DTRA WEAPONS EFFECTS TESTING:
A THIRTY YEAR PERSPECTIVE

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ABSTRACT

During the mid 1980s Dr. Don Linger, the Defense Nuclear Agency's Director of Testing, decided to consolidate the agency's high explosive weapon effects testing at White Sands Missile Range (WSMR). His concept was to conduct large-scale nuclear simulation tests every few years in support of National Command and NATO requirements, supplemented by smaller HE tests using a full range of both active and passive measurements to improve understanding of weapon effects and to benchmark state-of the-art calculations. Three test sites were developed in the dry desert alluvium of northern WSMR near the Trinity Site: the Large Scale Testbed (well-known to the MABS community who participated on several 4 kT High Explosive tests); the Intermediate Testbed (for calibration tests with yields up to 20 T) and the Precision Testbed (for small-scale special experiments). A fourth testbed was located several miles down range at Queen-15 where a high water table exists. At that time, primary interest was directed toward nuclear simulations of airblast, ground shock, cratering and thermal effects against a wide range of above-ground and buried structures. Early in the 1990s the agency's mission shifted away from nuclear simulation testing to Weapons of Mass Destruction (WMD). Testing centered on air-delivered conventional weapons and terrorist placed bombs against a new set of above ground and buried structures including tunnels in rock. Effects of interest included penetration into soil/rock/concrete, blast-resistant beams/columns/windows and new energetic explosives. Over the years major investments in technology and infrastructure have been made to understand the explosive environment and resulting structural damage with the highest precision. Sensor and recording response has been greatly improved from cumbersome and time consuming analogue recording to high fidelity digital recording. Photographic techniques were also greatly improved, from film-based images to high resolution real-time digital records. The all important Bomb Damage Assessments rely on a number of state-of-the-art photographic, acoustic and seismic sensors. Today these testbeds remain very active hosting a wide range of testing. This paper summarizes the first 30 years of Defense Threat Reduction Agency testing at WSMR and other locations.

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INTRODUCTION

This paper provides a brief overview of the advances in test technology as used for conventional weapons effects testing at WSMR and other DTRA test sites. Test technology incorporates a broad range of skills and capabilities, including knowledge of conventional weapon effects, weapon-target interaction, operational guided weapon delivery profiles, instrumentation and recording, specialized sensors and high speed photography, target damage documentation, data analysis, and the application of a wide range of empirical and first-principles computer codes. Each of the above areas has been an important tool in the overall understanding and assessment of weapon effects under a broad range of weapon delivery conditions, ranging from static placement to operational guided deliveries.

The advances in test technology would not have been possible without the foresight of Dr. Don Linger, who for many years was the Chief of Test at the Defense Nuclear Agency (DNA). Thirty years ago, he sought to improve high explosive and weapon effects testing at White Sands Missile Range (WSMR). The testing vision he had was to improve our understanding of weapon effects through both active and passive measurements in ways that would be directly applicable to the warfighter. A new term was coined, “Weaponeering,” which incorporated the overall process of weapon platform and tactics, weapon release, weapon delivery to the target, weapon interaction with the target, weapon detonation, prompt weapon effects and post-test damage observations.

THE WATERSHEDS

There were two “watersheds” in the Test Technology process since 1988. The first was the decline, followed by the total elimination, of underground nuclear testing. Nuclear testing was a main component of testing prior to 1988, and from 1988 through 1993. Associated with the nuclear testing were large-scale high explosive (HE) airblast simulation tests and radiation simulators. The Large Scale Test Bed at the White Sands Missile Range (WSMR) was well-known within the MABS community because of the up to 4-kiloton HE ANFO nuclear airblast simulation events which were conducted there. These large-scale HE tests were conducted to expose experiments to above-ground simulated above-ground nuclear airblast effects generated in the 1-8 kiloton yield range. Figure 1 shows photographs of some of the large-scale ANFO experiments and conducted during this era and some of the experiment types which were conducted. Thermal radiation simulator testing was conducted in conjunction with some of these tests by using specialized machines to produce spectral distributions of radiation types similar to those developed by above-ground nuclear bursts. In terms of overall Test Requirements, nuclear testing died out, but the large scale airblast simulations continued for a few years. Simulated nuclear airblast, and combined airblast and thermal testing were both replaced in the mid-1990s by a large shock tube, called the Large Blast and Thermal Simulator (LB/TS), also shown in Figure 1. A small number of thermal radiation simulators are still maintained to support various testing requirements. The basic premise of our testing is that we wish to further understand weapon effects of interest for a broad range of military and civilian programs.

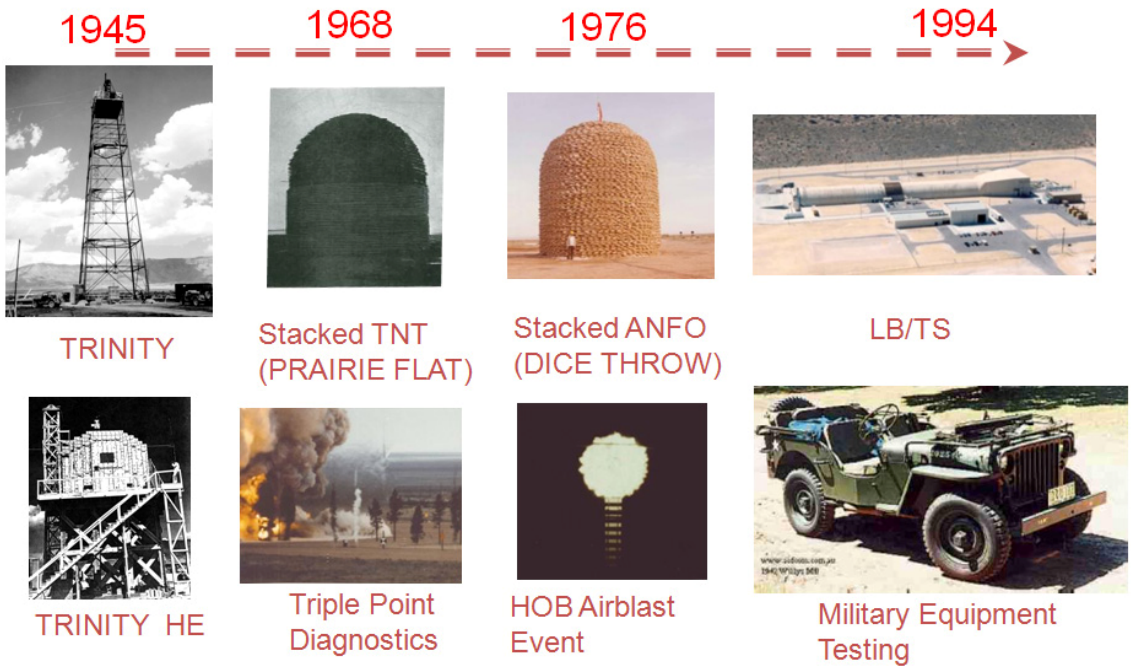


Figure 1. A pictorial progression of nuclear airblast simulation testing.

We strive to measure the important weapon effects on all the tests we conduct at WSMR or at other test sites. In the 1990s, the overall strategy for transitioning the technologies developed during the era of nuclear and nuclear simulation testing to modern conventional weapons testing was begun. The main elements of the conventional weapons effects testing that the older technologies transitioned to are shown in Figure 2.

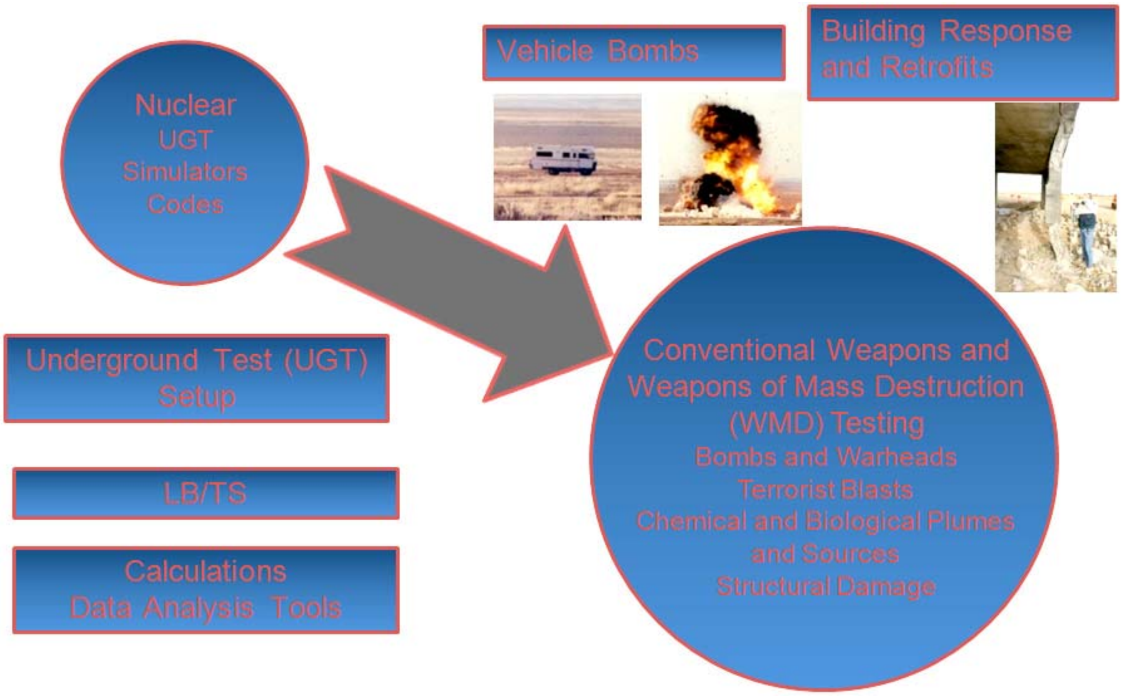


Figure 2. Applying nuclear technologies to conventional weapon environments.

After the 1992 watershed, test technology was greatly improved for conventional weapons testing, that is, weapons filled with various types of HE. Figure 3 presents the basic structure and leveraged resources of the conventional weapons testing as it evolved from the nuclear simulation testing area, which followed the end of the nuclear testing effort, and reduction in the associated nuclear simulator testing efforts. Weapons supplied by operational services are typically delivered to targets by operational means, including fixed wing aircraft, rotary wing aircraft, cruise missile, or other types. Incorporation of the delivery method, along with the participation of the crews performing the deliveries, formed about 1/3 of the test integration effort. Getting the weapon from the delivery platform to the target was also important, and advances in warhead guidance were rapid following the start of the conventional weapons testing effort. These operational developments, along with improvements in the actual bombs being delivered, formed about another 1/3 of the test integration effort. The final 1/3 was in weapon effects, specifically the effects of interest when the weapon arrives at the target and detonates. This strategy formed the basis of the test strategy as it was applied in a new testing era after the technology transition. The second watershed developed after 9/11. The need for rapidly delivering proven weapon concepts to our warfighters allowed development of faster acquisition methods.

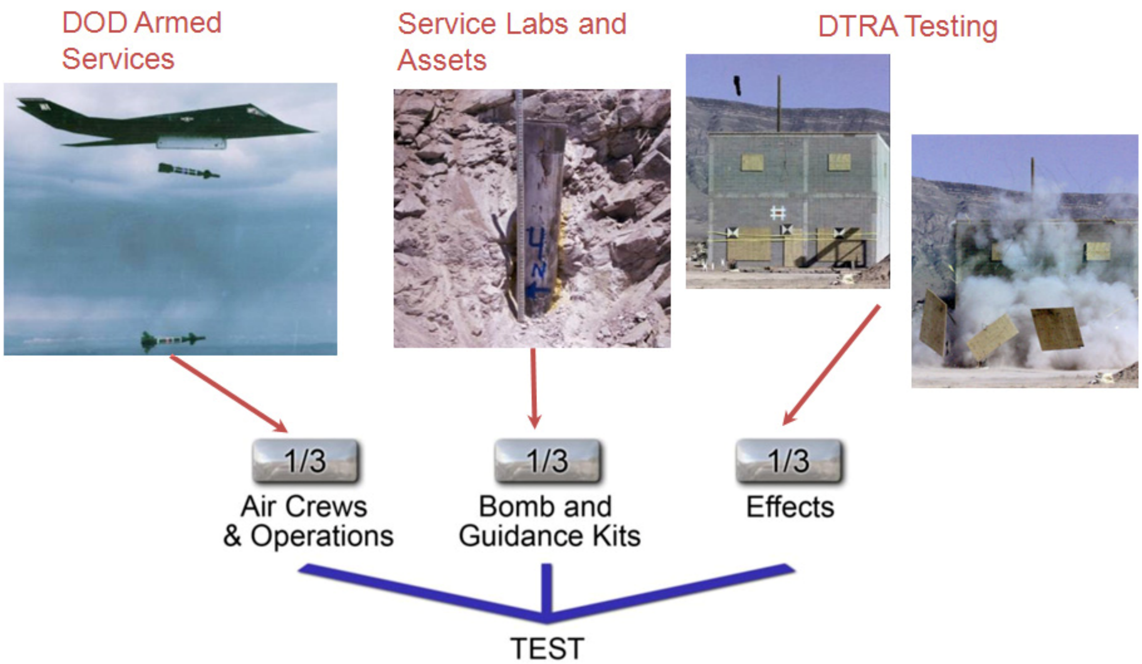


Figure 3. Overview of the conventional weapons testing process as it evolved from leveraging the technologies developed in the nuclear simulation testing era.

During this 30-year period, we also monitored Comprehensive Test Ban Treaty (CTBT) compliance with regards to underground nuclear testing. This involved mobile instrumentation vans containing specialized diagnostics and other testing equipment. These vans could be transported overseas to directly monitor underground nuclear tests conducted by other countries. The Treaty Compliance efforts were also supported by a series of HE tests conducted within the U.S. to monitor and improve close-in sensor performance, intermediate ground shock and acoustic sensor performance, and to calibrate far-field seismic monitoring techniques. Major portions of this monitoring capability are still active.

THE FIRST WATERSHED: ADVANCEMENTS IN CONVENTIONAL WEAPONS EFFECTS TEST TECHNOLOGIES IN PLACE OF NUCLEAR TESTING

Post-1992 the conventional weapons testing effort was significantly increased in scope, and there were significant advancements in testing capabilities and technologies. This effort was driven by both the transition of older, tried and true technologies developed during the nuclear and simulated nuclear testing era, and the by rapid advances in new and improved technology which happened within the 30-year time period. In addition to the rapidly improved control and guidance technologies required to deliver conventional weapons to targets, two areas stand out with respect to technological advancement: weapons effects phenomenology and instrumentation development. Without significant advances in both these areas, the conventional weapons testing effort would not have succeeded. These two principal areas are discussed below:

Weapon Effects Phenomenology: Development of Conventional Weapons Testing Technology

Conventional weapon effects were previously codified in basic forms in empirical Effects Manuals which preceded this effort. These manuals provided the basic effects, but did not provide the basic understanding of these effects. In other words, they provided for the empirical prediction of basic weapon effects including penetration, blast, fragmentation, ground shock and cratering for specific, standardized test geometries, but provided little insight into the underlying phenomenology which would permit extrapolation of the empirically-based effects to new warheads or targets. The manuals were empirically-based and were meant to support protective structural design, but were not capable of being extended to the tactics and damage caused by the new generations of aircraft and penetrating warheads. In other words, new, more detailed, phenomenology needed to be developed to support the next generation of weaponeering manuals. In particular, weaponeering manuals needed to provide insight in extending the range of weapon effects to a new set of hardened targets which included surface and buried reinforced concrete bunkers which incorporated various protective mechanisms (layered soil with burster slabs, rock rubble layers, etc.) and tunnels. The manuals also needed to quantify specific hardened target defeat mechanisms, such as structural collapse, internal structural damage, and various functional defeat mechanisms associated with operating equipment such as airblast, fragmentation, or thermal.

The genesis of weapon effects phenomenology, based on the nuclear airblast simulation efforts, included the large scale HE tests at WSMR which began in the 1970s and continued into the early 1990s. Tests utilized large hemispherical capped cylinders of bagged explosive, shown in Figure 4 which were eventually replaced with specially built fiberglass hemispherical containers shown in Figure 5 containing bulk explosive. Charge weights ranged from 500 tons to several kilotons of chemical explosive. Nuclear airbursts were simulated using spherical containers filled with high-grade explosives, as shown in Figure 4.

Figure 4. Photograph of a stacked explosive charge for a large scale test simulating nuclear airblast from a surface burst (1970s).

Figure 5. Photo of a hemispherical explosive charge for a large scale test simulating nuclear airblast from a surface burst (1980-1990s).

All experiments of this type were conducted to expose a wide range of military equipment and surface or near-surface structures to nuclear-like airblast effects. The seeds of weapons effects technology were incorporated into these tests by employing high speed photography to examine detailed fireball expansion and airblast effects (airblast front, triple point formation, dynamic pressure fields, etc.), as shown in Figure 6. The new era of conventional weapons effects testing required detailed knowledge of airblast, but from HE charges up to a few thousand lbs, well below the kiloton range. In addition, the charges were heavily cased due to the requirements of penetration, so that case expansion, case breakup, fragmentation needed to be understood in addition to the influence of casing on the explosive blast wave. Finally, localized damage to hardened structures due to internal and external blast, thermal and case fragmentation effects needed to be understood, instead of wide-area damage caused by blast and thermal environments.

a. Photograph of a spherical explosive charge simulating nuclear airblast from an above-ground burst (1990s).

b. Initial fireball expansion for an large-scale above-ground HE burst.

c. Measurement of airblast propagation for a large-scale HE surface burst.

Figure 6. Examples of airblast technology development using high speed photography.

Therefore, weapons effects technologies were expanded to include the above wider range of effects specifically relevant to conventional weapons. Also, since one of the principal new defeat mechanisms involved penetration of a heavily cased weapon into or through the roof of a hardened structure in order to detonate inside a hardened facility, a technology effort to improve weapon penetration models was begun. As shown for the weapon penetration shown in Figure 3, there was a need to develop more physics-based penetration codes to calculate penetration for a wide range of weapon impact parameters (weapon impact velocity, incident angle, angle of attack). This was done first in two dimensions (2-D) and then in three dimensions (3-D) for penetration codes that were designed to provide answers quickly using the technologies developed for personal computers (PCs), which were rapidly developing in this era.

Penetration mechanics also needed to be expanded to include new target types. Effects included the depth and damage caused by weapon penetration into both reinforced concrete, through multi-layered protective systems, and into rock above tunnel targets, followed by the target damaging effects of detonation. The target damage caused by weapon penetration and weapon detonation were sometimes intentionally separated in time so that the effects of each could be examined. This area became known as “target damage documentation,” and involved detailed examination of damaged structures, the physical marking of penetration holes, cracks, structural separation failures, craters, and exposed or cut reinforcing bars. Figure 7 presents an example of the penetration of a reinforced concrete target which was impacted by an air-delivered weapon. Multiple frames are shown during weapon impact to highlight the weapon impact trajectory prior to the weapon detonation within the test structure.

• High Speed Photography

- Camera Type:	Film	Film	Film/Digital	Digital
- Speed:	Milliseconds	Milliseconds	Milliseconds	Microseconds
- Duration:	0.1 sec	0.5 sec	0.5 sec	1 sec

Figure 7. Example of an air-delivered conventional weapon trajectory above, and detonation within a reinforced concrete target.

Calculations of a new generation of explosive mixes greatly helped by providing insight into specific weapons effects. The areas of interest included detonation and subsequent reactions within the detonation products of fine metal powders and other materials contained within certain “thermobaric” explosive fills. They also provided insight into the airblast propagation within both simple structures and complex, multi-room structures. A key computational fluid dynamics (CFD) code developed during the era of nuclear airblast simulation, the Second-Order Adaptive Mesh Refinement Code (SHAMRC), was improved to model the detonations within cased weapons, weapon case expansion, weapon case fragmentation, fragmentation trajectories for both direct and ricochet fragments, as well as reactions within the detonation products before and after the case breakup, and the resulting blast wave.

Weapon Effects Testing: Application of Conventional Weapons Testing Technology at Full Scale

Concurrent with the development of testing technology during the 1990s was the direct application of new technology developments to full scale testing. Scaled testing provided key insights into the phenomenology of conventional weapons effects, and the lessons learned could be then applied at full-scale. However, in many cases, full scale sizes of 100 to 2,000 lbs, typical bomb loads, made it easier to test at full scale. Indeed, it was found that scaled tests could be less cost effective for certain test geometries. Similar effects observed at full-scale could then be further addressed at sub-scale to understand gaps in technology, thereby establishing a “feedback loop”. The underlying fact associated with full scale testing is that unexpected things happen, despite well-developed plans and procedures. Sometimes, the “unexpected happenings” turned out to be new effects which could be exploited in new tactical ways. The full-scale testing procedures are illustrated in Figure 3, showing weapon delivery by an aircraft, followed by penetration and detonation inside a target. Weapon fuzing has particularly been an issue, since the desire is to delay weapon detonation until the weapon has penetrated inside a structure, but the fuze itself has to survive and function within the severe environment caused by penetration.

Advances in Anti-Terrorism Testing Efforts

Almost concurrent with the conventional weapons effects efforts, an extensive program devoted to the understanding of blast-related effects of weapons typically used by terrorists was started. The earliest efforts concentrated on understanding of effects of weapons used by terrorists. For example, cars and other vehicles were filled with varying amounts of low-grade explosives and detonated to gather information on the overall blast effects and debris field extents, and more specifically to relate the debris to vehicle types though forensics including vehicle placement (over concrete, asphalt, soil, etc.), explosive amounts, cratering effects, and identification of various vehicle parts. Figure 8 shows a typical test of a large vehicle bomb being detonated.

Figure 8. Vehicle bomb test conducted as part of the Anti-Terrorism testing effort.

Efforts to understand blast effects on structural components also began. The effects of blasts on various types of windows defined the pressure and impulse levels where window failure occurred, how they failed, and the extent and damage caused by window debris (glass shards). Following assessment of the damaging effects of window failure, testing efforts were conducted on various types of blast-resistant windows. These tests used innovative types of blast-resistant windows by retrofitting existing windows and window frames with various materials. Finally, structural components of buildings were looked at in great detail. These concentrated on the effects of external blasts on features such as exposed columns and beams which are typically found in multi-story office buildings. A multiple story test structure was constructed and an extensive series of tests involving explosive detonations was conducted. Figure 2 showed a test result for a test of an explosive blast against a reinforced, but not retrofitted, column. An expanded view is shown in Figure 9.

Advances in Instrumentation, Recording and High Speed Photography

Concurrently, there were significant improvements in instrumentation techniques used to monitor environments and motions during tests involving severe blast effects. A key decision made early in the testing process was that all of our testing required high precision measurements in sufficient number to understand the key weapons effects. Pressure, acceleration, velocity, displacement and temperature were measured using specialized sensors. There were improvements in various sensors, but many techniques were previously available from the nuclear simulation testing era.

Figure 9. Testing of structural columns in multi-story office buildings to exterior blast effects.

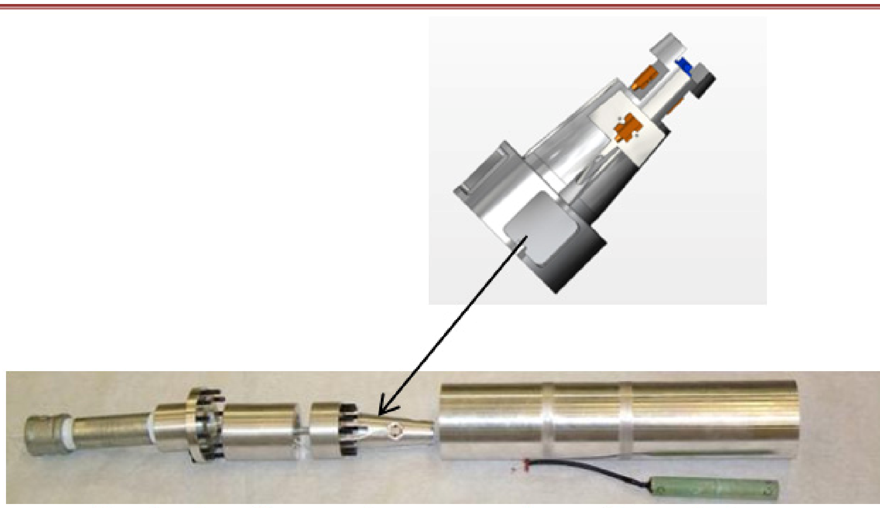
Recording of the signals from these sensors in the fast-risetime, multiple peak shock environments inherent in conventional blast effects was the most dramatically improved area, since during the time period of the 1990s spanned a transition from analog to digital recording. Digital recording was not totally reliable at first, so the testing process demanded that digital recording be supplemented with analog tape recording ("tape backup"). This provided more than the backup at the time. Since in the mid-1990s the time frame of the digital record was fairly short (about 0.5 ms at a time step of 2 μs), the longer recording time available on magnetic tape (minutes or tens of minutes) could be used to monitor longer duration signals from emplaced sensors. Gradually, the duration of digitally recorded records increased, signal resolution (bit rate) increased, and the recording time step decreased, as shown in Figure 10. With increasing reliability, this eventually led to the complete elimination of analog tape backup recording equipment.

In parallel, high speed photography changed dramatically. Mechanical, film-based high speed cameras had been available for many years, the time period discussed here marked the transition from film-based to digital photography. As with analog tape recording, digital cameras were gradually phased in, but were not initially used as the sole source of data. Inter-frame times on digital cameras remained relatively constant (ms) until very recently, but camera reliability, recording time and picture resolution all generally increased, as shown in Figure 7. Following these improvements, use of film-based high speed cameras decreased substantially, and their use at this time is only occasional.

- Recording Rates
  - Digital: More Precise
  - Much Faster (~10 MHz)
  - Duration Longer (hours)
- Software Able to Scan Hundreds of Records and List Peaks, & Durations

Instrumentation Development

• Recording	1980s	1990s	2000s	Current
- Type:	Analog Tape	Digital (Analog Backup)	Digital	Digital (Digital Backup)
- Signal Resolution:	Low Bit Rate	8-Bit	12-Bit	12-Bit
- Time Resolution:	Milliseconds	Microseconds	Microseconds	Microseconds
- Recording Times:	Minutes	Milliseconds	Seconds	Minutes



3-Axis Accelerometer Canisters: Ongoing Usage

Figure 10. Advances in gage recording during the 30-year period

Digital high-speed photographic techniques are used almost entirely today, and Figure 11 shows an advantage of computer-based digital photographic analysis techniques: the ability to subtract two digital frames, yielding the position of the air shock above a testbed.

For blast effects, sensor types of interest include pressure, acceleration, velocity, displacement, structure and rock strain, stress, and temperature. Basic types of all of these sensors predate the period discussed in this paper, but improvements were made in almost all types, most particularly in gage response time, sensor mounting, and increase in signal-to-noise levels. Some techniques previously used extensively to measure high pressure airblast (up to 1-5 MPa) , such as the bar gage, were largely abandoned due to the lack of requirements, and the expertise to design, fabricate, field these types of gages now resides an only a very small handful of individuals. Other types, such as Kulite and PCB pressure sensors, Endevco accelerometers and other types, are commercially available and continually being "improved", but for below-ground use must be protected in canisters, as shown in Figure 11. Significant advances were also made in the optical and infrared measurement of gas temperatures in HE generated fireballs, so that temperatures within and at the fireball surface can now be measured at recording rates of milliseconds or less, which greatly exceed the response time of thin wire thermocouples.

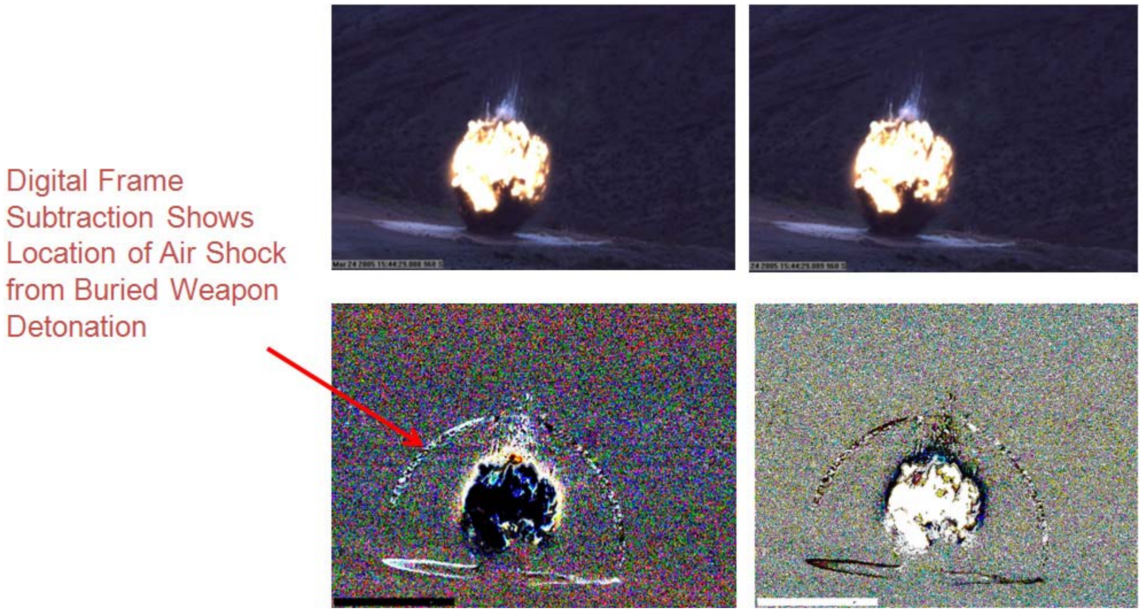


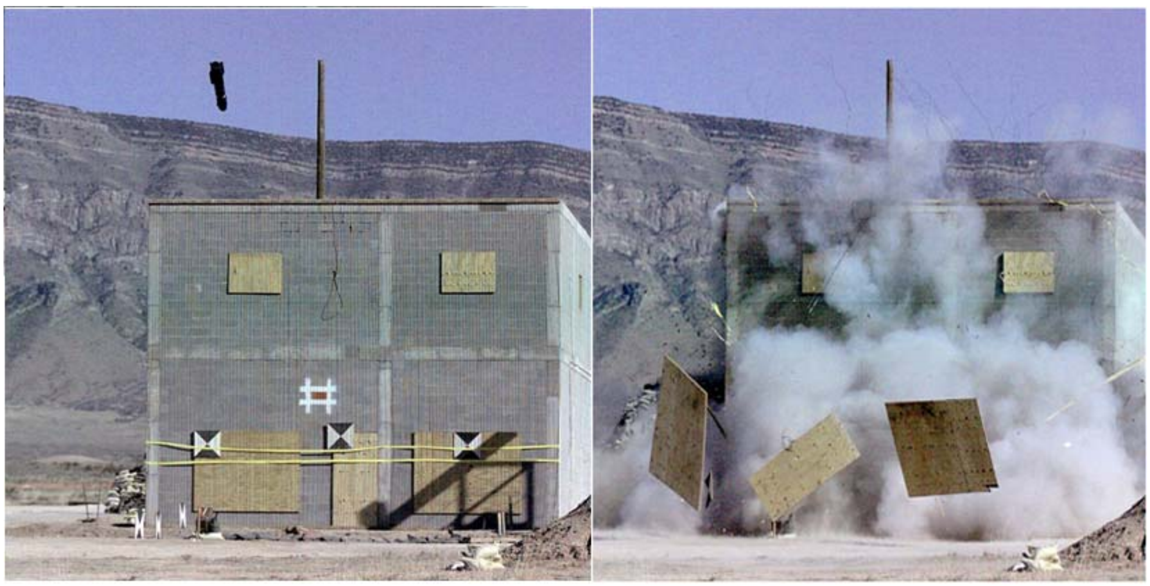
Figure 11. Advantages of digital high speed photography.

THE SECOND WATERSHED: 9/11 AND POST EVENT IMPROVEMENTS

The events of September 11, 2001 (9/11) came as a "wake-up call" in many parts of the US government. They affected DTRA and its contractors directly through Accelerated Test Programs, new weapons development, and increased efforts to understand weapons effects at a new level. These efforts led to large test programs such as Advanced Technology Demonstrations (ATDs) and Advanced Concept Technology Demonstrations (ACTDs) where new weapon concepts in the development stage were tested against "real-world" targets. Many of the weapons developed after 9/11 had their genesis well before then, but the pressure to advance led to more rapid weaponzation. Demonstration test programs were not new, but the urgent need to provide new weapons to the fighting branches of the military (Warfighters) led to a highly accelerated test schedule. For example, testing of new weapons to defeat tunnels and caves typically had taken 12 months to plan and execute; after 9/11, similar tests were planned and executed in less than 1 week each. Had the technology, experienced personnel and leadership not been in place during the decade prior to 9/11, this spectacular ramp-up in testing could not have taken place.

Advances in Warhead Development

As mentioned above, holding tunnel targets at risk was a specific, urgent need. Tunnels are very hard targets which must be defeated by means other than inducing total collapse. Thermobaric sources, discussed above, were tested against tunnels. This class of explosives delivers high detonation pressures and following detonation, the explosive products, particulate metals and other ingredients continue to react with each otehr and the surrounding air, producing “after-burn” energy. These effects enhanced the propagation of airblast pressures within tunnel targets. Several small-scale test series were conducted where many different explosive mixes were tested. The criteria were simple: 1.) The mix had to be stable (safe to handle, store and transport); 2.) The mix had to exhibit full detonation prior to testing in a tunnel; and 3.) The mix had to demonstrate effectiveness within the fixed volume of a standardized steel casing. The two photos on the right side of Figure 3, shown to larger scale in Figure 12 show a typical test of a source tested against a realistic, two-story above-ground test structure which was constructed for a warhead Demonstration Test in the post-9/11 era.



a. Warhead approaching the target . a. Detonation of the warhead within the structure .

Figure 12. High-speed camera frames from a full scale demonstration test of an advanced warhead against a typical two-story above-ground target.

<u>Advances in Penetration Technology</u>

Understanding of penetration mechanics required that the deceleration history of penetrating warheads into various types of targets be thoroughly understood. To this end, both full scale and subscale instrumented penetrating weapons with inert fills were launched into various targets. The on-board acceleration history, typically obtained from records of hardened accelerometers, were recovered after each penetration event and carefully analyzed. Figure 13 demonstrates the utility of on board digital recording as applied to the penetration deceleration problem. Accelerometers were used for years during the nuclear test era, but gage survival was only possible at low stress environments, and at low resolution, as shown in the left hand side of Figure 13. In contrast, the decelerations involved are of much higher amplitude and occur with extremely fast risetimes.

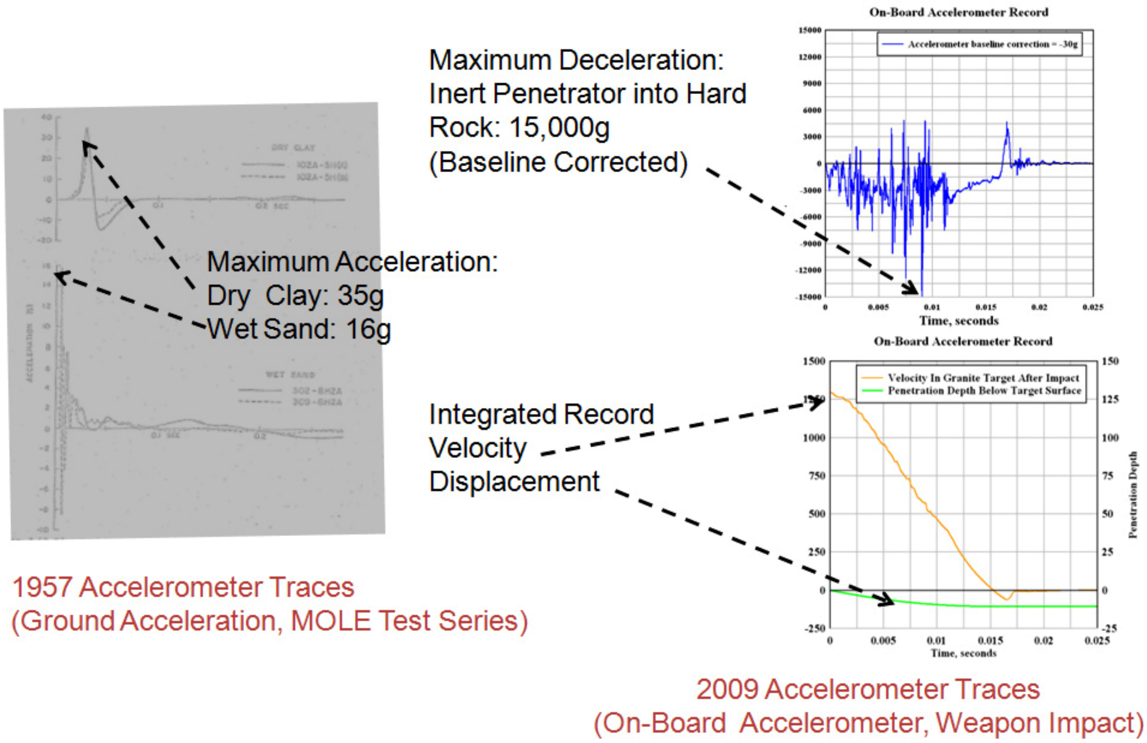


Figure 13. Advances in data analysis techniques, as applied to the understanding of penetrator deceleration.

<u>Advances in Anti-Terrorism Testing Efforts</u>

After 9/11, efforts to understand the external blast effects on various structures also increased, with the emphasis on how to retrofit certain structural members to decrease their overall vulnerability. Structural columns continued to be tested, but there was the realization that the details of how the column was actually connected to the overall support framework were very important. These tests used a re-usable reaction structure to support the assembly, thereby reducing costs and efficiently testing many different designs. Other types of structures, such as multi-story wood structures, were also tested to evaluate the probability of progressive collapse.

TESTING INFRASTRUCTURE ADVANCES

During the past 30 years, DTRA has expanded the number and use of test ranges, which were limited to WSMR at the start of the transition era. A summary of current test ranges is shown in Figure 14. The Nevada Test Site (NTS) was previously used for nuclear testing, but was used by DTRA for both operational and statically placed conventional weapons tests. A significant amount of scaled testing and full-scale component testing was instigated at several test sites at Kirtland Air Force Base (KAFB) in Albuquerque, New Mexico. Other test ranges were used for tests with specific test objectives, such as a limestone test bed in a quarry in Indiana.

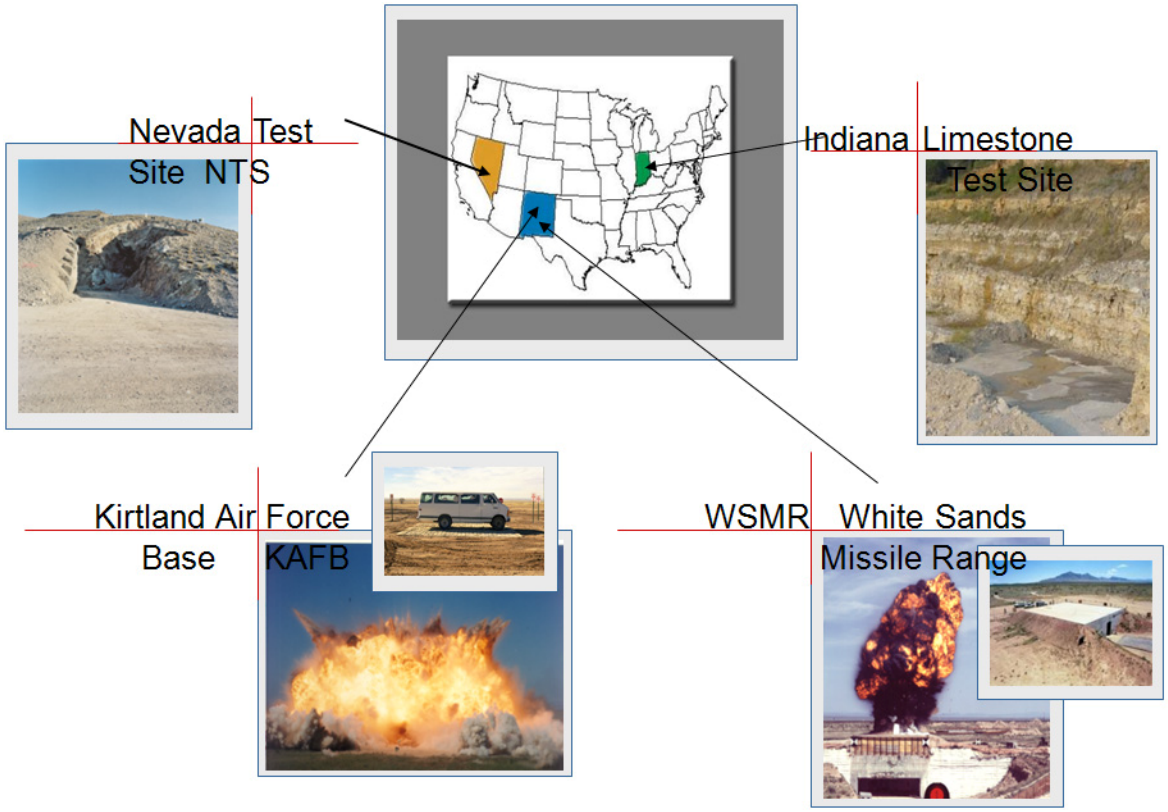
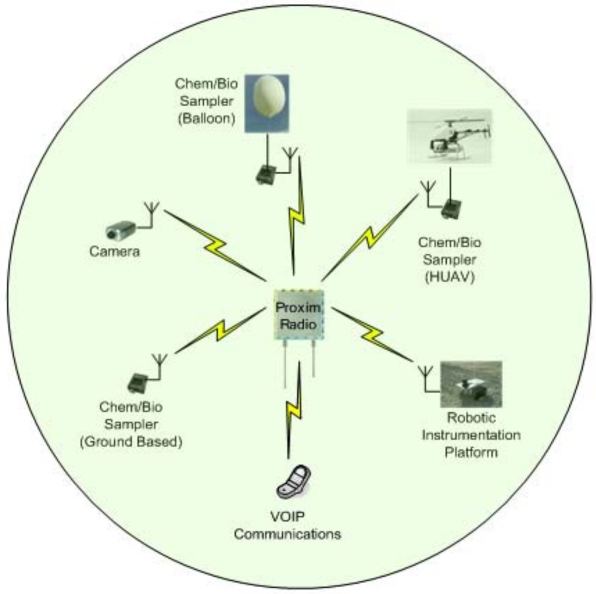


Figure 14. Current DTRA test ranges.

At all active sites, the extensive instrumentation infrastructure was established, as shown in Figure 15. The equipment, which is continuously being upgraded, is used to establish and enforce test bed protocols, safely initiate explosive detonation, and concurrently record the signals from various gage arrays. The figure shows the transition from the older, magnetic tape based recording to the new digital recording systems. To meet the objectives of a wide variety of tests, communications now include wi-fi systems which permit complete control of testbed activities for all test types, and integrate timing and firing with high speed cameras, test bed sensors, and airborne sensors, as shown in Figure 16.

Figure 15.Insrumentation development, and testbed command and control.

40 Channels of Data Recording Per Rack



½ Mile Radius Coverage

Local Wi-Fi Systems for Testbed Control

40 Channels of Data Recording Per Rack

Figure 16. New recording and communications systems.

CONCLUSION

Thirty years ago, the Chief of Test, DNA, Dr Don Linger, sought to improve high explosive and weapon effects testing at White Sands Missile Range (WSMR). The testing vision he had was to improve our understanding of conventional weapon effects through both active and passive measurements in ways that would be directly applicable to the warfighter. Weapon effects of highest interest included: penetration, blast, fragmentation, and thermal effects in the near-field, and acoustic and seismic effects in the far-field. The advances made after two significant events ("watersheds") were discussed. The first, circa 1992, was the phase-out and then the end of nuclear testing and the associated diagnostics and technology associated with that testing, and was marked over a period of about 10 years by a concurrent rise in the application of nuclear weapons effects technology and diagnostics to conventional weapons effects testing. This testing continued throughout the 1990s and was significantly improved by the rapid advances new analytical and instrumentation techniques, high speed computers, the rise of digital high speed data recording and high-speed digital photography, and a concurrent rapid rise in the capability, capacity and speed of personal computers (PCs). The second significant event occurred on September 11, 2001 (9/11). After this event, the rapid improvements regarding weaponization improvements, along with the associated increase in Demonstration Testing, led to new classes of air-delivered weapons which could hold new classes of tunnel targets and above-ground structural targets at risk.

IN MEMORIAM: Fred M. Sauer

The authors regret the passing of Mr. Fred Sauer, a colleague and friend, who died in June of 2010. He was a highly respected member of the MABS technical community. He will be greatly missed, as many of his colleagues present at MABS 21 can attest, as he attended and provided significant contributions at many past MABS symposia. Fred was highly regarded in the testing area, demanding standards of excellence in all test-related activities. Many of these high standards have been incorporated in test techniques which are ingrained in today's testing processes at DTRA, which require extensive test planning, written fielding procedures, careful gage placement, and accurate recording systems. One of his greatest contributions was his writing of the DTRA Graybeard Airblast Guide, where he provided a written history of key events in the nuclear test era as well ensuring that airblast records from many events were preserved for posterity.