The Essential Role of Science in Explosives Safety

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1 Introduction

Historically, the sudden release of chemical energy in an explosion has been used as a destructive or propelling outward moving force. Towards the end of World War II, scientists and engineers learned to use this force creatively. By focusing the energy inwardly, they were able to rapidly change fissile metal from a subcritical state to a supercritical one. The development of the implosion-assembled atomic bomb during the Manhattan Project required explosives to be used in a new and different way. Rather than using explosives as bursting charges encased within metal shells for military effect, specially-designed charges were assembled so as to entirely encompass the fissile metal. When detonated, the spherically converging pressure wave compressed the fissile metal to a condition of nuclear supercriticality. In order to achieve this, precisely shaped pieces of solid explosives with accurately measured detonation velocities initiated by detonators with minimal timing irregularities (low jitter or high simultaneity) were required. This stimulated the science of high explosives performance to mature rapidly.

As military objectives evolved, more efficient implosion methods were investigated. New explosives were invented and sometimes the power within was released unexpectedly resulting in the tragic loss of human life. Administrative controls such as written operating procedures and remote machining operations were emphasized. In addition, the scope of high explosives science broadened to include a focus on understanding the potential mechanisms for *unintended* initiation. New methods for characterizing the safety of consolidated explosives charges, not just the precursor powdered forms, were developed. This paper recalls three fatal explosives accidents that instantly killed eight people within an eight-month period in 1959 and draws upon decades of experience by the authors in separate countries to emphasize the continuing need for science to play an essential role in explosives safety.

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2 The Treachery of Transitions in Technology

Complacency can kill. This is axiomatic for the industrial safety professional in any area of specialty and generally promotes an important focus on human performance factors. However, the explosives worker has the additional risk of encountering unknown initiation mechanisms. Consider the progression in types of explosives that have been used in nuclear weapons over the past several decades.

Trinitrotoluene (TNT) was the most commonly used military explosive of the twentieth century, either by itself or as the principal constituent in a variety of compositions. TNT has an intrinsic characteristic that was first recognized as a boon to operational efficiency - it melts at 80ºC. The raw material could be melted in an industrial-scale vessel and poured into the open end of metal casings to rapidly load conventional munitions. Apparently it was not until many years later that this property was also credited with mitigating the potential for a violent explosion in many accident scenarios. A melting temperature far below decomposition temperature dissipates energy from nascent hot spots and provides some measure of lubrication to prevent further heating in the case of many mechanical threats. For TNT, the science of performance outpaced the science of safety.

After the discovery of RDX and HMX, TNT transitioned from acting as the principal constituent to serving the role of an energetic binder. The first atomic bombs used such compositions. As implosion technology advanced and missiles were developed to deliver new warheads, higher energy density explosives were needed. The melt-casting process was only feasible for compositions with up to 75 weight percent loading of RDX or HMX crystals. So, new methods were developed for higher loadings, such as using a small percentage of polymeric substance for the binder and then compacting the formulation in a heated press. These compositions came to be known as Plastic Bonded Explosives (PBXs). Explosives scientists focused on the substantial gains made in performance did not consider that eliminating the TNT would remove a safing mechanism and potentially introduce a new initiation mechanism. For early PBXs, the science of performance again outpaced the science of safety.

Also, our historical research suggests that in the 1950s explosives were considered more hazardous in particulate form than in the compacted form of a charge. Particles were considered susceptible to ignition by pinching, friction and electrostatic spark discharge (ESD) whereas charges were not. Although it was not a good idea to drop a charge, it was thought more likely to crack and break apart than to explode. After all, a charge needed a detonator to make it function. Safety characterization testing was performed on explosives as powders rather than charges. Common experience had taught these things and conditioned the operating culture of the day until the perfect storm hit in 1959 killing eight people conducting routine operations in three separate accidents in two different countries.

The first explosion killed two machinists who were standing at a drill press cutting a tiny hole into a charge. This operation had been performed hundreds of times before without incident. [1] The second explosion killed two workers when a charge fell onto pavement from the height of a few feet. [2], [3] The third explosion killed four workers while unloading a truck containing charges of waste explosives and preparing to burn residue from PBX machining operations. [4]

Explosives scientists quickly realized that a new initiation mechanism was in play and began seeking to understand it in earnest. Tests that had been developed for characterizing the safety of explosives powders were deemed necessary but not sufficient. New safety tests, such as the Skid or Charge Oblique Impact Test [5], [6] and the AWRE Laboratory Scale Explosiveness Test (LABSET) [7], [8] were developed for consolidated pieces. Such testing has provided useful information but a predictive model of the mechanism continues to invite scientific inquiry.

Researchers sought to improve inherent safety for PBXs. Fleming, et al. developed tailored formulations with two levels of HMX, two types of particle distributions (coarse/fine and micronized), and three different binders. The coarse formulations were significantly more hazardous and there was a consistent (though second-order) trend of increasing violence with dynamic mechanical properties. [8]

Parker, et al. recently completed a study using four different PBX compositions which had the same nominal weight percentage of HMX (94% to 95.5%) but different binder systems. [9] They used a rigid-arm pendulum to conduct oblique impact tests and reported a distinct rank ordering in reaction violence and blast overpressure measurements. Considered from the point of view of safe handling, PBX 9404 was the worst and PBX 9501 was the best. Yet we must remain alert to the possibility that there is an undiscovered initiation mechanism in PBX 9501.

Another approach was to use an insensitive molecular explosive rather than a conventional one. Triaminiotrinitrobenzene (TATB) is the iconic example. It is generally considered invulnerable to ignition in ordinary accident scenarios. Many researchers tout the reaction zone thickness, which is much greater than for conventional explosives, as a significant factor in the insensitiveness. But does it also introduce a new vulnerability? Does it create an undiscovered initiation mechanism that is different than for HMX-based materials in accident scenarios? Does the inherent characteristic of TATB that gives it a longer run time to detonation for a sustained planar shock also allow time for multiple low-level pressure waves to coalesce into a strong shock and produce detonation? [10]

3 A Call for Science

The authors have reviewed the details of the three accidents and searched for guiding principles that could prevent future accidents. We have eliminated factors that are typically present in other industrial accidents because they were not present in these three and been left with the simple fact that a scientific understanding of relevant initiation mechanisms was lacking.

We affirm the conclusions of the investigators from that time period that the accidents were neither the result of negligence on the part of managers or workers nor a willful violation of the policies and practices of the day. The people who were killed were competent and seasoned laborers performing routine tasks in accordance with their understanding of the hazards. To address administrative aspects of explosives operational safety today, we commend the significant advances in the understanding of human performance factors that contribute to worker safety in many fields of endeavor and encourage their implementation.

According to the material safety data as interpreted in the accounts of the accidents, the specific lots of explosives involved in the accidents did not exhibit unusual or more sensitive characteristics than other lots. The sensitivity appeared to be similar to that of other materials handled in large quantities without incident. There was no reason to suppose that these materials represented a special hazard in high explosives handling. They were the normal high explosives of the day. An explanation for the accidents must accordingly be sought elsewhere than in any change in properties of the material.

Also, it appears that there were no equipment failures (electrical or mechanical) which contributed to the cause of the accidents. And even though two of the accidents were outdoors, the weather was not a factor. Both accidents occurred in broad daylight and fair weather.

We are left with the assertion that explosives researchers and workers in 1959 were surprised by the perfect storm due to an inadequate understanding of initiation mechanisms. Subsequent practitioners of the craft have done more safety characterization testing at small and large-scales, conducted more operations remotely, invented materials with enhanced inherent safety, and developed a greater understanding of the mechanisms involved in accident scenarios. For example, today's understanding of the Deflagration-to-Detonation Transition (DDT) is now quite mature and a general awareness of its relevance to handling safety is quite prevalent in the explosives community. [11] Acquired over decades of experimental research and mathematical modelling at various institutions, it has become a notable example of science improving safety.

4 Drilling as a Case Study

The first fatal explosives accident we mentioned occurred while drilling a tiny hole (1/16-inch diameter) two inches deep into the flat face of a right circular cylinder of PBX 9404 that weighed 7.5 pounds. It was estimated that the same operation had been performed previously 471 times without incident. The final paragraph in the Conclusions section of the accident report states: "Possibly the accumulation of a body of evidence of successful remote drilling of holes less than 1/4-inch in diameter, may in the future renew confidence in the wisdom of permitting small hole drilling as an operator-attended procedure. At the present state of the art, we feel that it is prudent to abandon this as an operator-attended procedure."

Rather than seeking scientific understanding of the mechanism that led to the explosion, it seems that the initial effort was to show that the accident was unlikely to happen again. From April and into May of that year 1,005 holes (1/4-inch diameter, 3-inches deep) were drilled into PBX 9404 charges using a single stroke (without intermittent withdrawals of the bit to clear the hole as this was considered the most likely condition to produce an incident).

A report from the time includes this summary. "All holes except four (865 through 868) were clean and showed no signs of decomposition, overheating, or discoloration. Holes 865 through 868 showed a greenish-yellow discoloration. The exact nature of the discoloration has not been determined. The gun drill broke during the 865th operation and all pieces of the carbide tip were found in the HE. The shank remained intact and true. Holes 866, 867, and 868 were drilled inadvertently with the tipless shank." [12]

In the next two months, a second series of 1,000 holes was completed using different feed, speed, and dwell time parameters without incident. [13] Then plans were made to drill 2,000 holes 1/8-inch diameter and 2,000 holes 1/16-inch diameter into PBX 9404 charges. Plans were also made to insert a thermocouple and measure the temperature near the drill tip using varying quantities of cooling water. [14] Before these plans could be carried out, four more people were killed in the final fatal accident of that year and explosives operations were halted for several months.

In the years 1967 to 1970, another extensive effort was made to understand the parameters that led to the drilling accident. Drill bits were fitted with thermocouples and the temperature at the drill tip was measured for various feeds and speeds without any water for cooling or lubrication. In order to accommodate the thermocouple wires, the drill was held stationary and the charge was rotated. Some "pops" and minor explosions were experienced but nothing matched the violence of intentional detonation. [15] Figure 1 shows the setup before the full-scale test and the minimal damage to the drill press that resulted. The initiation mechanism for the drilling accident remains a mystery. In an effort to understand the safe conditions for drilling contemporary high explosives, Young recently reported peak temperature while drilling PBX 9501 under a variety of conditions. [16]

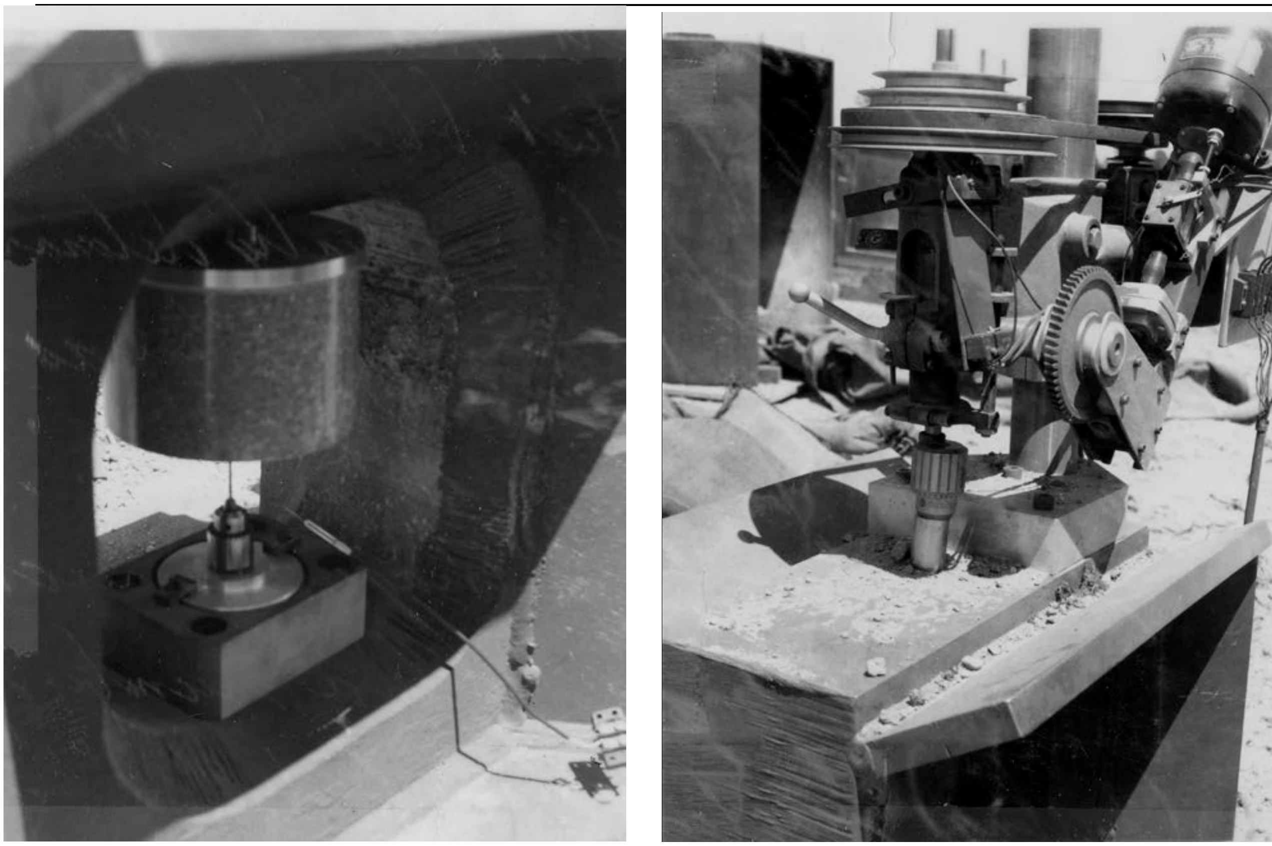

Figure 1. Left: Setup for full-scale test; right: Minimal damage from full-scale test

5 Conclusion

Unfortunately the explosives community has a sad history of discovering new mechanisms through fatal accidents. We applaud every effort that has been made to improve safety through competent science and recognition of the importance of risk reduction through engineering controls such as remote handling and machining. We also offer a few words of caution. There are still surprises. One only needs to go to a firing site when a new experiment is about to commence to hear the discussion and sometimes even good-natured wagers as to the predicted outcome of the test. We still don't know enough about the fundamental laws that govern ignition to make predictions that are dependable and repeatable in most accident scenarios. Elicitation of an expert's opinion regarding whether ignition may or may not occur could have a proper role to play in prioritizing areas for investigation but it should not be relied upon as a line of defense in making a safety case. Science must continue to play an essential role in explosives safety.

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