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Impactful Times: Memories of 60 Years of Shock Wave Research at Sandia National Laboratories

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Abstract. Sandia National Laboratories' origin began during World War II. In July 1945 our forerunner, Sandia Base, was established to develop, test, and assemble non-nuclear parts of weapons. Shock wave research became essential in the 1950s with the advent of supersonic and exoatmospheric missiles. A major concern was effects of radiation-produced shocks on materials. As a result, we developed a wide range of experimental, diagnostic, modeling, and computational capabilities. These have addressed complex issues related to both weapons and basic science. Notable applications have included analysis of the cause of the turret explosion aboard the USS Iowa and predicting the response to the Shoemaker-Levy comet impact on Jupiter. Six decades later, our research encompasses all aspects of material science from high energy density physics to low density plasma surface interactions.

INTRODUCTION

The forerunner of the national security laboratory now known as Sandia National Laboratories was established near the end of World War II when the Z Division associated with Project Y of the Manhattan Project moved from what is now called Los Alamos National Laboratory to Sandia Base in Albuquerque, New Mexico. Production, test, and assembly of nuclear weapon components was easier in Albuquerque, which had ready access to transportation and the military at Kirtland Army Air Base. A major concern at Sandia was to ensure the weapons would operate safely and reliably if deployed and could not be detonated unintentionally. The response of materials to dynamic loading at tens of kbars in periods less than a μs was not understood at Sandia or elsewhere at that time. Hopkinson bars could provide data at stresses of just a few kbars and strain rates of 1000/s. Rapid growth of shock wave research occurred at the laboratory in the 1950s and early 1960s. New experimental techniques and diagnostic tools were developed to measure the material response, and methods were developed to model and simulate the resultant behavior. Methods to produce shock loading were limited to planar explosive loading and plate impact loading, as illustrated in Fig. 1. With gas guns as precision impact launchers, use of explosive methods declined. The first light gas gun was developed at the New Mexico Institute of Mining and Technology in Socorro, New Mexico [1]. Figure 2 shows a photo of Sandia's original air gun, which was a modified artillery gun, and schematics of an early gas gun and later two-stage gun. By using helium instead of pressurized air in the gas gun, the launch velocity increased from ~0.3 km/s to ~1 km/s in the early 1960s. By substituting a propellant and including a piston to compress the gas in a conical section, the velocity increased to 8 km/s in the 1970s. Improvements in ensuing decades increased the velocity to 12 km/s (Hypervelocity Launcher), 20 km/s (Enhanced Hypervelocity Launcher), and 46 km/s (magnetic flyer).

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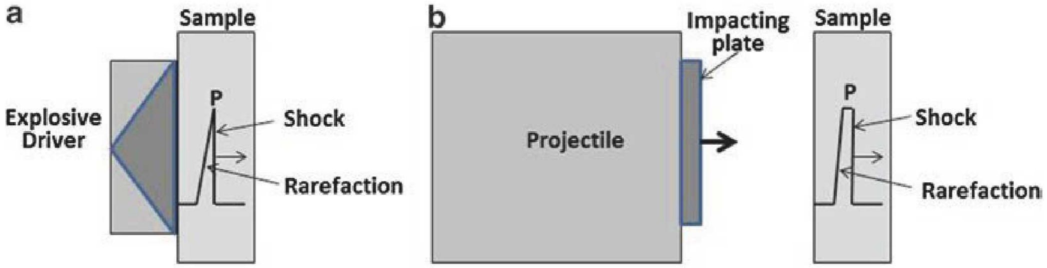


FIGURE 1. Explosive and plate impact methods to shock load sample. a) For planar explosive loading, a slow explosive is used in the dark region and a fast explosive in the two light regions on either side. Explosive loading produces a sharp increase in pressure. Shock velocity is determined from transit time through the sample and pressure from a stress gauge. A rarefaction wave travels faster than the shock front and attenuates it, making study of material properties at a given pressure difficult. b) For plate impact loading, shock wave amplitude is constant until a rarefaction wave catches up with the shock and attenuates it; hence, properties can be measured more accurately until that occurs. In both cases, only unperturbed region at sample center produces good data. (Reprinted from Asay *et al.* 2017, Fig. 2.6, Copyright 2017, with permission of Springer Science + Business Media)

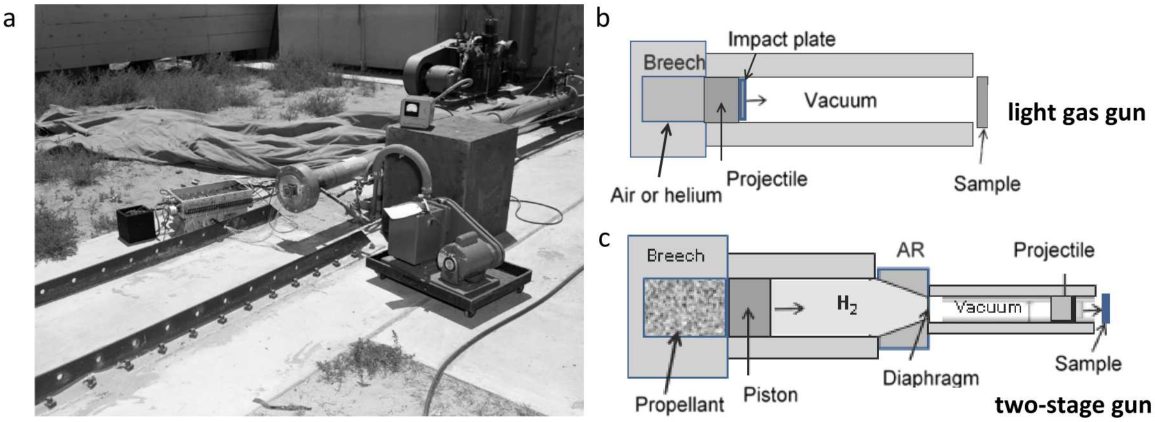


FIGURE 2. a) Sandia's first gun launcher constructed for precision shock wave research. The gun fired samples across the mesa at ~0.3 km/s into a sawdust-filled bunker. (June 27, 1958 photo reprinted with permission of Sandia National Laboratories) Schematics of b) Don Lundergun's light gas gun and c) a two-stage light gas gun, showing a conical acceleration reservoir (AR). (Reprinted from Asay *et al.* 2017, Fig. 2.9, Copyright 2017, with permission of Springer Science + Business Media)

EXPLOSIVE GROWTH IN DIAGNOSTICS, MODELING, AND SIMULATION

The emphasis of early research was on the response of ferroelectric and piezoelectric materials subjected to shock loading. Frank Neilson, Bill Benedick, and Bob Graham conducted experiments with explosive plane wave generators and gas guns and developed a three-zone model to predict the current produced in piezoelectric crystals by shock compression [2, 3, 4]. The extreme environments required stress gauges to resolve shock wave structures at ns resolution. Frank, Bill, and Bob shared a patent [5] for the quartz gauge (Fig. 3) that provided quantitative data.

Don Lundergan's group concentrated on techniques in the 1960s to obtain accurate particle velocity data at the back surface of a shocked material. Lynn Barker developed a slant-wire resistor gauge in 1961 and a velocity interferometer later in the decade that used a laser to measure particle velocity directly via the fringe shift. Barker then invented the Velocity Interferometer System for Any Reflector (VISAR) in 1972 [6]. The VISAR optically differentiates the reflected laser beam from a diffused surface, using two optical delay legs and photomultiplier tubes to record the fringe images (Fig. 4). The VISAR can make equation-of-state measurements and evaluate shock-induced phase transitions, stress loading and unloading, material compaction, and spallation of metals. Figure 5 shows data on the $\alpha-\varepsilon$ phase transition of iron obtained with the VISAR in 1974 [7].

Meanwhile, theoretical and computational understanding progressed as well. Jim Johnson, Orval Jones (who later was Sandia's executive vice president), and Tom Michaels (a Washington State graduate student) developed dislocation theories of elastic yielding [8]. Theories compared favorably with experimental profiles for single-crystal copper [9], but for LiF the dislocation density had to be increased two to three orders of magnitude to get fair agreement [10]. In the ensuing decades, understanding of elastic yielding has vastly changed; see especially papers by Yukio Sano [11]. In 1967 Walt Herrmann developed the 1-D hydrodynamic code WONDY [12] and its 2-D version TOODY [14] to solve shock wave propagation in elastic-plastic materials. Walt developed a compaction model for porous materials in 1972 [12], and models based on quantitative data allowed realistic simulations of material fracture [15]. The powerful computers in the 1970s allowed researchers to solve complex dynamic material problems with TOODY and with Sam Thompson's 2-D CSQ code [16]. An example of the 2-D capability [17] was the comparison to experimental data of a TOODY simulation of a nylon sphere impacting a steel plate (see Fig. 7).

FIGURE 3. Frank Neilson, Bill Benedick, and Bob Graham shared a patent for the quartz gauge in 1967. (Reprinted with permission of Sandia National Laboratories)

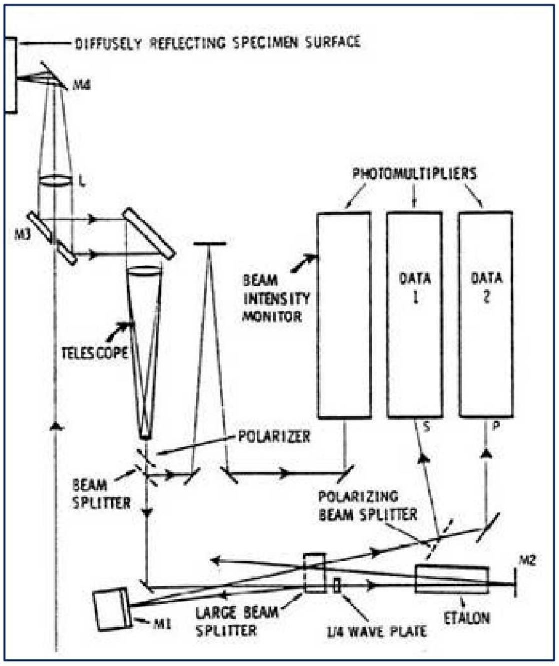


FIGURE 4. VISAR schematic. (Reprinted with permission from Barker, Hollenbach 1972, Copyright 1972, AIP Publishing LLC)

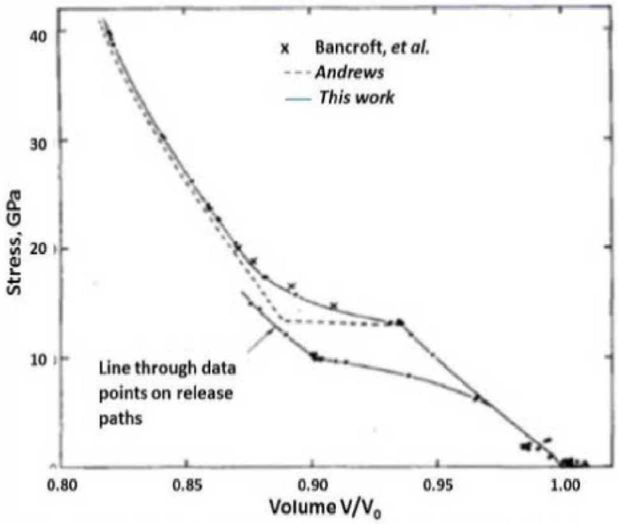


FIGURE 5. Shock compression of iron above α–ε phase transition at ~130 kbars. (Reprinted with permission from Barker, Hollenbach 1974, Copyright 1974, AIP Publishing LLC)

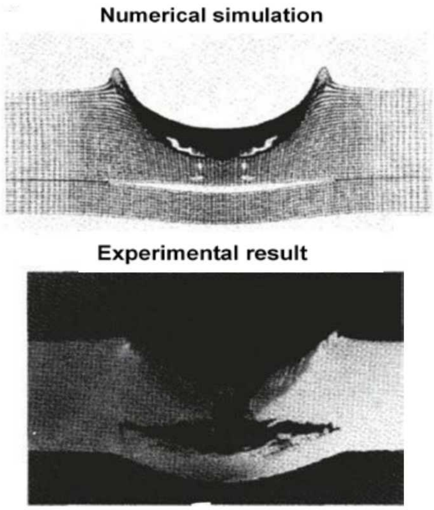


FIGURE 6. TOODY simulation of nylon sphere impacting steel plate at 5.18 km/s compared to experimental image (Reprinted with permission from Bertholf *et al.* 1975, Copyright 1975, AIP Publishing LLC)

TURRET EXPLOSION ABOARD USS IOWA AND COMET IMPACT ON JUPITER

Sandia's extensive shock wave capabilities contributed to addressing problems of broad national and international interest. These included the Three Mile Island nuclear reactor accident in 1979, the turret explosion aboard the USS Iowa in 1989, the Shoemaker-Levy 9 comet impact on Jupiter in 1994, the TWA 800 accident in 1996, and the Columbia shuttle crash in 2003. Two of these problems are briefly summarized below.

On April 19, 1989, a turret explosion damaged the USS Iowa and killed 47 Navy crewmen. The Navy and the U.S. General Accounting Office (GAO) investigated the accident. Sandia aided the GAO investigation with Richard Schwoebel, Director of Systems Evaluation, as technical lead. The Navy concluded that a crew member had deliberately caused the accident via a chemical ignition device. Sandia's team conducted chemical, structural, explosive, experimental, computational, and analytic analyses and came to a different conclusion. James Borders' chemical and material analysis group found no explicit physical evidence for the Navy's theory. Sandia determined that the probable cause was accidental over-ramming of powder bags too hard and too fast into the gun's breech from human error or an equipment failure. Karl Schuler's modeling analysis group suggested the powder bags had been over rammed by 3.3 inches. Figure 7 shows a photo after the explosion, a schematic of the 16-inch gun that exploded, and comparison of a 3-D simulation to two scaled tests. Mel Baer modified the 3-D CTH multi-physics code [18] to treat multiphase flow to analyze the interior ballistics and evaluate the dynamic loading of the propellant pellets. Paul Cooper, an explosives engineer, conducted drop tests of small bags of nitrocellulose propellant pellets to simulate an over ram against the projectile. The subscale tests confirmed that the pellets could experience brittle fracture and set off an explosion. Sandia reported these findings at the Senate Armed Services Committee (SASC) hearing on May 25, 1990 and released an initial report in June 1990. At the end of the hearing, SASC asked Sandia to continue its evaluation and participate in a reopened investigation. The Navy then conducted full-scale vertical drop tests and horizontal 16-inch gun rammer tests with Sandia's participation. Those tests confirmed that ram loading at low impact velocities could cause violent explosions. GAO issued Sandia's 95-page final report in August 1991 [19]. In 1999, Dick Schwoebel published a book based on the investigation [20].

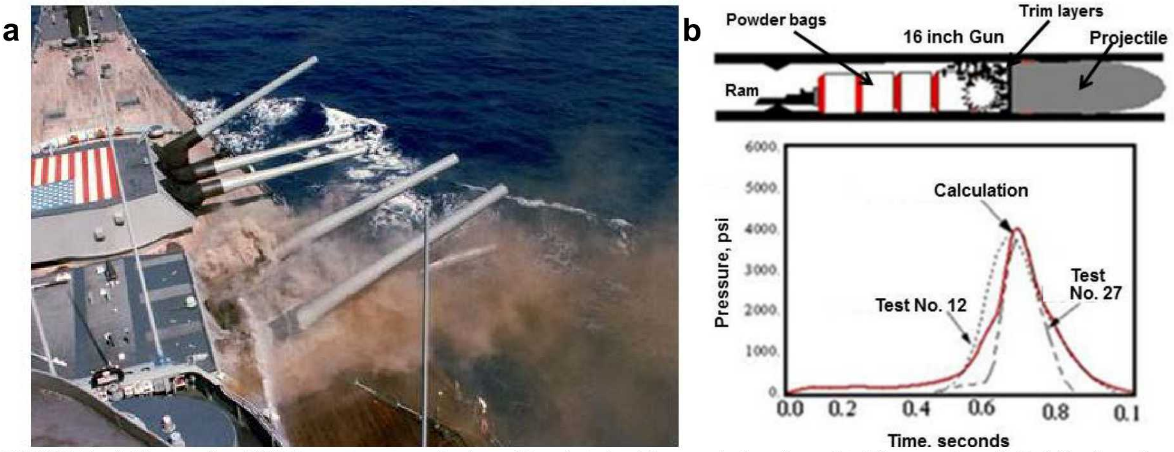


FIGURE 7. a) Photo after USS Iowa turret explosion. (Reprinted with permission from Lt. Thomas Jarrell. Public domain, released to Public ID: DN-SC-90-05388 U.S. Navy, 1989, http://commons.wikimedia.org/ wiki/File: USS_Iowa_BB61_Iowa_Explosions_1989.jpg) b) Schematic of powder bags accidentally over rammed. CTH simulations indicated the explosion likely began at trim layer in forward bag, Graph shows comparison of a simulation with two tests. (Baer 2013, private collection).

On March 25, 1993, Carolyn and Eugene Shoemaker identified a comet on an image plate, polluted by glare from Jupiter, while observing from Palomar observatory. [21] At that time, Mark Boslough, who had taken a course on impact craters from Gene at CalTech, worked at STAR. Calculations by Gene and other planetary scientists indicated the comet impact would occur on Jupiter's *far side* in July 1994 and would not be directly visible from the Earth. Mark and his coworkers (Dave Crawford, Time Trucano, and Allen Robinson) decided to use the CTH code to estimate the size of comet fragments that would impact Jupiter's surface and predict the behavior of an ice fragment as it entered Jupiter's atmosphere. They predicted (Fig. 8), contrary to the expectations of others, that the Hubble Space Telescope would see a rising vapor plume during the comet impact [22, 23, 24]. Figure 9 compares the 3-D prediction of a 3-km ice fragment with actual Hubble images after the impact. [24]

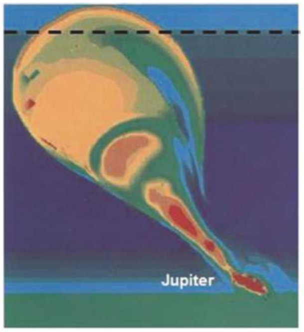
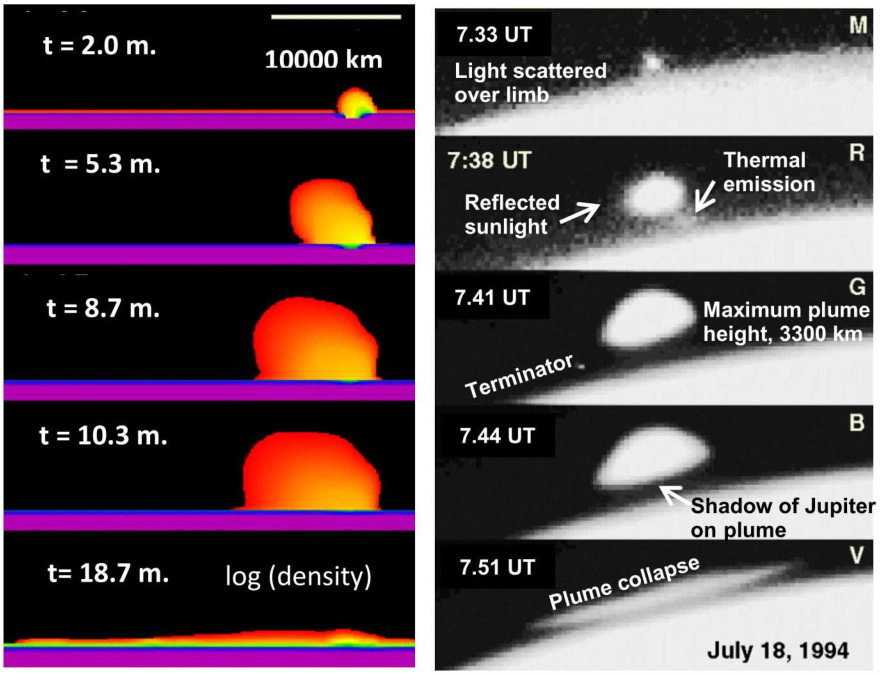


FIGURE 8. CTH prediction of 3-km fragment of water ice 55 s after comet impact of Jupiter. Plume temperature in simulation is blue = 100 K, red = 3000 K. (Reprinted from Crawford *et al.* 1994, Fig. 4, Copyright 1994, with permission of Springer Science + Business Media)



a) 3-D fireball simulation **b) Hubble images of impact**

FIGURE 9. a) Simulation of 3-D fireball and plume evolution after impact of 3-km ice fragment with times in minutes. b) Hubble Space Telescope images at different times after impact for similarly sized fragment (Reprinted with permission from Boslough, Crawford 1997, Fig. 6, Copyright 2006, John Wiley and Sons. NASA and Space Telescope Science Institute are acknowledged for use of the Hubble image.)

CONCLUSIONS

Shock compression of condensed matter research was essential in the 1950s to address the material response to insults at relatively low pressures and stresses. In the ensuing decades, the laboratory developed a wide range of experimental, diagnostic, modeling, and computational capabilities to address issues related to weapons, high energy density physics, and basic science. Six decades later, research at Sandia and elsewhere is extremely interdisciplinary and covers all types of materials and environmental responses. In 5 pages we can only provide a cursory catalog of those achievements; for further details, see our book [25] of about 660 pages. We encourage others (experts, early-career scientists, and graduate and undergraduate students of science and engineering) to consider contributing to this field. Materials are important everywhere and their response can have big effects. New advances are being made, many challenges remain to be solved, and new avenues of research are continuing to emerge.

ACKNOWLEDGMENTS

Many researchers contributed to this six-decade effort to develop capabilities to probe, analyze, and model the behavior of shocked materials. Our impetus to document Sandia's long history of shock wave research was the queries by Sandia National Laboratories staff who joined the effort in the late 1990s and early 2000s. Moreover, 40-some key players in this research supplied personal reminiscences that constitute the largest part of our *Impactful Times* book. We also wish to acknowledge our deep appreciation to the staff and management in the Pulsed Power Sciences Center for providing continual support and interest in the documentation of these efforts.

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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