of TNT, 18 kilotons, a great fireball lighting up the predawn morning, thrusting into the pristine desert air on a stem of roiling gas and smoke. "No one who saw it could forget it," said the director of the test, Ken Bainbridge; he called it "a foul and awesome display" (10). That same morning, the destroyer Indianapolis steamed out of San Francisco Bay carrying Little Boy and its uranium bullet, bound for Tinian Island in the Marianas, a thousand miles from Japan, where the specially-configured B-29's that would carry the weapons to the Japanese homeland had staged out in June and July. Little Boy's target assembly followed by air on July 26th. So did two high-explosive assemblies for plutonium bombs—the spherical implosion weapon nicknamed Fat Man, to be used after Little Boy, and a second Fat Man for which a plutonium core would be ready on August 12th. More atomic bombs would be ready if needed, Oppenheimer projected in late July: "…from possibly three in September," he told Groves, "to we hope seven or more in December" (11).

President Harry Truman was waiting eagerly at the Potsdam Conference for word of a successful test. It bucked him up. The Soviet Union was still officially neutral in the Pacific War; Stalin had promised to declare war and begin fighting the Japanese on August 15th, and until the news came of the successful test in New Mexico, Truman's major concern had been to shore up Stalin's commitment. The test changed the stakes; now Truman wanted to end the war before the Russians joined it, to avoid a political division of Japan like the political division developing in Germany. As Truman confided to his diary, "Believe Japs will fold up before Russia comes in. I am sure they will when Manhattan appears over their homeland" (12).General George Marshall, the Army chief of staff, whose judgment everyone respected, remembered later why there was not more discussion in those final days of summer about demonstrating or pocketing the bomb:

We regarded the matter of dropping the [atomic] bomb as exceedingly important [Marshall said]. We had just gone through a bitter experience at Okinawa [the last major island campaign, when the United States lost more than 12,500 men killed and missing and Japan more than 100,000 killed in eighty-two grim days of fighting]. This had been preceded by a number of similar experiences in other Pacific islands, north of Australia. The Japanese had demonstrated in each case [Marshall goes on] [that] they would not surrender and would fight to the death….It was expected that resistance in Japan, with their home ties, would be even more severe. We had had the one hundred thousand people killed in Tokyo in one night of [conventional fire-] bombs, and it had had seemingly no effect whatsoever. It destroyed the Japanese cities, yes, but their morale was not affected as far as we could tell, not at all. So it seemed quite necessary, if we could, to shock them into action….We had to end the war [Marshall concludes], we had to save American lives (13).

And Japanese lives as well, I might add. And in truth the first atomic bombs would not be even a quantitative extension of the destruction strategic bombing had already wreaked on the cities of Japan; since late April, Air Force General Curtis LeMay's B-29's had been systematically firebombing Japanese cities one by one to utter destruction, killing hundreds of thousands of civilians in the process; by August 1st the B-29's were burning down cities of less than 50,000 population, almost the only cities left in Japan to burn. Hiroshima and Nagasaki survived to be atomic-bombed only because they had been deliberately reserved as targets, so that the effects of those first bombs could be assessed.

The devastation of Hiroshima on August 6th was complete. Little Boy yielded 15 kilotons. Of 76,000 buildings in the southern port city spread across the seven estuaries of the Ota River, 70,000 were damaged or destroyed, 48,000 totally. Ninety percent of all Hiroshima medical personnel were killed or disabled. Up to September 1st at least 70,000 people died. More died later of the effects of radiation.

George Marshall remembered that he was surprised and shocked that the Japanese didn't immediately sue for peace. "What we did not take into account," he said, "…was that the destruction would be so complete that it would be an appreciable time before the actual facts of the case would get to Tokyo….There was no communication for at least a day, I think, and maybe longer" (14). The Air Force distributed millions of leaflets over Japanese cities in the next several days suggesting that skeptics "make inquiry as to what happened to Hiroshima" and asking the Japanese people to "petition the Emperor to end the war" (15). Conventional bombing continued as well.

But there was now a struggle for power between civilian and military leaders within the Japanese government, no surrender emerged, and on August 9th Fat Man exploded over Nagasaki with a 22-kiloton yield, killing at least another 40,000 people and devastating another Japanese city. The Soviet Union entered the war as well, confronting the Japanese leadership with fresh armies and navies attacking in Manchuria and down from the north into Hokkaido. Finally, breaking tradition, Emperor Hirohito insisted that the government communicate its surrender, and reluctantly it did. In his historic broadcast to his people on August 15th, Hirohito specifically cited "a new and most cruel bomb, the power of which to do damage is indeed incalculable, taking the toll of many innocent lives" as "the reason why We have ordered the acceptance of the provisions of the Joint declaration of the Powers" (16).

The atomic bombs that exploded over Hiroshima and Nagasaki didn't win the Pacific war, but contributed crucially to ending the war. What might have followed had the bombs not been used, no one can say with certainty, except that the two cities that were atomic-bombed would certainly have been firebombed, probably to equivalent loss of life. The Japanese might have surrendered. Or the Allies might have had to invade the Japanese home islands, as they were vigorously preparing to do. The Russians would have joined in that invasion, and having done so would certainly have insisted on a larger share of the spoils than the Kuril Islands. Japan might have been partitioned as Korea and Germany were partitioned.

Was it necessary to drop the bombs? Were they weapons of mass destruction? Was their use a crime against humanity? I think such questions as these beg the real question, which is why war became so much more destructive in the first half of the 20th century than ever before in the history of our species. It did so, I believe, because efficient killing technologies made the traditional exercise of national sovereignty pathological. To quote the United States Strategic Bombing Survey:

"The number of civilian deaths in Japan greatly exceeded the number of strictly military deaths inflicted on the Japanese in combat by the armed forces of the United States. This statement is pregnant with significance, for if there still be doubt that the emphasis in warfare has shifted from military forces to the civilian population, then this fact should dissipate all uncertainty (17)."

With disease, blockade, famine and fire it had sometimes been possible to kill large numbers of people in the past. The 20th century arsenal of massed artillery and aerial bombardment made such slaughter more certain and more efficient—made it industrial, mass-produced it, so that the number of deaths became a direct function of time and resources invested in the work, death cranked out like sausages or cars. The atomic bomb was the culmination of that trend, a mechanism that visited total death upon its targets cheaply, indiscriminately and almost instantaneously: whether or not people died at Hiroshima and Nagasaki depended not on their identities—whether combatants or noncombatants, Korean forced laborers, American prisoners of war, pregnant women, children, grandmothers, newborn babies or Shinto priests—but merely on the accident of their distance from ground zero that day.

The closing days of the Second World War mark a turning point in human history, the point of entry into a new era when humankind for the first time acquired the means of its own destruction. Niels Bohr liked to say that the goal of science is not universal truth. Rather, Bohr thought, the modest but relentless goal of science is what he called "the gradual removal of prejudices" (18). The discovery that the earth revolves around the sun removed the prejudice that the earth is the center of the universe. The discovery of microbes removed the prejudice that disease is a punishment from God. The discovery of evolution removed the prejudice that Home sapiens is a separate and special creation. The discovery of how to release nuclear energy, and its application to build weapons of mass destruction, is gradually removing the prejudice on which war itself is based: the insupportable conviction that there is a limited amount of energy available in the world to concentrate into explosives, that it is possible to accumulate more of such energy than one's enemies and thereby militarily to prevail. So cheap, so portable, so holocaustal did nuclear weapons eventually become that even nation-states as belligerent as the United States and the Soviet Union preferred to sacrifice a portion of their sovereignty—preferred to forego the power to make total war—rather than be destroyed in their fury. Lesser wars continue, and will continue until the world community is sufficiently impressed with their destructive futility to forge new instruments of protection and new forms of citizenship. But world-scale war at least has been revealed to be historical, not universal, a manifestation of destructive technologies of limited scale. In the long history of human slaughter, that is no small achievement.

These are hard truths, but total war is harder. As the Polish mathematician Stanislaw Ulam, the coinventor of the hydrogen bomb, comments in his autobiography, "It is still an unending source of surprise for me to see how a few scribbles on a blackboard or on a sheet of paper could change the course of human affairs" (19).

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