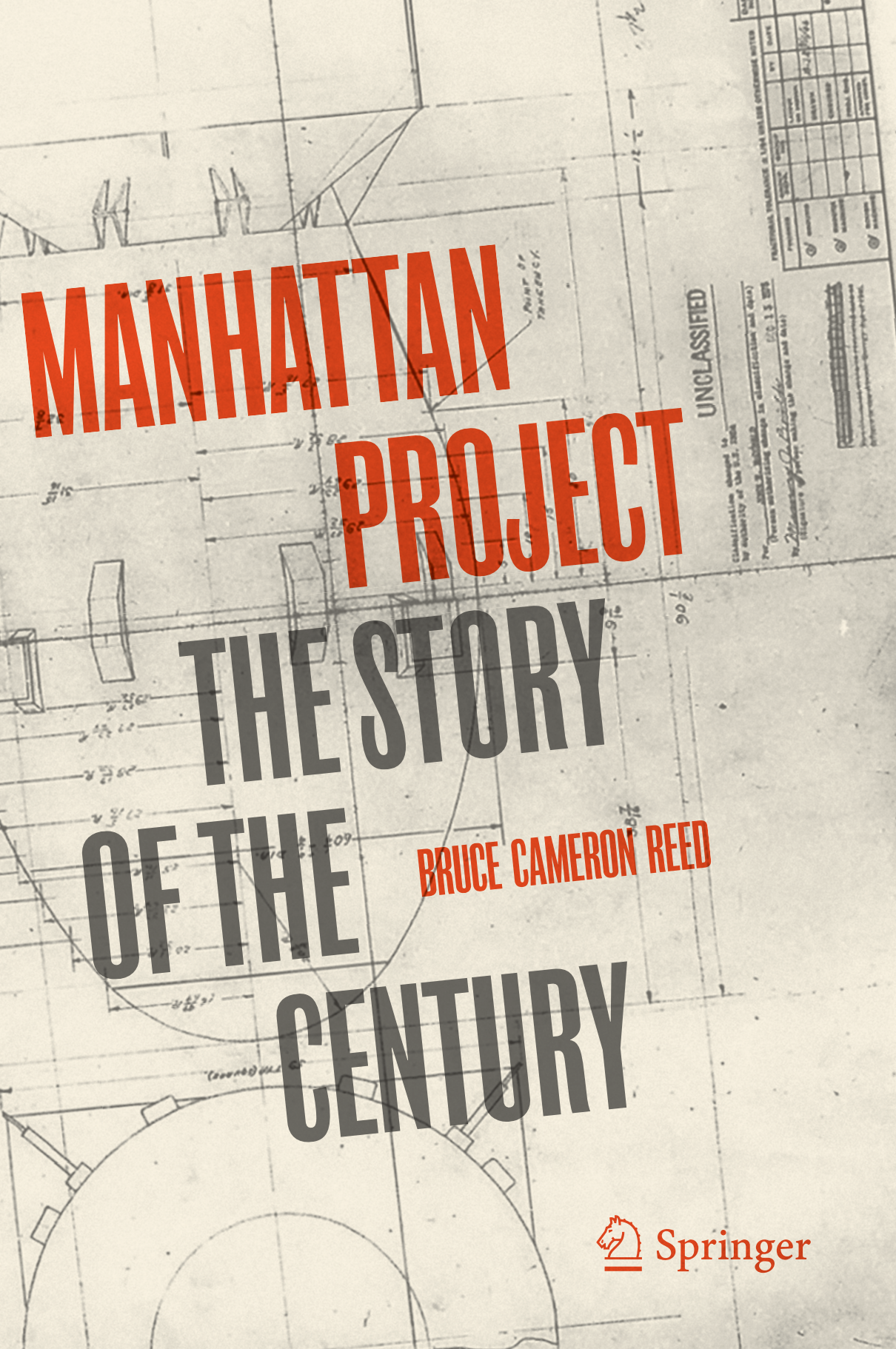
MANHATTAN PROJECT
THE STORY OF THE CENTURY
BRUCE CAMERON REED
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Manhattan Project

Bruce Cameron Reed

Manhattan Project

The Story of the Century

Springer

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For Laurie.
And Fred, Leo, Stella, Cassie, Nyx, and Newton.

Prologue

Nuclear weapons are the most destructive devices ever developed by human beings. A single one can cause a level of destruction to a large city akin to that of an earthquake, tsunami, or hurricane, while also depositing radioactive fallout over a large area. A modest-scale nuclear war could loft enough dust into the atmosphere to cause climatic effects like that of an asteroid strike, posing a truly existential threat to human civilization. Since their development in World War II, thousands of nuclear weapons have been constructed, over 2,000 have been tested, and thousands remain in the arsenals of the world's nuclear powers. At any time, hundreds are deployed on bombers, missiles, and submarines, ready for essentially immediate use.

The development and use of nuclear weapons was one of the pivotal events of human history, and certainly the watershed event of the twentieth century. The bombings of Hiroshima and Nagasaki helped bring World War II to a close. The number of people killed by the bombs was estimated to be about 125,000, with a further 130,000–160,000 injured. A similar number of deaths had occurred a few months earlier in one night in a fire-bombing raid of Tokyo, but that raid involved nearly 300 bombers carrying about 1,700 tons of bombs. In contrast, the Hiroshima and Nagasaki atomic bombs, *Little Boy* and *Fat Man*, each exploded with energies equivalent to over 10,000 tons of conventional explosive.

The ramifications were staggering. A single bomber could now obliterate an entire city with a single bomb. Advances in science and engineering had

given humanity the capability of annihilating itself on a global scale if an accidental or deliberate large-scale nuclear war were to break out. Nations that saw themselves as global powers would henceforth depend as much on the depth of their scientific and technological prowess as on traditional military capabilities as a measure of their influence. The Cold War, nuclear proliferation, the possibility of nuclear terrorism, the stockpiles of nuclear weapons currently held by various countries, and public fear of radioactivity and nuclear power are all legacies of 1945.

Little Boy and *Fat Man* were the products of what has come to be known as the Manhattan Project. Carried out by the United States Army between 1942 and 1945, this project was properly known as the Manhattan Engineer District. The scale and cost of Manhattan were just as enormous as its eventual significance. Physics Nobel Laureate Niels Bohr, who contributed much to the understanding of the process of nuclear fission, initially thought the idea of a nuclear weapon so improbable as to state that "It can never be done unless you turn the United States into one huge factory." To some extent, that is exactly what happened. Some 480,000 people were employed in the Project's laboratories and factories at one time or another, about one out of every 250 people in the country at the time. Peak employment reached just over 125,000 in late 1944. By mid-1945 the cost of the Project was approaching $2 billion, an enormous amount for two bombs. The Project's own official record, the *Manhattan District History*, lists nearly 1,000 government agencies, universities, individuals, businesses, and industrial contractors that contributed to the work.

In this book I examine the scientific basis of nuclear weapons, how they function, how the Manhattan Project came to be organized, why the bombs required exotic materials for their construction, why they were so difficult and expensive to make, and the circumstances of the Hiroshima and Nagasaki bombing missions. While thousands of articles and books have been written about Manhattan, my motivation in preparing this volume is to offer readers an authoritative treatment of the Project prepared by a professional physicist who has spent over 25 years studying it.

Any author who takes on the Manhattan Project faces a dilemma: how much detail to cover? The *Manhattan District History* runs to thousands of pages; no single-volume account can hope to be comprehensive. We know what scientific theories and industrial processes proved correct and workable, that the bombs dropped at Hiroshima and Nagasaki functioned properly, that the war ended soon thereafter, and that America entered the Cold War as the world's preeminent power. It is easy to think that this is the way it all had to play out once the United States had committed the resources, money, and

political support to developing atomic bombs. But this is not so: *none* of these events were preordained. So many aspects of the Project were so chancy that the entire effort could easily have played *no* role in ending the war. After the discovery of uranium fission in late 1938, it took some of the leading researchers of the time well over a year to appreciate how the subtleties of nuclear reactions might be exploited to make a weapon or a reactor. By the time of the Japanese attack at Pearl Harbor in December, 1941, experimental tests and theoretical analyses were beginning to clarify the situation, but the technical challenges involved in realizing the liberation of nuclear energy on a practical scale looked so overwhelming as to make the idea of a deliverable nuclear weapon seem more a matter of science-fiction than real-world engineering. The administrators, scientists, and engineers who organized and carried out the Project faced immense and unique challenges which required ingenuity and perseverance to surmount. In relating the story of Manhattan, I have aimed for a middle ground which gives a reasonable treatment of the major advances, setbacks, personalities and uncertainties involved, without attempting to dissect every last detail. The mine runs deep.

I have benefited from spoken and electronic conversations, correspondence, suggestions, willingness to read and comment on draft material, and general encouragement from John Abelson, Joseph-James Ahern, John Altholz, Dana Aspinall, Albert Bartlett, Jeremy Bernstein, Alan Carr, David Cassidy, John Coster-Mullen, Steve Croft, Gene Deci, Eric Erpelding, Patricia Ezzell, Charles Ferguson, Henry Frisch, Ed Gerjuoy, Chris Gould, Dick Groves, Robert Hayward, Dave Hafemeister, Art Hobson, Cindy Kelly, William Lanouette, Irving Lerch, Harry Lustig, Mike Magras, Jeffrey Marque, Albert Menard, Tony Murphy, Robert S. Norris, Peter Pesic, Klaus Rohe, Bob Sadlowe, Frank Settle, Ruth Sime, D. Ray Smith, Roger Stuewer, Arthur Tassel, Linda Thomas, Michael Traynor, Mark Walker, Alex Wellerstein, Bill Wilcox, John Yates, and Pete Zimmerman. If I have forgotten anybody, I apologize; you are in this list in spirit. A few of these individuals are, sadly, no longer with us. Alma College interlibrary loan specialists Susan Cross and Angie Kelleher have never failed to dig up any obscure document which I have requested; they are true professionals. Angela Lahee and her colleagues at Springer deserve a big nod of thanks for believing in and seeing through this project.

In addition to the individuals listed above, the fingerprints of a lifetime's worth of family members, teachers, classmates, professors, mentors, colleagues, students, collaborators, and friends are all over these pages; a work like this is never accomplished alone. I thank them all.

Most of all I thank Laurie, who bore with it. Again.

Halifax, NS, Canada
June 2019

Bruce Cameron Reed

Contents

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The Big Picture: A Survey of the Manhattan Project

1.1 Atoms, Nuclei, and Isotopes

To develop an appreciation of how nuclear weapons are designed and function requires some understanding of the basic properties of atoms, nuclei, isotopes, and the process of nuclear fission. Buckle up for a whirlwind tour of the atomic landscape and how the Manhattan Project came to be.

That atoms can be imagined as being constructed like miniature solar systems is a staple of every high-school chemistry and physics class. The development of this picture began with the discovery of the electron in 1897, and was essentially completed with the discovery of the neutron in early 1932. In the solar system analogy, the Sun is played by nuclei at the centers of atoms, combinations of electrically-positive protons and electrically-neutral neutrons. Surrounding nuclei at various distances are negatively-charged orbiting electrons, the particles which sustain the electric currents that course through our houses, bodies, workplaces, and computers. The numbers of these various particles in a given atom depends on what chemical element the atom identifies with. In any atom, the number of orbiting electrons usually equals the number of protons in the nucleus, making the overall structure electrically neutral. The number of protons in the nucleus is the same for all atoms of the same element, and is the "atomic number" of the element.

A very important refinement to this picture is that different elements can occur in a variety of forms: isotopes. Different isotopes of the same element contain differing numbers of neutrons in their nuclei, but they all have the same electrical and chemical properties because they contain the same number of protons and electrons. The atomic number is always designated by the

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letter Z. For atoms of life-sustaining oxygen, $Z = 8$, that is, they all contain eight protons in their nuclei and have eight orbiting electrons (unless they have been ionized). But there are three naturally-occurring stable isotopes of oxygen: one contains eight neutrons, another nine, and another ten. In these three types there are consequently totals of 16, 17, or 18 protons plus neutrons in the nuclei: Oxygen-16, Oxygen-17, and Oxygen-18, or just O-16, O-17, and O-18. O-16 is by far the most common type, accounting for over 99.7% of naturally-occurring oxygen, but you can and do breathe the other two types.

Neutrons can be thought of as a sort of nuclear glue that holds nuclei together against the immense repulsive electrical forces that act between the like-charged protons. The total number of neutrons plus protons in the nucleus is known as its atomic weight (a bit of a misnomer), and also as its mass number. This is always designated with the letter A. Adopting N to designate the number of neutrons, it follows that $N = A - Z$. Any isotope can be represented by the shorthand notation ${}^{A}_{Z}\mathrm{X}$, where X is the symbol for the element involved, A is the mass number, and Z the atomic number corresponding to the element X. The three oxygen isotopes are then abbreviated as ${}^{16}_{8}\mathrm{O}$, ${}^{17}_{8}\mathrm{O}$, and ${}^{18}_{8}\mathrm{O}$.

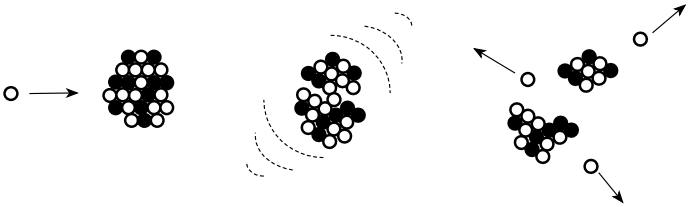
All nuclear weapons ultimately derive their power from reactions involving isotopes of the very heavy elements uranium ($Z = 92$) and plutonium ($Z = 94$). Two isotopes of uranium and one of plutonium are involved in the Manhattan Project: U-235 $\left({}^{235}_{92}U\right)$, U-238 $\left({}^{238}_{92}U\right)$, and Pu-239 $\left({}^{239}_{94}Pu\right)$. All U-235 nuclei contain 143 neutrons ($N = A - Z = 235 - 92 = 143$), while all U-238 nuclei contain 146 neutrons. The three-neutron difference plays a huge role. Only U-235 can be used to make a nuclear weapon, but this isotope makes up only about 0.7% of naturally-occurring uranium. The remaining 99.3% is U-238, which is useless for making a first-generation nuclear weapon. Plutonium is an artificially-prepared element, and its mass-239 isotope makes for a very efficient nuclear explosive.

1.2 Fission, Neutrons, and Chain Reactions

The process by which uranium and plutonium release their energy in nuclear weapons is termed nuclear fission. Fission, which is synonymous with "splitting"—the word was in fact borrowed from the process of cell division in biology—was discovered quasi-serendipitously in Berlin in late 1938. This discovery involved the realization that nuclei of uranium atoms could be

caused to break apart when struck by incoming neutrons. That the bombarding particles are neutrons is important. Fission cannot be induced by striking a uranium nucleus with one of another element; the repulsive forces between the protons in the nuclei are so great that it is practically impossible to have the nuclei come into contact with each other. But because neutrons are electrically neutral, they experience no repulsion: there is nothing to stop them from striking a target nucleus that lies in their path. It was quickly realized that the disintegrated nucleus loses a small amount of mass, but this mass corresponds to a huge amount of energy thanks to Albert Einstein's famous equation $E = mc^2$. The amount of energy released per fission of a single nucleus proved, atom-for-atom, to be millions of times that released in any known chemical reaction.

It was immediately apparent to researchers that if such reactions could be induced on a large scale, millions of pounds of conventional explosive could be replaced with a few pounds of nuclear explosive. A few weeks after the discovery, it was found that a by-product of each fission was the simultaneous liberation of two or three neutrons from the fissioned nucleus, "secondary" neutrons. These neutrons, if they do not escape the mass of uranium involved, can go on to fission other nuclei and initiate a chain reaction. In theory, this process can continue until all of the uranium is fissioned, releasing an enormous amount of energy.



A sketch of the fission process. A nucleus comprising protons (filled circles) and neutrons (open circles) is struck by an incoming neutron (left). The nucleus captures the neutron, becomes agitated (middle), and then fragments into two product nuclei and three neutrons (right). In a real uranium nucleus there are many more protons and neutrons than are drawn here

These discoveries raised a host of questions. Were any other elements fissile? Was there a minimum amount of uranium that would have to be arranged in one place to realize a chain reaction? Did one or both uranium isotopes undergo fission? Could the process be controlled by human intervention to create a power source (a nuclear reactor), or would the result be

an uncontrollable explosion? Why hadn't all of the uranium ores in the Earth spontaneously fissioned themselves into oblivion millions of years ago?

1.3 Understanding Fission: Neutrons Fast and Slow

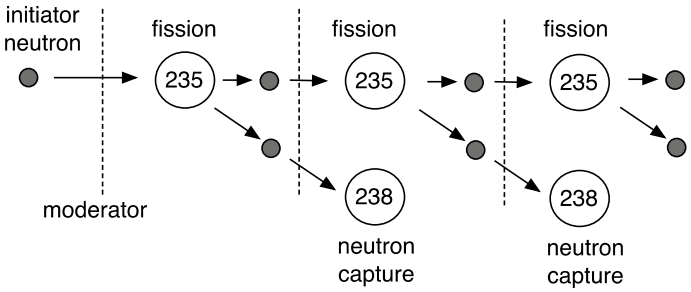
By the time of the outbreak of World War II in September, 1939, physicists had developed theoretical arguments which indicated that only the very heavy elements thorium ($Z = 90$) and uranium were likely to be fissile. The element between thorium and uranium, protactinium, is so rare as to be of no practical use in the nuclear weapons business. Thorium would prove unworkable for either a bomb or a reactor. In the case of uranium, the theory indicated that only the rare U-235 isotope would fission under neutron bombardment, whereas U-238 nuclei would tend to capture incoming neutrons without fissioning. These predictions were confirmed experimentally in early 1940. With the overwhelming preponderance of U-238 in natural uranium, this capture effect promised to literally poison the prospect for a chain reaction using uranium of natural isotopic abundance. To obtain a chain reaction would require isolating a sample of pure U-235 from its sister isotope, or at least processing uranium in some way to isolate a sub-sample with a dramatically increased percentage of U-235. Given that 993 of every 1,000 lb of uranium ore extracted from the Earth will be of the undesirable U-238 isotope, this presents an immense challenge. Isotope enrichment is very difficult, even for a technically advanced country. Since isotopes of any element behave identically so far as their chemical properties are concerned, no chemical reaction can be used to achieve enrichment: only techniques that depend on the mass difference between the two isotopes can be used. In the case of uranium, the three-neutron difference amounts to a mass difference of only about 1% between the two isotopes. Physicists and chemists had developed three workable enrichment techniques, namely centrifugation, mass spectrometry, and a process known as diffusion, but these had been applied successfully only in very limited laboratory settings involving minute samples of much lighter elements where the mass differences between isotopes was relatively large. For uranium, the prospects looked dim to non-existent.

By mid-1940, understanding of the differing responses of the two isotopes of uranium to bombarding neutrons had led to the development of a new

idea for obtaining a controlled (not explosive) chain reaction using natural uranium without enrichment. When a nucleus is struck by a neutron, various reactions are possible: the nucleus might fission, it might capture the neutron without fissioning, or it can deflect the neutron just as a billiard ball would an incoming marble. Each result has some probability of occurring, and these probabilities depend on the speed of the incoming neutrons. Neutrons released in fission reactions are extremely energetic, emerging with average speeds of about 45 million miles per hour. For obvious reasons, such neutrons are termed "fast." U-238 nuclei tend to capture fast neutrons emitted in fissions of U-235 nuclei and not subsequently fission. But when a nucleus of U-238 is struck by a neutron traveling at a pokey few thousand miles per hour, it behaves as a much more benign target, with scattering of the neutron being about three times as likely as capture. But—and this is a key point—U-235 nuclei turn out to have an enormous probability for undergoing fission when struck by slow neutrons: over 200 times the slow-neutron capture probability of U-238. This factor is large enough to compensate for the small natural abundance of U-235 to the extent that, in a sample of natural-abundance uranium, a slow neutron is about as likely to fission a nucleus of U-235 as it is to be captured by one of U-238. This speed-sensitive behavior is what makes possible the slow-neutron chain reactions used in power-producing nuclear reactors. In effect, slowing fission-liberated neutrons is equivalent to enriching the abundance percentage of U-235. This point is so important that it bears reiterating: if a neutron emitted in a fission can be slowed, then it has about as good a chance of going on to fission another U-235 nucleus as it does of being uselessly captured by a nucleus of U-238. In actuality, both processes proceed simultaneously within a reactor: U-235 fissions generate energy and liberate neutrons, while U-238 nuclei capture some of the neutrons and become a waste product. In a curious twist, however, this very waste product turned out to be the seed material for producing the bomb-suitable isotope plutonium-239.

The trick to slowing neutrons during the very brief interval between when they are emitted in fissions and when they strike other nuclei is to work not with a single large mass of uranium, but rather to disperse it as small chunks within a surrounding medium which slows neutrons without capturing them. The medium is known as a moderator, and the entire package is a reactor. During the Manhattan Project, the synonymous term "pile" was used in the literal sense of an arrangement of slugs of uranium metal embedded within a heap of moderating material. Ordinary water can serve as a moderator, but, at the time, graphite—like that used in pencils—proved easier to employ. By

introducing moveable rods of neutron-capturing material into the pile, the reaction can be controlled by adjusting them as necessary. It is in this way that natural-abundance uranium proved capable of sustaining a controlled nuclear reaction, although not an explosive one. All power-producing nuclear reactors operate via slow-neutron chain-reactions. But you can sleep comfortably. Reactors cannot behave like bombs; the reaction is far too slow, and even if the control rods are rendered inoperative, the reactor will melt rather than blow up. Video footage of the explosion of a reactor at Fukushima, Japan, actually showed a steam explosion involving the reactor's cooling water, not a nuclear explosion.



Schematic illustration of a chain reaction utilizing moderated neutrons. Each fission of a U-235 liberates two secondary neutrons, one of which goes on to fission another U-235 nucleus while the other is captured by a nucleus of U-238. From Reed, Atomic Bomb (2015) Fig. 1.2

1.4 Reactors and Plutonium

By mid-1940, it appeared that to make a chain-reaction mediated by fast neutrons—a bomb—would require isolating pure U-235. However, it was soon appreciated that the moderated-neutron concept could be used in an indirect way to make a different fissile material for use in a nuclear weapon. As a reactor operates, neutron capture by U-238 nuclei proceeds alongside fission of U-235 nuclei to about the same degree of probability. On capturing a neutron, a nucleus of U-238 becomes one of U-239. Based on projecting from known patterns of the stability of nuclei, it was predicted that U-239 nuclei might decay within a short time to nuclei of atomic number 94 (later called

plutonium), and that such an element might be very similar to U-235 in its fissility properties. If this proved so, then a reactor could be used to "breed" plutonium through neutron capture by U-238 nuclei, while maintaining a self-sustaining reaction via U-235 fissions. The advantage of this would be that the plutonium could subsequently be separated from the mass of parent uranium fuel by chemical processing, which would allow engineers to circumvent the need to develop enrichment techniques. These predictions were soon confirmed on a laboratory scale by creating a tiny sample of plutonium via neutron-bombardment of uranium.

By the time of the Japanese attack at Pearl Harbor in December, 1941, two possible routes to developing a nuclear explosive had been identified: isolate tens of kilograms of U-235, or develop reactors to breed plutonium. U-235 was considered practically certain to make an excellent nuclear explosive, but the tens of kilograms necessary would have to be separated atom by atom from tons of uranium ore. In the case of plutonium, the likely chemical separation techniques were understood by chemical engineers, but nobody had ever constructed an operating reactor or isolated any significant quantity of the new element. Fundamental questions of engineering and physics loomed. Could a large-scale reactor be safely controlled? What if plutonium proved to have some property that rendered it useless as an explosive? With the possibility that German scientists could be thinking along the same lines, the leaders of the Manhattan Project made the only decision that they could in such a circumstance: both methods would be tried.

1.5 The Manhattan Engineer District

The possibility that nuclear fission might have military applications was brought to the attention of President Franklin Roosevelt in the fall of 1939, and support for research was soon organized under the direction of a committee that he ordered assembled. Until mid-1942, this effort was under the authority of various civilian branches of the government, although the work was being conducted in secrecy. By that time, researchers in both Britain and America had reached the conclusion that reactors and weapons could be feasible, but that isolating the relevant materials would require large-scale factories. The only organization capable of carrying out the work with the necessary secrecy was the United States Army, and the project was assigned to

the Army's Corps of Engineers in August, 1942. To carry out the work, the Corps established a new administrative entity, the Manhattan Engineer District (MED). In September, overall command of the MED was assigned to Brigadier General Leslie Richard Groves, who had extensive experience with large construction projects.

Left: Brigadier (later Major) General Leslie R. Groves (1896–1970). Right: Robert Oppenheimer (1904–1967) ca. 1944. Sources: http://commons.wikimedia.org/wiki/File:Leslie_Groves.jpg; http://commons.wikimedia.org/wiki/File:JROppenheimer-LosAlamos.jpg

Manhattan Project work was focused in two major directions: acquiring fissile material (U-235 and Pu-239), and designing and testing possible configurations for actual bombs. Fissile materials were produced at enormous factory complexes located at Oak Ridge, Tennessee (uranium enrichment) and Hanford, Washington (plutonium production reactors). The vast majority of MED funding went into the construction and operation of these facilities. At the same time, a highly-secret bomb-design laboratory was established at Los Alamos, New Mexico. The Los Alamos Laboratory began operating in the spring of 1943, and was directed by theoretical physicist Dr. J(ulius) Robert Oppenheimer of the University of California.

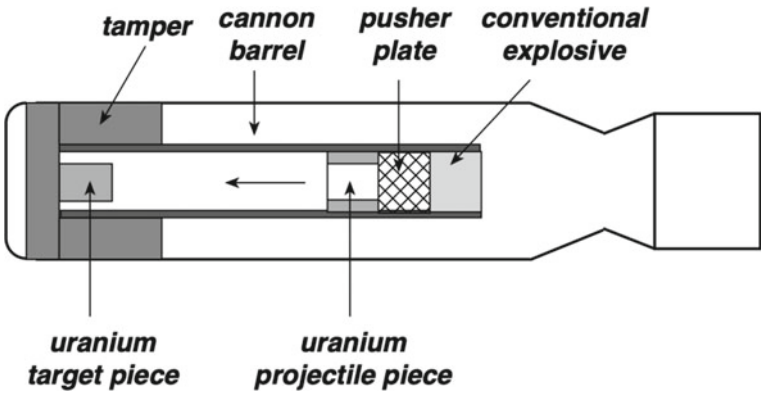
Locations of major Manhattan Project research and production sites. Other sites were located in Montreal and British Columbia, Canada. From Reed (2014a)

In theory, the tasks facing Los Alamos scientists seemed straightforward. Fissile isotopes such as U-235 or Pu-239 possess a so-called critical mass, a minimum mass necessary to achieve a chain reaction. The value of the critical mass depends on factors such as the density of the material, its probability for undergoing fission, and the number of neutrons liberated per fission. Much of the experimental work at Los Alamos was directed toward obtaining accurate measurements of these quantities. With these data, critical masses could be calculated by using mathematical relationships adopted from a well-established branch of physics known as diffusion theory.

1.6 Little Boy, Fat Man, Trinity, Hiroshima, and Nagasaki

By mid-1945, Oak Ridge and Hanford were beginning to produce critical-mass quantities of U-235 and Pu-239. For U-235, the critical mass is about 50 kg. A more efficient explosion can be created if you have more material available than just one critical mass, so imagine that you have 70 kg available. To make a bomb, divide the 70 kg into two pieces, and then arrange to bring them together when you are ready to have the device detonate. This is

exactly what was done in the uranium-based Hiroshima "Little Boy" bomb. Ordnance engineers mounted the barrel of a naval artillery cannon inside a bomb casing, and placed one piece of uranium, the "target piece", at the nose end of the barrel. The second piece, the "projectile piece", was placed at the tail end. When radars mounted on the bomb indicated that it had fallen to a pre-programmed detonation height, a conventional powder charge was set off to propel the projectile piece into the target piece. A source of neutrons must be supplied to initiate the chain reaction, but this is the essence of a "gun-type" fission bomb.

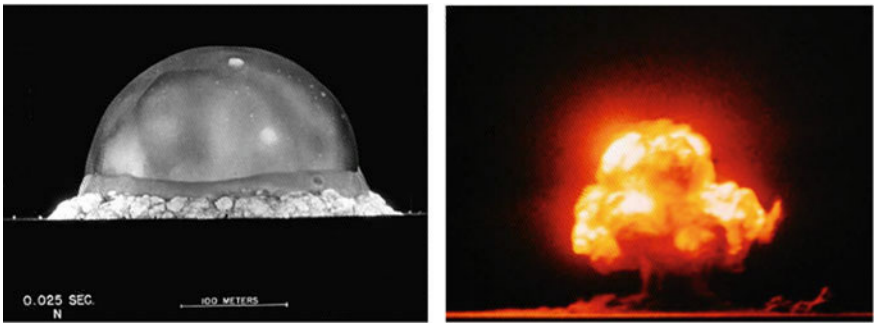


Schematic illustration of a gun-type fission weapon

The Hiroshima bomb contained about 60 kg of U-235, but weighed nearly five tons overall. Much of this was the weight of the cannon, but a significant contributor was that the target end of the cannon was surrounded by a steel tamper weighing several hundred kilograms. The tamper served three essential functions. First, it stopped the projectile piece from flying through the front end of the bomb; unlike in an artillery cannon, the projectile piece has to remain seated around the target piece while the reaction proceeds. Second, the tamper briefly retards the expansion of the assembled bomb core as it detonates, buying a bit more time (microseconds) over which the chain reaction can operate. Third, by making the tamper of a material which reflects escaping neutrons back into the assembled target and projectile pieces, they will have a chance to cause further fissions; this effectively decreases the nec-

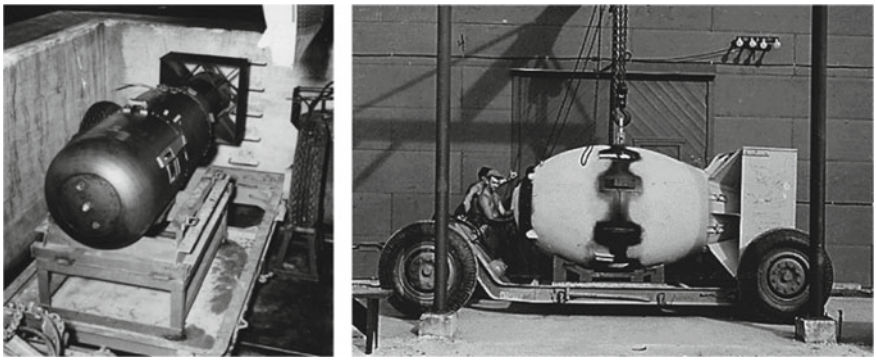
essary critical mass. These effects all enhance the efficiency of the weapon by a factor of ten or more over an untamped device, so a tamper is certainly a worthwhile investment despite its being dead weight.

The plutonium bomb was a much more difficult matter. Reactor-produced plutonium proved to fission spontaneously, a completely uncontrollable process. Los Alamos scientists calculated that if they tried to make a gun-type bomb using plutonium, the nuclear explosion would self-initiate before the target and projectile pieces were fully mated, and that the result would be an expensive but very low-efficiency "fizzle" explosion. Two approaches to overcoming this setback looked plausible: either find a way to use less fissile material (fewer spontaneous fissions), and/or assemble the sub-critical pieces more rapidly than could be achieved with the gun mechanism in order to lower the pre-detonation probability. Both approaches were adopted. The critical mass of a fissile material depends on its density; a greater density means a lower critical mass. A mass of material that would be sub-critical at normal density can be made critical by crushing it to a higher density, a feature that lets you get away with using less material than would "normally" be required. This led to the idea of an "implosion" weapon wherein a small subcritical core with a naturally low rate of spontaneous fissions is surrounded with a fast-burning explosive configured to detonate inwards to crush the core to high density in a very short time. For maximum efficiency, the implosion has to be essentially perfectly symmetric: all of the pieces of surrounding explosive need to be triggered within about a microsecond of each other. The feasibility of implosion was considered so uncertain that it was decided to perform a full-scale test of the method. This was the *Trinity* test of July 16, 1945, the world's first nuclear explosion. The test succeeded, and three weeks later the method was put to use in the Nagasaki "Fat Man" bomb. The Little Boy bomb was not tested in advance: by August, 1945, there was only enough U-235 available for one bomb.

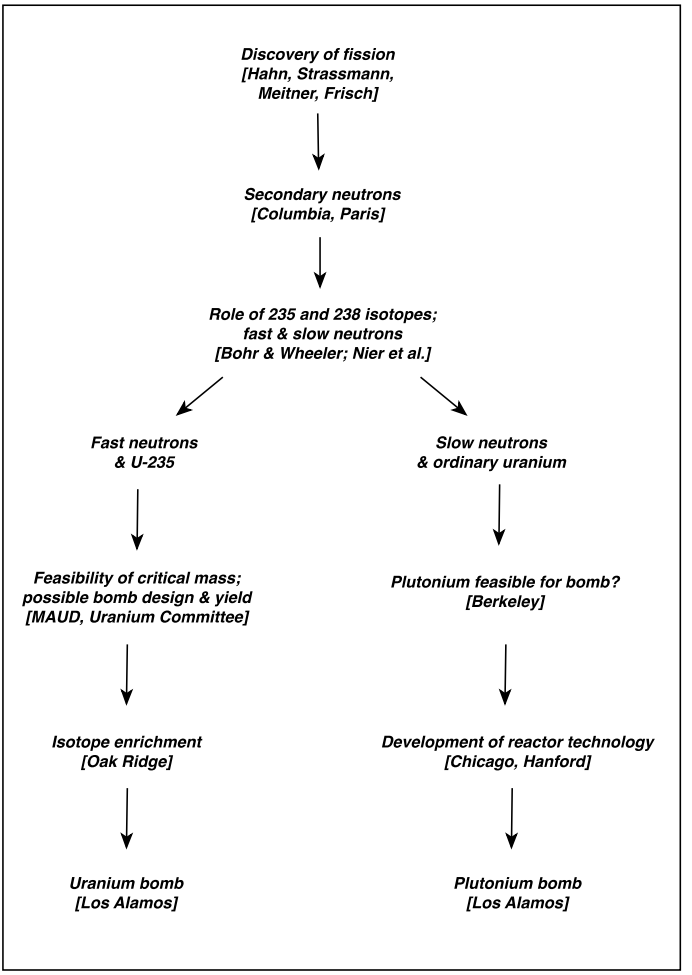


Left: The Trinity fireball 25 ms *after detonation. Right: The fireball a few seconds later. Sources: Left:* http://commons.wikimedia.org/wiki/File:Trinity_Test_Fireball_25ms.jpg*; Right: Courtesy of the Los Alamos National Laboratory Archives*

The combat bombs used at Hiroshima and Nagasaki reflected these designs. *Little Boy* was a cylindrically-shaped mechanism that looked like a regular bomb, but *Fat Man* required a bulbous configuration to accommodate its spherical implosion assembly. General Groves' two-billion-dollar gamble paid off in spectacular fashion, and nuclear physics brought the world into a new era.



Left: Little Boy in its loading pit. Right: The Fat Man bomb. Note graffiti on tail. Sources: Left: http://commons.wikimedia.org/wiki/File:Atombombe_Little_Boy_2.jpg*; Right:* http://commons.wikimedia.org/wiki/File:Fat_Man_on_Trailer.jpg



Flowchart summarizing major elements of the Manhattan Project

2

From Atoms to Nuclei: An Inward Journey

The modern scientific picture of atoms as having nuclei of protons and neutrons surrounded by clouds of orbiting electrons emerged between the late 1890s and the early 1930s. Once this understanding was in place, research began shifting toward exploring the internal structure of nuclei, and reactions that could happen with them: nuclear physics. During the 1930s, an immense amount of knowledge on nuclear reactions was accumulated, setting the stage for the discovery of nuclear fission in late 1938. At just the time when events in Europe were heading toward another World War, physicists were beginning to appreciate that fission might hold the key to developing immensely powerful new sources of energy and weapons. What had been a quiet area of academic research was about to assume profound importance in world affairs.

This chapter describes the development of our understanding of atomic structure.

2.1 X-Rays and Radioactivity

In late 1895, German physicist Wilhelm Conrad Röntgen accidentally discovered X-rays. He soon found that his mysterious rays could not only pass through objects such as his hand, but that they also ionized air when they passed through it. This was the first known example of "ionizing radiation." Electrons had not been formally discovered in 1895 (though their existence

B. C. Reed, *Manhattan Project*,
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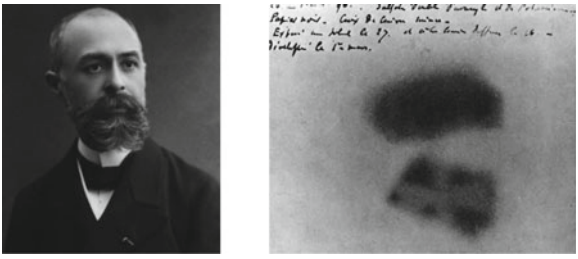
was strongly suspected); the ionization was caused by X-rays, which are essentially a high-energy form of light, knocking electrons from molecules in the air as they passed through it, leaving the molecules with net electrical charges.

To see X-ray images, Röntgen used a cardboard screen coated with a phosphorescent compound which glowed when struck by the X-rays; when holding his hand in front of the screen, he would be treated to a ghostly image of his bones. That phosphorescence seemed to be involved caught the attention of French mineralogist Antoine Henri Becquerel. Becquerel was an expert on phosphorescence, and wondered if phosphorescent materials such as uranium salts might be induced to emit X-rays if they were exposed to sunlight. While this supposition proved incorrect, investigating it led him, in February 1896, to the accidental discovery of radioactivity. Becquerel observed that samples of uranium ores left on top of wrapped photographic plates would cause them to be exposed, even in the absence of any external illumination. The exposures seemed to be created by the uranium itself; when the plates were unwrapped and developed, images of the samples appeared. Nuclear physics originated with this discovery.



Henri Becquerel (1852–1908) and the first image created by "Becquerel rays" emitted by uranium salts placed on a wrapped photographic plate. In the lower part of the plate a Maltese cross was placed between the plate and the lump of uranium ore. Sources: http://upload.wikimedia.org/wikipedia/commons/a/a3/Henri_Becquerel.jpg; http://upload.wikimedia.org/wikipedia/commons/1/1e/Becquerel_plate.jpg

These exposures are now understood to be due to so-called "alpha" and "beta" particles emitted by nuclei of uranium and other heavy elements as they naturally decay to more stable elements. Some of the decay timescales are fleeting at minutes or seconds only, while others are astronomically long at hundreds of millions or billions of years. In the latter cases it is only because there are so many trillions upon trillions of individual atoms in even a small

lump of ore that enough decay within a span of seconds or minutes to leave an image on a film or trigger a Geiger counter. A third type of decay particles, "gamma rays," were subsequently discovered by French chemist Paul Villard in 1900. Gamma-rays are photons just like those by which we see, but of energies about a million times greater than visible-light photons. X-ray photons are intermediate in energy between visible-light photons and gamma-ray photons.

2.2 Marie Curie: Polonium, Radium, and Radioactivity

Becquerel's discovery did not attract much attention at first. Unlike X-rays, which could be created with cathode ray tubes and focused on a target, uranium-generated images required having a sample of ore, tended to be indistinct, and required long exposure times. But the phenomenon of "Becquerel rays" came to the attention of Marie Sklodowski, a native of Poland who had graduated from the Sorbonne (University of Paris) in July 1893 with a degree in physics, ranking first in her class, and then again in mathematics in July, 1894. In 1895 she married Pierre Curie, a physicist at the École Municipale de Physique et de Chimie Industrielles. Seeking a subject for a doctoral thesis, she decided to follow up Becquerel's work, and set up a laboratory in her husband's institution in late 1897.



Marie (1867–1934) and Pierre (1859–1906) Curie; Right: Irène (1897–1956) and Frédéric Joliot-Curie (1900–1958) in 1935. Sources: http://commons.wikimedia.org/wiki/File:Mariecurie.jpg; http://commons.wikimedia.org/wiki/File:PierreCurie.jpg; http://commons.wikimedia.org/wiki/File:Irène_et_Frédéric_Joliot-Curie_1935.jpg

Curie's work began from the observation that X-rays could ionize air. Pierre Curie and his brother had developed a device for detecting minute electrical currents, which Marie used to determine that the amount of electricity generated was directly proportional to the amount of uranium in a sample. On testing other ores, she found that the heavy element thorium also emitted Becquerel rays, although not as many per second as an equal weight of uranium. Further work revealed that samples of pitchblende ore, a blackish material rich in uranium compounds mined in Joachimstal, northwest of Prague, emitted more Becquerel rays than could be accounted for solely by the quantity of uranium that they contained. Inferring that there must be some other active element present, Curie began the laborious and very unpleasant task of chemically isolating it from the tons of ore she had available. Pierre soon abandoned his own research on the properties of crystals in order to join Marie in her work. Between 1898 and Pierre's death in 1906, the Curies would acquire over 23,000 kg of waste Joachimstal ores.

Spectroscopic and chemical analyses of the active substance showed that it was a new, previously unknown element. Christening their find "polonium" in honor of Marie's native country, they published their discovery in the weekly journal of the French Academy of Sciences in July, 1898. In this paper they introduced two new words of scientific jargon: "radioactivity" to designate whatever process deep within atoms was giving rise to Becquerel's ionizing rays, and "radioelement" to designate any element that possessed the property of doing so. The term "radioisotope" is now more commonly used as not all of the individual isotopes of elements that exhibit radioactivity are themselves radioactive.

In December of the same year, the Curies announced that they had found a second radioactive substance, which they dubbed "radium." By the spring of 1902, they had isolated a mere tenth of a gram of radium from ten tons of pitchblende ore, enough for spectroscopic confirmation of its status as a new element. In the summer of 1903 Marie defended her thesis, "Researches on Radioactive Substances," and received her doctorate from the Sorbonne. In the fall of that year the Curies would be awarded half of the 1903 Nobel Prize for Physics; Henri Becquerel received the other half.