

The Trinity High-Explosive Implosion System: The Foundation for Precision Explosive Applications

Eric N. Brown & Dan L. Borovina

To cite this article: Eric N. Brown & Dan L. Borovina (2021) The Trinity High-Explosive Implosion System: The Foundation for Precision Explosive Applications, Nuclear Technology, 207:sup1, S204-S221, DOI: [10.1080/00295450.2021.1913954](https://doi.org/10.1080/00295450.2021.1913954)

To link to this article: <https://doi.org/10.1080/00295450.2021.1913954>



This material is published by permission of Los Alamos National Laboratory, for the U.S. Department of Energy under Contract No. 89233218CNA000001. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, non-exclusive, and irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.



Published online: 16 Nov 2021.



Submit your article to this journal 



Article views: 7999



View related articles 



View Crossmark data 



Citing articles: 2 View citing articles 



Critical Review

The Trinity High-Explosive Implosion System: The Foundation for Precision Explosive Applications

Eric N. Brown* and Dan L. Borovina

Los Alamos National Laboratory, Los Alamos, New Mexico

Received January 31, 2021

Accepted for Publication April 4, 2021

Abstract — This paper is set during the 1944 and 1945 final push to complete Project Y—the Manhattan Project at Los Alamos—and focuses primarily on overcoming the challenge of creating and demonstrating a successful convergent explosive implosion to turn a subcritical quantity of plutonium into a critical mass. The critical mass would then efficiently yield kilotons of trinitrotoluene (TNT)-equivalent energy in about a microsecond, demonstrating the implosion atomic bomb concept. This work culminated in the Trinity atomic test near Alamogordo, New Mexico, on July 16, 1945. This implosion effect demarcated the approach to explosive science and technology that the Los Alamos National Laboratory has followed ever since, including development of high-explosive synthesis and formulation, small and large test and diagnostic facilities, shock dynamics theory, high-explosive system design engineering, and three-dimensional implosion modeling and simulation using some of the fastest computers in the world. This work also ushered in new generations of interdisciplinary scientists contributing to the field of explosives and a period of broader application of precision high explosives in conventional munitions, demolition, mining and oil exploration, and space travel.

Keywords — Trinity, high explosive, lens, Composition B, Baratol.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

The summer of 1944 at Los Alamos was a defining moment for the Manhattan Project.¹ Not only did the focus and direction of technical research and development (R&D)

change drastically in its aim to build a war-ending weapon by August 1945, but it also marked the beginning of a successful new era—the era of big science and technology where technical collaboration went beyond the theoretical and developed practical applications that could make a difference in the world. Aside from ending World War II and greatly altering the direction and history of the world, the completion of the implosion project at Los Alamos, culminating in the Trinity atomic test of the Christy Gadget² near Alamogordo, New Mexico, on July 16, 1945, proved that a multidisciplinary, multifacility endeavor with steadfast leadership can be successfully undertaken even though believed impossible by most, including by other major nations in the world, such as Germany, Japan, and the Soviet Union. Numerous books have been written about the broader Manhattan Project, Project Y at Los Alamos, and the Trinity test (see, for example, Refs. 3 through 9). Here we focus on the development of the convergent explosive implosion system that was

*E-mail: en_brown@lanl.gov

This material is published by permission of Los Alamos National Laboratory, for the U.S. Department of Energy under Contract No. 89233218CNA000001. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, non-exclusive, and irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

employed in the Trinity Christy Gadget test device, sometimes simply referred to as the Gadget, and in the Fat Man bomb that was detonated over the Japanese city of Nagasaki on August 9, 1945.

The Manhattan Project team of dedicated scientists and engineers, led by a secret contingent in Los Alamos, New Mexico, succeeded in their quest despite the fact that, by the spring of 1944, many important concepts needed for an implosion weapon were still practically unknown. These unknown concepts included (1) the spontaneous fission rate of reactor-made plutonium, (2) the theoretical and practical challenges of turning many diverging explosions into a single converging “implosion,” (3) the ability to do so simultaneously and in a short period of time, (4) the lack of any significant quantity of plutonium to test, and (5) the theory and safety of dynamically critical plutonium at different densities. The challenges faced at the time by the Los Alamos group spanned many engineering technical fields as well as scientific disciplines.

The clear direction and ultimate goal of the Manhattan Project, coming from the highest national political authority, was to deliver a usable weapon so powerful that it would end the war and potentially limit armed escalations in the future. It was the original intent of Los Alamos leadership and relevant national technical committees, including the National Defense Research Committee (NDRC), which later became the Office of Scientific Research and Development (OSRD), that this would be accomplished through a gun weapon using either uranium or plutonium as the fissionable material. However, it became clear in the spring and summer of 1944, that the preferred gun design that later became Little Boy would not generate a technically viable path to a plutonium-based weapon. Unlike ^{235}U , the surprising, faster spontaneous fission rate seen in plutonium received from the B reactor at the Hanford site¹⁰ made it practically impossible to fire a conventional gun weapon without seeing a predetonation of the nuclear material. At that point in 1944, the two options discussed for a plutonium weapon involved either a much larger and much faster (by orders of magnitude) gun weapon option or a three-dimensional (3-D) implosion option involving the dynamic compression of a subcritical quantity of plutonium into a critical mass in microseconds. Richard Tolman, chief technical adviser to General Leslie Groves on the Manhattan Project and who had received his PhD in physical chemistry from the Massachusetts Institute of Technology, codeveloped the Tolman-Oppenheimer-Volkoff equation¹¹ while on the faculty of the California Institute of Technology and served as chairman of the Armor and Ordnance Division of the NDRC. Tolman had

proposed implosion as a mechanism to assemble a critical mass as early as 1942, but it received little interest among Los Alamos laboratory scientists.

As physicists at Los Alamos struggled to make implosion a reality, Oppenheimer reached out to James Conant, then chairman of the NDRC, who suggested George Kistiakowsky, a chemist, for help. Kistiakowsky was considered the “number one civilian explosives expert” at the time and had experience with dynamic experiment diagnostics. John von Neumann, Luis Alvarez, and others eventually joined the effort, and ultimately, after hundreds of experiments and months of testing, the Explosives (X) Division finally produced a promising configuration for implosion.

II. OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT

The NDRC was hugely consequential to U.S. war-time scientific advances, including secret radar development and the Manhattan Project. The NDRC was created by Vannevar Bush “to coordinate, supervise, and conduct scientific research on the problems underlying the development, production, and use of mechanisms and devices of warfare”¹² in the United States on June 27, 1940. Most of the NDRC’s work was done with the strictest secrecy, and it researched what would become some of the most important technology during World War II. The NDRC was superseded by the OSRD on June 28, 1941 to address issues the NDRC was facing as they struggled to bridge from scientific research into military technology and applications. Many of the key personnel associated with leading the high-explosive (HE) and implosion research at Los Alamos either came directly from the NDRC and OSRD, from other projects funded by those organizations, or through connections and recommendations from the NDRC and OSRD leadership.

III. KEY PERSONNEL

The success of the explosives work during the Manhattan Project resulted from the contributions of many people. Military personnel worked alongside civilians from the local communities and those moving in from across the country and world to work on the Manhattan Project. We highlight Seth H. Neddermeyer, George B. Kistiakowsky, John von Neumann, Luis W. Alvarez, and James L. Tuck as key personnel who led the conceptual design and implantation of HE and implosion research at Los Alamos. With the overwhelming majority of the Project Y explosives workforce being men and the language of the time, the people working with raw explosives powder were nicknamed “powder men,” as illustrated in Fig. 1. While many



Fig. 1. “The Powder Men” by John Hull depicts Los Alamos physicist McAllister Hull introducing eight newly arrived “powder men” during the Manhattan Project years of the Los Alamos laboratory.¹³

women contributed to the Manhattan Project and war effort overall, their contributions are too often lost to history. We highlight the four women known to have contributed to the explosives effort of the Manhattan Project: Frances Dunne, Margaret Ramsey, Lilli Hornig, and Elizabeth Boggs. We share Manhattan Project badge pictures from historical records, noting that no badge pictures could be found for Margaret Ramsey and Elizabeth Boggs.

III.A. Manhattan Project Women in the Explosives Workforce

While about 30% of the Manhattan Project workforce in Los Alamos were women by October of 1944, only four—Frances Dunne, Margaret Ramsey, Lilli Hornig, and Elizabeth Boggs (introduced here)—are reported to have worked in explosives and had their stories captured by Howes and Herzenberg.⁸

Frances Dunne (1903 or 1910–1993, Figs. 2a and 2b), who had been a senior aircraft mechanic at Kirtland Field when the war began, was hired by Kistiakowsky into the Explosives Group for her mechanical skills. She worked as a technician and explosives supervisor in Explosives Assembly alongside 13 tech sergeants in Los Alamos. She was the only one not to go to Tinian for Project Alberta—the wartime delivery of the completed atomic bomb—because of the United States barring women from combat. After the war she worked for the Federal Bureau of Investigation.

Margaret Ramsey (1923–2016) came to Los Alamos after receiving her undergraduate degree in physics from the University of Rochester, where she worked on astrophysics.

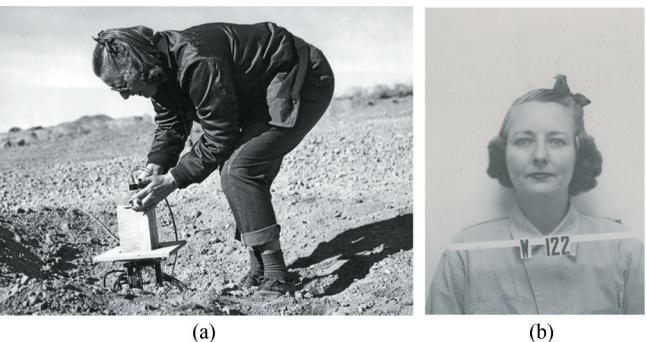


Fig. 2. (a) Frances Dunne setting an explosives point in the spring of 1945 at R site or Two Mile Mesa (source: Los Alamos Historical Society Photo Archives). (b) Badge picture for Frances Dunne.

At Los Alamos she was interested in pursuing theoretical work and was assigned to the Explosives Group with a focus on the explosives used in detonators. After the war she worked on beta-decay experiments before leaving Los Alamos and eventually leaving the field of physics.

Lilli Hornig (1921–2017, Fig. 3) was born in Czechoslovakia and immigrated to the United States in



Fig. 3. Badge picture for Lilli Hornig.

1933 to escape the rise of fascism. She came to Los Alamos with an almost complete PhD in chemistry from Harvard, which she completed after the war. While she initially worked on plutonium purification, she transferred to the Explosives Division where she led a section working on the development and fabrication of the explosive lenses and X-ray imaging of implosion experiments. A witness to the Trinity test, she recalls the vivid colors of the blast. Hornig went on to be a chemistry professor at Brown University and a chairwoman of the Chemistry Department at Trinity College in Washington, D.C.; to serve on several committees on equal opportunities, including for the National Science Foundation and the American Association for the Advancement of Science; and to write several books on the topic, including “Equal Rites, Unequal Outcomes: Women in American Research Universities.”¹⁴

Elizabeth Boggs (1913–1996) worked at the Explosives Research Laboratory in Bruceton, Pennsylvania after earning her PhD in Theoretical Chemistry at the University of Cambridge. Boggs had earlier demonstrated a similar independently developed explosive lens system that achieved some convergence, the details of which Duncan MacDougal who also worked at the Explosives Research Laboratory and worked at Los Alamos for much of his later career—had sent to Los Alamos.⁷ Soon after, she was recruited to work on war-related explosives research at Los Alamos. Following her son having a neonatal illness leaving him with a lifelong disability, Boggs eventually shifted her focus to advocacy and the development of public policy for people with disabilities and was a founder of the National Association for Retarded Children.

III.B. Seth H. Neddermeyer

Seth Neddermeyer (1907–1988, Fig. 4) was the early believer and high-impact leader for the first implosion device. He had received his PhD in physics at the California Institute of Technology and done work at the Carnegie Institution of Washington and the National Bureau of Standards on the proximity fuze, another NDRC project.⁴ Recruited to work on the Manhattan Project by Robert Oppenheimer, Seth was a strong early advocate for employing implosion. Although Oppenheimer was personally doubtful of the feasibility of the implosion method in time for the delivery deadline (set for July of 1945 to match the availability of the first significant quantity of reactor-produced plutonium), he appointed Neddermeyer as group leader for implosion experiments in



Fig. 4. Badge picture for Seth H. Neddermeyer.

the Ordnance Division after some promising technical analysis.⁷ In collaboration with Hugh Bradner, another physicist who had received his PhD from the California Institute of Technology, and James L. Tuck, a physicist from the British Mission,¹⁵ Neddermeyer conceived the early idea of explosive implosion. From his October 23, 1944 patent,¹⁶ his simple concept only involved

[...] positioning explosive material around the periphery of the fissile material so that portions of said explosive material are oppositely disposed relative to said fissile material, [...] detonating the explosive material whereby the resulting force of the explosion by reason of its opposite disposition compresses the fissile material.

However, the group struggled with implementing the idea of explosive implosion into a practical experiment. During a Project Y (Los Alamos laboratory) reorganization in 1945 in which the first incarnation of M-Division was formed, Neddermeyer became leader of M-10, the Betatron Group.⁵ Neddermeyer later submitted a more complete patent along with Tuck and von Neumann on the Trinity lens system.¹⁷

III.C. George B. Kistiakowsky

George Kistiakowsky led several explosives research organizations. In January of 1944, James Conant, then chairman of the NDRC, recruited George Kistiakowsky to join the Manhattan Project. Kistiakowsky (1900–1982, Fig. 5) was a Ukrainian-American physical chemistry professor at Harvard who had in 1940 been appointed head of Section A-1 (Explosives) in Division B (Bombs, Fuels, Gases, Chemical Problems) of the NDRC. When the NDRC became the OSRD, Kistiakowsky became head of Division B and subsequently the head of Division 8 responsible for explosives and propellants, until being recruited into the Manhattan Project. Within 6 months of arriving at Los Alamos, Oppenheimer asked Kistiakowsky to assume the role of associate division leader of the Explosives Division⁴ for all work on implosion and demoted Neddermeyer to senior technical advisor. The resulting implosion design went on to be used in the Trinity test roughly 1 year later on July 16, 1945 (Ref. 18) at the U.S. Army Air Force (USAAF)

Alamogordo Bombing and Gunnery Range and in the Fat Man bomb detonated over Nagasaki, Japan, on August 9, 1945.

III.D. John von Neumann

John von Neumann made numerous theoretical contributions to modeling explosives and implosion. One of the Hungarian-American contributors to the Los Alamos design effort, John von Neumann (1903–1957, Fig. 6) was a mathematician and physicist who would today be considered an extraordinary computer scientist for his modeling and simulation work. Although von Neumann made major contributions to many fields (mathematics, genetics, and others), during the Manhattan Project he worked with theoretical physicist Edward Teller, mathematician Stanislaw Ulam, and George Kistiakowsky to develop the mathematical models behind the explosive lenses used in the implosion-type atomic weapon. Von Neumann also coined the term “kiloton” [of trinitrotoluene (TNT)-equivalent energy] as a measure of the

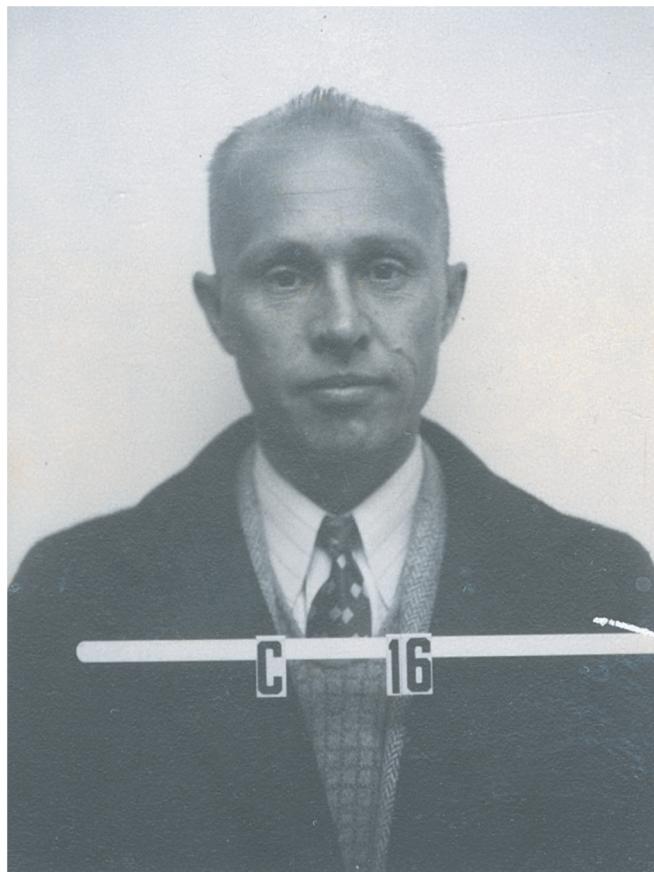


Fig. 5. Badge picture for George B. Kistiakowsky.



Fig. 6. Badge picture for John von Neumann.

explosive force generated by an atomic explosion, and later designed and promoted the concept of “Mutually Assured Destruction” to try and limit the subsequent nuclear arms race. Of the key personnel outlined in this paper who contributed to the development of the HE implosion system for the Trinity device, he was the only one reported to be among the distinguished visitors who observed the event along with General Groves at the nearest observation point to the tower, located a mere 10 000 yards away. Everyone at this nearest observation point was instructed to lie on the ground, face downward, heads away from the direction of the blast.⁴ After the war, von Neumann went to the Institute of Advanced Studies at Princeton University, but continued as a consultant in the Los Alamos Scientific Laboratory Theoretical Division.⁵

III.E. Luis W. Alvarez

Luis Alvarez made key contributions to the initiation of explosives and diagnostics for measuring explosive performance and implosion. After contributing to the secret radar project and working with Enrico Fermi at the

University of Chicago, Luis Alvarez (1911–1988, Fig. 7) was recruited by Robert Oppenheimer to come to Los Alamos where he led the Electronic Detonators Group, G-7, for a time and became Kistiakowsky’s deputy in the X (Explosives) Division. Luis was an American experimental physicist, inventor, and professor and was considered “one of the most brilliant and productive experimental physicists of the twentieth century.”¹⁹ During the Los Alamos effort, he provided a bridgewire detonator initiation system that ensured the required simultaneity of the Trinity implosion design. He also led the instrumentation team that developed and deployed a set of calibrated microphones to measure the strength of the blast wave from the atomic explosions Trinity and Little Boy. Among his many awards and acknowledgments, Alvarez was awarded the Nobel Prize in Physics in 1968 for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, which was made possible through his development of the technique of using hydrogen bubble chamber and data analysis. Later, working with his son, Walter, Luis was also instrumental in using isotope ratios in the iridium layer at the Cretaceous and Tertiary boundary to prove the most recent great extinction came from an extraterrestrial asteroid impact.²⁰ His achievements are often celebrated as part of National Hispanic Heritage Month.

III.F. James L. Tuck

James Tuck brought ideas from the early work on shaped-charge jets to HE lenses. While pursuing his PhD at the Victoria University of Manchester, British-born James L. Tuck (1910–1980, Fig. 8) was pulled into the war effort in 1939 to serve as scientific advisor to Prime Minister Churchill’s Private Office, where he was tasked with researching shaped charges that were eventually used in antitank weapons and for which he received the Order of the British Empire in 1944. Tuck was sent to Los Alamos in April 1944 to serve as the principal scientific officer on the British Mission during the Manhattan Project.²¹ His work on shaped charges, as a stepping stone into precision explosives, guided his significant contributions in designing explosive lenses for implosion.^{4,22} He outlined the lens design in his 1945 patent²³ with Hans A. Bethe as

[...] outward of the shell a spherical arrangement of explosive lenses are incorporated to convert the nominally divergent waves created by the detonation of the multiplicity of explosive initiators to a converging spherical wave.



Fig. 7. Badge picture for Luis W. Alvarez.



Fig. 8. Badge picture for James L. Tuck.

After attending the Trinity test and running a large diagnostics team for Operation Crossroads at Bikini Atoll, during the Los Alamos laboratory reorganization in 1945, M-7, the Super Mechanics Group, was formed under Tuck's leadership to pursue experimental studies of proposed mechanical methods of initiating thermonuclear reactions.⁵ He returned to the United Kingdom to see about completing his PhD thesis but was notified by the Victoria University of Manchester that the statute of limitations on presenting a thesis had run out. While never receiving a PhD, he went on to serve as the associate division leader for the Physics Division at Los Alamos National Laboratory²⁴ (LANL) from 1956 to 1973 and was named a Fellow of the American Physical Society (APS) and American Association for the Advancement of Science²⁵ (AAAS).

IV. USING MULTIPLE EXPLOSIONS TO CREATE THE PERFECT IMPLOSION: “GOING AGAINST NATURE”

Developing and refining the explosives lenses for the implosion bomb was one of the greatest challenges for

Los Alamos scientists and engineers. Expanding on the one-dimensional gun assembly bomb concept, the implosion concept envisioned by Richard Tolman and Seth Neddermeyer aimed to combine multiple subcritical pieces of fissionable material into a critical mass for a brief period of time, and then initiate the fission reaction using a controlled neutron source.

Conceptually, this could be attained by simply increasing the external pressure of the material relative to the internal pressure until the core's density is maximized and its volume minimized. In practice, because of the timeframes (microseconds) involved, this could only be attained using HEs and provided many challenges. Some of these challenges included using divergent HE detonation shockwaves to create a single, spherically symmetric implosion around the plutonium core, doing so simultaneously using explosive lenses with multiple surface detonators, visualizing and quantifying the detonation shockwave velocities of available (badly characterized) HEs and combining them coherently, modeling the detonation shockwave velocities and pressures to predict the core movement and ultimate density, and designing a suite of tests using the available diagnostic capability to capture correct data and iterate design improvements.

V. HIGH EXPLOSIVES WORK ON IMPLOSION

Whether employed for military applications or for commercial applications such as mining, explosives had always been a very crude and destructive tool. For hundreds of years before the Manhattan Project, the field of explosives, grown out of the development of gunpowder in the ninth century by Taoist Chinese alchemists, was used primarily to harness the brute divergent force created by reacting energetic chemical compounds. The Manhattan Project finally introduced and advanced the concepts of precision use, diagnostics, modeling, and control of explosives and detonation, all needed (and still employed today) for the practical realization of implosion-type fission weapons.

In an interview in 1982 with Richard Rhodes, Kistiakowsky explained the implosion concept:

Each initiation point would be centered on a lens, which would convert a divergent beam of an explosion wave into a convergent beam. Very much like an optical lens converts divergent light into a convergent light if you put it right.

However, little was known at the time about how to produce imploding shock waves, or about shaping and

arranging explosives to achieve controlled detonation waves. Kistiakowsky based the lens design on experiments performed by Bruno Rossi. Rossi was an Italian physicist of Jewish faith who was pressured to leave because of new Italian racial laws, and who made his way to a professorship at Cornell through multiple stops, including some time with Enrico Fermi in Chicago. He joined Los Alamos in 1943 and became the leader of the diagnostic detector group—an early example of the increasingly critical relationship between advancements in state-of-the-art diagnostics and advancements in HE and weapons R&D.

The explosive lenses concept employed two explosives with different detonation velocities. When a detonator creates a point initiation in the faster explosive, a nominally divergent spherical shockwave propagates out at constant velocity. If center lit on one end of a cylinder of constant cross section, the detonation will break out at the center of the other end before doing so at its circumference, consistent with the difference in distance to the initiation point. For implosion to work, the detonation wave needs to uniformly reach the inner surface (or the “tamper”) at the same time (see Fig. 9). By replacing some of the faster explosive with a slower detonation velocity explosive, the breakout time at a given point on the inner surface of the explosive can be designed based on the ratio of detonation velocities of the two explosives, and on the total length between the initiation point and the surface, to determine the ratio of lengths of fast and slow explosives required along that ray.

The height of the cone is proportional to the detonation velocity of the slower explosive, and the slant height is proportional to the detonation velocity of the faster

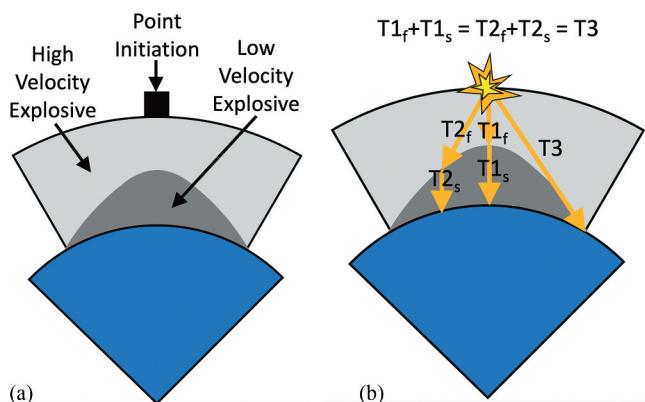


Fig. 9. (a) The conceptual arrangement of a lens system in an implosion weapon. (b) Detonation shockwave travel time from the detonator to the tamper surface is the same for all paths.

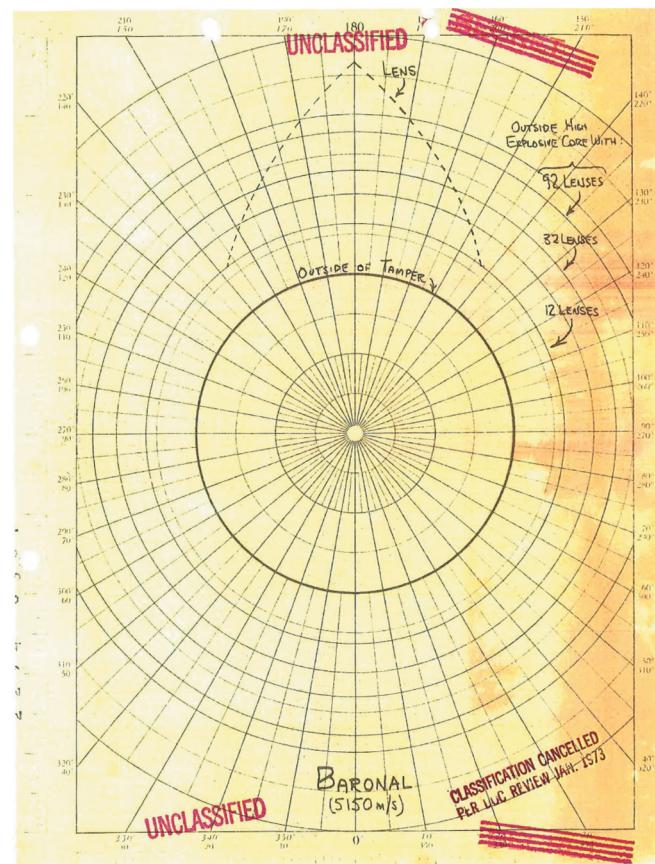


Fig. 10. Unclassified lens profile design for varied numbers of lenses.²⁹

explosive (Fig. 10). The height can be shortened relative to the base's diameter by increasing the difference between the two explosives' detonation velocities.^{26–28}

This concept is still frequently used today for modern HE plane-wave lenses. Most common solid explosives exhibit detonation velocities between 3 and 10 mm/μs, although many have undesirable output pressure, sensitivity, manufacturability, stability, or mechanical properties, making them unattractive for producing explosive lenses. Kistiakowsky selected Composition B and Baratol as the two explosives for the lenses, both of which are melt-castable explosives with a TNT binder (see photo in Fig. 11). While the final lenses produced for the Trinity

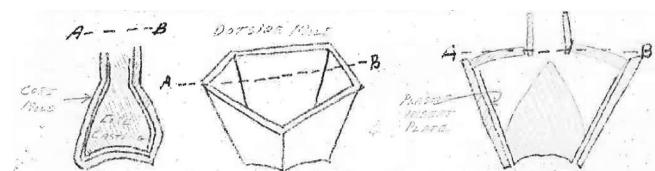


Fig. 11. Kistiakowsky's hand-drawn notes on lens mold designs.²⁹

device employed Composition B and Baratol pieces that were separately melt-cast and precision machined to fit, during the design George B. Kistiakowsky²⁹ reported that

To prosecute successfully research work on explosives lenses, several groups in the H.E. [High Explosive] Project need a large variety of moulds and expendable components for casting and assembly of explosive lenses.

To meet this demand, he went on to outline various methods for casting one explosive over the other and to manufacture the lens by packing loose explosive powder to shape for one the components.

VI. COMPOSITION B: A NEW MOLECULE AND EXPLOSIVE FOR WORLD WAR II OFFERS A FAST EXPLOSIVE

Composition B enabled the ability to realize an implosion device. The fast type of explosive in the lenses was Composition B, often referred to as Comp B, a mixture of 59.5 wt% Research Department Explosive (RDX), 39.5 wt% TNT, and 1.0 wt% wax desensitizer. It is one of the family of mixtures of RDX and TNT (molecular structures shown in Fig. 12) known as cyclotols. Composition B has been a common melt-castable HE for a wide range of conventional explosive ordnance, including artillery projectiles, rockets, landmines, hand grenades, and various other munitions. It is worth noting that unlike TNT, which had been around since 1863, RDX was not initially developed until the early days of World War II by Britain's Woolwich Arsenal.³⁰ It offers about 1.5 times the explosive energy of TNT per unit weight and about 2.0 times per unit volume, so for security reasons, Britain named it "Research Department Explosive," which continues on as RDX. The British discovered that by adding TNT to a mixture with RDX,

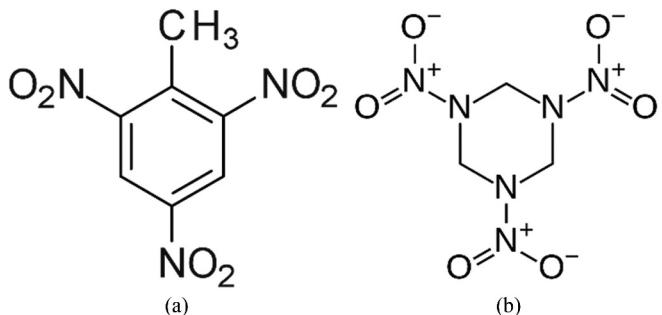


Fig. 12. (a) Molecular depiction of TNT (2,4,6-Trinitrotoluene), and (b) RDX (1,3,5-Trinitro-1,3,5-triazine).

the resulting product was more stable during shipping, and they named it Composition B.

Recognizing that Woolwich did not have the capacity to meet the Royal Air Force production needs for RDX, British leaders lobbied the United States to start production. However, in the early 1940s, the major U.S. explosive manufacturers—E. I. du Pont de Nemours & Company and Hercules—had several decades of experience manufacturing TNT and were not interested in expanding into new explosives. U.S. Army Ordnance held the same viewpoint, wanting to continue using TNT. RDX had been tested by the Picatinny Arsenal, which regarded it as too expensive and too sensitive, and the Navy proposed to continue using ammonium picrate.³

Enter the NDRC and OSRD, which had visited The Royal Arsenal at Woolwich in the United Kingdom and thought new explosives were necessary for the war effort. James Conant, who recruited Kistiakowsky to the Manhattan Project, wished to involve academic research into this area and set up an experimental explosives research laboratory at the Bureau of Mines, Bruceton, Pennsylvania. NDRC research into new processes lead to major advances in RDX and Composition B production. The United Kingdom's "Woolwich" method of manufacture of RDX was expensive, requiring 10 kg of strong nitric acid for every 1 kg of RDX (Ref. 31), and there were no adequate sources of natural beeswax to desensitize the vast production of RDX. At least three laboratories at Cornell, Michigan, and Pennsylvania State universities³ were instructed to develop better production methods for RDX. Werner Bachmann successfully developed the "combination process" by combining the Canadian process with direct nitration,^{3,32} which ultimately became known as the Bachmann process. A substitute stabilizer based on petroleum instead of beeswax was developed at the Bruceton Explosives Research Laboratory.³

Kistiakowsky indicated Composition B was chosen for the Christy Gadget and Fat Man because one of his "associate organic chemists, primarily Dr. Bachmann of the University of Michigan, discovered the so-called Process B (Bachmann) of making RDX relatively economically" going back to his connections from his NDRC and OSRD days. Based on these advances, and being convinced of Composition B's superior qualities, the Army hired the Eastman Kodak Company of Rochester, New York, to manage the production of RDX. Kodak established a subsidiary, the Tennessee Eastman Company, to operate what is now known as the Holston Army Ammunition Plant. The site is presently the primary U.S. supplier of explosive materials for the U.S. Department of Defense

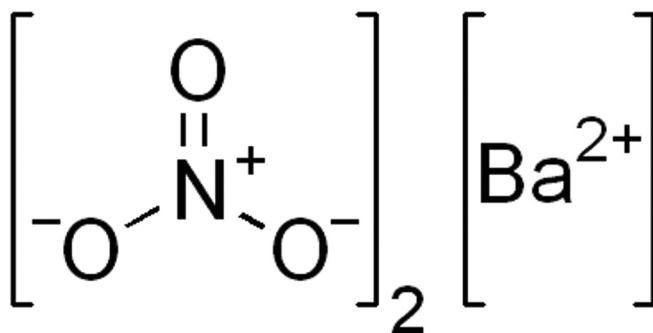


Fig. 13. Barium dinitrate.

(DOD) and the U.S. Department of Energy's (DOE's) National Nuclear Security Administration (NNSA), and is today the sole U.S. producer for RDX, HMX, and 1,3,5-Triaminotrinitrobenzene, as well as formulated molding powder for polymer-bonded explosives (PBX) 9501 and PBX 9502. While Composition B is still widely used in conventional munitions, the DOD is slowly replacing Composition B with insensitive high-explosive (IHE) formulations such as with Insensitive Munitions Explosive (IMX) 101 in U.S. military artillery shells and with IMX 104 in mortar rounds and hand grenades.³³ For plane-wave lenses to support R&D, in the mid-1980s LANL changed over to using pressed plastic-bonded explosive PBX 9501 for the fast component.²⁸

From Gibbs and Popolato,³⁴ Composition B is manufactured by melting the TNT in a steam-jacketed kettle equipped with a stirrer, brought to about 100°C. Water-wet RDX is slowly added. The mixture is heated and stirred until most of the water is evaporated, at which point the desensitizing wax is thoroughly mixed in. The material is typically cast into strips or chips to be later

remelted and either directly cast into munition cases or into desired shapes. To achieve higher densities, a vacuum may be applied to the melted Composition B before casting. Nominal properties for Composition B are reported in Table I. Significant work continues at LANL into characterizing Composition B, including understanding the effect of temperature on molten viscosity,³⁵ using X-ray scattering to probe the structural evolution of detonation carbon,³⁶ and measuring the effect of hot isostatically pressing on shock initiation.³⁷

VII. BARATOL: CALLING ON OLD FRIENDS FOR A SLOW TUNABLE EXPLOSIVE

Critical to realizing the implosion lens design was a second, much slower explosive. This second (slow) type of explosive in the lenses was Baratol. Baratol is a melt-castable HE mixture of barium nitrate (molecular structures shown in Fig. 13) and TNT and actually refers to all ratios of those two components. During World War II, the British developed Baratol formulations with roughly 20 wt% barium nitrate. This was part of a broad effort to develop explosives that could replace straight TNT ordnance fills because of the shortage of TNT.

Similarly, the explosive Amatol consisting of a mechanics mixture of TNT and ammonium nitrate was developed during World War I and used extensively during World War II in mines and warheads. The United States used Baratols with slightly more barium nitrate to fill depth charges and other limited munitions. Needing an explosive of a very low detonation velocity to pair with the Composition B in the lenses for Fat Man, Kistiakowsky noted⁴⁰ that he "assigned the job to his

TABLE I
Properties of Composition B

Theoretical density	1.737 g/cm ³	Ref. 34
Melt-cast density	1.68 to 1.70 g/cm ³	Ref. 34
Vacuum melt-cast density	1.715 to 1.720 g/cm ³	Ref. 34
Melt temperature	79°C	Ref. 34
Nominal detonation velocity	8.018 mm/μs	Ref. 38
Detonation pressure	29.22 GPa	Ref. 38
Unreacted shock velocity	$U_s = 2.71 + 1.86 U_p$ for particle velocity of $0 < U_p < 1 \text{ mm}/\mu\text{s}$	Ref. 39
Drop weigh sensitivity impact test	59 cm for a type-12 tool and 109 cm for a type-12B tool	Ref. 34
Ultimate tensile strength	0.9 to 1.0 MPa at room temperature	Ref. 34
Ultimate compressive strength	11.4 to 14.2 MPa at room temperature; 9.0 to 10.3 MPa at 50°C	Ref. 34
Compressive modulus	14.5 to 18.6 GPa at room temperature; 4.3 to 4.4 GPa at 50°C	Ref. 34

friends at an Explosives Research Laboratory in Pittsburgh, the so-called Bruceton Laboratory, of which I was the chief until I went to Los Alamos." At the Pittsburgh laboratory, Dr. Duncan MacDougall and an associate developed the Baratol explosive containing up to 76 wt% of barium nitrate. Duncan MacDougall also ultimately made his way to Los Alamos, where he succeeded Kistiakowsky as the X Division leader. In 1948, MacDougall led the merger of the X Division with the M (Implosion) Division, which had been led by Darol Froman, and the G (Gadget) Division, which had been led Robert Bacher, to form the GMX Division. MacDougall went on to lead the GMX Division until 1970.

From Gibbs and Popolato,³⁴ Baratol is manufactured from finely ground barium nitrate added to molten TNT to form a castable slurry. About 0.1 wt% of nitrocellulose is added to the TNT before adding the barium nitrate to reduce the slurry viscosity. Subsequent to the addition of the barium nitrate and just before applying a vacuum to the melt, 0.05 to 0.1 wt% decylgallophenone or stearoxyacetic acid is added to prevent cracking. Before casting, a vacuum is applied to the melt to remove dissolved and occluded gas to achieve a higher and more uniform density. Nominal properties for Baratol are reported in Table II. The nominal detonation velocity is tunable by varying the percentage of barium nitrate. It is worth noting that during the Manhattan Project scientists needed to develop rate stick tests with an adequate booster to avoid anomalously low-velocity measurements from a point detonation and edge effects. They also found the refractive index between the fast and slow explosives could only be determined by experimental iteration, and the slow explosives velocity was observed to be faster in the lens configuration than measured from a rate stick test.⁷

VIII. DIAGNOSTICS

Following the summer of 1944, several experimental diagnostics were advanced and developed to characterize, and iteratively improve, the converging implosion lens system of the Christy Gadget. The Radioactive Lanthanum or RaLa experiment measured changes of absorption of gamma rays from large quantities of a short-lived radioisotope ¹⁴⁰La to measure the spherical implosion caused by converging explosive shock waves. This novel diagnostic of implosion was based on placing a gamma-ray source at the center of a spherical implosion assembly. The emitted gamma rays would travel outward radially. Because increasing compression of the metal caused the gamma rays to be increasingly absorbed, the emerging gamma rays, monitored by detectors set around the HEs, would provide information on density changes in the collapsing sphere of metal. The data would indicate the time of collapse, the degree of compression, and the symmetry, by comparing the gamma-ray intensity in different directions.⁷

A magnetic method was also developed to measure the movement of metal during implosion within a static magnetic field. When applied in the Creutz test, the technique yielded anomalous results, raising last minute concerns about the Trinity test. An overnight reanalysis by Hans Bethe and subsequent quick peer reviews convinced everyone to continue forward with the Trinity test.

The HE program made extensive use of high-speed photography, including flash photography and rotating mirror cameras, and X-ray diagnostics, many of which were brought to Los Alamos by the British Mission.²²

In 1944, Oppenheimer had the Betatron at the University of Illinois Urbana-Champaign, which had been developed by Donald Kerst, shipped to Los Alamos for the

TABLE II
Properties of Baratol with 76 wt% Barium Nitrate and 24% TNT

Theoretical density	2.634 g/cm ³	Ref. 34
Melt-cast density	2.60 to 2.62 g/cm ³	Ref. 34
Melt temperature	79°C to 80°C	Ref. 34
Nominal detonation velocity	4.925 mm/μs	Ref. 34
Detonation pressure	14 GPa	Ref. 34
Unreacted shock velocity	$U_s = 2.40 + 1.66 U_p$ for particile velocity of $0 < U_p < .75 \text{ mm}/\mu\text{s}$; $U_s = 1.50 + 2.16 U_p$ for particile velocity of $0.75 < U_p < 1.25 \text{ mm}/\mu\text{s}$	Ref. 41
Drop weigh sensitivity impact test	110 cm for a type-12 tool and 140 cm for a type-12B tool	Ref. 34
Ultimate tensile strength	2.6 to 3.1 MPa at room temperature	Ref. 34
Ultimate compressive strength	39.3 to 55.8 MPa at room temperature	Ref. 34
Compressive modulus	10.3 to 13.8 GPa at room temperature	Ref. 34

study of implosion. The Betatron method was similar to X-ray radiography but using higher-energy gamma rays.

The pin method was a technique where metal pins were erected in the space near the imploding object and connected to electrical circuits. As the implosion proceeded, these pins were struck and an oscilloscope displayed accurately timed current bursts. The pin method ultimately gave the most accurate implosion timing information and was particularly useful in studying jets.⁷

IX. WORKING AND LIVING WITH EXPLOSIVES, 1943–1945

Given an unparalleled opportunity to combine the development of basic knowledge and the art of science to benefit the country and the allied war effort, many engineers and scientists, including George Kistiakowsky, spent many hours of every day and night working to develop and perfect an implosion design clearly intended to change the world as they knew it. Many scientists believed initially that it would be impossible to create a functional implosion atomic bomb. When it became clear that it could actually be built, they raced to develop it before Heisenberg and the Germans, and they hoped that the Christy Gadget they created would not just end the war, but end all “great” wars. Their spirits were high, and the enthusiasm for success had no bounds. The tempo, while unsustainable for an extended period of time, was extremely high and generated many opportunities for ingenious improvisation and decision making. For balance, given limited vacation or travel opportunities, scientists and engineers made do with creative parties, hiking, and skiing in the nearby hills (Fig. 14). Work was often merged with entertainment, and

as the explosive’s division leader, Kistiakowsky was a prime example of this. To quickly improve a ski run for the many Europeans working on the hill who loved skiing, Kistiakowsky creatively used surplus plastic explosives to cut down the trees. “If one builds a half necklace around the tree,” he recalled, “then the explosion cuts it as if it were a chainsaw – and it’s faster. A little noisier, though.”⁶

Always a “hands-on” explosives expert, Kistiakowsky and his colleagues would X-ray the implosion-shaped charges and identify flaws, such as air pockets. For the Trinity charges, hours before the test, he worked through the night using a dentist’s drill to reach the voids to fill them with explosive. When asked about working with large quantities of explosives—during a time when the hazards of explosives were much less understood and there were not today’s HE safety programs⁴²—Kistiakowsky was quoted as saying, “I was completely confident. Besides, you don’t worry about it. I mean if fifty pounds of explosive goes [off] in your lap, you have no worries.”⁴⁰ Despite his pragmatic attitude toward explosives handling, he also wrote an excellent explosives safety manual in early 1945, detailing some of the safety concepts and issues that are still causing difficulties today, such as impact, burning, detonation, friction, and drop sensitivities.⁴³ In part thanks to his efforts, there were no explosive operations fatalities in Los Alamos during the Manhattan Project.

X. LASTING INFLUENCE OF DEVELOPMENT OF PRECISION EXPLOSIVES

While the implosion system for the Trinity device was uniquely developed for the purpose of the atomic

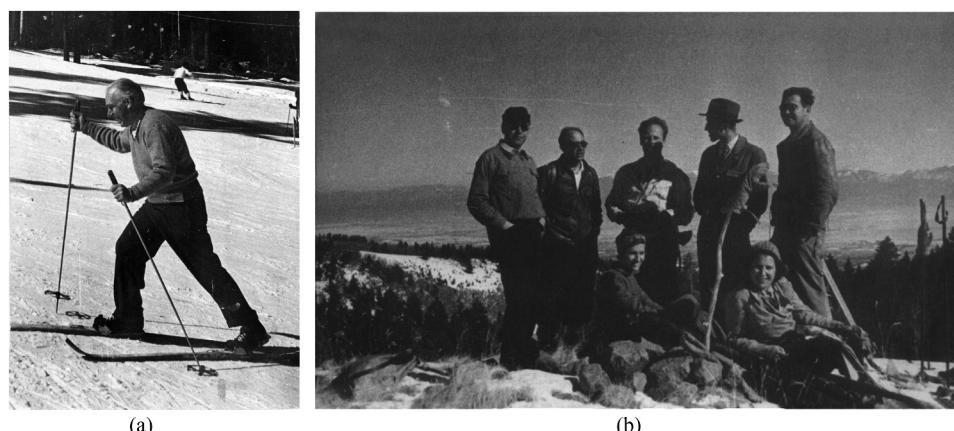


Fig. 14. (a) Niels Bohr skiing at Sawyer’s Hill during the Manhattan Project (early 1945). The photograph was classified until 1950 to protect the work performed at Los Alamos. The Los Alamos staff worked a 6-day week, making Sundays the time for recreation. (b) On a hike, from left to right, standing, Emilio Segré, Enrico Fermi, Hans Bethe, H. H. Staub, and Victor Weisskopf; seated, Erika Staub and Elfriede Segré (source: American Institute of Physics Emilio Segré Visual Archives).

bomb, the concepts of engineered, high-precision explosives and directed-energy explosives has had broader impacts in the intervening 75 years.^{44,45} Going back to the early work of James Tuck on shaped charges²² that were employed in antitank weapons by the British in World War II, HE lens concepts have been extensively employed in shaped charges for conventional military and civilian applications. A shaped charge is a specially designed class of explosive charges in which the geometry is selected to focus the effect of the energy coming from the detonation on a point or small area relative to the diameter of the charge (displayed in Fig. 15). In bare charges with a void or material cutaway at the surface, this focusing is known as the Munroe effect, named for Charles E. Munroe, a chemist at the Naval Torpedo Station and War College at Newport, Rhode Island, who discovered the effect in 1888 (Ref. 46). While not named,

the concept of a cutaway to compound the explosive energy had previously been employed, as an example, for detonators in an 1886 patent,⁴⁷ show in Fig. 16. Typically, a ductile metal liner is placed along the surface of the cutaway in the explosive, as either a simple right cone, a hemisphere, or a more complex tuned geometry, similar to the interface between the high- and low-velocity explosives in the HE lens. When the explosive is detonated, the liner collapses along the center axis, with the converging material projecting a hypersonic jet along the axis of the charge capable of penetrating steel to a depth multiple times the diameter of the charge. Although most shaped charges are a single explosive with the similarity to lenses coming through the timing of the detonation reaching the liner as it would reach the second explosive in a shaped charge, work has also been done with two explosives designs for shaped-charge

Aug. 13, 1963 T. C. POULTER 3,100,445
SHAPED CHARGE AND METHOD OF FIRING THE SAME
Filed Jan. 14, 1959 2 Sheets-Sheet 1

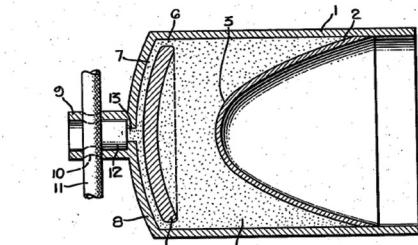


FIG. 1.

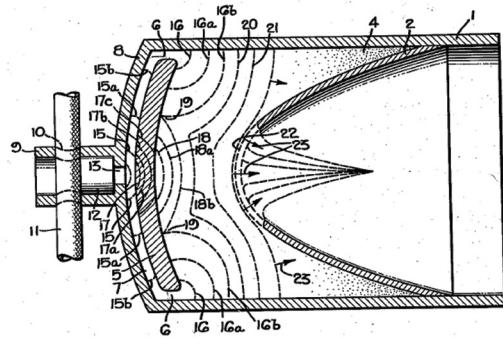
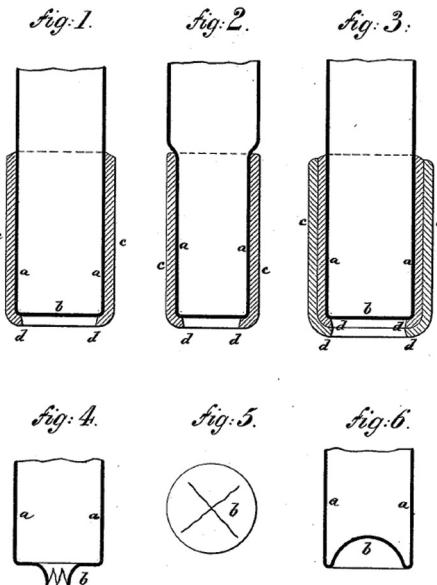


FIG. 2.

THOMAS C. POULTER,
INVENTOR.BY *Lyon & Lyon*
ATTORNEYS

Fig. 15. Shaped-charge patent from Haliburton Company⁷⁵ for perforation of well casing and subterranean formations surrounding oil, gas, and water wells.

(No Model.)
G. BLOEM.
SHELL FOR DETONATING CAPS.
No. 342,423. Patented May 25, 1886.



WITNESSES:
Gustav Schimpke.
John M. Speer.

INVENTOR
Gustav Bloem
BY Briesen & Steele
ATTORNEYS.

Fig. 16. The 1886 patent showing detonator sleeves pressed inward hemispherically to improve performance.⁴⁷

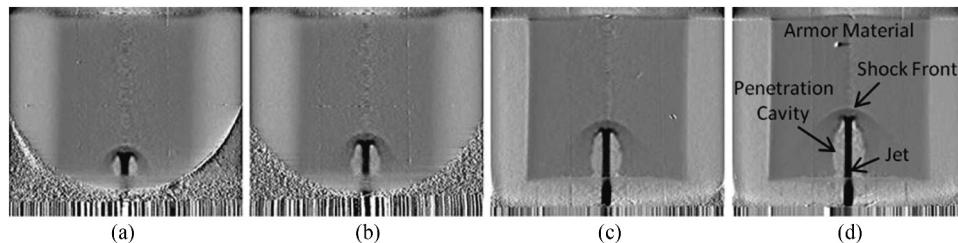


Fig. 17. Movie of a metallic jet penetrating up into a cylindrically shaped armor material. Time increases from the (a) to the (d) image.⁵¹

jets.⁴⁸ While highly effective as a conventional munition⁴⁹ for penetrating heavily armored vehicles at close range, shaped charges are also an effective tool at breaching concrete. Extensive work has been performed by the DOD on the development of shaped-charge jets and their interaction with targets, often employing DOE NNSA modeling and simulation tools and experimental capabilities. Proton radiography has been employed at Los Alamos to image shaped-charge jet penetration into metal and ceramic armor materials,^{50,51} as shown in Fig. 17. Because of the hazard from combatant or accidental impact of shaped-charge jets into military explosive munitions, the North Atlantic Treaty Organization has established a policy for the introduction and assessment of Insensitive Munitions in Standardization Agreement (STANAG) 4439 to promote the development of safer munitions and increase interoperability with the established STANAG 4526, “Shaped Charge Jet Munition Test Procedures.”⁵² Explosive lenses are also employed in conventional munitions to optimize the explosive transfer between booster and warhead.⁵³ In civilian applications, shaped charges are commonly employed in mining and oil exploration as a way to quickly and effectively perforate geological materials, as illustrated in Fig. 18 (Ref. 54). While a single shaped charge can be placed to provide a more directed perforation when compared to a simple explosive charge, a perforating gun is frequently employed to provide effective flow communication between a cased wellbore and a productive reservoir. The perforating gun houses numerous shaped charges pointing radially from the axis of the gun—typically 12 to 36 charges per meter each with 3 to 60 g of explosives—housed in a heavy walled tube. When fired, most of the charge debris remains in the carrier, which is recovered from the well after firing. In addition to the axisymmetric-shaped charges, linear-shaped charges with a plane of symmetry create planar jets that can serve as a knife to cut through material. Linear-shaped charges are commonly employed in demolition work (see Fig. 19). Through precision application of linear-shaped charges, large structures

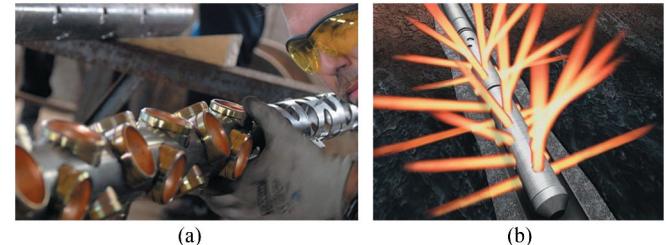


Fig. 18. (a) Perforating charges assembled into a cannon and (b) an illustration of radial perforating of geological materials (source: Petropedia).



Fig. 19. Time sequence of controlled demolition blasting of a chimney at the former Henninger brewery in Frankfurt am Main, Germany, Sachsenhausen (source: Heptagon, Wikimedia Commons).

can be felled in a controlled small footprint. As illustrated in the time lapse of the controlled demolition blasting of a chimney at the former Henninger brewery, the multistory-tall chimney is controlled to fall almost entirely straight down. This type of precision demolition allows for large structures to be quickly and efficiently removed without affecting surrounding buildings. Higher-precision applications of linear-shaped charges include separating the stages of multistage rockets in flight. As illustrated in Fig. 20 (Refs. 55 and 56), the modern SpaceX Crew Dragon capsule Flight Termination System (FTS) uses a linear-shaped charge assembly mounted onto the exterior case that houses the Falcon 9 rocket’s motors and liquid fuel tanks.⁵⁷ The precision linear-shaped charges allow for very rapid and clean separation of stages.



Fig. 20. Illustration of SpaceX Crew Dragon capsule separating from the Falcon 9 rockets in flight (source: SpaceX from the Associated Press). The FTS on the inaugural Falcon 9 launch uses a linear-shaped charge assembly mounted onto the exterior case that houses the rocket's motors and liquid fuel tanks.⁵⁷

Plane-wave lenses themselves continue to be a valuable tool in research for creating a uniform shock loading to very high pressure. Baratol is now deemed a hazardous waste because of the barium content, and numerous efforts have been undertaken to develop similar low-velocity explosives for plane-wave lenses, displayed in Fig. 21, to support R&D work^{26,28} within the DOE NNSA and DOD. Recent advances include the application of additive manufacturing (3-D printing) to simplify the production of plane-wave lenses.⁵⁸ Plane-wave lenses themselves are frequently employed to either provide a direct high-pressure impulsive Taylor wave load,^{59–67} to launch a flier plate to achieve a high-pressure square wave load,^{68,69} to achieve planer detonation of an explosive sample,^{51,70,71} or to provide a uniform dynamic drive from explosive byproducts^{72,73} for shock and detonation physics experiments.

Both the field of explosives science, engineering, and technology and LANL have become more inclusive since the 1940s and continue to make progress in engaging a diverse workforce in contributing to national security. A rich cross section of our explosives workforce is highlighted in our recent High Explosives Research & Development Strategy.⁷⁴ We also are benefiting from rising diversity in our highly recognized researchers, leaders, and managers contributing to the field of explosives, of which we highlight just a few of our senior scientists and managers. Dr. Dana Dattelbaum is a senior scientist working in shock and detonation physics and the recipient of the DOE E. O. Lawrence Award, an APS Fellow, an LANL Fellow, and manages the Dynamic Material Properties Program. Dr. David Chavez is a senior scientist working in explosive synthesis and a recipient of the DOE E. O. Lawrence

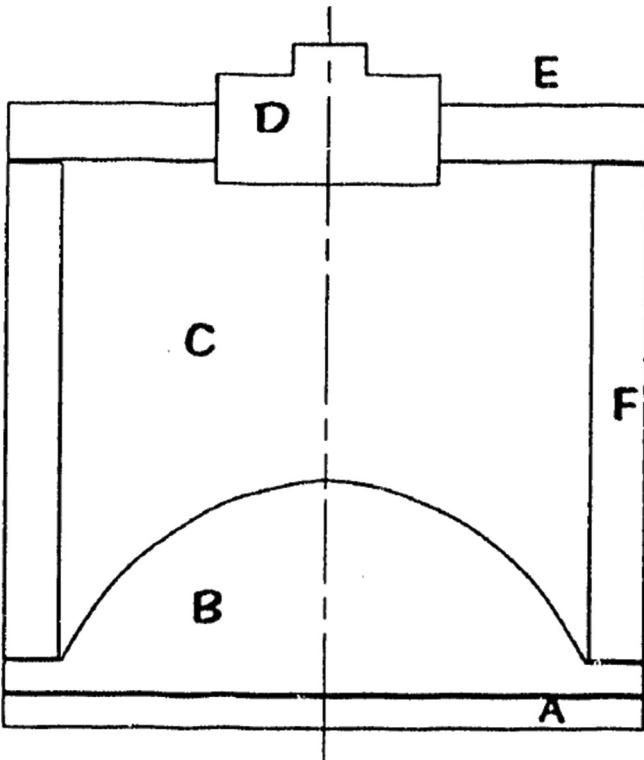


Fig. 21. Schematic of Fritz plane-wave lens²⁶: A = acceptor explosive, B = plastic wave shaper, C = donor explosive, D = detonator, E = detonator support and lid for explosive, and F = plastic cylinder to hold in explosive.

Award, an AAAS Fellow, and is deputy group leader for the High Explosives Science and Technology Group. Dr. Laura Smilowitz is a senior scientist working on imaging of the explosive deflagration and an APS Fellow, an AAAS Fellow, and an LANL Fellow. Dr. Michelle Espy is a senior scientist working on explosive detection and an APS Fellow. Dr. Margo Greenfield is the group leader for the High Explosives Science and Technology Group. Dr. Kimberley Scott and Dr. Jennifer Young are the LANL program directors for the Experimental Science Program and Directed Stockpile Work Program Integration, respectively, which in combination support the majority of HE work at the Los Alamos laboratory. Thomas Sisneros is the deputy facilities operations director overseeing Explosives Operations.

XI. CONCLUSION

The extraordinary effort, undertaken at Los Alamos in the mid-1940s to develop the Trinity implosion design, instigated new precision explosive design tools unlike any seen previously, including HE synthesis and formulation,

test and diagnostic facilities, shock dynamics theory, HE system design engineering, and 3-D modeling and simulation. The HE characterization and development process for precision implosion at Los Alamos, which began in 1944 under such dire circumstances, has persisted ever since, with LANL leading the way in the invention of PBXs, IHEs, more environmentally friendly “green” explosives, and a wide range of advanced manufacturing techniques. In addition to LANL’s role in explosives to support the U.S. nuclear deterrent, LANL works with the DOD, industry, and academia to bring advances in precision explosives to many other applications. It has kindled a technical understanding of explosive behavior and design that allowed for a much broader application of precision HEs in conventional munitions, demolition, mining and oil exploration, and space travel. These subsequent “constructive” applications, born from such destructive tools as explosives, owe their foundation to a highly improbable secret project that began on a cottonwood-lined mesa in the northern high desert of New Mexico.

Acknowledgments

This work was supported by the DOE through the LANL. The LANL is operated by Triad National Security, LLC, for the NNSA of the DOE (contract number 89233218CNA000001). We would like to thank Mark Chadwick and Alan Carr for helpful discussions and Madeline Whitacre, Daniel Alcazar, and John Moore of the Los Alamos National Security National Security Research Center for finding and digitizing historical documents from Site Y of the Manhattan Project.

References

1. A. B. CARR, “Thirty Minutes Before the Dawn,” *Nucl. Technol.*, **207**, S1, S1 (2021); <https://doi.org/10.1080/00295450.2021.1927625>.
2. T. A. CHADWICK and M. B. CHADWICK, “Who Invented the Trinity Nuclear Test’s Christy Gadget? Patents and Evidence from the Archives,” *Nucl. Technol.*, **207**, S1, S356 (2021); <https://doi.org/10.1080/00295450.2021.1903300>.
3. J. P. BAXTER, *Scientists Against Time*, Little, Brown and Company, Boston, Massachusetts (1946).
4. D. HAWKINS, *Manhattan District History Project Y the Los Alamos Project. Vol. I. Inception Until August 1945*, Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico (1961).
5. E. C. TRUSLOW and R. C. SMITH, *Manhattan District History Project Y the Los Alamos Project. Vol. II. August 1945 Through December 1946*, Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico (1961).
6. L. BADASH, J. O. HIRSCHFELDER, and H. P. BROIDA, *Reminiscences of Los Alamos 1943–1945*, D. Reidel Publishing Company, Dordrecht, Holland (1980).
7. L. HODDESON et al., *Critical Assembly: A Technical History of Los Alamos During the Oppenheimer Years, 1943–1945*, Cambridge University Press, Cambridge (1993).
8. R. H. HOWES and C. C. HERZENBERG, *Their Day in the Sun: Women of the Manhattan Project*, Temple University Press, Philadelphia, Pennsylvania (2003).
9. J. KUNETKA, *The General and the Genius: Groves and Oppenheimer—The Unlikely Partnership that Built the Atom Bomb*, Regnery History, Washington, District of Columbia (2015).
10. J. C. MARTZ, F. J. FREIBERT, and D. L. CLARK, “The Taming of Plutonium: Plutonium Metallurgy and the Manhattan Project,” *Nucl. Technol.*, **207**, S1, S266 (2021); <https://doi.org/10.1080/00295450.2021.1913035>.
11. J. R. OPPENHEIMER and G. M. VOLKOFF, “On Massive Neutron Cores,” *Phys. Rev.*, **55**, 4, 374 (1939); <https://doi.org/10.1103/PhysRev.55.374>.
12. “The Office of Scientific Research and Development (OSRD) Collection,” Science Reference Services, Library of Congress (2015); <https://www.loc.gov/rr/scitech/trs/trsosrd.html> (current as of Jan. 6, 2021).
13. J. HULL, “The Powder Men,” Bradbury Science Museum Fine Art collection (2020); <https://www.lanl.gov/museum/news/newsletter/2020/12/artifact-powder-men.php> (current as of Jan. 6, 2021).
14. L. S. HORNING, *Equal Rites, Unequal Outcomes: Women in American Research Universities*, Springer Science and Business Media, LLC, New York (2003).
15. D. C. FAKLEY, “The British Mission,” *Los Alamos Sci.*, **7**, 186 (1983).
16. S. H. NEDDERMEYER, “S-666x,” United States Patent Office (Oct. 23, 1944).
17. S. H. NEDDERMEYER, J. L. TUCK, and J. V. NEUMANN, “S-2730,” United States Patent Office (1946).
18. K. T. BAINBRIDGE, *Trinity*, Los Alamos Scientific Laboratory (May 1976).
19. C. G. WOHL, “Scientist as Detective: Luis Alvarez and the Pyramid Burial Chambers, the JFK Assassination, and the End of the Dinosaurs,” *Am. J. Phys.*, **75**, 11, 968 (2007); <https://doi.org/10.1119/1.2772290>.
20. L. W. ALVAREZ et al., “Extraterrestrial Cause for the Cretaceous-Tertiary Extinction,” *Science*, **208**, 4448,

- 1095 (1980); <https://doi.org/10.1126/science.208.4448.1095>.
21. D. A. BAKER et al., “Obituaries: James Leslie Tuck,” *Phys. Today*, **34**, 3, 87 (1981); <https://doi.org/10.1063/1.2914494>.
 22. R. MOORE and E. N. BROWN, “Woolwich, Bruceton, Los Alamos: Monroe Jets and the Trinity Gadget,” *Nucl. Technol.*, **207**, S1, S222 (2021); <https://doi.org/10.1080/00295450.2021.1905463>.
 23. J. L. TUCK and H. A. BETHE, “S-4301x,” United States Patent Office (Dec. 1, 1945).
 24. E. F. HAMMEL, *Los Alamos Scientific Laboratory Energy-Related History, Research, Managerial Reorganization Proposals, Actions Taken, and Results 1945–1979*, Los Alamos National Laboratory (1997).
 25. J. L. TUCK, “James L. Tuck 1974 Curriculum Vitae,” A-83-0001, Los Alamos Scientific Laboratory (1974).
 26. J. N. FRITZ, “A Simple Plane-wave Explosive Lens,” LA-11956-MS, Los Alamos National Laboratory (Dec. 1990).
 27. B. OLINGER, “Solid Explosive Plane-Wave Lenses Pressed-to-Shape with Dies,” LA-14347, Los Alamos National Laboratory (Nov. 2007).
 28. D. E. CHAVEZ, H. H. HARRY, and B. W. OLINGER, “An Environmentally Friendly Baratol Replacement for Plane Wave Generator Applications,” *J. Energetic Mater.*, **32**, 2, 129 (2014); <https://doi.org/10.1080/07370652.2013.794888>.
 29. G. B. KISTIAKOWSKY, “Molds for Explosive Lenses,” Los Alamos Scientific Laboratory (Aug. 1944).
 30. C. F. BAXTER, *The Secret History of RDX: The Super-Explosive that Helped Win World War II*, The University Press of Kentucky, Lexington, Kentucky (2018).
 31. “Historic Properties Report, Newport Army Ammunition Plant, Newport Indiana,” AD-A175 818, MacDonald and Mack Partnership (Aug. 1984).
 32. T. URBAŃSKI, *Chemistry and Technology of Explosives*, Vol. 3, Polish Scientific Publishers, Poland (1967).
 33. M. R. WALSH et al., “Energetic Residues from the Detonation of IMX-104 Insensitive Munitions,” *Propellants Explos. Pyrotech.*, **39**, 2, 243 (2014); <https://doi.org/10.1002/prep.201300095>.
 34. T. R. GIBBS and A. POPOLATO, *LASL Explosive Property Data*, University of California Press, Berkley, California (1980).
 35. D. K. ZERKLE, M. P. NÚÑEZ, and J. M. ZUCKER, “Molten Composition B Viscosity at Elevated Temperature,” *J. Energetic Mater.*, **34**, 4, 368 (2016); <https://doi.org/10.1080/07370652.2015.1102179>.
 36. M. A. FIRESTONE et al., “Structural Evolution of Detonation Carbon in Composition B by X-ray Scattering,” *Proc. Shock Compression of Condensed Matter* (2015), Tampa, Florida, June 14–19, 2015, Vol. 1793, p. 30010, AIP Conference Proceedings (2017).
 37. M. J. BURNS et al., “One Dimensional Shock Initiation of Hot Isostatically Pressed Composition B,” *Proc. Shock Compression of Condensed Matter* (2017), St Louis, Missouri, July 9–14, 2017, Vol. 1979, p. 150007, AIP Conference Proceedings (2018).
 38. W. E. DEAL, “Measurement of Chapman-Jouguet Pressure for Explosives,” *J. Chem. Phys.*, **27**, 3, 796 (1957); <https://doi.org/10.1063/1.1743831>.
 39. N. L. COLEBURN and T. P. LIDDIARD JR., “Hugoniot Equations of State of Several Unreacted Explosives,” *J. Chem. Phys.*, **44**, 5, 1929 (1966); <https://doi.org/10.1063/1.1726963>.
 40. R. RHODES, “Voices of the Manhattan Project: George Kistiakowsky’s Interview,” January 15, 1982; <https://www.manhattanprojectvoices.org/oral-histories/george-kistiakowskys-interview> (current as of Jan. 6, 2021).
 41. V. BOYLE, R. JAMESON, and M. SULTANOFF, “Determination of Shock Hugoniots for Several Condensed Phase Explosives,” *Proc. 4th Symp. (Int.) on Detonation*, White Oak, Maryland, October 12–15, 1965, p. 241, Office of Naval Research-Department of the Navy (1965).
 42. “Explosives Safety,” DOE-STD-1212-2019, U.S. Department of Energy (Nov. 2019).
 43. G. B. KISTIAKOWSKY, *Explosives*, Los Alamos Scientific Laboratory (Feb. 1945).
 44. W. P. WALTERS and J. A. ZUKAS, *Fundamentals of Shaped Charges*, Wiley-Interscience, Hoboken, New Jersey (1989).
 45. D. R. KENNEDY, *History of the Shaped Charge Effect: The First 100 Years*, Los Alamos National Laboratory (1990).
 46. C. A. BROWNE, “Charles Edward Munroe 1849–1938,” *J. Am. Chem. Soc.*, **61**, 5, 1301 (1939); <https://doi.org/10.1021/ja01874a600>.
 47. G. BLOEM, “Shell for Detonator Caps,” 342423, United States Patent Office (May, 1886).
 48. N. A. LOUIE, A. L. MOTTET, and I. LIEBERMAN, “Study and Application of Mach Wave Techniques,” AFATL-TR-68-60, Air Force Armament Laboratory (May 1968).
 49. E. L. BAKER et al., “Shaped Charge Jet Characterization and Initiation Test Configuration for IM Threat Testing,” *Procedia Eng.*, **56**, 58 (2103).
 50. M. B. ZELLNER et al., “Shaped Charge Jet Penetration of Alon® Ceramic Assessed by Proton Radiography and Computational Simulations,” *Procedia Eng.*, **103**, 663 (2015); <https://doi.org/10.1016/j.proeng.2015.04.086>.

51. C. L. MORRIS et al., "New Developments in Proton Radiography at the Los Alamos Neutron Science Center (LANSCE)," *Exp. Mech.*, **56**, 1, 111 (2016); <https://doi.org/10.1007/s11340-015-0077-2>.
52. B. FUCHS et al., "Review and Update of STANAG 4526 Shaped Charge Jet, Munitions Test Procedure," presented at the Int. Explosives Safety Symp. & Exposition, San Diego California, August 6–9, 2018 (2018).
53. E. R. ALTHOF, W. R. HAWKINS, and H. Y. KIM, "Warhead Booster Explosive Lens," 7,921,775B1, United States Patent Office (Apr. 12, 2011).
54. E. GALANTE, A. HADDAD, and N. MARQUES, "Application of Explosives in the Oil Industry," *Int. J. Oil Gas Coal Eng.*, **1**, 2, 16 (2003); <https://doi.org/10.11648/j.ogce.20130102.11>.
55. H. F. HALSTED, *The Design and Operation of Multi-Stage Rocket Vehicles*, North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development (July 1961).
56. D. H. MITCHELL, "Flight Separation Mechanisms," NASA SP-8056, National Aeronautics and Space Administration (Oct. 1970).
57. B. BERGER, "Flight Termination System Testing Drives Falcon 9 Schedule," Space News, April 12, 2010; <https://spacenews.com/flight-termination-system-testing-drives-falcon-9-schedule/> (current as of Jan. 6, 2021).
58. J. P. LICHTHARDT et al., "A Simple 3D Printed Plane Wave Explosive Lens Based on Fritz Parameters," *AIP Conf. Proc.*, **2272**, 1, 30018 (2020).
59. N. K. BOURNE and J. E. FIELD, "Explosive Ignition by the Collapse of Cavities," *Proc. R. Soc. London A*, **455**, 1987, 2411 (1999); <https://doi.org/10.1098/rspa.1999.0410>.
60. A. ROHATGI, K. S. VECCHIO, and G. T. GRAY, "A Metallographic and Quantitative Analysis of the Influence of Stacking Fault Energy on Shock-Hardening in Cu and Cu-Al Alloys," *Acta Mater.*, **49**, 3, 427 (2001); [https://doi.org/10.1016/S1359-6454\(00\)00335-9](https://doi.org/10.1016/S1359-6454(00)00335-9).
61. N. K. BOURNE and A. M. MILNE, "The Temperature of a Shock-Collapsed Cavity," *Proc. R. Soc. A*, **459**, 2036, 1851 (2003).
62. J. L. JORDAN et al., "Shock Equation of State of a Multi-Phase Epoxy-Based Composite (Al-MnO₂-Epoxy)," *J. Appl. Phys.*, **107**, 10, 103528 (2010); <https://doi.org/10.1063/1.3357314>.
63. E. N. BROWN et al., "Characterization of Shocked Beryllium," *Proc. Journal of Physics: Conf. Series*, Seattle, Washington, July 7–12, 2013, Vol. 500, 112013 (2014); <https://doi.org/10.1088/1742-6596/500/11/112013>.
64. W. T. BUTTLER et al., "Second Shock Ejecta Measurements with an Explosively Driven Two-Shockwave Drive," *J. Appl. Phys.*, **116**, 10, 103519 (2014); <https://doi.org/10.1063/1.4895053>.
65. Y. CHEN et al., "Experimental Examination of Ejecta Production on Shock-Melted Sn Targets Under Various Surface Roughnesses," *J. Dyn. Behav. Mater.*, **3**, 2, 174 (2017); <https://doi.org/10.1007/s40870-016-0089-8>.
66. M. B. PRIME et al., "Estimation of Metal Strength at Very High Rates Using Free-Surface Richtmyer-Meshkov Instabilities," *J. Dyn. Behav. Mater.*, **3**, 2, 189 (2017); <https://doi.org/10.1007/s40870-017-0103-9>.
67. R. J. LEE et al., "Techniques for Collection and Analysis of Pop-Plot Data for Use in Parameterization of Reactive Flow Models," *Proc. Shock Compression of Condensed Matter 2017*, St. Louis, Missouri, July 9–14, 2017, Vol. 1979 (2018).
68. D. C. SWIFT et al., "On High Explosive Launching of Projectiles for Shock Physics Experiments," *Rev. Sci. Instrum.*, **78**, 6, 63904 (2007); <https://doi.org/10.1063/1.2746769>.
69. F. R. SVINGALA, P. M. GIANNUZZI, and H. W. SANDUSKY, "Simple Explosive Plane Wave Booster Designs for 1-D Shock Experiments," *AIP Conf. Proc.*, **1979**, 1, 160027 (2018).
70. W. C. DAVIS et al., "Explosive-Driven Shock Waves in Argon," *Proc. 13th Int. Detonation Symp.*, Norfolk, Virginia, July 23–28, 2007, p. 1035 (2006).
71. P. RAE, "Determining Velocity of Detonation Using High-Resolution Time Domain Reflectometry," *Rev. Sci. Instrum.*, **90**, 8, 85005 (2019); <https://doi.org/10.1063/1.5100750>.
72. J. L. BELOF et al., "Rayleigh-Taylor Strength Experiments of the Pressure-Induced $\alpha \rightarrow \epsilon \rightarrow \alpha'$ Phase Transition in Iron," *Shock Comp. Condensed Matter*, **2011**, 1426 (2012).
73. R. T. OLSON et al., "The Effect of Microstructure on Rayleigh-Taylor Instability Growth in Solids," *Proc. Journal of Physics: Conference Series*, Seattle, Washington, July 7–12, 2013, Vol. 500, 112048 (2014); <https://doi.org/10.1088/1742-6596/500/11/112048>.
74. D. M. DATTELBAUM, E. K. CERRETA, and J. YOUNG, "Los Alamos National Laboratory: High Explosives Research and Development," LA-UR-19-32099, Los Alamos National Laboratory (2020).
75. T. C. POULTER, "Shaped Charge and Method of Firing the Same," 3100445, United States Patent Office (Aug. 1963).