Revisiting *The Los Alamos Primer* FREE

A concise packet of lecture notes offers a window into one of the turning points of 20th-century history.

B. Cameron Reed

Physics Today **70** (9), 42–49 (2017);
https://doi.org/10.1063/PT.3.3692

Cameron Reed is a professor of physics at Alma College in Michigan.

REVISITING THE LOS ALAMOS PRIMER

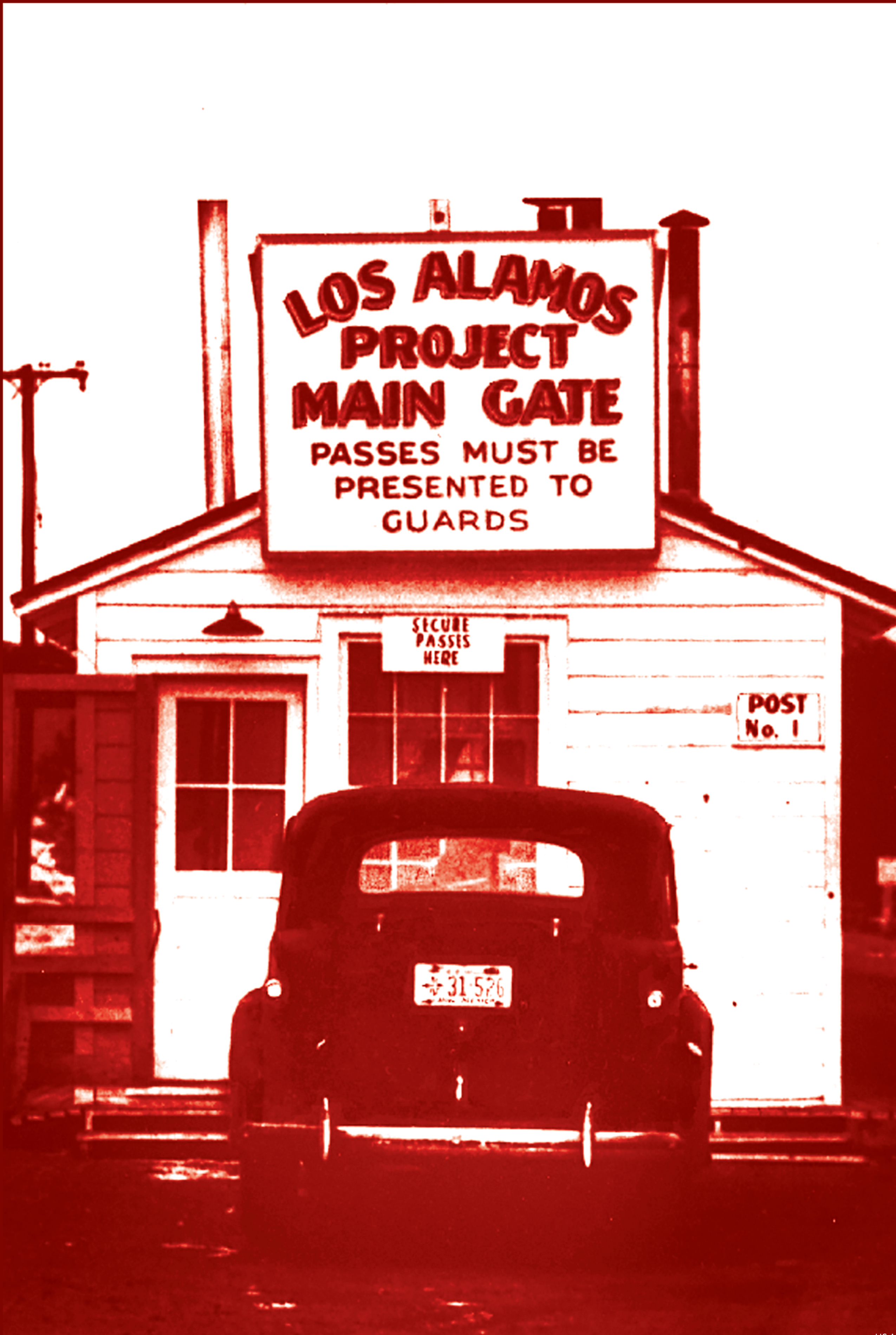
B. Cameron Reed

A concise packet of lecture notes offers a window into one of the turning points of 20th-century history.

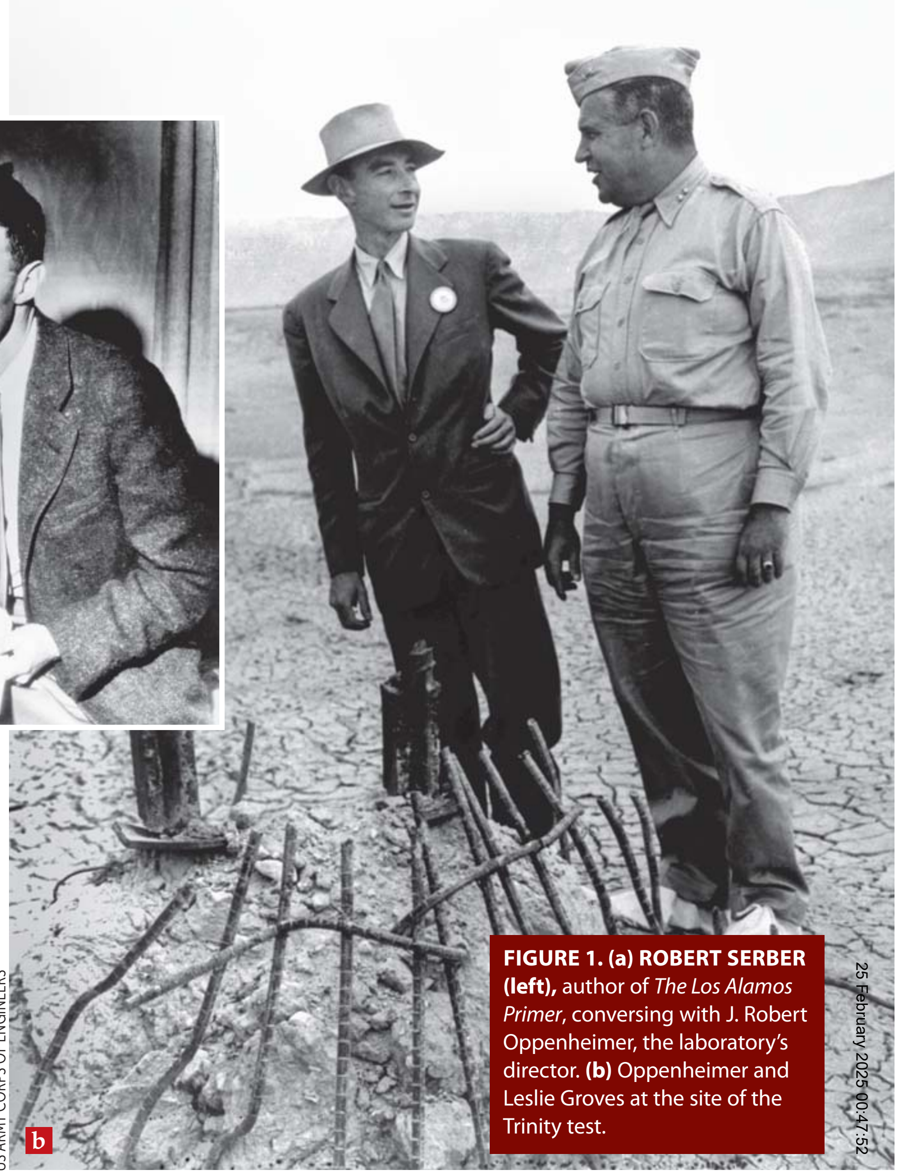
In April 1943, scientists began gathering at a top-secret new laboratory in Los Alamos, New Mexico, to design and build the world's first atomic bombs. Most of them had been involved in nuclear fission research, but due to secrecy restrictions, few had any sense of the immensity of the project they were about to undertake. Their goal was to leverage the phenomenon of nuclear fission, discovered only four years earlier, to produce nuclear weapons in time to affect World War II. Twenty-eight months later the world would learn that they had succeeded when Hiroshima and Nagasaki were devastated by the most powerful weapons history had ever seen. The war came to a close—and the Cold War and its nuclear arms race soon broke out on the world stage.

Interested readers can find no shortage of accounts of the wartime history of Los Alamos. David Hawkins's *Project Y*, prepared in 1946–47, is a detailed internal history from one who was there.[1] Richard Hewlett and Oscar Anderson Jr's history of the Atomic Energy Commission describes the work of Los Alamos in the larger context of the Manhattan Project.[2] Those interested in technical details will appreciate the trove of information compiled by Lillian Hoddeson and coauthors,[3] and numerous personal memoirs add compelling human-interest angles to the story.[4-6] But of the thousands of pages that have been written about Los Alamos, one document stands out as mandatory reading for anyone interested in the origins of nuclear weapons: *The Los Alamos Primer*.

One of the few participants at the April 1943 gathering with a sense of the overall program was 34-year-old Robert Serber, shown in figure 1 with J. Robert Oppenheimer, the laboratory's director and Serber's former collaborator. To bring the group up to speed, Serber delivered a series of lectures on what was known of the physics of nuclear weapons. The lectures drew on the research carried out between the discovery of fission in late 1938 and the opening of Los Alamos.[7] (For more on the discovery of fission, see the article by Michael Pearson, PHYSICS


LOS ALAMOS
PROJECT
MAIN GATE
PASSES MUST BE
PRESENTED TO
GUARDS
SECURE
PASSES
HERE
POST
No. 1
US ARMY

NEW YORK TIMES/REDUX



US ARMY CORPS OF ENGINEERS

FIGURE 1. (a) ROBERT SERBER (left), author of *The Los Alamos Primer*, conversing with J. Robert Oppenheimer, the laboratory's director. **(b)** Oppenheimer and Leslie Groves at the site of the Trinity test.

TODAY, June 2015, page 40.) Notes on the lectures were typed up by Edward Condon into a report that became the *Primer*. Copies can be found on various websites,[8] and in 1992 it was published in book form with annotations by Serber.[9]

The *Primer* is an extraordinary document. Perusing it gives one a sense of being there at the start of the Los Alamos project. In its 24 pages, Serber both adroitly summarized the state of existing knowledge and laid out a prescient road map for the work ahead and the challenges that might arise. In this article I describe how the *Primer* came to be and examine some of its contents.

Background

The initiating event of the Manhattan Project, Leo Szilard and Edward Teller's prevailing upon Albert Einstein to sign a letter alerting President Franklin D. Roosevelt to the possibility of fission bombs, is related in numerous sources. (See, for example, reference 2, chapter 2, or reference 7, chapter 4.) After the letter reached Roosevelt in October 1939, presidential aides saw to the formation of the Advisory Committee on Uranium in the National Bureau of Standards to fund and coordinate research. In June 1940 the committee was transferred to the National Defense Research Committee and a year later to the NDRC's successor agency, the Office of Scientific Research and Development. Both the NDRC and the OSRD were directed by Vannevar Bush, an electrical engineer from MIT. By the time of the Japanese attack on Pearl Harbor, funding for research on fission and isotope separation had reached $300 000. From the spring to the late fall of 1941, a committee led by Arthur Compton prepared reports on the feasibility of reactors and bombs; the final report, which Bush took to Roosevelt just before Pearl Harbor, laid out the prospects for fission bombs in considerable detail.

The last Compton report was heavily influenced by one prepared in the UK. In March 1940 Otto Frisch and Rudolf Peierls, then at Birmingham University, prepared their now-famous memorandum in which they estimated the critical mass of uranium-235 to be about a pound.[10] (It was well known that uranium's most abundant isotope, ^{238}U, is nonfissile.) That value turned out to be an underestimate caused by the assumption of too high a fission cross section; the correct critical mass is 52 kg, or more than 100 pounds. The Frisch–Peierls memorandum reached Henry Tizard, chairman of the British government's Committee for the Scientific Survey of Air Warfare, who asked physicist George Thomson to investigate the feasibility of bombs and isotope enrichment. Thomson assembled a committee, which in July 1941 produced an extensive report on the possibility of producing bombs and the necessary industrial infrastructure. The report—far ahead of American efforts at the time—reached Bush in October of that year, and he briefed Roosevelt on its contents.

Just after Pearl Harbor, Oppenheimer, who had been involved with the Compton committee, recruited Serber to the fission project. The two had worked together before: Serber had joined Oppenheimer's research group at the University of California, Berkeley, in 1934 under a National Research Council fellowship for postdoctoral work, and he even oversaw Oppenheimer's graduate students for a time. Serber left Berkeley in 1938 for a faculty position at the University of Illinois at Urbana-Champaign; he returned in April 1942 to join Oppenheimer's group, which was tasked with refining the Thomson and Compton reports' estimates of critical mass and bomb efficiency.

At about the time Serber returned to Berkeley, Bush reported to Roosevelt that fission bombs could probably be made in time to affect the war, but that enormous factories would be required to isolate ^{235}U and synthesize plutonium-239. (Those facilities, which would be built in Oak Ridge, Tennessee, and Hanford, Washington, ultimately employed hundreds of thousands of people at a cost of close to $2 billion in 1945 dollars.) Roosevelt and Bush agreed that only the US Army could carry out such an effort with the required secrecy, and the army established the Manhattan Engineer District in August 1942. The district was so named because its first leader, James Marshall, had his headquarters near Columbia University in New York, where some of the research was being conducted; it was unusual among army engineer districts, however, in that it had no restrictions on where its facilities could be located. In September the district came under the command of Leslie Groves, who was in charge of all domestic military construction; his most recent large project had been the Pentagon.[11] In October 1942 Oppenheimer met Groves and proposed a centralized laboratory to coordinate research: Los Alamos.

Introduction to the bomb

For readers who want to learn fission-bomb physics, the *Primer* can be a difficult document. When Serber gave his lectures, experimental groups at Los Alamos were under pressure to begin work. He had no time for detailed derivations, and his results often appear to come out of thin air.

The *Primer*'s 22 sections cover three main areas: Characteristics of fission reactions; estimates of critical mass, efficiency, and damage; and issues involved in triggering an explosion. The first section, entitled "Object," is short and impactful enough to be worth reproducing in its entirety (emphasis as in original):

> The object of the project is to produce a *practical military weapon* in the form of a bomb in which the energy is released by a fast neutron chain reaction in one or more of the materials known to show nuclear fission.

That is, the goal of Los Alamos was not only to produce weapons but also to make them robust enough to be carried on a long-range mission in a B-29 bomber in combat conditions.

The *Primer*'s first few sections give a minicourse on the physics of fission. They cover cross sections, neutron emission and energetics, the fact that ordinary unenriched uranium cannot sustain a fast-neutron chain reaction because ^{238}U nuclei inelastically scatter and capture neutrons without undergoing fission, and the possibility of producing plutonium via slow-neutron bombardment of ^{238}U in a reactor. (The word "plutonium" never appears in the *Primer*; Serber refers to it only as "material 49.") The fission energy latent in a single kilogram of ^{235}U is correctly estimated at about 20 kilotons TNT equivalent, and it is explained that the average speed of fission-generated neutrons is so great, about 2×10^7 m/s, that only a microsecond is required to fission every nucleus in 1 kg of ^{235}U, a striking testament to the brevity of a nuclear explosion.

However, Serber emphasizes early in the *Primer* that because a bomb core heats up and expands as the chain reaction proceeds, the fraction of fissile material that actually undergoes fission—the efficiency of the device—is inherently low. The condition of criticality, the circumstance necessary to create and maintain a chain reaction, depends on the product of the core's radius and its density. As the core expands, its density must drop, and it inevitably reaches a radius at which criticality can no longer be sustained (see the box below). For a core of two critical masses of ^{235}U, the radial expansion for criticality shutdown is only about 1 cm, and the efficiency is limited to a few percent at most.

The importance of the efficiency issue can be illustrated by this rough order-of-magnitude calculation adapted from one in the *Primer*. Efficiency is compromised when the core expands so quickly that criticality is lost before the entire core is fissioned. For an expansion of 1 cm over a time of 1 μs, the tolerable expansion speed works out to 10 000 m/s. Suppose a single neutron initiates the chain reaction, each fission releases n

THE CRITICAL MASS

For a fissile material to explode, enough of it must be assembled in one place for the rate of neutrons created by fissions to exceed the rate of neutrons lost by causing fissions or escaping to the outside world. Diffusion theory applied to a spherical bomb core gives the neutron number density N as a function of time t and distance r from the center of the core:

$$N(t,r) = N_0 e^{(\alpha/\tau)t} \frac{\sin(\kappa r)}{r}, \qquad (1)$$

where N_0 is the initial number density of neutrons at the center (provided by some neutron generator), τ is the average time a neutron travels before causing a fission (related to λ_{fiss}, the fission mean free path), α is a dimensionless parameter that determines whether the reaction is supercritical or subcritical, and κ is given by

$$\kappa = \sqrt{\frac{3(\nu - 1 - \alpha)}{\lambda_{\text{fiss}}\lambda_{\text{trans}}}}, \qquad (2)$$

where ν is the average number of neutrons created per fission and λ_{trans} is the transport mean free path, the average distance a neutron travels before it scatters or causes a fission. For uranium-235, ν is 2.6, λ_{fiss} is 17 cm, and λ_{trans} is 3.5 cm.

At the surface of a core of radius R_{core}, the neutron density is proportional to $\sin(\kappa R_{\text{core}})/R_{\text{core}}$. Robert Serber imposed a boundary condition by requiring that there be no escape of neutrons. That is, $\sin(\kappa R_{\text{core}}) = 0$, or $\kappa R_{\text{core}} = \pi$, which in combination with equation 2 gives

$$\alpha = (\nu - 1) - \frac{\pi^2 \lambda_{\text{fiss}}\lambda_{\text{trans}}}{3R_{\text{core}}^2}. \qquad (3)$$

The threshold critical radius R_{crit} is the value of R_{core} for which $\alpha = 0$:

$$R_{\text{crit}} = \pi \sqrt{\frac{\lambda_{\text{fiss}}\lambda_{\text{trans}}}{3(\nu - 1)}}. \qquad (4)$$

For ^{235}U, Serber estimated an R_{crit} of 13.5 cm and a critical mass of 200 kg. The same calculation with modern values for the parameters gives 11 cm and 106 kg. As discussed in the text, all those values are overestimates, because Serber's boundary condition is too restrictive.

In equation 4, λ_{fiss} and λ_{trans} are inversely proportional to the material density. The critical radius can thus be decreased by compressing the fissile material, as is done in implosion weapons.

neutrons, and G fission generations occur. The total number of neutrons released is thus of order n^G. Assuming that all the energy released by those fissions goes into the kinetic energy of the expanding core, one can estimate the number of generations required to achieve a given expansion speed. For a 60 kg core (the mass of the Hiroshima uranium bomb) and $n = 2$ neutrons per fission, 66 generations are required for a speed of 10^4 m/s, and the total energy released amounts to less than a single ton TNT equivalent. Even if the tolerable speed is relaxed to 10^6 m/s, the efficiency is still less than 1%. Serber summarized the situation as follows: "Since only the last few [fission] generations will release enough energy to produce much expansion, it is just possible for the reaction to occur to an interesting extent before it is stopped by the spreading of the active material." His use of "interesting" to describe an explosion that would wreak vast destruction may seem striking, but his style throughout the *Primer* does have an engaging dryness.

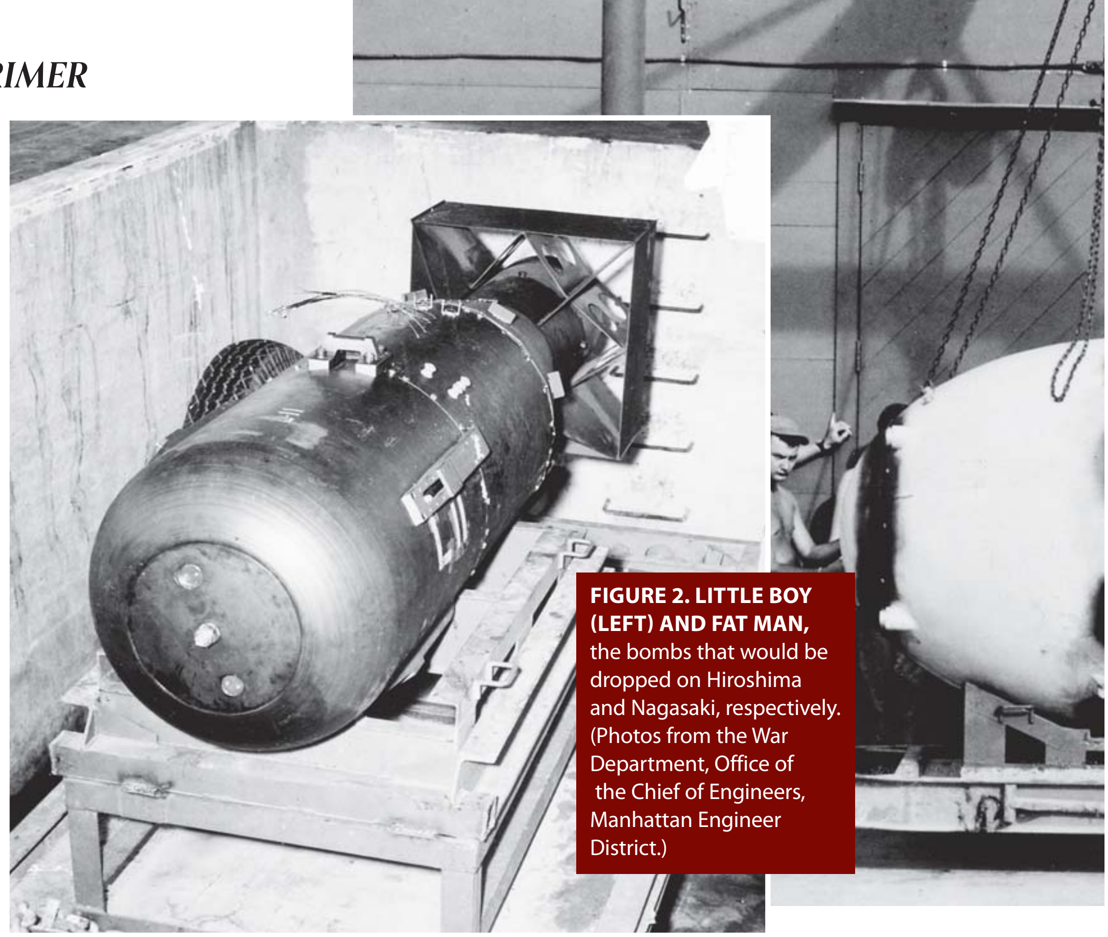


FIGURE 2. LITTLE BOY (LEFT) AND FAT MAN, the bombs that would be dropped on Hiroshima and Nagasaki, respectively. (Photos from the War Department, Office of the Chief of Engineers, Manhattan Engineer District.)

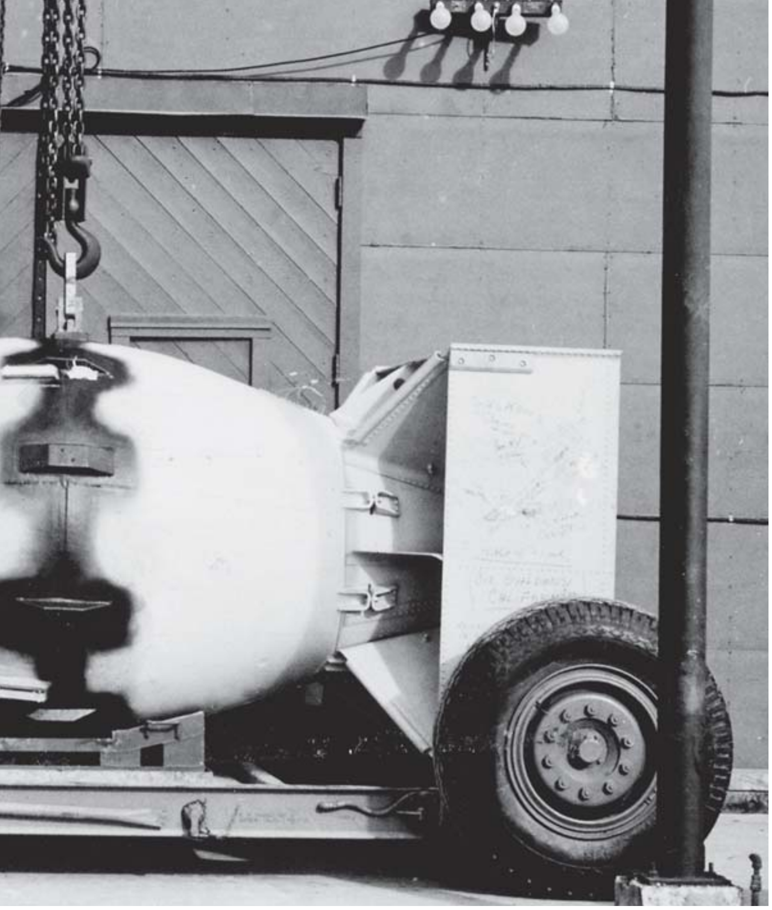
Section 10 of the *Primer* presents a calculation of critical mass. Serber used diffusion theory to model the flight of neutrons in a bomb core as they scatter, cause fissions, and leak out through the surface. The analysis revealed that the neutron population evolves in time as $e^{\alpha t/\tau}$, where τ is the average time a neutron travels before causing a fission—about 10 ns—and α is a dimensionless constant that dictates whether the chain reaction is supercritical and growing in time ($\alpha > 0$), subcritical and declining ($\alpha < 0$), or in a threshold-critical steady state ($\alpha = 0$). By requiring that no neutrons be lost from the core, Serber derived an expression for α in terms of the core radius and solved for threshold-critical radius for which $\alpha = 0$. For ^{235}U, he arrived at a critical mass of 200 kg—too high by a factor of four—because he underestimated the number of neutrons per fission and also because his no-loss requirement, despite yielding an appealing analytical solution for the critical radius, was too stringent. More than one neutron is produced per fission, so some can be allowed to escape. The later, published version of the *Primer*[9] supplements the original calculation with a more refined treatment of neutron loss at the core surface. The new analysis gives a critical mass of 60 kg with Serber's parameter values or 45 kg with modern values.

Practicalities

Serber next introduces the idea of surrounding the core with a tamper, a snug metal shell that reflects escaping neutrons back into the core to generate more fissions and thereby lower the critical mass and improve the bomb's efficiency. A tamper only a few centimeters thick is reflective enough to reduce the critical mass by a factor of two or more. The Little Boy uranium bomb used at Hiroshima and the Fat Man plutonium bomb used at Nagasaki (both shown in figure 2) were both heavily tamped, the former with tungsten carbide and the latter with nested shells of natural uranium and aluminum. Little Boy's tungsten carbide tamper was important not just for its neutron reflectivity but also for its strength. The weapon was triggered by a shooting method, sketched in figure 3a and discussed below, whereby a supercritical core was assembled from two subcritical pieces of fissile material in the barrel of an artillery gun. The target piece was held stationary while the complementary projectile piece was propelled into it by a conventional explosive. The tamper had to be strong enough to stop the projectile from blowing through the target. Fat Man's inner ^{238}U tamper boosted the bomb's yield through very high-energy neutrons fissioning the otherwise nonfissile ^{238}U nuclei; an estimated 20% of Fat Man's yield was contributed by that effect.

Section 12 of the *Primer* presents a sobering analysis of the anticipated effects of a nuclear explosion. Serber examined three causes of damage: neutron irradiation, radioactivity, and shock waves. Energetic neutrons can cause cellular damage; from a straightforward analysis based on neutron scattering properties in air, Serber determined that "severe pathological effects" would occur at distances up to half a mile from ground zero. The effects of radioactivity would be more variable, with dependence on local geography, weather, and detonation altitude. Serber estimated that residual radiation after 10 days would be on the order of a million curies, the equivalent of 1000 kg of radium.

A later analysis[12] by Samuel Glasstone and Philip Dolan found values somewhat higher but roughly in line with Serber's: The radioactivity from a 1 kt explosion would be on the order of 30 billion curies after one minute and would decay



thereafter in proportion to the time in minutes to the power −1.2. A 20 kt explosion, then, would result in 6 million curies after 10 days and 1.6 million after 30 days.

Millions of curies is an enormous amount of radiation, but human exposure also depends on how widely the radiation is distributed. The Hiroshima and Nagasaki bombs were programmed to be detonated at an altitude of 1600 feet to minimize radioactivity induced by neutron capture in soil and debris and to allow fission products to widely disperse. In September 1945, the month after the bombs were dropped, Serber was part of a survey team that visited Hiroshima and Nagasaki and found no lingering radioactivity. The vast majority of victims died of blast and burn effects, not radiation.

To estimate the damage from the physical explosion, Serber extrapolated from the known relationship for conventional bombs between peak shock-wave pressure, bomb yield, and distance. For a yield of 100 kt, he estimated the shock wave would propagate for two miles. He does not explain why he assumed 100 kt, which is a much higher yield than appears anywhere else in the *Primer*. The Nagasaki bomb yielded about 20 kt and caused severe structural damage to steel-frame buildings more than a mile from ground zero.

In the published *Primer*, Serber remarks that he overlooked one other damage effect: the blinding light and tremendous heat released in a nuclear explosion. Just after the explosion, an observer a mile away would see a fireball 350 times as large as the Sun and three times as bright. In Hiroshima, people suffered burns as far as 1.5 miles from ground zero.

Section 13 of the *Primer* returns the discussion to bomb physics, with a deeper analysis of the expected efficiency of an untamped bomb. Serber calls on a staple of basic physics, the work–energy theorem $dW = P\,dV$, where W is work, P is pressure, and V is volume. The pressure in the core as a function of time is determined by the energy of the fissions that have occurred before that time, the work done over some time interval can be expressed in terms of the change in the kinetic energy of the core, and the change in core volume is related to its expansion speed. Integrating the equations gives the core radius as a function of time, so from the expansion radius at which criticality shuts down, one can estimate the total energy released. Serber invokes various approximations and arrives at a final efficiency estimate of less than 1%. He does not offer an opinion on an acceptable minimum efficiency; the tamped Hiroshima bomb had an efficiency of about 2% and still caused immense destruction.

Triggering the explosion

The final sections of the *Primer* consider several interlinked issues regarding how to trigger a nuclear weapon and maximize its efficiency. A central concern was avoiding a so-called predetonation—the initiation of a chain reaction while the core assembly was only partially complete—which would result in an explosion of much lower efficiency than intended.

In the shooting method shown in figure 3a, the greatest achievable projectile velocity was about 1000 m/s. For projectile

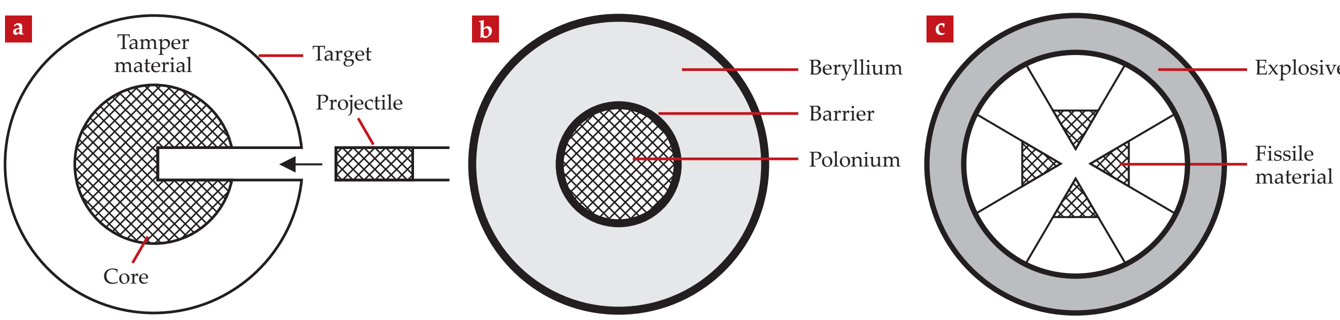


FIGURE 3. CONCEPTS FOR TRIGGERING an atomic bomb. **(a)** In the shooting method, a projectile of fissile material is propelled into the target. Neither piece alone constitutes a critical mass by itself, but when combined, they do. **(b)** The initiator, the device that starts the chain reaction, contains a few milligrams of polonium surrounded by a layer of beryllium. When the barrier is ruptured by the assembling bomb core, the elements mix, and the alpha–n effect creates a torrent of neutrons to initiate the reaction. **(c)** In the implosion method, wedge-shaped pieces are pushed together to form a critical mass by detonating an explosive. Implosion is faster than the shooting method and is more suitable for plutonium-based weapons.

dimensions on the order of 10 cm, 100 μs would elapse between the projectile's first entry into the target and the completion of assembly. If, during that time, a stray neutron were to cause a fission in the nearly complete core, a predetonation could result.

Stray neutrons can arise from three sources: cosmic rays, spontaneous fissions in the fissile material itself, and so-called alpha–n reactions in which alpha particles naturally emitted by the fissile material strike light-element nuclei and impurities present and liberate neutrons. Those processes are all inherently random and must be analyzed probabilistically. Cosmic rays are inconsequential; their flux is too low to have any chance of causing a predetonation. Likewise, the spontaneous-fission and alpha-decay rates of both ^{235}U and ^{239}Pu are low enough to ensure low predetonation probabilities, although ^{239}Pu's relatively short alpha-decay half-life, 24 000 years (^{235}U's is 705 million years), would demand that any light-element impurities in a plutonium bomb be present at no more than ppm levels. In fact, the alpha–n process was central to the initiators used to trigger the weapons once their cores were assembled. A golf-ball-sized capsule, as shown in figure 3b, contained alpha-emitting polonium and the light element beryllium, initially separated by a metal foil barrier. The capsule was crushed by the assembling core, thereby mixing the elements, releasing neutrons, and initiating the chain reaction.

But in the summer of 1944, plutonium was discovered to have a much more serious stray-neutron problem than the impurity issue. When a ^{239}Pu nucleus in a reactor is struck by a neutron, it has some chance of capturing the neutron to become ^{240}Pu. Reactor-produced plutonium therefore inevitably contains some ^{240}Pu, which has a spontaneous fission rate of nearly half a million events per second per kilogram. The Nagasaki bomb contained 6 kg of plutonium. If such a mass were contaminated with even 1% ^{240}Pu, the neutron emission rate would be over 70 000 per second, or 7 over a 100 μs core-assembly time, enough to virtually guarantee a predetonation.

FIGURE 4. THE TRINITY TEST of a plutonium-based bomb in New Mexico on 16 July 1945, the first-ever detonation of an atomic bomb.

JACK AEBY

Glenn Seaborg, the discoverer of plutonium, theoretically anticipated the possibility of ^{240}Pu contamination and spontaneous fission at about the time of Serber's lectures, but no experimental data were yet available. The effect was considered such a serious crisis that Oppenheimer promptly reorganized several Los Alamos research groups to deal with it. The only feasible option was to develop a new process to assemble a core in no more than a few microseconds. The result was the implosion method, illustrated in figure 3c as it was originally conceived: subcritical pieces of fissile material mounted on the inside of a tube or sphere and pushed together into a supercritical whole. The plutonium-based Nagasaki bomb employed a modified version of the method in that its subcritical core was a solid sphere that was crushed to critical density at high speed by a surrounding shell of conventional explosive. (For an illustration of this approach, see the article by Alex Wellerstein and Edward Geist, PHYSICS TODAY, April 2017, page 40.) The implosion mechanism not only solved the predetonation problem but also took advantage of the lower critical mass afforded by the higher density of a rapidly crushed core. The mechanism was tested in the Trinity bomb, set off in southern New Mexico on 16 July 1945, as shown in figure 4. In contrast, for the uranium-based Hiroshima bomb, the slower and simpler shooting method of assembly sufficed. In view of the simplicity of its design and the scarcity of ^{235}U, it was deployed without a test.

Legacy of the *Primer*

At the time of Serber's lectures, an enormous amount of work lay ahead for the Los Alamos scientists. They would have to accurately measure fission and scattering cross sections, secondary neutron numbers, and the energy spectrum of neutrons. They would refine theoretical calculations, design high-speed electronics for diagnostic experiments and triggering mechanisms, develop initiators, and undertake dangerous experiments with near-critical assemblies of fissile material. They would discover the spontaneous fission challenge and overcome it. And eventually, they would integrate everything they learned with existing military logistics and practices. Atomic bombs were a tremendous gamble. Had history played out a little differently at Los Alamos or in the Pacific, they might have played no role in ending the war.

That Serber anticipated many of the unknowns and challenges speaks to his extraordinary command of the experimental, theoretical, and engineering issues of the project. His *Primer* analyses were elegant and compact yet sensibly accurate, and they stand in marked contrast to Werner Heisenberg's famously garbled analysis of even so basic a quantity as the critical mass.[13] (See also the feature articles in PHYSICS TODAY, August 1995 and July 2000, especially the July article by Hans Bethe, page 34.) The work of Los Alamos culminated in the Trinity test and the bombings of Hiroshima and Nagasaki. The laboratory's legacy lives on in the form of the world's nuclear arsenals and the controversy over peaceful nuclear energy.

After the war, Serber worked for a few years at Ernest Lawrence's radiation laboratory at Berkeley before taking a position at Columbia University, where he worked on nuclear structure, cosmic rays, and particle accelerators, among other topics, and served on numerous government committees and boards. He retired in 1978 and passed away in 1997, but his name will be forever associated with one of the most pivotal developments in the history of physics.

I am grateful to Laurie Reed for her valuable comments and to students in my Fall 2016 Modern Physics class for helpful feedback. A longer version of this article was published in Physica Scripta ***91****, 113002 (2016).*

REFERENCES

1. D. Hawkins, *Manhattan District History. Project Y: The Los Alamos Project. Volume I: Inception Until August 1945*, Los Alamos Scientific Laboratory (1947).
2. R. G. Hewlett, O. E. Anderson, *A History of the United States Atomic Energy Commission. Volume I. The New World 1939/1946*, Pennsylvania State U. Press (1962).
3. L. Hoddeson et al., *Critical Assembly: A Technical History of Los Alamos During the Oppenheimer Years 1943–1945*, Cambridge U. Press (1993).
4. J. C. Allred et al., *Behind Tall Fences: Stories and Experiences About Los Alamos at Its Beginning*, Los Alamos Historical Society and Exceptional Books (1996).
5. L. Badash, J. O. Hirschfelder, H. P. Broida, eds., *Reminiscences of Los Alamos 1943–1945*, Reidel (1980).
6. J. Wilson, ed., *All in Our Time: The Reminiscences of Twelve Nuclear Pioneers*, Bulletin of the Atomic Scientists (1975).
7. B. C. Reed, *The History and Science of the Manhattan Project*, Springer (2014).
8. See, for example, http://www.fas.org/sgp/othergov/doe/lanl/docs1/00349710.pdf.
9. R. Serber, *The Los Alamos Primer: The First Lectures on How to Build an Atomic Bomb*, U. California Press (1992).
10. J. Bernstein, *Am. J. Phys.* **79**, 440 (2011).
11. R. S. Norris, *Racing for the Bomb: General Leslie R. Groves, the Manhattan Project's Indispensable Man*, Steerforth Press (2002).
12. S. Glasstone, P. J. Dolan, eds., *The Effects of Nuclear Weapons*, 3rd ed., US Department of Defense and Energy Research and Development Administration (1977).
13. J. Logan, *Am. Sci.* **84**, 263 (1996).

PT