2

Building the Bomb

The “Gadget” (Figure 2-1) stood fully assembled atop a 100-foot steel tower in a remote section of the Alamogordo Air Base in New Mexico[1]. It was roughly spherical in shape with a diameter of about six feet, with electrical cables draped crazily over its surface. Inside the metal casing, 2.5 tons of high explosives surrounded a 13.5 pound plutonium core, no larger than a grapefruit. The final assembly had taken place under unusual and ominous weather conditions, amid heavy rains, thunder, and lightning. Code-named Trinity, this was to be the first full-scale test of the Manhattan Project’s highly secret atomic bomb research.

[Figure 2-1 about here]

On July 16, 1945, at 5:30 A.M., electrical signals ignited the explosives, which sent a powerful shockwave into the plutonium core, compressing it into a supercritical mass. In less than a millionth of a second the resulting chain reaction in the plutonium was over, the temperature of the core had risen to about 100 million degrees, and its pressure had risen to about 100 million atmospheres. Shining many times brighter than the noonday sun, the glowing core of hot plasma became a rapidly expanding fireball (Figure 2-2), vaporizing everything in its path, and lighting up the clouds and nearby mountain ranges with an eerie brilliance. Pound for pound, the nuclear explosive yielded more than a million times as much energy as the chemical explosives in conventional bombs. “Trinity” was a complete success, exceeding the expectations of most of its builders. The assembled scientists who were, or were to become, the luminaries of American physics were jubilant. The gray skies, however, bore silent testimony to a future more ominous than anyone there could have foreseen.

[Figure 2-2 about here]

The bomb represented the confluence of three forces: fifty years of scientific research to understand the physics of the atom, the political lobbying of individuals who wanted to arouse the United

States to the danger of science in the service of Nazi Germany, and the ability of the American government to organize the massive engineering effort needed to build a deliverable nuclear explosive. Critical nuclear experiments on the heavy metal uranium—the beginning point for all nuclear weapons—had been done in a Berlin laboratory since 1934. Scientists there and elsewhere had discovered that when uranium was bombarded with neutrons, different elements had appeared in the sample that had not been there before bombardment. In late 1938, two German scientists, Otto Hahn and Fritz Strassmann, were finally able to identify two lighter elements in such a sample. Hahn communicated the results to a former colleague, Lise Meitner, in Sweden, a refugee from Nazi anti-Semitism. She and her nephew, the physicist Otto Frisch, quickly hypothesized that the large mass uranium atoms had split or "fissioned" (Frisch's term) into those two smaller mass elements. Their published conclusions and personal communications among the network of scientists, particularly those who had led left fascist Europe and emigrated to the United States, spurred further scientific investigation.

Physicists realized that fissioning or "splitting" of uranium atoms released extraordinary amounts of energy per atom, so that if the fissioning could be made self-sustaining, unprecedented amounts of energy might be quickly released, and that in turn suggested a military application for this new phenomenon. Several refugee scientists urged Albert Einstein, their most famous colleague in exile in the United States, to write President Franklin Roosevelt. Although Einstein was a consistent advocate of pacifism and world government, as a German emigré his fear that Hitler might obtain the atomic bomb was so great that he agreed to do so, alerting the President to the military potential of nuclear fission and urging him to provide government support for further research. Roosevelt's support helped bring the "Committee on Uranium" into existence along with a modest allotment of funds ($6,000) in November, 1939, two months after Nazi Germany invaded Poland. When France and Britain had come to Poland's defense in early September, Europe entered its Second World War

Initial government interest in the fissioning process in the United States—and in Germany and the Soviet Union—was cautious.[2] The political and military leaders of the time did not know that it would be possible to create nuclear weapons. Indeed, the very idea that one could achieve a self-sustaining fission process and then build that into a deliverable weapon of war was but an untested hypothesis. As these nations were at war—or in the case of the United States, laboring to rearm—other claimants for government revenues could make a much more convincing case that the then-existing technologies, be they in warships or tanks or aircraft, would provide the war-winning weapon, if only enough funds, resources, and personnel were devoted to these enterprises. As it would happen, the right combination of individuals, resources, and organization in the United States (with significant help from Great Britain[3]) first revealed the secrets of the enormous destructive force that we saw in the last chapter.

In this chapter we briefly explore how the bomb works, not only in terms of the physics of nuclear weapons, but also in terms of the technologies that are necessary in order for a state or a group to build nuclear weapons. As you come to understand the problems faced by the nuclear physicists and engineers, their ingenious solutions, and the extraordinary physical conditions created by nuclear explosions, you will be able to appreciate the fascination which this subject holds for them, a fascination which undoubtedly played some role in the development of nuclear weapons. Nuclear weapons are a consequence of a widespread human endeavor to know and control the physical world. They are an inevitable artifact of the human experience.[4] Moreover, to understand how nuclear weapons came to be built is to appreciate the role that governments and the publics they represent play in the process. Nuclear weapons are the results of political decisions made by humans. Finally, to understand nuclear weapons is to demystify them. To see them as any other human artifact gives us the power to see that control of nuclear weapons is possible.[5]

THE DISCOVERY OF A NEW WORLD

The science that would produce nuclear weapons was a young science, coming of age at the dawn of the Twentieth Century when scientists in Europe made crucial discoveries.[6] Henri Becquerel found that the heavy metal uranium gave off strange rays that would darken photographic plates. Subsequent experiments on other naturally occurring radioactive elements by Marie and Pierre Currie and Ernest Rutherford, among others, revealed that three physically distinct types of rays were being given off. Since the properties and nature of these emissions were poorly understood, they were simply designated by the first three letters of the Greek alphabet: *alpha*, *beta*, and *gamma rays*. (This is the *natural radioactivity* of uranium.) How, they asked themselves, could an element, presumably the smallest, indivisible and permanent manifestation of matter, produce such effects? Rutherford concluded that upon emitting its radiation, a radioactive element such as uranium transformed itself into a different chemical element. That transformation was possible only if a uranium *atom* itself was composed of several parts that could undergo change. The challenge was to identify the parts, how they were arranged, and what held them together.

By the early 1930s, physicists had developed what came to be called the planetary model of the atom's parts. (See Figure 2-3.) In the atom's center is the *nucleus*, composed of small, heavy, positively-charged particles called *protons* and other small, heavy particles with no electric charge called *neutrons*. Collectively, the protons and neutrons are called the *nucleons* of an atom. 99.95 percent of an atom's mass or weight is due to its nucleons. Surrounding the positively-charged nucleus are light, negatively charged *electrons* orbiting at relatively large distances from the nucleus, just as the Earth and the other planets orbit the sun. If an oxygen atom, for instance, were enlarged until the nucleus was the size of a baseball, the atomic electrons could be found as far as almost a mile away. Electrostatic attraction (now called the Coulomb force) between the positively charged protons and negatively charged electrons keeps the electrons in orbit. While this model of the atom has been superceded by a more sophisticated one,[7] it provided physicists of the time with a fruitful insight into the world of the atom.

[Figure 2-3 about here]

The chemical properties of each element such as hydrogen, oxygen, and uranium are unique and are determined by the number of electrons surrounding the nucleus, which must in turn equal the number of protons in the nucleus. However, the number of neutrons can vary somewhat. Indeed, an element such as uranium may exist in more than one form, differing only in the number of neutrons in the nucleus. Such different forms of a particular element are known as the *isotopes* of that element. Different isotopes of an element are chemically almost identical, despite the slight differences in weight—the difference in weight of the isotope depending upon the different number of neutrons in the nucleus.

Any particular isotope is completely specified by giving its element name and its atomic mass number, as in uranium-235. All uranium atoms have 92 protons, which means that an atom of the isotope uranium-235 consists of a nucleus of 92 protons and 143 neutrons (235 – 92 = 143), surrounded by 92 electrons. By the same token, uranium-238 consists of a nucleus of 92 protons and 146 neutrons, surrounded by 92 electrons. These seemingly trivial differences would make all the difference in the world when it came to making nuclear weapons.

This model of the atom, as insightful as it was, seemed to be built upon a critical contradiction: All the positively charged protons crammed into the nucleus should repel each other because of the electrostatic repulsion of the Coulomb force. This force increases rapidly as the distance between like-charged particles decreases, so that the protons clustered in the nucleus must repel each other very powerfully. The model of the atom now had to include hypothesize that a much stronger attractive force (not surprisingly called *the strong nuclear force*) capable of resisting the Coulomb repulsion and holding the protons in the nucleus. This force between the nucleons would be very strong when they were together, but rapidly drop to zero if they moved even a small distance apart. Each proton finds itself attracted by only three or four protons in its immediate neighborhood, but is repelled by all the other protons in the nucleus (as the Coulomb force of repulsion acts over very large distances).

The *neutrons* in the nucleus help to hold the protons together as well, since they contribute to the strong nuclear force between adjacent protons and neutrons, but as they have no electrical charge, they do not contribute to the repulsive Coulomb force. Thus, having more neutrons than protons in the nucleus can—up to a point—help keep the nucleus stable because they help overcome the ever-present Coulomb force. If, however, one were able to destabilize the nucleus—to weaken the hold of the strong nuclear force—the protons would fly apart with great velocities and the repulsion energy would be released. How might this be accomplished?

For large nuclei such as uranium, the strong nuclear force barely keeps the protons together. Suppose we sent a neutron toward a U-235 nucleus. Neutrons are critical for nuclear weapons as they have no electrical charge; thus the protons in the uranium nucleus do not repel neutrons as they approach the nucleus. If a neutron enters a U-235 nucleus and disturbs the nucleons in such a way that the strong nuclear force is briefly diminished, the repulsive Coulomb force will begin to drive the protons apart, further weakening the strong nuclear force and accelerating the protons even more. The nucleus of the heavy uranium atom then splits apart (or fissions), creating two lighter elements and a few left-over neutrons that move apart at great velocities, carrying away great amounts of energy. If the strong nuclear force in other uranium atoms can be disrupted at the same time, in a very brief moment we have the makings of a very powerful explosive device.

The schematic diagram of Figure 2-4 illustrates what happens in the process of *neutron-induced fission*. A relatively unenergetic neutron collides with a U-235 nucleus and is absorbed, temporarily forming the isotope U-236. However, the energy and disruption which it brings with it is too great for this precariously unstable nucleus, which spontaneously breaks into two main pieces and a few free neutrons.

Figure 2-4 about here

What are the important features of this fissioning process? First and foremost, the smaller nuclei and neutrons that emerge from the reaction come off with very great velocities and energies. It is this energy that is utilized in a nuclear explosion—and in nuclear power plants designed to generate electricity. Second, the neutrons that emerge from the fissioning may collide with other heavy nuclei, causing them to fission, thus leading to the possibility of a self-sustaining *chain reaction* and the release of great amounts of energy. Nuclear weapons (and power plants) must be able to create and control this chain reaction. Third, when heavy nuclei fission, they break into two different nuclei, but not always the same two. In fact, more than 300 different isotopes of 36 light elements have been found in the products of nuclear fission. These fission products are themselves unstable, and undergo further transformations, creating the *radioactivity* that is a central aspect of nuclear weapons.

RADIOACTIVITY

Isotopes of unstable elements spontaneously reach stability by emitting energetic particles and electro-magnetic radiation. This is the radiation that early physicists observed when uranium was placed near photographic plates. An *alpha ray* (now called an alpha particle) is frequently emitted by very heavy nuclei which are unstable by virtue of their large size. The alpha particle turned out to be a small nucleus consisting of two protons and two neutrons bound tightly together. This emission transmutes the original element into another. For example,

U-238 —> Th-234 + alpha particle

In this way, the uranium nucleus quickly loses two destabilizing protons and four units of mass, becoming the element thorium in the process. Subsequent emissions may occur until the atom reaches stability.

Beta rays turned out to be electrons with either a negative or positive electric charge (the *positron*). Protons can turn into neutrons and neutrons into protons, in the process creating positrons and electrons, respectively, which are then ejected from the nucleus. The transmutation moves the new element closer to stability. Finally, a radioactive element may emit a *gamma ray*, very energetic photons of "light," a light with frequencies well beyond the visible and ultraviolet regions of the electromagnetic spectrum. Nuclei emit gamma rays, thereby reducing their energy without changing their proton and neutron composition.

These natural transformations continue to occur in all unstable or radioactive elements. Each radioactive element has a characteristic property called its *half-life*. A half-life is the time needed for half of the unstable atoms in a sample to transform themselves into stable atoms. For example, one of the isotopes of tin, Sn-121, has a half-life of 27 hours while one isotope of silver, Ag-97, has a half-life of 23 seconds. Uranium-238, on the other hand, has a half-life of 4.5 billion years. This naturally occurring half-life decay has implications for nuclear weapons as well. Tritium, an isotope of hydrogen (H-3), found in many modern nuclear warheads, has to be replenished periodically for in roughly 12 years, half of it will have become Helium-3.

When uranium fissions in a nuclear weapon or a power reactor, the fission fragments (two lighter elements) are radioactive isotopes, which will give off alpha, beta, and gamma rays. In a nuclear explosion, these fission fragments will be blown into the environment, fused to dust and debris and carried into the atmosphere by the fireball and updraft from the heat of the explosion, falling back to earth many miles from the point of detonation. These unstable elements will move toward stability by continuing to shower the contaminated area for years with radioactivity, damaging the living cells in humans, animals, and plants that they strike.

ENGINEERING THE BOMB

Although Hahn and Strassmann's discovery of nuclear fission in 1938 immediately suggested to physicists the possibility of an energy-releasing fission chain reaction, there was no clear answer to *how* this might be done. As it turned out, practical chain reactions could be achieved, but only with great difficulty. The effort and expense needed were so great that in the 1940s, only a major national power could marshal the needed scientific, technical, and economic resources. In recognition of the large industrial effort called for, in August, 1942, the American Army Corps of Engineers established a unit called the Manhattan District to oversee all work on the bomb.[8] General Leslie Groves was placed in command of what would come to be a far-flung enterprise, with research and test facilities constructed at Los Alamos, production facilities in Hanford, Washington and Oak Ridge, Tennessee, and continuing nuclear research at the University of Chicago, the University of California, Princeton University, and Columbia University, to name a few.

There were four basic challenges that the Manhattan Project (or any effort to acquire nuclear weapons) had to solve: (1) It had to collect sufficient *fissile material*—material capable of being fissioned. (2) That material and the way it was put together had to release enough neutrons to sustain the process of fissioning and thus produce a *chain reaction*. (3) Once the chain reaction started, the fissile material had to *stay intact* long enough to complete the reaction rather than being blown apart and ending the explosion in a "fizzle." (4) *The device had to be small and rugged enough to be deliverable to the target*.

Let us first consider *the problem of a sustained chain reaction*. As we have already seen, nuclear fission itself releases neutrons. Those neutrons may collide with other unstable nuclei and cause them to fission, producing yet more itinerant neutrons. If one fissioning atom can, by releasing a neutron, cause another fission, which releases another neutron, and the process continues, we say that the fissile material has reached a *critical mass*. That would be enough to sustain the heat-generating activities of a nuclear reactor, but it does not produce an explosion. We need to accelerate the fissioning process by having more than one neutron being released in each fission. For the two most commonly used fissionable isotopes in nuclear weapons, uranium-235 and plutonium-239, the average number of new neutrons per fission is about 2.5 and 3 respectively, and so this requirement is satisfied.

Simply freeing more neutrons is not enough, however, for each itinerant neutron can do something other than strike the nucleus of the fissile material:

1. It may leave the fissionable material entirely before causing another fission.
2. The very act of beginning the chain reaction may blow the fissile material apart. Many neutrons no longer encounter another nucleus to fission.
3. The neutron may be absorbed by a nonfissioning nucleus before causing another fission. For example, there may be impurity atoms in the material whose nuclei absorb neutrons without fissioning.

How do bomb makers cope with these three problems? Consider the impurity problem. Uranium itself is at the heart of this problem. Uranium-235 has a high probability of capturing a neutron and fissioning, but uranium-238 can capture a neutron without fissioning at all. Since naturally occurring uranium is 99.3 percent uranium-238 and only 0.7 percent uranium-235, a significant number of neutrons would be lost to the U-238 in a sample of natural uranium, and sustaining a chain reaction would be rendered more difficult. For this reason, natural uranium is usually processed to remove some of the U-238 to produce reactor-grade uranium for electrical power generation or to remove most of the U-238 for weapons-grade or Highly Enriched Uranium (HEU). Weapons-grade uranium is typically enriched to 95 percent U-235 whereas uranium enriched to 4 percent U-235 is adequate for most power reactors. Beyond the presence of U-238, great care is taken to eliminate other neutron-absorbing impurities from power plant fuel rods and nuclear weapon cores.

There are four techniques to deal with the problem of neutrons' leaving the sample of fissile material: (a) Make the sample of fissionable material larger. This provides the neutron with more chances of meeting a fissionable nucleus before it arrives at the boundary of the sample. (b) Surround the sample with a neutron reflector, like beryllium, so that neutrons are reflected back in as they try to escape. (c) Choose a shape for the sample that minimizes the surface area through which neutrons may escape. A sphere, for instance, has the minimum surface area for a given volume. (d) Increase the density of the sample by judicious choice of its chemical form or by compressing it. If the atoms are packed closer together, there is a greater chance that a neutron will run into a fissionable nucleus before escaping entirely.

As for the problem of the *premature blowing apart of the fissile material*, we need to look more closely at the nature of the problem to understand the technical solutions to overcome it.[9] Consider the speed of a nuclear chain reaction. A fission-produced neutron in highly enriched fissionable material takes only about .01 microseconds (.01 millionths of a second) to be captured by a fissionable nucleus and to produce another fission. Let us suppose that on the average two neutrons from each fission survive to produce additional neutron-induced fissions.

A single trigger neutron, after .01 microseconds, will have caused one fission, released 180 MeV (180 million electron volts) of energy, and sent two neutrons flying through the material to fission more nuclei. After an additional .01 microsecond, two more nuclei will have fissioned, producing 360 MeV of prompt energy and four more neutrons. Each .01 microsecond results in a new generation of fissions and neutrons, and the number of fissions grows very rapidly. This is analogous to the population explosion that occurs when a birth rate is significantly greater than the death rate, though on a much shorter time scale. Within the first .5 microseconds, there will be a significant release of energy—enough to scatter the fissile material far and wide (and do great damage to the immediate vicinity) but without producing an explosion equivalent to, say, 20,000 tons of TNT (20 Kt) that can destroy the heart of city. That power will be released in roughly the next .2 microseconds, but only if the fissile material remains intact long enough.

The trick to making a fission explosion is to take a mass of fissionable material that is not critical, suddenly turn it into a critical mass and keep it critical long enough for the reaction to produce the desired energy. The simplest way to do this is to take two sub-critical masses, each of which is too small to be critical, and rapidly bring them together to form a critical mass. The earliest American design accomplished this by the so-called *gun assembly technique*, in which a precisely shaped piece of uranium-235 is shot down a gun barrel into a larger piece of uranium-235 at the other end. The larger piece contains a hole to receive the smaller slug. The speed of the driven slug must be sufficiently high to continue its progress into the other mass long enough after the reaction has begun to produce the desired energy yield. The weapons designers were so confident of this design that it was not tested before its use on the city of Hiroshima where it produced a 12.5 Kt explosion.

The weapons tested at Trinity and dropped on Nagasaki employed a different design and produced explosions of about 22 Kt. In this design, a critical mass is achieved by taking a sphere of Plutonium-239 that is not critical, surrounding it with specially shaped conventional high explosives, and detonating all of the explosives simultaneously. This produces a powerful shock wave that drives inward and compresses the fissionable material until it has reached a density sufficient to make it critical, giving the name *implosion device* to this type of weapon. Figure 2-5 illustrates this and also introduces a few additional features. Most of the fission weapons in the current arsenals of the major powers are of this type. (Uranium-235 can be used in place of Pu-239).

[Figure 2-5 about here]

The detonators are placed at strategic positions around the shell of explosives and must be triggered simultaneously so that the implosion will be symmetrical and compress the core uniformly from all sides. Otherwise, the core may be blasted into a nonspherical, noncritical shape. The layer of uranium-238, which is very dense and heavy, is given a high inward velocity and acts as a driver. It is the inertia of this high-speed heavy metal that helps to keep the compression of the core proceeding, even after the nuclear chain reaction has begun, and thus keeps the core at a supercritical density long enough for the requisite number of generations of neutrons to be born. The vacuum layer shown in the diagram allows the uranium to achieve full velocity before hitting the core. The U-238 driver also acts as a neutron reflector and aids in making the compressed core supercritical.

The complete fission of 2.2 pounds of fissionable material would produce a 17.5 Kt explosion. Since fission explosions never succeed in fissioning all of their material, a typical 17.5 Kt bomb would require larger amounts of fissionable material, the exact amount depending on the efficiency of the bomb design.

The Manhattan Project scientists kept in mind that a nuclear device that could not be delivered to a target would not be an effective weapon of war. It had to fit into the bomb-bay of the largest American aircraft of the time, the B-29 (which by 1945 had demonstrated great effectiveness in penetrating Japanese air defenses). It had to remain sub-critical during transport to the forward operating base and on the flight, then become critical only at the moment it reached the target. And it had to work reliably. Both the gun assembly and implosion devices met these requirements.

ACQUIRING FISSILE MATERIALS

Access to uranium in sufficiently large quantities is the first step in making nuclear weapons. Uranium is a naturally occurring heavy metal whose concentrated deposits were initially thought to be relatively scarce; today we know they are relatively abundant and widespread globally. The metal when mined is intermixed with other elements that need to be separated from the uranium ore through a mechanical and chemical process that typically leaves a compound of uranium, uranium oxide, that goes by the name *yellowcake* from the its yellow or orange tint.

Naturally occurring uranium, however, is not going to make a bomb as most of it is U-238 which does not easily fission. How can we separate the fissionable U-235 from the much more abundant U-238? U-235 is chemically almost identical to U-238, so there is no practical chemical method to effect this separation.

There are four *mechanical* methods to accomplish what is now called the *enrichment process*, where the proportion of U-235 is increased in the sample of the material. Each of them is technically very difficult and time-consuming.:

Gaseous diffusion utilizes the fact that when a gas of atoms is forced through a porous medium with very small pores, the lighter isotopes make their way through somewhat more easily, and so the gas emerging from the other side is slightly richer in the lighter isotopes. Since U-235 is fractionally only slightly lighter than U-238, the enrichment after a single pass through such a filter is very small. Therefore the gas must be passed repeatedly through a series of filters before a significant enrichment is achieved. The development of suitable filter materials was a technical problem of considerable difficulty, and a suitable gaseous form of uranium had to be found. Uranium hexafluoride, a very corrosive gas at elevated temperatures, was the only practical candidate.

The Manhattan Project built an enormous gaseous diffusion plant at Oak Ridge, consisting of cascades of diffusion units each feeding a subsequent one. Thousands of pumps were needed, specially designed to resist the highly corrosive effects of the uranium hexafluoride and possessing seals that were effective in keeping lubricants out of the gases and the gases from leaking out of the system. Thousands of kilowatts of electrical power were needed to run these pumps, and one of the largest steam power plants ever built was constructed at Oak Ridge to provide the necessary power. After the enriched gas leaves such a gaseous diffusion separator, it is chemically converted into uranium metal or an oxide of uranium suitable for use in a reactor or a weapon. This became the principal method for enrichment by the United States during the Cold War.

The *electromagnetic separation* method consists of producing a gas of uranium ions and accelerating them in a vacuum chamber into a large magnetic field. The trajectories of moving charged particles in a magnetic field are circles whose diameters depend on the mass of the particles. This means that U-235 and U-238 would follow different trajectories, and by placing a collector at the correct position in the magnetic field, U-235 ions could be collected ion by ion. Large-scale versions of such separators, known as calutrons, were built at Oak Ridge and provided U-235 for the first uranium bomb.

The *centrifuge* method also takes advantage of the differing weights of the atoms of U-235 and U-238. Uranium hexafluoride gas is introduced into a long vacuum tube inside of which a rotor spins at extremely high speed. With its three more neutrons, the slightly heavier U-238 is pushed away from the rotor, increasing by a small amount the proportion of U-235 toward the center of the tube. The gas in the center of the tube is moved to another vacuum tube and the process is repeated over and over through a cascade of tubes until the amount of U-235 reaches the percentage desired. The Manhattan Project gave up on this approach but over the last several decades it has become a favored route for the creation of HEU.

Laser separation methods are the newest candidate for enriching uranium.[10] A finely-tuned laser, for instance, can ionize one isotope of uranium which can then be withdrawn as a gas from the sample. While these technologies are available, they have yet to demonstrate a capacity to produce enriched uranium more cheaply than the older methods. A state interested in acquiring nuclear weapons, however, may be willing to pay the cost of laser separation. Iran, for instance, has contracted to purchase an AVLIS (atomic vapor laser isotope separator) from Russia, a sale that the United States has pressured the Russian government to reverse.

Each of these methods uses unusual and highly specialized equipment (such as ultra-high speed centrifuges) in large numbers, often located in large buildings, and requires large amounts of electrical energy. Tracking the flow of these materials into nations and observing the construction of facilities by satellite or aircraft reconnaissance can provide some degree of warning that a state is engaged in a uranium enrichment program which is the precursor to the development of nuclear weapons. Of course, during World War II, the United States was able to produce its own enrichment machinery, and the intelligence systems of the Axis were unable to observe construction of large-scale facilities like Oak Ridge. Soviet intelligence organizations, aided by the fact that the United States was an ally of the Soviet Union, did keep watch on American efforts during the war. Today, American satellites and communications monitoring systems watch the globe for tell-tale uranium enrichment activities.

PLUTONIUM

Soon after the discovery of the fissioning of U-235 in 1938, there was speculation about other isotopes that might be fissionable. In particular, it was predicted on theoretical grounds that a hitherto undetected element with a fissionable isotope could be produced from U-238. This new element, *plutonium*, can be produced in the reaction shown below. A nucleus of U-238 absorbs a neutron and becomes U-239. The U-239 is unstable but does not fission; rather, it decays to neptunium-239, which in turn decays to plutonium-239, emitting an electron and a neutrino (a subatomic particle with rather unusual properties) in the process.

Pu-239 + e- + neutrino

Pu-239 itself is unstable, decaying to U-235 by expelling alpha particles. It has a half-life of 24,000 years. This accounts for the fact that no Pu-239 is found occurring naturally on the earth. Any Pu-239 with which the solar system may have been endowed at its inception has long since vanished. This means that every single atom of plutonium used in the production of nuclear explosives has to be produced artificially. Once created, however, it becomes a candidate for nuclear weapons as it is fissionable.

What is needed for the production of Pu-239? Only a copious supply of neutrons and U-238. U-238 is quite plentiful, of course, which leaves only the problem of producing neutrons in large quantities. That can be done, as we have seen, by fissioning U-235, this time in nuclear reactors where the speed of the fissioning is carefully controlled by using control rods to absorb some of the neutrons, thus preventing an explosion. The Manhattan Project constructed a large Pu-239 producing facility at Hanford, Washington. Reactor production of Pu-239 and its subsequent chemical separation from the other elements in which it was embedded proved to be successful, providing the fissile material for the Trinity and Nagasaki weapons.

After the war, weapons-grade plutonium would be made in nuclear reactors specifically designed for this purpose. But there is an alternative route. Nuclear power reactors that supply electrical energy use uranium in which U-238 is the principal component. They thus produce plutonium as a byproduct of their operation. For this reason, fears about nuclear proliferation center on the widespread availability of nuclear power reactors and the possibility of their being used to produce weapons-grade plutonium. We shall return to this problem shortly.

THE HYDROGEN OR FUSION BOMB

We conclude our technical consideration of nuclear explosives with an account of the hydrogen bomb. As we shall see in Chapter 4, after the successful development and testing of fission devices, a debate arose in governmental, scientific, and military circles as to whether or not the United States should proceed with the development of yet more powerful nuclear explosives based on the *fusion* of light nuclei. Edward Teller, one of the physicists active in the nuclear weapons project from the beginning, tirelessly promoted the project.

Just what is an H-bomb, and how does it differ from the fission bombs we have been considering? The H-bomb derives its energy from *fusing* small nuclei together to form larger nuclei rather than from splitting large nuclei to produce smaller ones. Consider two small nuclei, those of hydrogen, for example. Each consists of a single proton. Since the Coulomb repulsion of two protons is not very great compared to the strength of the strong nuclear force, why does the strong nuclear force not pull them together to form a single nucleus? It is because the nuclear force has a short range and is not felt until the protons come very close together. Under ordinary circumstances, the Coulomb repulsion will keep nuclei from approaching each other that closely. However, if we succeed in bringing two nuclei sufficiently close together, the nuclear force will completely overwhelm the Coulomb repulsion, and they will come crashing together, releasing energy in the process.

How can we bring light nuclei close enough to allow the strong nuclear force to take over? Our sun and the other stars accomplish this feat in their interiors, supplying the energy that keeps them radiating. We can duplicate this by *heating light nuclei* to a temperature high enough to form a gas of particles with thermal velocities great enough to produce close encounters of protons in spite of the Coulomb repulsion. It is for this reason that fusion weapons are also called *thermonuclear* weapons.

The temperatures needed are in the tens of millions of degrees, temperatures found ordinarily only in the interior of stars—and since 1945 in the initial fireball of a fission bomb explosion. The trick then is to detonate a fission device in the vicinity of some light nuclei, heat them to a very high temperature and then allow the resulting fusion reaction to proceed. It was not easy to devise a way to heat the fusion material hot enough before the force of the explosion blew it away. The U.S. solution to this problem was devised by Teller and other scientists. It was one of those very “sweet” (meaning beautifully ingenious) technical ideas that so exhilarates scientists and engineers.

The technical details of nuclear weapons designs are highly classified secrets. However, there is much information in the public domain, which, when considered in the light of known principles of physics, can give rise to educated guesses that are probably not too far from the truth.[11] The H-bomb description that follows, including the diagram in Figure 2-6, is based largely on these sources, particularly Howard Morland’s work.

[Figure 2-6 about here]

Stage 1 of the device (the upper stage) consists of an ordinary fission bomb of the sort we have already considered. It provides the high temperatures needed to initiate fusion in the second stage. Stage 2 consists of a heavy U-238 tamper shell, which encloses the fusion material. A rod of fission material (U-235 in Figure 2-6) is imbedded at the center of the fusion fuel, and the space between the tamper shell and the outer casing is filled with a polystyrene-type foam. A heavy shield between stages 1 and 2 helps to protect stage 2 against the direct blast for a brief instant. X-rays from the stage 1 blast, traveling at the speed of light, are reflected from the casing walls onto the polystyrene-type foam which absorbs them to become a hot plasma, imploding on the stage 2 fusion material, simultaneously heating and compressing it.

The heavy U-238 tamper provides the inertia that keeps the implosion moving inward and the reaction contained long enough for it to proceed to completion. The fusion material, which consists of lithium deuteride (LiD), is an interesting feature of the device, and worthy of some explanation.

The most easily attained fusion reaction uses two isotopes of hydrogen—deuterium (D), which is hydrogen-2, and tritium (T), which is hydrogen-3. They can fuse via the following reaction:

D + T —> He-4 + N + 17.6 MeV

Unfortunately, both deuterium and tritium are gases at ordinary temperatures and pressures. Gases have very low densities and so require large volumes if an appreciable mass is to be achieved. One way to achieve a large mass with a small volume for the hydrogen isotopes is to liquify them by cooling them to temperatures near absolute zero. The first successful U.S. fusion device utilized liquid hydrogen isotopes, weighed 62 tons and included cryogenic equipment to keep the deuterium and tritium liquified. Obviously such a device is not suitable as a deliverable weapon. The Russians and the Americans, apparently independently, arrived at the same solution to this problem.

The solution consists of using another element for the fusion fuel which is stable and solid at ordinary temperatures and which is converted into tritium when it is bombarded with neutrons. The light element Lithium-6 (Li-6) is such an isotope, undergoing the following reaction upon neutron bombardment.

Li-6 + *N* —> Li-7 —> H-3 (tritium) + He-4

Where do the neutrons come from? This is where the rod of fissionable material buried within the fusion material comes into play. It is compressed to supercriticality and begins to fission, in the process providing neutrons to begin transforming lithium to tritium. As the fusion reaction progresses (D + T —> He-4 + *N*) the neutrons which it produces continue the process of converting lithium-6 into tritium.

But where does the deuterium (H-2) come from? Lithium hydride (LiH) is a solid compound of lithium and hydrogen. If this compound is made from the Li-6 isotope of lithium and the H-2 (deuterium) isotope of hydrogen, one has LiD which incorporates the necessary fusion fuel isotopes in close proximity and in convenient physical form.

There is yet a third stage to many thermonuclear devices. U-238 incorporated into the bomb can be made to fission by the high energy neutrons which are produced by the D + T fusion reaction. Thus the U-238 tamper will fission, and if the casing of the device is also made of U-238, it too will fission. In this way the energy of the fusion neutrons can be turned into blast energy and the yield of the weapon increased. Thus a typical thermonuclear explosion is a fission-fusion-fission device, in which about half of the energy comes from fusion and the other half comes from fission.

Fusion can also be used in other ways. To make a "clean" bomb—one that does not create high levels of long-lasting radioactivity, one makes the stage 1 fission trigger as small as possible and removes any uranium from stage 2. In this way, the fission fragment production is reduced to a minimum, but the flood of neutrons that shower the blast region will kill or incapacitate individuals in the vicinity by damaging their central nervous systems. This type of weapon has been popularly called the neutron bomb.

Fusion is also used to "boost" fission bombs. If some gaseous deuterium and tritium are introduced under pressure into a small volume in the center of an ordinary implosion type fission device, the heat from the fission reaction will cause them to fuse, emitting high-energy neutrons.. These neutrons in turn produce additional fissions in the fissionable material. What is more, because of the high energy of these neutrons, the fissions they produce give off more than the usual number of free neutrons which enhances or "boosts" the subsequent chain reaction. The energy coming directly from the fusion process itself does not make a significant contribution to the boosted weapon's output. The fusion reaction simply makes the fission reaction more efficient, so that a greater fraction of the fissionable material actually undergoes fission before the reaction ends.

The yield of a fusion-boosted weapon is adjustable by varying the amount of tritium and deuterium in the core. This can be done in the field and makes possible the dial-a-yield weapons which are widely deployed today. (This is the tritium that needs periodic replacement as it has a half-life of 12.3 years.)

As the technology to produce thermonuclear weapons demands a greater effort by a society, states with fission bombs do not automatically move on to develop fusion devices. At the present time, only the original big five of the nuclear club (the United States, Soviet Union/Russia, Great Britain, France, and China) have demonstrated a thermonuclear capability. The essential secret of these weapons, however, is known to everyone: they can be produced if the state is willing to commit its resources to do so.

BECOMING A NUCLEAR POWER

The Manhattan Project marshaled the science and technology to solve the principal problems of procuring fissionable material and then assembling it into an explosive device. The choice of the Los Alamos site for a bomb design laboratory in November 1942 provided a focus for the project. J. Robert Oppenheimer, the director of the laboratory, arrived at the site in March 1943 and was soon followed by a stream of scientists, technicians, and support personnel. To Los Alamos came the U-235 and Pu-239 being produced at Oak Ridge and Hanford, at first in a trickle, and later in increasing amounts. To Los Alamos came the results of measurements at Chicago and elsewhere of neutron absorption probabilities, critical masses, neutron reflectors, and a host of other matters. And from Los Alamos came the "Gadget" (Figure 1-1), "Little Boy," and "Fat Man" (Figure 1-2) which demonstrated so dramatically the feasibility of a self-sustaining nuclear fission reaction of enormous power.

The detonation of the "atomic bomb" over Hiroshima marked the beginning of the nuclear age for everyone, for the basic secret was out: A nuclear bomb could be built. The United States had produced a nuclear weapon from scratch in three and a half years. Is the ability to do so—and perhaps as quickly as that—within the reach of any nation or group, relying on its own efforts? The American government was interested in that question. In May 1964, one of its labs selected several young physicists who had no background in nuclear weapons and no access to the secrets of the weapon. In seven months of research and testing (the "testing" consisted of answers provided by weapons experts to the research tests proposed by the participants), the physicists discovered and passed over the gun-type as too easy to build and went for the more interesting implosion device—not knowing that both avenues had been adopted by the Manhattan Project and that implosion remained the preferred approach. In 18 months, they had a rough design for a plutonium bomb; in 27 months, blueprints. The weapons experts concluded that their design would work.[12] Given the materials, well-trained physicists anywhere can design nuclear weapons in short order.

The bottleneck remains the acquisition of fissile materials. To enrich U-235 or create Pu-239 demands engineering and production capabilities and technologies of a relatively high order (or the wherewithal to purchase them, often clandestinely, as there are usually prohibitions or restrictions on the sale of materiel that has the potential to create nuclear weapons). Such requirements have been met by ten states who have gone on to produce nuclear weapons, but many other states are candidates for nuclear status. It is the case that most industrialized states can, given the time and money, solve the engineering and production problems, and relatively wealthy but less industrialized states (such as China, India, and Pakistan) can as well.

The processes of *proliferation*—the expansion of the number of nuclear weapons states—is a key part of the nuclear predicament and a central feature of the first nuclear age. Proliferation remains a central if not *the* critical issue of the second nuclear age. In Chapter 8 we will discuss the reasons why states might choose—or not choose—to proliferate. Here we are concerned with the *pathways to proliferation*. What approaches are open to the political and military leaders?

1. *A crash program to match a rival's capabilities*: A state can mimic the Manhattan Project by concentrating its efforts to build a nuclear weapon in a short period of time. The Soviet approach is the only other example we have of such a pathway. (The Americans had no *nuclear* rival when they undertook their project.) While Joseph Stalin had ordered a small pilot project begun in 1942, it took Hiroshima to push him to action. "A single demand of you, comrades," he said to the officials involved in the Soviet effort. "Provide us with atomic weapons in the shortest possible time. You know that Hiroshima has shaken the whole world. The balance has been destroyed. Provide the bomb—it will remove a great danger for us."[13] Soviet scientists told Stalin in August 1945 that it would take five years to produce the bomb. It took four. The successful Soviet test of a fission device came in August 1949.

2. *Longer-term programs to create nuclear weapons*. This pathway involves an early, conscious choice to go nuclear, but the program is not driven by a sense of impending destruction at the hands of an opponent. Britain's development of the bomb in 1952 and China's in 1964 are the two programs that best fit this category. Pakistan's approach appears to fit here as well, as does the South African effort (although among all the nuclear powers, it alone subsequently decided to scrap all of its weapons). Iraq until its defeat in 1991 had embarked on a similar pathway. As we shall see in Chapter 7, the case of the Democratic People's Republic of Korea ("North Korea") is ambiguous, possibly reflecting this or the following pathway.

3. *Longer-term programs that make a nuclear option possible*. This pathway gives the state the option to go nuclear at some point without actually committing the political leadership to develop the weapon at the start of the project. Avner Cohen suggests that the French and Israeli

governments took this approach to nuclear weapons. David Ben Gurian, the first Israeli prime minister, took the position of minister of defense as well so that he could secretly launch a program that could produce a nuclear weapon, and only later revealed his plans to selected political and military leaders. Cohen notes that "apparently Ben Gurian himself was not clear in his own mind those days how far Israel should go with its nuclear pursuits." Similarly, he notes that "under the [French] Fourth Republic, important nuclear activities were made piecemeal by sympathetic politicians and administrators acting on their own, while the official government could maintain, and rightly so, that no final political decision on nuclear weapons had been made."[14]

Both, however, did ultimately choose to develop such weapons, the French publicly and the Israel government secretly. Israel became a nuclear state during the period 1968-1971. It has never tested a device, and has publically said that it would not be the first to introduce nuclear weapons in the region. There is every reason to believe, however, that Israel has at least 50-100 warheads, possibly 200, in its arsenal. Refusing to acknowledge being a nuclear power even though most informed observers and governments are convinced that the state is a nuclear power has been called *opaque proliferation*.

India's approach to nuclear weapons is similar. In 1974, it tested a nuclear device that demonstrated its capability, but the government declared itself interested in nuclear devices for peaceful purposes only (such as the excavation of large areas as conventional blasting does). It did not build a nuclear weapons force and refrained from any further tests until the 1990s. The Indian government was, however, "a screwdriver away" from having nuclear weapons after 1974 (although it would still take some time to develop the wherewithal and military organization to deliver such quickly constructed weapons to their targets). Iran seems to be following this pathway at the present.

4. *Acquiring nuclear weapons from others*. States have sought to acquire nuclear weapons from their possessors. China, for instance, sought to become a nuclear weapons state through its alliance with the Soviet Union. The Soviets refused to give or sell nuclear weapons to the Chinese but for several years the USSR did help Chinese scientists with indigenous development. President Nasser of Egypt, fearing that the Israelis would develop nuclear weapons, apparently asked the Soviet government to sell atomic bombs to Egypt. The Soviets refused, but may have offered to protect Egypt with their nuclear weapons. (Such an approach is called *extending the nuclear umbrella*). There were reports during the 1970s that Libya sought (unsuccessfully) to purchase nuclear weapons. In the early 2000s, many expressed the fear that North Korea's Kim Jong Il would sell nuclear weapons to whomever had the cash.

   While the direct delivery of nuclear weapons has not yet occurred, there has been a recurrent pattern of the transfer of nuclear plans and technologies between states. In some cases, it came with the cooperation of an existing nuclear weapons state, as the Soviet Union initially aided Chinese efforts, and China and North Korea probably aided Pakistan in the development of its weapons by sharing technical expertise and materials. Pakistan provided similar help to North Korea in return for the North's missiles. Currently there are fears that North Korea remains amenable to such transfers some observers have expressed concerns that if Islamic militants come to power in Pakistan, they might be willing to transfer nuclear technologies if not the weapon to other Islamic states.

These government-to-government exchanges are but one avenue to proliferation, however. When Libya ended its nuclear program in 2004 and submitted to inspections, the world learned that Libya was able to order centrifuges for U-235 enrichment through commercial suppliers who attempt (often successfully) to avoid the controls placed on such sales. Indeed, Libya seemed at the time to be on the verge of acquiring a turn-key plant to enrich uranium. The history of the nuclear age, however, suggests that technology transfer also happens not only on the black market but in the open market as well, where states have acquired nuclear weapons technologies or so-called "dual use" items that can be used for non-nuclear purposes as well as to build a nuclear weapons program.. And the most open transfer of technologies and expertise came with the sale or gift of nuclear-power plants and research reactors by their developers. Granted, these latter transfers do not provide the weapon or its technologies, but they move the recipients closer to acquiring the weapon.

NUCLEAR POWERS AND NUCLEAR ASPIRANTS

How many states have attempted to go nuclear? How many have seen their programs through to fruition? Table 2-1 summarizes nuclear weapons histories of various states. At the present time, nine states have entered the nuclear club: the United States, the Soviet Union, Britain, France, China, Israel, India, South Africa, and Pakistan.[16] (Soon after acquisition, the South African government destroyed its small nuclear arsenal.) In 1991, the nuclear club momentarily expanded as the Soviet Union collapsed and three newly independent republics (Belarus, Ukraine, and Kazakhstan) inherited parts of the Soviet nuclear arsenal along with the new Russian state. By the fall of 1996, however, all the warheads were back in Russia and none of the three governments actually had control over the warheads, as they remained under a military organization controlled by the Russian government. North Korea has declared that it is a nuclear weapons state, making it the tenth nation to have acquired the bomb—if in fact it has actually produced the weapons.

[Table 2-1 goes about here]

Table 2-1 shows that a large number of states began nuclear weapons programs or followed the "option" pathway but then decided against constructing nuclear weapons. Many of those states such as Germany and Japan are leading industrial and technological powers. Given access to fissile materials (in many cases readily available, as we shall see, from nuclear power plants within those states), those states could proliferate very quickly if the political leadership decided to do so. And as the cases of Iraq, North Korea, and Iran demonstrate, *any* state with sufficient funds, an indigenous scientific establishment, access to fissile materials, and the political will, can undertake a nuclear weapons program with a strong probability of producing a nuclear device. With all these factors in place, a state starting essentially from scratch might count on a working fission device after 4-5 years of a crash program, and 7-15 years in a normal (but still costly) program.

A state could accelerate the process by using espionage (as the Soviets did in their penetration of the Manhattan Project during and immediately after the war) or through theft (as the Israelis did in acquisition of some fissile materials) or by purchasing dual-use equipment on the open market (as Iraq did) to reduce the time to reach nuclear status. Or states might acquire materials covertly from existing nuclear states—for instance, through the semi-official Pakistani network run by A. Q. Khan, the developer of Pakistani nuclear weapons. Covert programs (like Libya's and Iraq's) that must rely on such networking and shadowy suppliers are likely to take on the characteristics of Libya's program: "ambitious, [but also] disorganized, incomplete, and likely years away from producing actual nuclear warheads."[17]

Acquisition of nuclear weapons by a terrorist group would be far more difficult but not impossible, a topic we take up in Chapter 9. Such a group could not make its own weapons unless it had the physical facilities to do so, and those would have to be under relatively long-term protection of a host government in order to have the time to follow a production pathway. Most potential host governments would probably be extremely reluctant to permit such an operation because of the high probability of attack by other states. Purchase or theft are more likely pathways for terrorist groups, but still quite difficult at the present time given the safeguards that nuclear weapons states have created around their existing weapons. In the second nuclear age, however, Russia became a cause for concern as Chechen terrorists fighting the Russian government have demonstrated an ability to bribe Russian officials to overlook the shipment of conventional weapons or to disregard security regulations which allowed suicide bombers on planes. While Russian nuclear weapons are controlled by an elite force, there have been reports that in the breakup of the Soviet Union, a number of small tactical nuclear devices could not be accounted for.

As for a nuclear weapons state or a governmental organization within such a state giving a nuclear device to a terrorist group to promote its policy goals, we believe such risks are low. The donor state is likely to be identified if the weapon were detonated and it would face severe—probably nuclear—retaliation. Moreover, the nuclear device might end up in the hands of a group hostile to the donor nation itself (for terrorists pursue their own agenda), which might produce a very frightful outcome for the donor. Therefore, at this moment, the more immediate threats are the theft of a nuclear weapon (perhaps with the connivance of low-level officials) and the use of radioactive materials to create a radiological device or "dirty bomb" (discussed below). Terrorist organizations currently seem to be most likely to obtain such devices through theft or bribery.

Why states or terrorist organizations seek a nuclear weapons capability is a crucial question that we explore in depth in Chapter 9. The history of the first nuclear age demonstrates that some states have felt *compelled* to acquire them and the advances in physics and engineering made such weapons conceivable and feasible. We expect such compulsion will continue for some governments and leaders far into the future. Ironically, the growing demand for energy means that globally, more governments will have an interest in nuclear matters, for it is likely that the controlled fission of the atom will become a principal source of electrical energy. Nuclear power plants, however, provide fissile materials for nuclear weapons and an ever-growing source for a particular type of radiological bomb. We now turn to that part of the story.

THE ROLE OF NUCLEAR POWER GENERATION IN PROLIFERATION

Without enriched uranium-235 or plutonium-239 there is no bomb. But both of these are natural parts of the nuclear power industry. In recent years, concerns about global warming from fossil fuels, the desire for independence from foreign oil imports, and the largely unmet need of less-developed countries for energy have renewed general interest in nuclear power. Europe and Japan have committed themselves to nuclear-produced electricity to a much greater extent than the United States has, but even in the latter, as current nuclear power plants reach obsolescence and the demand for energy continues to mount, there is a renewed interest in the construction of new nuclear reactors. Such a trend is not likely to be reversed in the near future.[18] Even if it turns out that the nuclear power industry does not return to a high-growth state for one reason or another, the currently existing reactors (about 430 worldwide) and the steady diffusion of technical expertise will continue to afford opportunities for proliferation.

Most civilian nuclear reactors are fueled with a mixture of U-235 and U-238, contained in long thin rods that are inserted into the reactor core in an array which leaves space for water to circulate between them. The U-235 slowly fissions, heating the water to produce steam, which then directly drives a turbine to generate electricity (a boiling water reactor), or the steam is piped to a heat exchanger where a separate supply of water is boiled to drive the turbine (a pressurized water reactor). Unlike a nuclear explosive, the uranium in a power reactor need not be highly enriched in U-235. In fact, natural uranium, containing only 0.7 percent U-235, will do if the water circulating in the reactor core is replaced with *heavy water*. Heavy water is D_2O where the usual hydrogen atom has been replaced by the heavy hydrogen isotope deuterium whose nucleus contains a proton and a neutron.. Lacking the neutron, ordinary water (called light water) has too great a probability of absorbing the neutrons needed to fission the U-235 unless more highly enriched U-235 is used.

Canadian nuclear reactors are generally heavy water reactors, employing natural, unenriched uranium as their fuel. Canada has exported this technology to other countries, enabling them to build and operate nuclear reactors without having to engage in the difficult uranium isotope separation process, although in this case they must obtain a significant quantity of heavy water in addition to the natural uranium. Heavy water does occur naturally, but the quantities needed generally mean that it must be imported, thus often making a state dependent upon foreign sources of supply for both the uranium and deuterium-rich water.

If, on the other hand, one uses ordinary water, then the fuel rods must contain uranium enriched to 3-4 percent in U-235. States with light-water reactors therefore must be able to enrich uranium or to purchase enriched uranium from supplier nations who generally exercise tight supervision over its use. For energy deficient states, the building of uranium enrichment facilities is justifiable in terms of meeting legitimate energy needs—and it is the right of any sovereign state to do so. This has been Iran's basic claim in its confrontation with the United States regarding the former's attempt to create a nuclear power-generating capability.

The ability to separate the isotopes of uranium for enrichment purposes is the first step towards nuclear power independence—and towards a nuclear weapons capability. Enrichment to weapons grade (approximately 90% U-235) takes greater effort but is prefigured in the initial mastery of the enrichment process. Nuclear weapons, however, can be built with far less U-235, but they will be bulkier—and therefore more difficult to deliver to the target and less efficient.

One other route to nuclear weapons or the expertise to develop them has come from *research reactors* which typically operate at 80-90% enrichment. Many of these reactors have come from the major nuclear powers, but donor states usually exercise tight control over the HEU fuel rods and the overall amount of HEU is quite small. Currently, however, there are about 275 active research reactors in nearly 70 countries.[19]

The second connection between nuclear power reactors and nuclear weapons is the Pu-239 which nuclear reactors create. Since the fuel rods contain an abundance of U-238, a significant amount of U-238 is converted into Pu-239 by the neutrons produced in the fissioning of the U-235. The Pu-239 can be chemically separated from spent fuel rods, but the extreme radioactivity of the rods makes such reprocessing a dangerous and technically sophisticated operation. Furthermore, commercial power reactors are designed to be refueled infrequently, with the rods left in the reactor for about a year. This results in the buildup of Pu-240, another isotope produced when U-238 is bombarded with neutrons. The presence of Pu-240 mixed in with the Pu-239 (and these isotopes cannot be chemically separated) renders the product ill-suited for nuclear weapons use. It is for this reason that nuclear weapons states obtain their plutonium from reactors which are specially designed to produce plutonium and not power.

This is not to say that a plutonium device with a surfeit of Pu-240 cannot produce a bomb of sorts, if one were willing to settle for a bomb of very low yield (say, from under 1 to perhaps 3 kt)[20]. In fact, in 1962 the United States successfully tested a nuclear device made with reactor-grade plutonium. Weapons-grade plutonium, however, is typically 6% Pu-240 and 93.5% Pu-239, while reactor grade plutonium is typically 23% Pu-240. The Pu-240 fissions too quickly, blowing the material apart prematurely, thus producing a nuclear fizzle; heat, blast, and prompt radiation would reach about a third of a mile from the point of detonation. The critical limitation, however, on building a weapon of reactor grade plutonium is the high radiation from Pu-240; it is intense enough to severely injure anyone working with the bomb. Of course, if technicians who assembled the bomb and those who were to deliver it accepted their deaths as a part of the mission, reactor-grade plutonium might be fashioned into a crude nuclear weapon.

The reprocessing of fuel rods to extract the Pu-239 is a relatively well-known technology because it was initially feared that the world's supply of uranium would run out. Thus, the major nuclear powers invested in programs to reprocess plutonium to be used in power reactors in place of uranium. Indeed, a properly designed reactor can produce more new nuclear fuel than it consumes—such reactors are known as breeder reactors. Even though the world's supply of uranium is nowhere near exhaustion, plutonium reprocessing continues (in part because it liberates the reprocessor from having to depend on imports of uranium).

The nuclear weapons states (and those that have sought nuclear weapons) have pursued both the uranium isotope separation strategies and the reprocessing of plutonium as the route to nuclear weapons. Plutonium reprocessing seems to have been the Israeli choice. In South Asia, "India's route… would be based on plutonium derived from its natural uranium fueled, heavy water cooled and moderated reactors, and separated in its established reprocessing facilities."[21] North Korea has pursued both uranium enrichment and plutonium separation to develop a nuclear capability.

RADIOLOGICAL WEAPONS

We have seen how radioactive materials constitute severe health risks to individuals exposed to the alpha, beta, and gamma rays they omit as they decay toward greater stability. Fissioning U-235 produces a vast array of such radioactive isotopes. Among these are cesium-137, cobalt-60, and iridium-192 (which today have uses in medicine and industry). In the early days of the Manhattan Project, when no one knew if *deliverable* nuclear weapon could be made, the United States Army considered combining such radiological materials and high explosives in a bomb. The blast would scatter the radioactive material, making the contaminated area uninhabitable.[22] While the Americans lost interest in the approach as they were able to build nuclear weapons, Iraq's inability to build a nuclear weapon led that nation to build and test "a dirty bomb in the 1980s before abandoning the program on the grounds that it was ineffective against military targets, according to U.N. weapons inspectors."[23]

The idea of a radiological or "dirty" bomb has re-emerged in the second nuclear era, as terrorist groups such as al Qaeda have shown an interest in such a device[24]—indeed, going so far as to give an American, Jose Padilla, the mission in 2002 of staging a dirty bomb attack against an American city. (Padilla was apprehended before he begin the assignment.) On the other hand, Chechen rebels fighting for independence from Russia did leave a radiological device in a Moscow park. Russian authorities rendered it harmless after the Chechens revealed its location, but the point was made. Dirty bombs were potential parts of a terrorist arsenal.

Terrorists seeking nuclear materials through purchase or theft are more likely to acquire the materials for radiological bombs than fissile materials for a nuclear weapon, as the former are in widespread use around the world. For instance, in the United States, there are an estimated two million licensed locations using radioactive materials.[25] The former Soviet Union, however, is the treasure trove for such materials, often weakly protected. In the first nuclear age, Soviet scientists explored a wide variety of applications of nuclear physics. "The Soviets are known to have produced tens of thousands of radioactive devices for uses ranging from medical diagnostics to military communications, and many were simply abandoned after the Soviet breakup in 1991. Some regions are so littered with such devices that published tourist guides caution travelers to watch out for them."[26] Agricultural experiments, for instance, used cesium-137, a highly radioactive isotope, to determine the effects of radiation on plants and seeds. The cesium was available at many sites, not all of which could be identified and secured. Calculations suggest that roughly 2 ounces of cesium-137 (with a half life of 30 years) could, if dispersed by a conventional explosive, make the area ten miles from the detonation point radioactive enough to cause people to abandon the area for years unless there was a very expensive clean-up.

Trafficking in radioactive isotopes has become a significant part of the criminal smuggling in the new republics in the Caucuses, with much of the activity centered in Georgia. For instance, in May 2003 police discovered a cab about to unload lead-lined boxes containing strontium and cesium at the railroad station in Tbilisi, the capital, for transhipment to unknown individuals.[27] (Georgia also has been the site of smuggling of kilogram quantities of uranium as well). As Georgia was in political turmoil and wracked by violent independence movements, such smuggling may have served as a means of raising money by selling such materials to other terrorists or as a way of raising the stakes in the confrontation with the Georgian government. The American government became so concerned that a radiological device may have already made its way into the hands of al Qaeda that in December 2003 it sent technicians to four (perhaps more) large American cities with equipment hidden in briefcases and golf bags to detect radiation from a radiological device.[28] None were found, but the growing consensus has been that such an attack may be increasingly likely in the near future.

Terrorists or states seeking to inflict radiological damage on their enemies need not, however, transport a dirty bomb to their target. Bennett Ramberg's book title captured an important truth: *Nuclear Power Plants as Weapons for the Enemy.*[29] Any nation that has a nuclear reactor has a radiological bomb in place. There are 65 sites in the United States with a total of 103 nuclear reactors. Around the world there are 438 commercial units. In the reactor core are the fissile materials and the radioactive byproducts of the fission process. As a rule, the core is shielded behind heavy concrete walls that are designed to withstand some forms of attack, but apparently most were not designed to withstand the impact of a large jet liner fully loaded with jet fuel.

Even more worrisome are the spent fuel rod storage areas located at the reactor sites in the United States. The fuel rods, depleted of their uranium, but now containing highly radioactive plutonium and fission fragment isotopes, are kept in cooling pools of water. The loss of water—say, from an attack on the storage pool—could lead to an uncontrollable fire that would dump Cesium 137 and other radioactive particles into the air. One estimate is that if a fire broke out at a Connecticut storage site, 29,000 square miles (including New York City and Long Island) might become uninhabitable.[30]

There are 40,000 tons of spent fuel in storage facilities in the United States. 11,000 tons will be added in the next several years. The United States Department of Energy planned to begin moving spent fuel rods to a massive underground storage facility at Yucca Mountain, Nevada. Political opposition to opening this site, however, will delay their transfer and the 2010 target date for opening the facility is likely to be missed. Moreover, there are 33,000 tons of spent fuel rods that Brazil, the Czech Republic, India, Japan, Mexico, Slovenia, South Korea, Switzerland, Taiwan, and member states of the European Union had originally obtained for their reactors from the United States and that the U.S. had pledged to take back. Political opposition in the United States may make that impossible now. Even if the United States were willing to do so, it will take time before those rods are removed from their individual storage sites. Russia has proposed to build a massive spent-fuel rod storage site and store the rods for a price. In the meantime, Russia's own nuclear waste is stored (often haphazardly) at nuclear power stations; in the vicinity of the cities set up as centers of nuclear research, fissile material production, and weapons making; and at military bases.

It might be modestly comforting to report that only in the former Soviet Union is there a danger of theft or removal of fissile or radiological material from nuclear sites . The danger is real there, but it is not absent in the United States. The Nuclear Regulatory Commission (NRC) has the responsibility to oversee the security at nuclear power plants in the United States. The NRC sets security guidelines and mandates periodic tests in what are called force-on-force exercises to see if a simulated terrorist group could reach the vital components of the reactor where they might be able to damage the controls or operating mechanisms sufficiently to produce a meltdown of the core or other events that would release radioactivity into the environment. In the recent past, the "terrorists" have reached those components in 50 percent of the tests, even when the security guards knew that a test was to be conducted at the site.[31]

In similar force-on-force tests conducted at sites under the Department of Energy's control where fissile materials are stored, the failure rate has been roughly the same. The details can be disheartening:

> [In a 1998 test] Navy SEALs successfully entered the site through a perimeter fence, gained entrance to a nearby building, 'stole' a significant quantity of plutonium, exited the building, and escaped through the fence, all without being caught. After this embarrassment, Rocky Flats management stipulated that in future tests the SEALs could not leave by the same way they came in. Instead, they were required to take the plutonium, climb a guard tower, and rope the material over the fence.[32]

The guards successfully defended the site in the re-test.

Given the heightened world-wide concern over terrorism, we might expect that security at sensitive sites such as power reactors or fuel rod storage ponds would be enhanced, so that the chances of diversion of or attacks on radiological or fissile material is likely to diminish. Such security, however, is costly and seeks to prevent relatively unlikely events. When economic conditions deteriorate and budgets become strained, societies are less likely to pay the extra cost until after the unlikely has happened.

CONCLUSION

Given the laws of physics, it may have been inevitable that humans would discover nuclear weapons. Their creation reflected the innate human curiosity about the natural world, coupled with increasingly powerful ways to understand that world. How and when they would emerge was far less predictable, but in retrospect it seems natural that the great war that engulfed the world in 1939 would spur the harnessing of this new nuclear science to war-waging. Equally important, many of the world's inhabitants perceived the war as a struggle between good and evil, a struggle in which the very survival of nations, peoples, and life-sustaining beliefs was in peril. Finding the war-winning weapon was imperative.

That nuclear weapons would emerge first in the United States was something of a surprise. Europe had been the heart of the golden age of physics, when humans began to make remarkable progress in understanding the basic building blocks of matter—what they consisted of and the forces that held them together. But Europe was also the heart of the rising threat of totalitarian fascism. Ironically, it was this shadow that drove the center of nuclear science to the more tranquil shores of the United States, where European physicists, American industrial might and engineering ingenuity, and the looming war converged to produce the awesome weapons of destruction.

The closing days of the Second World War ushered in the first nuclear age. Its arrival closed one chapter of this remarkable scientific and technological story. A new story then unfolded. Like the other fruits of science, nuclear fission was available to all, for this kind of human knowledge flows across frontiers without a passport. Scientists and engineers in other nations sought to duplicate the feats of the Manhattan Project, and American scientists turned their attention to warhead efficiencies, missile delivery systems, and harnessing nuclear fusion.

The arrival of the first nuclear age is not, however, just a story of the creation of nuclear weapons. It is also a story of how humans came to use that weapon. In the next chapter, we explore how the Truman administration decided to use nuclear weapons against Japan and how future leaders might choose to use the nuclear weapons at their command.

ENDNOTES

[1] For extensive accounts of the Trinity Test and the scientific and technological developments which led to it, see the following: Henry DeWolf Smyth, *Atomic Energy for Military Purposes: The Official Report on the Development of the Atomic Bomb under the Auspices of the U.S. Government, 1940-1945* (Princeton, NJ: Princeton University Press, 1945) and Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon & Schuster, 1986). For the early and later periods, see Gerard DeGroot, *The Bomb: A Life* (Cambridge, MA: Harvard University Press, 2005), and Charles Loeber, *Building the Bomb: A History of the Nuclear Weapons Complex* (Washington, DC: U.S. Government Printing Office, 2002).

[2] For the German experience with nuclear weapons see Thomas Powers, *Heisenberg's War: The Secret History of the German Bomb*, (New York: Knopf, 1993); Mark Waller, *German National Socialism and the Quest for Nuclear Power*, 1939-1949 (Cambridge, UK: Cambridge University Press, 1989); and Paul Lawrence Rose, *Heisenberg and the Nazi Atomic Bomb Project, 1939-1945,* 2nd ed. (Berkeley, CA: University of California Press, 2001).

[3] British contributions are detailed in Ferenc Morton Szasz, *British Scientists and the Manhattan Project: The Los Alamos Years*, (New York: Palgrave Macmillan, 1992).

[4] It is the case that nuclear physics emerged when it did out of a Western cultural tradition that chooses to see the world in a particular fashion, but it strikes us as implausible that other cultural traditions would not have come to the same understanding and same weapons, though perhaps at some other time. It may be, however, that how nuclear weapons became part of the political and cultural history of the times does reflect their birth within a Western culture.

[5] Howard Morland captured this nicely in the subtitle of his article, "The H-Bomb Secret: To know how is to ask why." *The Progressive* (November 1979), p. 245.

[6] See Diana Preston, *Before the Fallout: From Marie Curie to Hiroshima* (New York: Walker, 2005), for a history of the physics and people involved. Earlier studies include J. G. Feinberg, *The Story of Atomic Theory and Atomic Energy* (New York: Dover, 1960); Emilio Segre, *From X-rays to Quarks: Modern Physicists and Their Discoveries* (New York: W. H. Freeman, 1980). For personal accounts, see Laura Fermi, *Atoms in the Family* (Chicago: University of Chicago, 1954) and Eve Curie, *Madame Curie* (New York: Garden City Publishing Co., 1943).

[7] The development of quantum mechanics by Werner Heisenberg and Erwin Schrodinger replaced Bohr's "planetary" orbits of the electron with something called quantum states. The quantum state describes the probability of finding the electrons at different locations about the nucleus. There are a great many different quantum states available to electrons. For an in-depth presentation see Kenneth Krane, *Introductory Nuclear Physics* (New York: Wiley, 1987).

[8] For general accounts of the Manhattan Project, see Smyth, *Atomic Energy for Military Purposes*; Vincent C. Jones, *Manhattan: The Army and the Atomic Bomb* (Washington, D.C.: U.S. Army Center of Military History, 1985); and David Hawkins, Edith Trulow, and Ralph Carlisle Smith, *Project Y: The Los Alamos Story, Vol. II of A Series in the History of Modern Physics 1800-1950* (Los Angeles: Tomash Publishers, 1983). For the individuals, see Gregg Herken, *Brotherhood of the Bomb: The Tangled Lives and Loyalties of Robert Oppenheimer, Ernest Lawrence, and Edward Teller* (New York: Henry Holt, 2002); Kai Bird, *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer* (New York: Knopf, 2005); Jennet Conant, *109 East Palace: Robert Oppenheimer and the Secret City of Los Alamos* (New York: Simon & Shuster, 2005); and Robert S. Norris, *Racing for the Bomb: General Leslie R. Groves, the Manhattan Project's Indispensable Man* (South Royalton, VT: Steerforth Press, 2002).

[9] For more extended treatments of the physics of nuclear weapons, the following books will be helpful: Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons* (Washington, DC: Department of Defense and Energy Research and Development Administration, 1977); Smyth, *Atomic Energy for Military Purposes*; Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook Vol. I: U.S. Nuclear Forces and Capabilities* (Cambridge, MA: Ballinger, 1984); Kosta Tsipis, *Arsenal: Understanding Weapons in the Nuclear Age* (New York: Simon & Schuster, 1985); MIT Faculty, *The Nuclear Almanac: Confronting the Atom in War and Peace* (Reading, MA: Addison-Wesley, 1984), pp. 195-204, 447-494.

[10] For a fascinating though technical report by Iranian physicists, see P. Parvin et al., "Molecular Laser Isotope Separation Versus Atomic Vapor Laser Isotope Separation," *Progress in Nuclear Energy*, Vol. 44 (No. 4, 2004), pp. 331-345.

[11] Howard Morland, a former Air Force pilot who had taken some engineering courses while in college, engaged in this kind of sleuthing and published his conclusions in the November 1979 issue of *The Progressive.* The government sought unsuccessfully to obtain a court injunction to restrain its publication but did

succeed in delaying publication for half a year. Morland has written an interesting book chronicling his pursuit of the secret and his efforts to see it published. Howard Morland, *The Secret That Exploded* (New York: Random House, 1981). This was followed by a book entitled *Born Secret: The H-Bomb, the Progressive Case and National Security*. See also A. DeVolpi, G. E. Marsh, T. A. Postol, and G. S. Stanford, *Born Secret: The H-Bomb, the Progressive Case, and National Security* (New York: Pergamon, 1981).

[12] Dan Stober, "No Experience Necessary," *Bulletin of the Atomic Scientists*, Vol 59 (2, March/April 2003), pp. 57-63.

[13] Quoted by David Holloway, *The Soviet Union and the Arms Race* (New Haven, CT: Yale University Press, 1983), p. 20. In 1979 or 1980, a close advisor to the Ayatollah Khomeini reportedly used very similar language in speaking with an Iranian official in charge of the Shah's nuclear program: "It is your duty to build the atomic bomb for the Islamic Republican Party… . Our civilization is in danger and we have to have it." Quoted in Leonard Spector and Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons 1989-1990* (Boulder, CO: Westview, 1990), p. 208.

[14] Avner Cohen, "Israel's Nuclear Opacity: A Political Genealogy," in Steven L. Spiegel, Jennifer D. Kibbe, and Elizabeth G. Matthews (eds.), *The Dynamics of Middle East Nuclear Proliferation*, (Lewiston, NY: Edwin Mellen, 2001), p. 191. For an extensive analysis of the Israeli program, see Avner Cohen, *Israel and the Bomb* (New York, NY: Columbia University Press, 1998).

[15] Janice Gross Stein, "Proliferation, Non-Proliferation, and Anti-Proliferation: Egypt and Israel in the Middle East," in Spiegel et al. (eds.), *Dynamics*, p. 44, footnote.

[16] For a current accounting, see Joseph Cirincione, Jon B. Wolfsthal, and Miriam Rajkumar, *Deadly Arsenals: Nuclear, Biological, and Chemical Threats*, 2nd ed. (Washington, DC: Carnegie Endowment for International Peace, 2005).

[17] *Washington Post National Weekly Edition*, March 8-14, 2004), p. 16

[18] For a recent discussion, see James A. Lake, Ralph G. Bennett, and John F. Kotek, "Next-Generation Nuclear Power," *Scientific American*, Vol. 286 (January 2002), pp. 72-

[19] See Alexander Glaser and Frank N. von Hippel, "Thwarting Nuclear Terrorism," *Scientific American* (February, 2006), pp. 56-63.

[20] The following is adapted from Milton Heonig, "Terrorists Going Nuclear," in Yonah Alexander and Milton Hoenig (eds.), *Superterrorism: Biological, Chemical, and Nuclear* (Ardsley, NY: Transnational Publishers, 2001), pp. 32-36, especially footnote 5, and Dan Stober, "No Experience Necessary," *Bulletin of the Atomic Scientists*, Vol 59 (2, March/April 2003), pp. 62-63.

[21] P. R. Chari, *Indo-Pak Nuclear Standoff: The Role of the United States* (New Delhi, Manohar, 1995), p. 38.

[22] The Army also was developing the ability to use chemical warfare against the Japanese in a land invasion of Japan.

[23] Joby Warrick, "Tracking a Dirty Bomb," *Washington Post National Weekly Edition*, (December 8-14, 2003), p. 6.

[24] See Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, (November 2002), pp. 76-81.

[25] Charles D. Ferguson and William Potter, The Four Faces of Nuclear Terrorism, (New York: Routledge, 2005); research cited in Charles Hanley, "Study: Dirty Bombs Highly Likely for U.S." Durham, NC *Herald-Sun*, June 19, 2004, p. A2.

[26] Joby Warrick, "The Hunt for a Deadly Legacy," *Washington Post National Weekly Edition*, November 18-24, 2002, p. 16.

[27] Warrick, "Tracking," pp. 6-7.

[28] John Heilprin, "Experts Walk Streets to Detect Dirty Bomb," Durham NC *Herald-Sun*, January 8, 2004, p. A2.

[29] Bennett Ramberg, *Nuclear Power Plants as Weapons for the Enemy: An Unrecognized Military Peril* (Berkeley, CA: University of California Press, 1984).

[30] Robert Alvarez, "What about the Spent Fuel?" *Bulletin of the Atomic Scientists*, (January/February, 2002), pp. 45-47. See also Elizabeth Kolbert, "Indian Point Blank," *The New Yorker* (March 3, 2003), pp. 36-41 and Shankar Vedantam, "A Radioactive Secret," *Washington Post National Weekly Edition*, April 4-10, 2005, p. 29.

[31] Daniel Hirsch, "The NRC: What, Me Worry?" *Bulletin of the Atomic Scientists*, Vol. 58 (January/February, 2002), pp. 39-44. See also Mark Hertsgaard, "Nuclear Insecurity," *Vanity Fair*, (November 2003), pp. 175-184.

[32] Danielle Brian, Lynn Eisenman, and Peter D. H. Stockton, "The Weapons Complex: Who's Minding the Store," *Bulletin of the Atomic Scientists*, (January/February, 2002), p. 51.