Shock Wave and High Pressure Phenomena

James R. Asay
Lalit C. Chhabildas
R. Jeffery Lawrence
Mary Ann Sweeney

Impactful Times

Memories of 60 Years of Shock Wave Research at Sandia National Laboratories

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James R. Asay, retired
Sandia National Laboratories,
Albuquerque, NM, USA

Lalit C. Chhabildas, retired
Sandia National Laboratories,
Albuquerque, NM, USA

R. Jeffery Lawrence, retired
Sandia National Laboratories,
Albuquerque, NM, USA

Mary Ann Sweeney
Sandia National Laboratories,
Albuquerque, NM, USA

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Preface

The effort to document this history of shock wave research, entitled *Impactful Times: Memories of 60 Years of Shock Wave Research at Sandia National Laboratories*, began in the early fall of 2011. James (Jim) Asay and Lalit Chhabildas had been queried by many new staff who joined Sandia in the late 1990s and early 2000s about providing a history of shock wave technology development. To make this a comprehensive document, we decided to start from the mid 1950s, when shock wave research originated at Sandia, and carry the development of the technology and Sandia's accomplishments through to the present. *Impactful Times* includes the review of experiments in hypervelocity impact and magnetic loading to study the high-pressure response of materials, advanced models and *ab initio* theories to describe that response, and state-of-the-art computations applied to a wide range of real-world problems.

The two of us had a good knowledge of the shock wave research conducted at Sandia from the 1970s through to the present because we had joined the laboratory in the early to mid 1970s. We believed, however, that it was important to involve people who had participated in the research prior to that time as well. This was done in two ways. One was to ask those directly involved in the shock wave research back to the 1950s and 1960s to provide their personal recollections. We also talked with many of the early participants, including Lynn Barker, Al Chabai, Dennis Hayes, Roy (Red) Hollenbach, Orval Jones, Charles Karnes, Don Lundergan, Darrell Munson, and Ray Reed, to get their perspective on those early times. The other way was to invite Bob Graham to coauthor the publication, since he had initiated many of the early experimental techniques in the mid 1950s and has been a leader of shock wave research at Sandia and throughout the scientific community. Bob originally agreed to do this; however, other commitments prevented his long-term involvement. Later, R. Jeffery (Jeff) Lawrence and Mary Ann Sweeney joined the effort to produce this history. Jeff's involvement with shock wave research at Sandia dates back to 1963 when he was engaged in nuclear weapon vulnerability testing as an officer at Kirtland Air Force Base. His participation therefore provided an important part of the early history. Jeff was also closely connected to many efforts to develop the original models describing dynamic material behavior and the early computer codes for analyzing shock wave problems. A little later, Mary Ann Sweeney joined the team. As a member of the technical staff of the Pulsed Power Sciences Center at Sandia since the mid 1970s, who used Sam Thompson's computer codes in the 1970s and 1980s, and who more recently is also serving as the editor-in-chief of the annual Department of Energy (DOE) National Nuclear Security Administration (NNSA) *Stockpile Stewardship and Management Plan*, she provided knowledge of the DOE and NNSA research programs, along with technical and editing skills that not only added depth and breadth to the book but also resulted in a concise and balanced presentation.

We organized our book into two parts. Part I, "Building Shock Wave Capabilities," discusses the development of new experimental platforms at Sandia to produce precise loading conditions and novel diagnostics to probe the behavior of shocked materials, starting in the 1950s and continuing to the present. Topics also include the complementary development of theoretical and modeling activities, experimental shock wave drivers, and diagnostics development. Throughout the technical discussions, we have attempted to identify all the key players as well as the major technologies that were developed. A brief discussion of each advance is presented, along with its assessment and attributes.

To provide a more personal account of these developments, a large number of recollections are provided in Part II, "Memories of Shock Wave Research." These individual recollections present a window into the personal perspective and experience of researchers who participated in the shock wave program at Sandia. We made a strong effort to include as many people as possible. Over 80 were contacted, with around half providing their personal experiences. Each contributor was asked to summarize his or her role in shock wave research and to highlight interesting events and anecdotes that happened along the way. We purposely gave little guidance on style and format, which is why some recollections are written as a stream of consciousness while others are more technical and consist of short annotated summaries of major papers. The result is a rich and interesting mix that highlights individual personalities, personal struggles, and technical successes. The dates provided for each person represent their hiring and retirement date at Sandia; we have also made an attempt to identify the actual dates an individual participated in shock wave research. Quotations from the individual recollections are liberally sprinkled throughout the text to bring out the perspective of the research and to provide a pointer to further reading of the recollections. In some cases (e.g., Bob Graham, Walter Herrmann, Orval Jones, George Samara, and Sam Thompson), the recollections of others were used to capture the seminal contributions that individuals made to shock wave research. In summary, the technical discussions and recollections offer a unique insight into the shock wave program that covers six decades at Sandia.

A bibliography of almost 1000 references is provided for those interested in pursuing in more detail specific areas of shock wave research and technology at Sandia. The bibliography was developed by asking the contributors to the recollections to identify 20 or so of their key publications. These were used to prepare the discussion of experimental, modeling, and computational developments that occurred over each decade. In cases where people who made major contributions during that time did not provide their recollections or could not be contacted, a literature search was done to identify their significant contributions.

We also felt that attaching faces to those who participated in the shock wave program would add interest. Each of Chapters 2 through 7, which are organized by decade, contains a section at the end called "People and Places." The photographs in this section illustrate key facilities developed during the specific decade and the individuals who participated in shock wave research. It was not always possible to find a photograph for a person corresponding to the decade in which he or she did shock wave research; however, we were able to find photographs for most people at some point in their career, typically when they had achieved a specific milepost such as a promotion or had received an award or honor. While the photographs showing specific accomplishments are not complete, they are representative of the group's achievements. All photographs have been annotated, which helps put them in perspective. The photographs and the associated captions often tell a story in themselves.

The shock wave group as a whole has had a major impact in both management and technical arenas at Sandia National Laboratories and throughout the broader scientific community. Two individuals became executive vice presidents at Sandia, and one was appointed president of the Nevada Test Site (now known as the Nevada National Security Site), an organization involved with nuclear weapon testing activities. Many others were promoted to middle management positions within Sandia. Scientific accomplishments are equally wide-ranging. Three individuals within the Sandia shock wave program were elected to the National Academy of Engineering. A great many were promoted to top levels of scientific or engineering achievement at Sandia, either as a laboratory fellow, a distinguished member of technical staff, or a senior scientist; one retired from Sandia and became a Senior Technologist, a major scientific senior executive leadership and advisory position at the Air Force Research Laboratory, a large Department of Defense organization. A large number of individuals were also appointed fellows of various scientific societies and many received top awards for technical achievement in their respective scientific or engineering organizations. Another became a high-level program administrator at NNSA. These individual achievements are too extensive to report here, but the photographs in the People and Places sections provide a small glimpse into some of them. In summary, Sandia's shock wave research program has had a significant impact not only in managing technical activities but also in scientific accomplishments as part of the national and international community.

As will become apparent in our book, two major shock wave efforts have lasted for most of Sandia's history. One focused primarily on scientific aspects of shock wave phenomena, while the other emphasized engineering applications. Three of us (Asay, Chhabildas, and Lawrence) are from the engineering side, so there is a built-in bias toward this aspect of research. However, we tried to present a balanced picture of shock wave research, especially in identifying key shock wave technologies.

Also, some contributors to the recollections were involved with the science aspects of shock wave research, while others were involved with the engineering aspects of shock wave research; this gives a balanced perspective in many cases. Although we tried to be as objective as possible, we wish to apologize for any oversights that may have occurred by not recognizing specific individuals and their research.

Albuquerque, NM, USA

James R. Asay
Lalit C. Chhabildas
R. Jeffery Lawrence
Mary Ann Sweeney

Acknowledgments

Many individuals contributed to the successful completion of this book. First and foremost, we are grateful to our families and particularly to our spouses, Patricia (Pat) Asay, Annette Chhabildas, Jane Lawrence, and Edward Ricco, who patiently supported not only our careers but strongly encouraged the preparation of this book over several years. Secondly, the book would not have been possible without the contributions from researchers involved in shock wave studies who dedicated their time to prepare detailed recollections of their Sandia careers. They provided a personal touch, which became the focus for our descriptions of the technical developments in shock compression science at Sandia over the past 60 years.

Several individuals provided personal accounts that were crucial to our investigations into the early days of shock wave research at Sandia. Interviews with C. Donald (Don) Lundergan, combined with his recollections, clarified how shock wave research was organized in the 1950s; his integration of experiment, theory, and computation ultimately set the stage for the early pioneering challenges that researchers faced in bringing shock wave technology to a high-precision science. This vision for an integrated approach to shock wave research persists to the present day. Orval E. Jones complemented that early history by providing a high-level view of how shock compression science became one of the major research thrusts at Sandia. Early perspectives were also described by several researchers who helped shape the shock wave field through their innovative efforts and resulted in major advances throughout the shock wave community, while aiding Sandia's program as well. In particular, we recognize Robert (Bob) A. Graham for his groundbreaking contributions, which include the first time-resolved stress gauge that enabled many scientific and applied research applications, the initiation of research in shock chemistry at Sandia, and the founding of the Topical Group on Shock Compression of Condensed Matter as part of the American Physical Society. This topical group and its biennial conference have become the premier organization and forum for presenting and discussing shock wave research. Without these early visionary developments, our book would not have been possible. Bob was also instrumental to the development of this book by recommending initial ideas and suggestions on how a history of shock wave technologies should be organized. In addition, Lynn

M. Barker and Roy (Red) E. Hollenbach offered a unique perspective of the early history of shock wave research at Sandia by exemplifying how their innovative efforts in gun impact technologies and groundbreaking instrumentation, such as the VISAR, enabled Sandia National Laboratories to obtain and maintain leadership in the field. Albert (Al) J. Chabai, Dennis B. Hayes, and Ray P. Reed afforded additional personal perspectives of how the shock wave programs in the 1950s led to an expansion of Sandia's role to include nuclear testing at the Nevada Test Site (now known as the Nevada National Security Site).

Many others helped to investigate the early development of shock wave research at Sandia. The Sandia corporate archivist, Myra L. O'Canna, produced invaluable information by researching *Sandia Lab News* articles and archival photos of contributors who worked in the shock wave program at Sandia over the past 60 years. Her dedicated efforts clarified several issues regarding many of the individual research efforts. Marguerite E. Hess, Diana S. Gonzales, Alice Parsons, and Robert Martinez also assisted in resolving several historical questions relating to Sandia reports and copyright issues. Two corporate historians, Alan Carr at Los Alamos National Laboratory and Rebecca Ullrich at Sandia, provided information about the early years at both national security laboratories. Rebecca's efforts were also essential in locating additional archival photos.

Several investigators helped to make the manuscript more comprehensive, including (in alphabetical order) (1) Melvin (Mel) R. Baer for a descriptive rendition on the evolution of multiphase modeling of energetic materials at Sandia and a perceptive discussion of Sandia's role to help resolve the cause of the turret explosion on board the USS Battleship Iowa; (2) Mark B. Boslough for a fascinating personal account of the events leading up to the impact of the Shoemaker-Levy-9 comet on Jupiter and Sandia's participation in interpreting Hubble Space Telescope images of the event; (3) Michael (Mike) D. Furnish for a concise perspective of subcritical experiments at the Nevada National Security Site and also for his careful and diligent efforts in resolving many technical, programmatic, and publication issues; (4) Eugene (Gene) S. Hertel for an insightful and comprehensive discussion of computer code developments at Sandia National Laboratories; (5) James (Jim) E. Kennedy for laying out the events leading to an energetic materials research program at Sandia; (6) J. Michael (Mike) McGlaun for an explanation of computational developments and a firsthand narrative of Samuel (Sam) L. Thompson's contributions to computer code development at Sandia, which underlie many of the contributions to solving national and international shock wave research problems; and (7) Bruno Morosin for a detailed description of the research program initiated on solid-state shock chemistry in the 1980s.

Several researchers from other laboratories were also extremely helpful in preparing the book, including (in alphabetical order) (1) Eric L. Christiansen of NASA, Johnson Space Center, Houston, TX, for assistance in providing information on the space debris program; (2) John R. Cogar, Corvid Technologies, Mooresville, NC, and Brian L. Kiser, Naval Surface Warfare Center, Dahlgren Division, VA, for advice and for providing a graphic illustrating the technical issues related to high-velocity engagements of weapon systems; (3) Jerry W. Forbes, senior scientist at

Energetics Technology Center, St. Charles, MD, for advice on publishing shock wave physics books; (4) Christopher (Kit) H. Neel and David E. Lambert, Munitions Directorate, Eglin Air Force Base, Eglin, FL, who researched several technical issues regarding shock wave publications; and (5) William (Bill) J. Nellis, Harvard University, Cambridge, MA, for providing another perspective of Bob Graham's leadership and seminal contributions to the field of shock compression science.

The document could not have been completed without the support of many people, including (in alphabetical order) (1) Laveryn L. Apodaca for assistance in preparing parts of the manuscript, (2) Steven R. Asay for providing graphics support and preparing several of the figures used in the book, (3) Michael Beckett and Madelynne J. Farber for legal assistance in resolving copyright issues and providing advice on our negotiation of the contractual agreement with the Springer publishing company, (4) Darren L. Buie and Luis Paz for carefully reviewing all the individual recollections and chapters for classification and other sensitive issues, and (5) Amy L. Lucero for her assistance in organizing the bibliography for use in the manuscript.

Finally, we would like to acknowledge John M. Taylor for a thorough reading of the manuscript and for making concise recommendations to improve the accuracy of presentation and to clarify historical events. We also express our deep appreciation to the management and staff of Sandia National Laboratories, particularly in the Pulsed Power Sciences Center, for providing support and exhibiting strong interest in the completion of this book.

Contents

Part I
Building Shock Wave Capabilities

Chapter 1
Introduction

1.1 Sandia's Roots

The origin of Sandia National Laboratories began with World War II and the Manhattan Project.[1] Prior to the United States entering the war, the U.S. Army leased land then known as Oxnard Field on the desert outskirts of Albuquerque, New Mexico, to refuel and service Army and Navy aircraft in transit. In January 1941, the construction began on the Albuquerque Army Air Base, leading to the establishment near the end of the year of the "Bombardier School—Army Advanced Flying School." Shortly afterward the base was renamed Kirtland Field, after the Army military pilot Colonel Roy S. Kirtland and, in mid 1942, the Army acquired the installation. During the war, Kirtland Field expanded and served as a major Army Air Corps training installation.

General Leslie Groves and Dr. Robert Oppenheimer codirected the Manhattan Project.[2] Two major components of the Manhattan Project were Project Trinity and Project Alberta. Project Trinity prepared for the detonation, on July 16, 1945, of the first nuclear bomb (nicknamed "the Gadget") at the Trinity Site in New Mexico. Project Alberta involved the assembly, testing, arming, and delivery of the first airborne nuclear weapon (nicknamed "Little Boy"), a uranium gun-type nuclear

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[1] For additional details about Sandia's roots and early years, see the first externally published volume of the history of Sandia, by Necah Stewart Furman, *Sandia National Laboratories: The Postwar Decade* (University of New Mexico Press, Albuquerque, 1990). That 858-page treatise includes extensive notes and a substantial bibliography. See also Leland Johnson, "Sandia National Laboratories: A history of exceptional service in the national interest," ed. by C. Mora, J. Taylor, R. Ullrich, Sandia National Laboratories Report SAND97-1029, Albuquerque, NM, 1997.

[2] *Los Alamos National Laboratory: A Proud Past, an Exciting Future* appeared in 1995 as a special issue of *Dateline Los Alamos*, a monthly publication of the Public Affairs Office of Los Alamos National Laboratory. That 50-year Trinity anniversary issue provides an interesting retrospective with many recollections and photographs.

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device, to Hiroshima on August 6, 1945. "Fat Man," a plutonium implosion-type device, was delivered to Nagasaki 3 days later.

During the Manhattan Project, engineering activities at Project Y or Site Y,[3] the high-mesa hideaway in the Jemez Mountains northwest of Santa Fe, were carried out by "Z Division." Z Division was named for the division head, Jerrold Zacharias, a professor from the Radiation Laboratory at the Massachusetts Institute of Technology. The division was conceived as an ordnance design, testing, and assembly arm of the nuclear bomb program. In July 1945, the site of this forerunner of Sandia National Laboratories was established in Albuquerque to handle weapon development, testing, and bomb assembly.

Near the end of the war, Groves and Oppenheimer faced the challenge of turning the nuclear bomb effort into an operation to produce and maintain the Nation's stockpile and develop peaceful uses of nuclear energy. Space at Site Y was then at a premium. Moreover, the members of Z Division needed to work closely with the military, and the remoteness of the site made transport of weapon components difficult. In addition, to encourage personnel to stay after the end of the war, Groves and Oppenheimer decided to focus what became the Los Alamos Scientific Laboratory on weapon design and to relocate the weapon production and assembly elsewhere. In the several months before July 16, Oppenheimer began looking for a location to continue that weapon engineering work—especially its non-nuclear aspects. Kirtland Field had served the transportation needs for Projects Trinity and Alberta, hence, the decision to relocate Z Division there permanently. The military base was therefore transferred from the Army Air Corps to the U.S. Army Service Forces Chief of Engineering District and assigned to the Manhattan Engineer District of the War Department.

By the close of the war, Z Division had begun to consolidate weapon assembly at the Albuquerque site. By 1946, the site was known as "Sandia Base," after the nearby Sandia Mountains.[4] Figure 1.1 is an early photograph that includes the Albuquerque site. From 1947 to 1971, Sandia Base was the principal nuclear weapon installation of the U.S. Department of Defense (DOD). Over that period, nuclear weapon research that included development, design, testing, and training initiated by the Manhattan Project was conducted there and its subsidiary, Manzano Base. Fabrication, assembly, and storage of weapons were also performed at Sandia Base. In 1971, Sandia Base was merged into Kirtland Air Force Base.

By April 1, 1948, Z Division had grown to about 500 people and was renamed Sandia Laboratory. By mid 1948, it grew to around 1000 employees. On May 13, 1949,

[3] During the war, the term "Los Alamos" was not used to ensure secrecy. The earliest official reference to Los Alamos Scientific Laboratory, according to Alan Carr, the Los Alamos National Laboratory historian, was in mid October 1945. The name was changed to Los Alamos National Laboratory on January 1, 1981.

[4] These mountains were named for the Spanish word for watermelon because, as viewed from the west, they turn that color at sunset in the winter.

Fig. 1.1 Kirtland Army Air Base is in the foreground with Sandia Base in the background (1945). The Sandia mountains are visible in the far left background (Reprinted with permission of Sandia National Laboratories)

President Harry S. Truman sent a terse letter to Leroy Wilson, the president of the American Telephone and Telegraph Company (AT&T).

> I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico. This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction…. In my opinion, you have here an opportunity to render an exceptional service in the national interest….

On November 1, 1949, a no-fee contract was established with AT&T to manage Sandia Laboratory through Sandia Corporation, an AT&T subsidiary. In 1979, the U.S. Congress designated Sandia as a national laboratory. The AT&T contract to operate Sandia remained in effect until October 1993. At present, Sandia National Laboratories[5] (SNL) is managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation.

1.2 Science and Engineering[6]

Sandia's urgent task after the war was to build a stockpile of nuclear weapons. The early nuclear weapons were carried by subsonic aircraft. At that time, the structural and environmental requirements did not differ substantially from conventional weapons. Hence, the existing engineering procedures and materials for system design were sufficient, but nuclear weapons had stringent reliability and safety requirements. The engineering groups at Sandia actively developed innovative safety concepts and conducted extensive tests for operational reliability during this period. Parachutes to permit delayed delivery, weak-link and strong-link safety systems, and reliable barometric and contact fuzing were among the new subsystems that had to operate in all environments.

The advent of supersonic and exoatmospheric missile delivery systems imposed more demands. Addressing these issues required understanding the effects of adverse environments on components and subsystems. A major issue was the effect of radiation-produced shocks during a nuclear burst. The low-energy x-ray radiation often caused material ablation, and the ensuing shock waves could cause major damage. The resulting stress waves propagated through materials and often produced component or subsystem failure, which could preclude proper weapon reentry and operation. Resolving this issue required knowledge of the stress levels produced by the radiation pulse and the tensile failure strength (referred to as "spallation strength") of a broad range of materials. Knowledge of mechanical response, such as elastic–plastic behavior, did not exist at the stress and loading rates (usually referred to as "strain rates") experienced in these environments. Extrapolation of material response from low strain rates and stresses using the highest loading rates available at the time (typically provided by Hopkinson bars[7]) was not reliable. The extensive shock wave research at Los Alamos during and after the Manhattan Project provided information on the high-pressure equation of state (EOS) properties but essentially no

[5] Sandia operates laboratories and testing facilities in Albuquerque, New Mexico, in Livermore, California, at the Tonopah Test Range in Nevada and at the Kauai Test Facility in Hawaii. Sandia also has offices in Carlsbad, New Mexico (the Waste Isolation Pilot Plant), in Mercury, Nevada (to support the Nevada National Security Site), in Amarillo, Texas (the Weapons Evaluation Test Laboratory), and a program office in Washington, D.C.

[6] Much of the material in this section was summarized from the recollections of C.D. Lundergan, B.M. Butcher, A.J. Chabai, and R.P. Reed in Part II.

[7] Hopkinson bars provided data at loading stresses of a few kbars and strain rates up to about 1000/s.

information on mechanical properties in the tens of kbars[8] range and at loading times of less than 1 μs.

The response of materials subjected to impacts associated with delivery velocities and defensive countermeasures was also important. For reliable operation, the subsystem or component had to retain its integrity for several microseconds after impact with the ground or other structures or after activation of contact and other weapon fuzes, to prevent deformation and destruction. Hence, this issue concerned how large amplitude stress waves propagated through many materials.

Weapon systems were also becoming more complex as component miniaturization evolved. Furthermore, operation of a weapon was sequential, with each component operating fully before the next one was started. Hence, the size and timing were critical to weapon delivery. Coupled with miniaturization, another critical factor was the energy to power components such as gyros, triggers, and radar. All required power, either electrically or through mechanical actuation. Weapons would usually be stored for long periods and then have to function without failure. Small, on-board explosive devices were attractive since they could be stored and then detonated to produce significant power on demand.

The propagation of stress waves generated by the detonation of explosives can cause damage to adjacent components and subsystems. How the stress waves were generated and spread through the weapon system had to be determined. A basic understanding of solid material response at a few kbars and at high loading rates for engineering models did not exist.

The myriad issues facing weapon designers and the need to understand material properties prompted shock wave research on the following topics:

1. Dynamic response of mixtures, composites, and polymers in explosive power supplies to predict stress limits and operational times
2. Electromechanical effects and operational limits from shock loading piezoelectric and ferroelectric (FE) materials
3. Energetic materials for detonators and explosive power supplies
4. Pulsed radiation effects on weapon structures and components
5. Ground shock effects from nuclear explosions in geological media and the effects on above- and below-ground structures
6. Compaction behavior of porous materials for shock cushioning of components and subsystems
7. Time-resolved gauges to quantify material response to pulsed radiation

By the mid 1950s, Sandia management decided to establish a research program modeled after AT&T Bell Laboratories to support these engineering applications. An immediate outcome was the formation of the Physical Sciences Department and the Physical Research Department in the Research Directorate managed by Stuart C. Hight. By 1957, each department had 30 to 40 researchers in several scientific

[8] 1 kbar = 1000 atm or 14,500 lb per square inch (psi). The pressure units of kbar and Mbar (1 Mbar = 1000 kbars) are used throughout the text, although some figures show pressure in gigapascals or GPa (1 GPa = 10 kbars = 0.01 Mbar).

disciplines. The Physical Sciences Department under Richard Claassen was engaged in fundamental research, and the Physical Research Department under George Hansche was engaged in applied research. Other departments in the Research Directorate included the technical areas of weapon effects, mathematics, and aerodynamics.[9]

Two visionary individuals profoundly influenced the early and subsequent development of shock wave research at Sandia. One was Frank W. Neilson, and the other was C. Donald Lundergan. Neilson initiated a research effort in the mid 1950s to understand the response of FE ceramics to shock loading. That effort resulted in the ground-breaking development of time-resolved stress gauges.[10] As a division supervisor, Neilson recruited Orval Jones from the California Institute of Technology. Jones then played a major role in the development and application of shock wave research at Sandia.

On the engineering side, Charles Bild, Director of Materials and Process Development, also encouraged and strongly supported shock wave research for weapon component and system development. At the request of Leon Smith, manager of the Electrical Systems Department in that directorate, Lundergan was asked in 1957 to perform projectile impact experiments with an air-driven gun on contact fuzes that were being developed. This work laid the groundwork for a new program to measure the dynamic response of materials under precisely controlled impact conditions (see Chap. 2). Lundergan recognized the critical importance of the emerging shock wave technology to Sandia's mission and proposed a comprehensive plan for a new department focused on all aspects of the technology (theoretical modeling, computational capability, and experimental research). In 1959, he recruited Lynn Barker who, along with Roy (Red) Hollenbach, had a profound influence on the development and application of experimental shock wave techniques.[11] Later, in the mid 1960s, Lundergan recruited Walt Herrmann from the Massachusetts Institute of Technology (MIT) to initiate a program in material modeling and the development of hydrodynamic computer codes. Herrmann was successful in this challenging assignment and in closely coupling these activities to a strong experimental program, as discussed in the following chapters.

A third technical area at Sandia in which shock wave technology has played an important role is geological materials. Since its formation, Sandia has participated with the other two national security laboratories, Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL),[12] in field testing

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[9] These details are from a private discussion with Orval Jones in 2012. A tribute to Orval is included in Part II.

[10] This information is from Bob Graham's commemoration of George Samara's work at Sandia (George Samara Memorial Symposium, Sandia National Laboratories, on May 18, 2007. Bob's *in Memoriam* is included in Part II.

[11] Lynn Barker took a leave of absence to study for a PhD in physics at Cornell University in 1961 but returned to Sandia in 1962 after his wife became very ill.

[12] The laboratories have been known by those names since 1981. These acronyms are used in the rest of the text.

nuclear weapons. Aboveground testing was common until October 10, 1963, when the United States, Britain, and the Soviet Union signed a treaty on banning nuclear tests in the atmosphere, oceans, and space. Sandia continued to participate in underground tests at the Nevada Test Site[13] (NTS) led by its two sister laboratories.

Several Sandians made significant contributions to the national defense posture through nuclear testing in the early years, including Bob Bass, Carter Broyles, Ronald Carlson, Albert Chabai, Hunter DeVault, Doris Hankins, Bill Perrett, Carl T. Smith, and Luke Vortman. An important contribution was a new gauge technique to estimate the yield of nuclear weapons. In the early 1960s, Bass and Chabai adapted the SLIFER[14] technique, originally developed at LLNL, to obtain continuous shock wave attenuation data in geological materials (e.g., volcanic tuff, granite, desert alluvium, and salt). Bass and Chabai discovered a universal power–law relationship for shock position versus arrival time as a function of yield that was independent of the geological materials. Bob Brownlee of Los Alamos used the Sandia SLIFER technique and this relationship on many nuclear events at NTS, since it could provide yield estimates within an hour after the detonation of a device.

With the end of the Cold War and the Comprehensive Test Ban Treaty (CTBT), which has been signed but not yet ratified and so is not yet in force, all underground nuclear testing was discontinued. Since then the National Nuclear Security Administration (NNSA) has relied mainly on the Stockpile Stewardship Program (SSP) to sustain and assess the safety, security, and effectiveness of the stockpile through advanced computing and development of complex models based on laboratory experiments, without the use of underground nuclear tests. An extraordinary set of science, technology, and engineering facilities supports the SSP. At Sandia, the Z pulsed power facility and the Shock Thermodynamics and Applied Research (STAR) facility, in particular, support shock physics studies for materials of interest. These contributions are discussed in more detail in Chaps. 6 and 7.

1.3 Building Capability in Shock Wave Research

The decision to initiate a shock wave research program at Sandia was instrumental in the rapid development of capabilities to address a wide range of weapon science and basic science problems. In the mid 1950s, a small ongoing effort involving shock waves was directed toward understanding how the electrical output of FE crystals responded to dynamic impact, such as shock loading by small explosive charges. The motivation for that research was the need to develop various components, including explosively actuated power supplies, to detonate the nuclear weapon.

[13] The Nevada Test Site was renamed the Nevada National Security Site (NNSS) in August 2010.

[14] SLIFER is an acronym for Shorted Location Indicator by Frequency of Electrical Resonance.

1.3.1 Advances in Experimental, Diagnostic, and Modeling Capabilities

The pioneering team of Frank Neilson, Bill Benedick, and Bob Graham began by investigating the electrical output of FE ceramics subjected to shock loading. Barium titanate was one of the first materials studied to understand how loading conditions, such as peak stress and loading times, generated the electrical output. Understanding the coupled mechanical and electrical response required experiments with carefully controlled loading conditions. Precision diagnostics were also needed to measure the input stress and electrical time histories; controlled shock wave techniques and instrumentation were just beginning to become available in the mid 1950s.

The simplest configuration to produce well-controlled shock compression is planar loading of a thin disk. In this configuration, a planar shock wave propagates through the disk and is detected when it arrives at the back surface, thereby determining the shock velocity. In general, measurements are made of the shock velocity and either the input shock pressure or particle velocity produced by the shock wave.[15] These two quantities can then be applied in the equations for planar shock motion to determine the pressure and density, or the specific volume (inverse density), produced in a sample. By performing experiments at different initial shock pressures, a locus of pressure–density points is obtained, which is referred to as the Hugoniot curve for the material. This curve is used to develop material models to describe the dynamic response for various applications.

Facilities for laboratory shock wave experiments were extremely limited in the 1950s. The first experiments at Sandia were conducted with the high explosive (HE) loading technique developed as part of the Manhattan Project. Explosive shock wave generators, known as plane-wave lenses, were used to generate the high shock pressures. Similar techniques, but scaled to lower pressures, were used by Neilson's team. Accurate diagnostics, mainly time-of-arrival shorting pins that had been developed to detect the arrival of the shock wave at the back surface of a sample, were also used. In addition, the shock or mechanical response and the electrical output of FE materials were determined to quantify the coupled electromechanical behavior.

The HE experiments were conducted outdoors at a remote site in Tech Area III, about five miles south of Tech Area I at Sandia. In the mid 1960s, this effort evolved into a major thrust within the Physical Research Department that focused on the physics and chemistry of shock compression for a broad range of materials. The development and application of this work are discussed in more detail in Chaps. 3, 4, and 5.

[15] A longitudinal stress state is produced in a solid under planar loading. In a fluid, this is the pressure. In a solid, the difference between the two states is two-thirds of the yield stress of the solid, which is generally small, so stress and pressure are similar in most cases. Stress and pressure are used interchangeably throughout this book unless it is necessary to distinguish between the two in some discussions.

In parallel with shock wave research on FE materials, a similar program began in another organization to understand the response of contact fuzes and other weapon components and systems. This experimental effort under Don Lundergan began a few years after the explosives work on FEs and at first focused on the mechanical behavior and engineering aspects of component response. Along with Lundergan, Lynn Barker and Red Hollenbach were the principal participants in that parallel effort, which began around 1957.

Instead of explosive charges, in 1958 Lundergan took a different approach that had a lasting influence on shock wave research, not only at Sandia but in the entire shock wave community. He used a 100-mm-bore compressed air gun to accelerate a projectile with controlled velocities up to about 0.3 km/s that, upon impact, produced planar shock waves in a flat-disk target. The air gun was a “hand-me-down” that had been used to test the effects of impacts on weapon components. Precise perpendicular impact with minimal “tilt” was achieved by accurate boring and polishing of the gun bore, designing projectiles with flat, normal impact plates, and precisely aligning flat target samples to the normal impact plates. In addition, the use of compressed air as an accelerant rather than explosives avoided several operational restrictions, such as the location of the experiment and safety regulations associated with explosives. Later this gun was upgraded to use helium gas, which increased the impact velocity, and was moved to more comfortable quarters in Tech Area I as an all-weather indoor facility.

Lundergan’s initial air-gun launcher marked the start of a family of precision guns for material property studies and also prompted their development at other institutions, as described in Chap. 2. Figure 1.2 summarizes the development of gun capabilities at Sandia. In 1961, Bob Graham developed a 40-mm-bore powder gun for increased velocity (Graham, Ingram, and Ingram 1961). Somewhat later, Graham developed a helium gun to launch projectiles to about 1 km/s (Graham 1961a). This was a major achievement in shock wave experiments at the time. In 1969, Darrell Munson and Ray Reed implemented an 89-mm-bore powder gun that doubled the launch velocities to over 2 km/s, providing impact pressures of several hundred kbars. A few years later, Bob May achieved a major advance in launcher capability with the construction of a two-stage light-gas gun (Munson and May 1975), which tripled the velocity to over 7 km/s and gave impact pressures of 3 to 4 Mbars. Around 1990, Lalit Chhabildas invented a three-stage launcher, the HyperVelocity Launcher (HVL), which more than doubled the velocity to 16 km/s, as described in Chap. 5 (Chhabildas et al. 1992, 1995).

Along with the rapid advances in facilities, diagnostics for precision measurements advanced quickly. The initial instrumentation for measuring shock wave properties consisted primarily of electrical shorting pins of different heights on the back surface of a shocked sample. Shorting of the pins determined the displacement versus time history produced by a shock wave and thus the shock velocity (Smith and Barker 1962). This simple technique was not optimal for determining the structure of the shock wave. To provide more detail about the shock structure, Barker and Hollenbach devoted intense efforts to measuring the free-surface displacement continuously. Both a slant-wire resistor (Barker 1961, 1962; Barker and Hollenbach 1964) and displacement

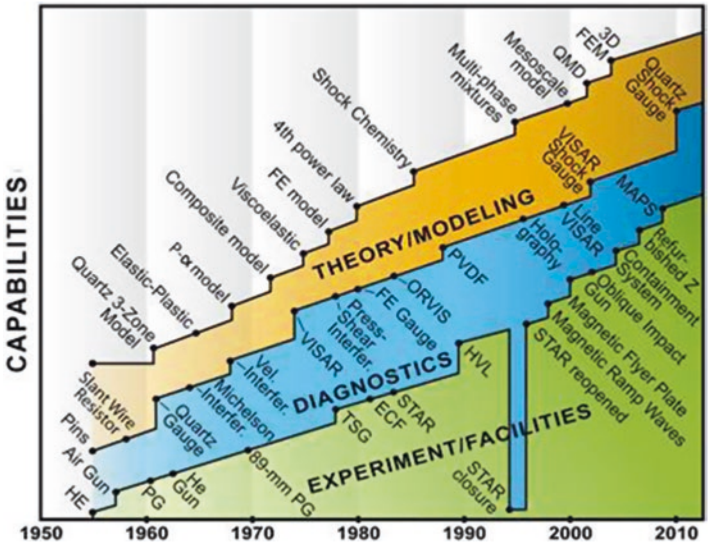

Fig. 1.2 Development of shock wave capabilities at Sandia. The large drop in experimental capabilities in 1994 resulted from the management decision to dismantle the STAR facility and eliminate all associated experimental activities. Acronyms used in the figure are: ECF (Explosives Component Facility), FE (ferroelectric), FEM (ferroelectric model), HE (high explosive), HVL (HyperVelocity Launcher), MAPS (magnetically applied pressure shear), ORVIS (Optically Recorded Velocity Interferometer), P-α model (model for response of porous materials), PG (powder gun), PVDF (polyvinylidene difluoride), QMD (quantum molecular dynamics), STAR (Shock Thermodynamics Applied Research), TSG (Two-Stage light gas Gun), VISAR (Velocity Interferometer System for Any Reflector)

interferometer techniques (Barker and Hollenbach 1965) were developed, as illustrated in Fig. 1.2. These developments are discussed in Chap. 3.

Two ground-breaking innovations in the 1960s discussed in Chap. 3 were the X-cut quartz gauge to measure stress directly (Neilson and Benedick 1960) and an interferometer technique to measure the particle velocity produced by a propagating shock wave (Barker 1968). Neilson, Benedick, and Graham's quartz gauge advance (Neilson and Benedick 1960; Neilson, Benedick, Brooks et al. 1962; Graham 1961b, 1975) provided a continuous measure of shock pressure (which is also referred to here as stress) versus time (i.e., a time-resolved shock profile). A game-changing advance in instrumentation was the 1972 invention of the VISAR (Velocity Interferometer System for Any Reflector), which allowed detailed shock wave studies of any material (Barker and Hollenbach 1972). These two innovations impacted shock wave research worldwide.

These applications include:

- dynamic elastic yielding,
- dynamic compressive and tensile strength,
- determination of phase changes produced by shock compression and the associated transformation kinetics,
- initiation and growth of energetic reactions,

- optical properties under shock compression, and
- effects of nonhomogeneous material properties on planar shock compression.

Other major advances followed the VISAR, including

- ORVIS (Optically Recorded Velocity Interferometer System),
- the piezoelectric polymer PVDF (polyvinylidene difluoride),
- the Line VISAR,
- dynamic holography for measuring nonuniform material motions, and
- the use of X-cut quartz as a shock velocity vs. time profile gauge, rather than as a stress vs. time (or particle velocity vs. time) profile gauge, at pressures exceeding 3 Mbars to measure shock velocity directly (Knudson and Desjarlais 2009).

All these developments are discussed further in subsequent chapters

Dynamic material models to predict the response for materials of interest to the Sandia weapons program (e.g., metals, viscoelastic materials, geological materials, mixtures and composites, ferroelectric and piezoelectric materials, porous materials, and explosives) were not available in the mid 1950s and early 1960s. The rapid advance in experimental capabilities led to new models to understand the fundamental deformation mechanisms and to predict how a material or component would respond to shock loading. The modeling deficiency was explicitly addressed in the 1960s, beginning with Neilson's three-zone model of the electrical response of shocked piezoelectrics (Neilson and Benedick 1960). That model had a major impact on the development of materials for shock wave gauges. Other models developed in this period were elastic–plastic models for metals, composite models for mixtures and laminated materials, models for energetic materials, and models for dynamic failure and fragmentation. Moreover, in the 2000s *ab initio* models, such as quantum molecular dynamics (QMD), began to predict very high pressure EOS response. Figure 1.2 above summarizes the progress in developing a theoretical understanding of shocked materials. That progress required integration of three activities: experimental advances, diagnostic development, and advances in theoretical modeling, as discussed in subsequent chapters.

1.3.2 Advances and Applications of Computational Capabilities

The development of realistic models for shock wave response allowed detailed analysis and prediction of the performance of weapon components and systems during dynamic loading. However, this step required advanced computer codes to simulate configurations in three dimensions and computers with sufficient speed and memory to perform simulations of complex configurations. Fortunately, both tools were developed in the same time frame as the shock wave capabilities in Fig. 1.2, thereby allowing increasingly larger and more realistic simulations. Figure 1.3 summarizes the major advances in codes and computer capabilities from the 1950s to the present.

In the 1950s and to some extent the 1960s, the computer capabilities and simulations for modeling shock wave propagation had not advanced to the point where com-

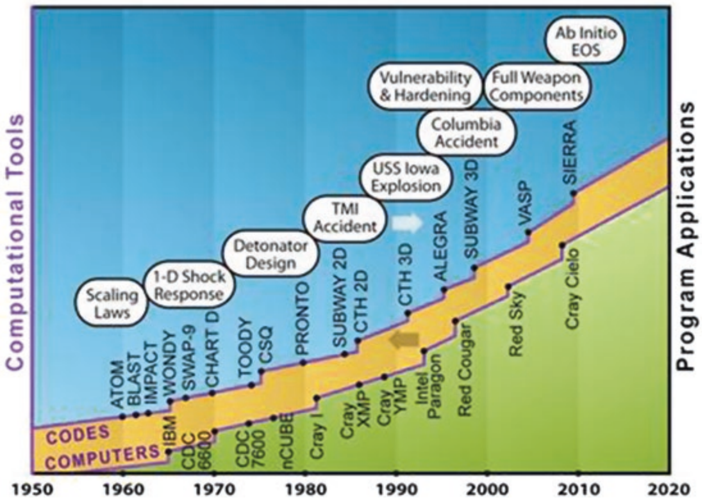

Fig. 1.3 Hydrodynamic computer codes (blue background) and main frame computers (green background) used for shock wave simulations. Acronyms used in the figure are: 1-D (one-dimensional), ALEGRA (Arbitrary Lagrangian Eulerian General Research Applications), CDC (Control Data Corporation), EOS (equation of state), IBM (International Business Machines), TMI (Three Mile Island). Balloons with white backgrounds identify a few major applications of Sandia analytical and computational capabilities used during the corresponding time periods

plex problems—such as crater formation from an explosive blast, underground shock propagation and interaction with a structure, or coupled radiation-shock response—could be simulated in realistic geometries. In the early years, many of the problems had to be addressed with a variety of scaling laws. With the rapid advances in simulation codes and more powerful computers, the situation began to change in the 1960s.

During this period, mainframe International Business Machines (IBM) computers were available, although they were limited by speed and memory that restricted their use to simple problems such as the design and analysis of planar shock wave experiments or one-dimensional (1-D) approximations of weapon components. In addition, the material models and the codes (usually referred to as "hydrodynamic codes" but sometimes as hydrocodes) were not available. In the mid 1960s, the only codes to simulate shock wave problems were the 1-D code WONDY, a finite-difference Lagrangian code, and SWAP-9, a characteristics-type code that tracked shock waves.

From the early 1950s to the early 1970s, the capability of mainframe computers grew a thousandfold, consistent with Moore's law,[16] which predicts a doubling of computing capability every 18 months. The Control Data Corporation (CDC) machines introduced in the early 1970s provided a major advance in computing power to develop the next-generation hydrodynamic codes, namely, the two-dimensional (2-D) codes TOODY and CSQ, as identified in Fig. 1.3. Sandia purchased a CDC 6600, considered to be the first supercomputer, around 1970. By

[16] What became known as Moore's law was published in the April 19, 1965, issue of the monthly magazine *Electronics*, by Intel co-founder Gordon Moore.

1976 two CDC 6600-class computers were available. Later, a CDC 7600-class computer was acquired, which was about ten times faster than the CDC-6600 and had 512 kbytes of memory. With these computers, the hydrocodes TOODY and CSQ solved increasingly complex problems, such as the hypervelocity impact of a nylon ball onto a steel plate or analysis of concrete rupture during the Three Mile Island (TMI) accident in 1979. The purchase of a Cray 1, with 8 Mbytes of memory, in the early 1980s significantly increased the capability to perform large shock wave problems.[17] The next large computer at Sandia was the Cray XMP, followed by a Cray YMP in the late 1980s. These machines had the capability to store the very large databases required for large numerical simulations.

The Cray YMP was followed by the massively parallel processing (MPP) computers in use today. The first MPP computer at Sandia was the Intel Paragon, which figured prominently in solving several large shock wave problems. The first production MPP computer for solving shock wave applications was the Accelerated Strategic Computing Initiative (ASCI) Red machine. Sandia researchers now routinely use the Cray Cielo supercomputer at LANL for the largest shock wave calculations. Cielo is ten million times faster than the Cray 1.[18]

The enormous increase in computing power over the last several decades has had a profound impact on the complexity, size, and type of shock wave problems that can be analyzed. The top part of Fig. 1.3 highlights a few of the many applications possible because of the increased capabilities. In the 1950s and early 1960s, scaling solutions were often used to predict the effects of complex shock wave propagation in geological media or the damage to structures by large explosions. In the mid-to-late 1960s, WONDY and SWAP-9 began to be used for 1-D shock response simulations, including the design and analysis of experiments and some weapon applications. Porous material crush up was of particular interest to the weapons program and could be predicted with WONDY, as discussed in Chap. 3.

In the 1970s, CSQ and TOODY simulated several important weapons problems as well as problems of national import, including the TMI nuclear reactor accident (discussed briefly in Chap. 4); in the late 1980s, as discussed in Chap. 5, the CTH code was used to analyze the turret explosion aboard the USS Iowa. The combined development in the early 1990s of three-dimensional (3-D) hydrodynamic codes, such as CTH, and the advent of fast MPP computing enabled a greater range and increased complexity of applications that could be addressed. Notable examples include analysis of the Shoemaker-Levy comet impact on Jupiter and missile intercept lethality, both of which are discussed in Chap. 6. The Jupiter impact simulation provided estimates of crater size and impact plumes, allowing observers on the Earth to interpret the astronomical observations obtained with the Hubble telescope. In the 2000s, these capabilities determined that the cause of the Columbia shuttle disaster was foam debris from the fuel tank impacting the orbiter wing.

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[17] An interesting aside is that the 2011 Smart Phone is equivalent in computer power to the early 1980s Cray 1.

[18] The fastest computer now available, LLNL's Sequoia, is about a thousand times faster than that predicted by Moore's law (Bob Schmitt, Sandia National Laboratories, 2013).