United States Department of Agriculture

Experiments on Wildfire Ignition by Exploding Targets

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Forest Service

Rocky Mountain Research Station

Research Paper RMRS-RP-108

September 2019

Finney, Mark A.; Smith, C. Todd; Maynard, Trevor B. 2019. Experiments on wildfire ignition by exploding targets. Res. Pap. RMRS-RP-108. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 29 p.

Abstract

Tests were conducted using 97 exploding targets (ammonium nitrate and aluminum powder) to examine the effects of product formulation, environment, and shooting on wildfire ignition. Tests in 2015 produced no ignitions in cold and humid weather conditions. Ignitions in 2018 under warm and dry conditions were positively related to the aluminum concentration (expressed as a percentage of the ammonium nitrate mass) and the placement of the target on a straw fuel bed rather than on a 6 in (15 cm) high steel pedestal. High speed videography and peak overpressure measured for each explosion suggested that differences in explosive characteristics were also related to other experimentally controlled variables and could help explain how wildfire ignition results from elements of product usage.

Keywords: exploding targets, explosives, fire causes, reactive targets, target shooting, wildfire ignition

Cover: Photo collage

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Acknowledgments

This study was supported by funding from the USDA Forest Service Missoula Fire Sciences Laboratory, Fire and Aviation Management, and National Fire Decision Support Center, and from the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Special thanks to Jon Skinner of the Bureau of Land Management for contributing funding for this project and Ralph Gonzales of the Forest Service's National Technology Development Program, San Dimas, CA, for purchasing the pressure sensors. Chris Froula of ATF was of great assistance in the 2015 tests. All field tests were dependent on the expertise of many Forest Service personnel, including Cyle Wold for pressure measurements; Isaac Grenfell for statistical analysis and data management; Randy Pryhorocki and Josh Deering for metal fabrication and field assistance; Sara McAllister and Ian Grob for photography; Ian Grob, Torben Grumstrup, and Andrew Gorris for videography; Jon Bergroos for careful target preparation; Chelsea Phillips for data management; and Jim Reardon and Bill Chatham for weather station operation and programming. Authors are grateful to John Jermain, Edward Bender, and Chris Barth for their critical reviews of the draft manuscript.

Introduction

Exploding targets are sold commercially for civilian recreational target shooting with the purpose of visibly and audibly reacting when struck by a projectile, usually a rifle bullet. The ability of exploding targets to cause wildfires has been well reported in the media (Gabbert 2013; Price 2018; Wang 2018). Numerous videos demonstrating ignitions after explosions have been uploaded to the Internet by the public. Though many fire investigators have attributed wildland fires to the use of exploding or binary targets, there are no available published studies documenting that these products can be a competent ignition source.

Not every explosion results in ignition, but the specific circumstances under which ignition might occur, and the physical mechanisms responsible for ignition of wildland vegetation, have not been formally investigated. Major questions remain as to how ignitions occur and what factors cause them. It has been unclear, for example, whether variations in target formulation or preparation, target environment, or bullet impact could explain the variability in the occurrence of wildfire ignition. Here we report on a series of tests that attempt to identify some of the principal factors affecting ignitions that might result after intended use of exploding target products.

The most common ingredients of exploding targets are the oxidizer ammonium nitrate (AN) and aluminum powder (AL) for fuel. Targets are sold with the two components separated and are thus sometimes referred to as “binary targets.” Only after mixing by the end user will a high velocity impact (by a bullet) cause explosion. It is not clear whether the explosion from these targets technically qualifies as a detonation or is instead a deflagration. Much of the research literature invokes the term “detonation” to apply to ammonium nitrate-aluminum mixtures, but this report will simply refer to the reaction as an “explosion.” Detonations involve chemical reactions propagated by a supersonic pressure wave (shock wave), whereas deflagrations propagate by heat transfer. It is possible that exploding targets can exhibit either reaction depending on the properties of the target mixture and impact of the projectile.

Most exploding targets are intended to be shot by centerfire rifle bullets having a velocity above about 2,000 ft/sec (610 m/sec). There are some formulations intended for lower velocity projectiles such as from rimfire cartridges (e.g., .22 Long Rifle) or pistols that rely on a greater percentage of AL or other ingredients to increase sensitivity to initiation. Many different vendors offer exploding targets on the commercial market, and the composition and concentrations of the ingredients vary. Lao and Jermain (2017) performed chemical analysis of 10 brands of commercial targets for centerfire rifles and 5 brands formulated for rimfire cartridges. Of those formulations tested, centerfire targets contained AN as the oxidizer and 1 to 7.3 percent AL as fuel. Rimfire targets contained up to 25 percent AL, but typically added potassium perchlorate, and sometimes sulfur, antimony, charcoal, and magnalium powder (an alloy of magnesium and aluminum). The sizes of the commercially available targets are commonly about 0.5 lb (0.2 kg) to 2.5 lb (1.1 kg), but vary from a few ounces for some rimfire products up to 25 lb (11.4 kg) for some centerfire targets. Users sometimes combine the contents of multiple targets or target kits to make larger and more powerful explosions although this is discouraged by manufacturers.

The detonation of ammonium nitrate-aluminum explosives (here after, ANAL) is well studied for the primary purposes of warfare and mining. This explosive is frequently encountered by U.S. and coalition forces in the Middle East, where it is one of the primary mixtures used for improvised explosive devices. While ANAL is a very effective explo sive, it is not a preferred explosive for the U.S. military or commercial explosives vendors due to the hygroscopic nature of AN, which reduces both performance and shelf life as the AN tends to clump or harden as it absorbs water. Aluminum makes the explosive more sensitive or more easily detonated than fuel oil, but is also more expensive. Fuel oil is more easily mixed with AN to form ammonium nitrate and fuel oil (ANFO), which is the most common explosive or “blasting agent” used around the world.

Detonation is defined as a rapid combustion reaction expanding at supersonic speeds and has characteristics of velocity, sensitivity to initiation, and energy yield. Components of ANAL vary in terms of the AN granularity (crystalline flakes vs. spheroidal “prills” and their sizes) and the mesh size of AL particles (Budzkowski and Zygmunt 2011; Paszula et al. 2008). Most commercially available targets use low density (or high density) AN prills (Lao and Jermain 2017). Other ingredients are often added to change the explosion characteristics, for example increasing the detonation velocity (velocity of reaction propagation through the mixture) and heat content, or reducing the sensitivity to shock by adding inert ingredients (e.g., clay) (Buczkowski and Zygmunt 2011; Maranda et al. 2003). Inert constituents serve as a diluent to the mixture and reduce the amount of energy released, detonation velocity, and sensitivity (Buczkowski and Zygmunt 2011).

Temperature at explosion of ANAL mixtures is about 6700 °F (4000 K) (Maranda 1990). Aluminum burning in air achieves temperatures of about 3860 to 4940 °F (2400 to 3000 K), but higher temperatures occur with greater oxygen (Beckstead 2004; Huang et al. 2009; Parigger et al. 2014). These reaction temperatures for the mixture and combustion of AL are obviously sufficient to ignite wildfires, being much greater than the nominal flaming ignition temperature of about 620 °F (600 K) for cellulosic wildland fuels. The possibility for melted and burning AL particles to accrete into a larger molten mass with longer collective burning time (Beckstead 2004) could also elevate the likelihood of wildland fire ignition. Longer burning implies greater duration of contact between high temperature AL particles and wildland fuels.

The mixture characteristics of ANAL (AL percentage of the AN mass in a given target) affect several important properties of the explosion. For high explosives, detonation must be initiated by a source of high pressure or shock wave of sufficient diameter, known as the critical diameter (Kobylkin et al. 1983; Maranda 1990). The impact of a rifle bullet exceeds this critical diameter for commercial mixtures. Studies suggest that the critical diameter decreases to a minimum at AL concentrations from about 5 to 10 percent, meaning the mixture becomes more sensitive (Miranda 1990). The completeness of the explosion reaction depends on the sufficiency of this initiating shock but also on the formulation or qualities of the explosive mixture itself. An incomplete explosion reaction may eject a portion of the ANAL components from the blast zone with the potential that some of the AL fuel ignites and burns rather than react in the explosion. For ANAL mixtures, the proportion of AL affects the detonation velocity, which is the speed of shock-wave propagation through the mixture (Maranda 1990). The detonation velocity and resulting amplitude of the pressure wave appear to decrease as AL concentrations exceed about 10 percent (Paszula et al. 2008), and mixtures with 40 percent AL become difficult to detonate. In exploding target applications, more AL in the mixture will increase the heat content of the reaction and perhaps produce localized excess of AL fuel because only the surface of the prill contacts the aluminum powder (not the interior volume). Ammonium nitrate is also hydrophilic and may absorb atmospheric moisture if stored improperly. It is not known what effect moisture content of AN has on reactivity of ANAL mixtures.

Methods and Materials

The primary hypothesis pursued in this study was that wildfire ignition results from contact of burning AL with wildland vegetation. Aluminum not consumed in the explosion reaction can be ignited and ejected from the blast seat (location on the ground directly beneath the explosive) and forced to contact nearby cellulosic fuels. This was a logical hypothesis given that the temperature of aluminum combustion is much higher than the nominal temperature required for flaming ignition of cellulose. Factors associated with each phase of product usage, including preparation and the AL content, target environment, and shooting, could affect the amount of burning AL in proximity to vegetation and were thus to be controlled and investigated (table 1).

Table 1—List of experimental factors associated with preparation, environment, and shooting that possibly affect wildfire ignition. Each factor was considered or involved in testing.

No.	Factor	Phase	Possible effect on wildfire ignition	Tested
1	Completeness of mixing of ammonium nitrate-aluminum components	Preparation	Incomplete mixing increases burning aluminum ejected into vegetation	Yes
2	Aluminum concentration	Preparation	Higher concentrations increase aluminum contact with vegetation	Yes
3	Target weight	Preparation	Larger targets may be more difficult to mix or react, meaning increased chance of ignition	Partial
4	Aluminum particle size	Preparation	Larger aluminum particles may be more likely to burn longer	No
5	Ammonium nitrate condition (moisture, particle properties such as sizes and density)	Preparation	Ammonium nitrate properties and moisture may affect reaction efficiency	No
6	Moisture content of vegetation	Environment	Dry dead vegetation is more likely to ignite	Partial
7	Target placement on vegetation vs. hard surface	Environment	Ignition is more likely with explosion contacting vegetation	Yes
8	Bullet placement on target	Shooting	Oblique or peripheral impact would decrease propagation of explosion through mixture, ejecting burning aluminum into vegetation	Partial

A factor that could increase the amount of burning AL was the completeness of mixing of the target components. Incomplete mixing of AL and AN could leave veins of concentrated aluminum in the mixture that could burn rather than react in the explosion. Vendors provide the proper amounts of each component in their products, but have no control over the thoroughness of end-user product preparation. Larger targets, depending on the container used for mixing, may be more difficult to mix thoroughly or explode completely and result in a larger amount of unconsumed AL available for burning. Due to the hygroscopic nature of AN as discussed earlier, older AN product may be clumped and therefore more difficult to properly mix with the AL. A similar effect could also occur with higher overall AL concentrations in the mixture that might not react in the explosion and therefore could burn afterward.

The environment in which the target is placed or exploded is likely to have a strong effect on the resulting chance of ignition. Foremost is the dryness of vegetation; moisture content of dead vegetation material is likely to affect incipient and sustained ignition similar to all other wildland fire contexts. Second, the proximity of ignitable wildland fuel material to the target was thought to be important because it is impacted by heat from the explosion as well as blast pressures and associated airflows. Positive pressure generated by the explosion initially causes airflow outward from the blast zone, which is then reversed with the subsequent negative pressure wave.

Another factor that could affect the initiation of the explosion reaction was bullet placement on the target. A non-ideal impact point on the target could reduce the critical diameter of the shock and influence the shape of the subsequent pressure wave as it travels through the mixture. Many exploding targets are sold in cylindrical containers, and a peripheral bullet impact contacts the cylinder at an increasingly oblique radius with the bullet proceeding through a shorter chord of the ANAL mixture. This factor was partially explored in tests in 2015 but not continued because of the difficulty of controlling shot placement within an unknown range of sensitivity.

Preliminary testing of 10 targets in 2014 was used to refine objectives and procedures. Subsequent field tests were conducted in November 2015 at a gravel pit on the Lolo National Forest near Missoula, Montana, and in September 2018 at the U.S. Army's Yakima Training Center in Washington State (table 2).

Table 2—Summary of field tests of exploding targets conducted in 2015 and 2018.

Test characteristics	Missoula, Montana, 2015	Yakima, Washington, 2018
Dates	November 3, 4	September 5, 6
Temperature	31–46 °F (-0.5–7.8 °C)	71–82 °F (20.2–28.2 °C)
Humidity	64–99%	14–23%
Fuel moisture content	20–27%	3–9%
Number of targets	46	51
Factors tested (table 1)	1, 3, (6), 8	1, 2, (6), 7
Number of ignitions	0	22
Cartridge	5.56x45 mm, 55 grain FMJ[1]	5.56x45 mm, 60 grain FMJ[1]

[1]FMJ is an abbreviation for full metal jacket; in these tests, a lead core and copper jacket.

The test procedures were designed to control the experimental variables rather than to re-create likely scenarios of target use. Dry straw bales in their original form were used as receptive fuel and were located about 3 ft (1 m) from each side of the target and firing lane (figs. 1, 2). In the 2015 tests, targets were placed on a steel pedestal 6 in (15 cm) high to provide better visibility for shooting (fig. 2A). Thirty of the targets in 2018 were supported by a pedestal and 21 were supported directly on a straw mat approximately 3 in (10 cm) thick. All shooting was conducted approximately 150 ft (50 m) from the target using commercial 5.56x45 mm ammunition (fig. 3, table 2). The sequence of targets was arranged in randomized order. After each test, the straw bales were inspected for smoldering or burning. Flaming ignitions were usually obvious within seconds of the explosion.

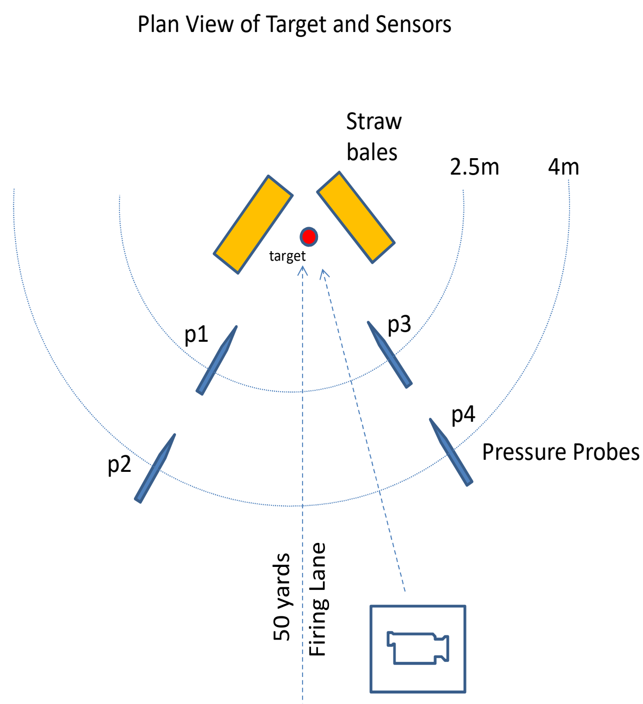

Figure 1—Schematic plan for field testing, showing the relative positions of target location, straw bales, pressure probes (P1–P4), and firing lane, and camera locations.

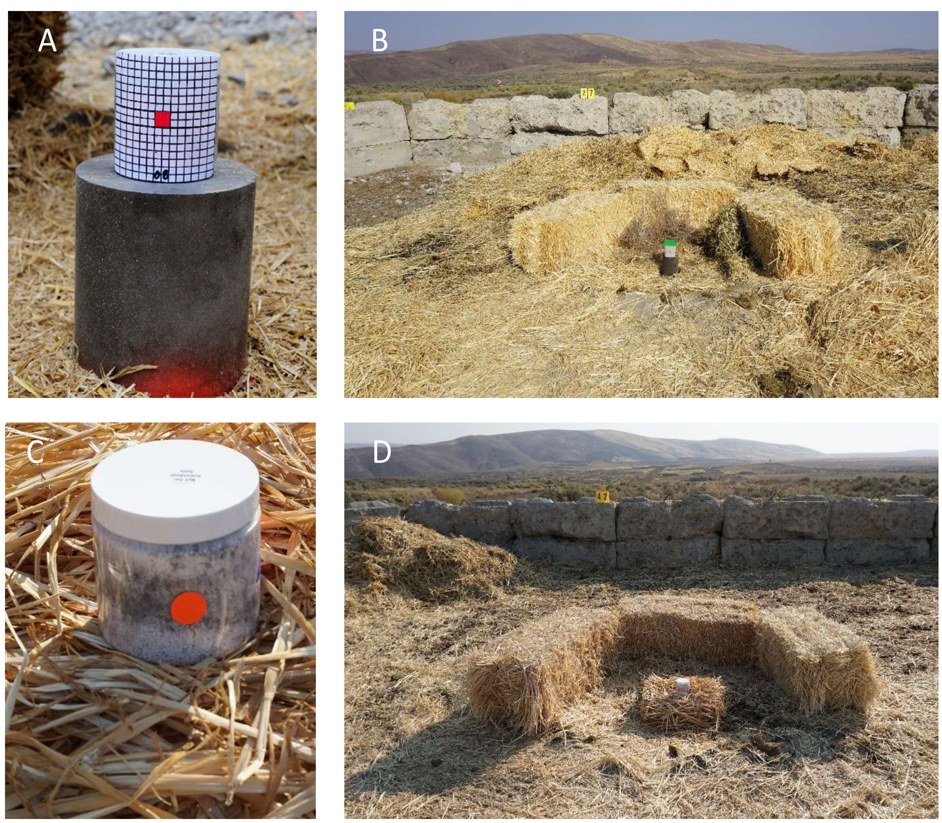

Figure 2—Photographs of target base material used in field tests: (A) close-up view of steel pedestal in 2015 tests, (B) pedestal in 2018, (C) close-up view of straw mat in 2018, and (D) straw mat in 2018.

Figure 3—Photographs of field tests of exploding targets in 2015 (A, C) and in 2018 (B).

Targets and Aluminum Concentration

The 2015 tests focused exclusively on Tannerite® (Tannerite Sports, Pleasant Hill, OR) targets, which come with a premeasured pouch of aluminum powder that appears black because charcoal is commonly added during manufacturing. The mass of AL in each pouch was determined to be approximately 1.6 percent of the AN mass formulated as spherical prills (fig. 4). Tannerite targets of 0.5 lb and 1.0 lb (0.4 kg) were used in 2015. The 2018 tests were conducted with Tannerite 1-lb targets as well as custom mixtures to control AL concentrations at 1 percent, 5 percent, and 10 percent. An electronic balance was used to obtain 1-lb samples of explosive-grade AN prills from a 50-lb (22 kg) bag. The aluminum was silver-colored spherical 325 mesh (13 micron) purchased in bulk.

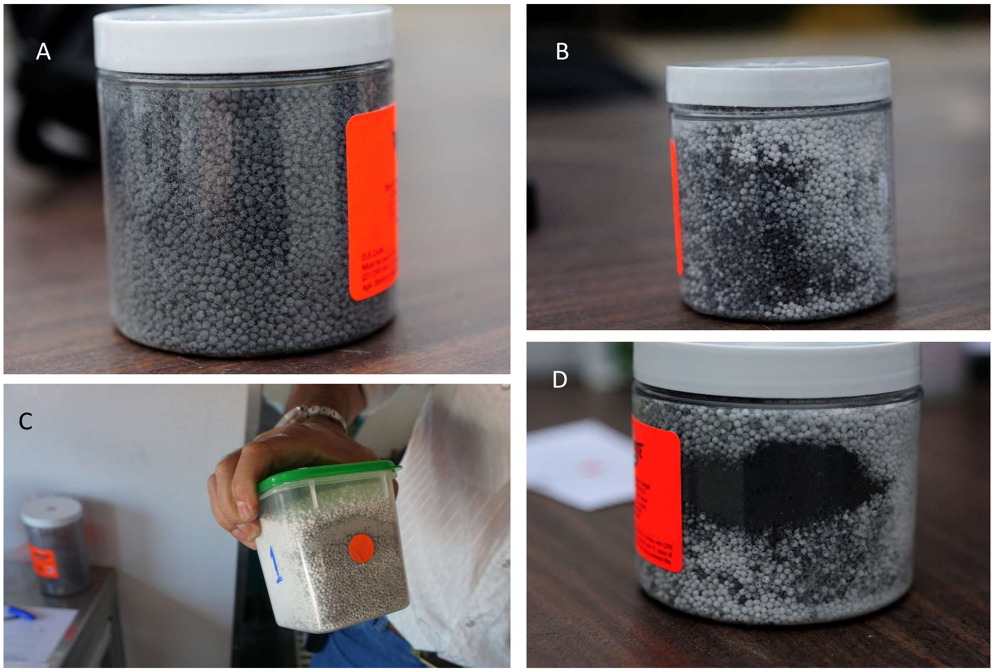

Figure 4—Example of (A) complete mixing of aluminum with ammonium nitrate in exploding target compared to the variability of (B) incomplete mixing (Tannerite 0.5-lb target), (C) incomplete mixing of custom target (2018), and (D) incomplete mixing (Tannerite 1-lb target). Localized concentrations of aluminum are clearly visible in the partially mixed targets.

Targets and Mixing

For each concentration of AL, the components were mixed immediately before each test to one of two levels of completeness. First, the AN prills were transferred to a container twice the volume of the target container and the AL added to the top surface. Complete target mixing was assumed after manually shaking the combined contents in the oversized container for 1 minute. The transparent plastic containers revealed how mixing transformed the general white appearance of pristine AN to a uniform gray when mixed with AL. The mixed contents were then transferred back to the original container for explosion testing. For partially mixed targets, the same procedure was used except the oversized container was rotated 180 degrees twice before transferring the contents to the original container. This resulted in a noticeably mottled coloration of the mixture (fig. 4). Veins of AL were visible within the mostly white AN matrix.

Videography and Weather

High speed videography was used in all tests. Two high speed cameras were used in 2015. One focused on the target to capture bullet impact location at 20,000 frames per second (fps) and the second provided a wide-angle view at 1,000 fps (fig. 5). To identify the bullet impact location, a projection-corrected grid of 0.2-in (0.5 cm) squares was affixed to the outside of the cylindrical plastic jars containing the Tannerite target mixture. In 2018, one high speed camera captured the wide-angle view at 1,000 fps along with a standard video camera at 60 fps to record the long-duration outcome of the tests. Hourly weather data, including temperature, relative humidity, solar radiation, and 10-hr fuel moisture were recorded in 2015 at the Nine Mile Remote Automated Weather Station located approximately 1 mi (1.6 km) from the test site. A portable weather station was installed on-site in 2018 (fig. 5A). Fuel moisture was sampled in 2018 by collecting straw from the bales at intervals throughout the day; weighing before and after oven drying established the moisture content on a dry-weight basis.

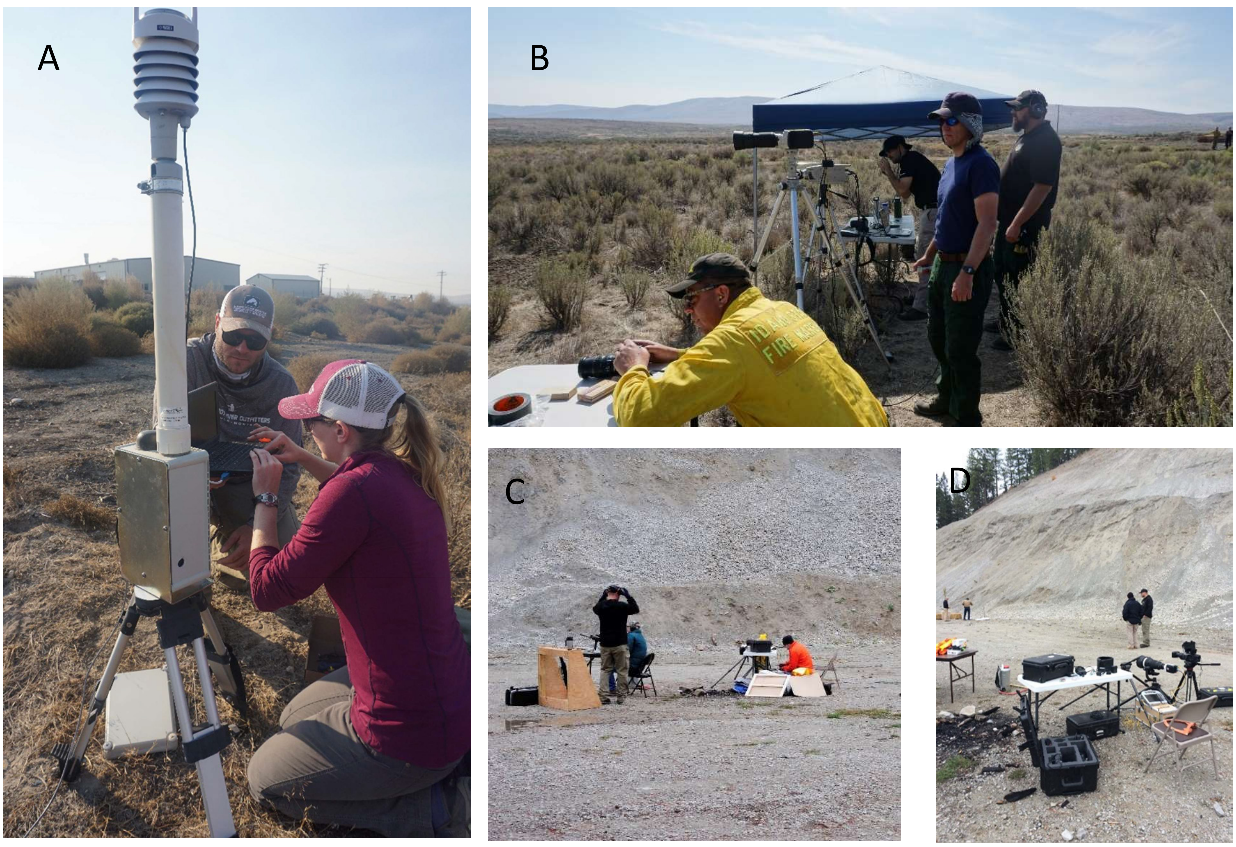

Figure 5—Photographs of (A) portable weather station used in 2018, (B) video cameras behind the firing line in 2018, (C) location of video cameras behind the firing line in 2015, and (D) close-up of video cameras in 2015.

Pressure

The overpressure from the explosion was measured using four ICP® blast pressure pencil probes, model 137B23B, quartz, free-field (PCB®, Depew, NY) (designated as P1 through P4), oriented toward the target at 20 in (0.5 m) above the ground and at distances of 8 ft (2.5 m) and 15 ft (4.5 m) (figs. 1, 6). Wires from the probes were extended back behind the firing line to a trailer (2015) or mobile laboratory (2018) where data were recorded and stored. Sampling from the probes was varied from 80 kHz to 1000 kHz, but there was no noticeable difference in resolution of the waveform and 80 kHz was used for all tests in 2018. The maximum overpressure is related to the explosion velocity and provides a direct measurement for estimating the energy release of the explosive reaction. Maximum overpressure was found to be the single best discriminator of variation in explosion characteristics and was redundant with time-integral of the overpressure. Average maximum overpressure was obtained for a given target size (0.5 lb vs. 1 lb), target mixing (partial and complete), and bullet placement (center vs. side) by averaging maximum overpressure measurements from the P1 probe from all targets in that category.

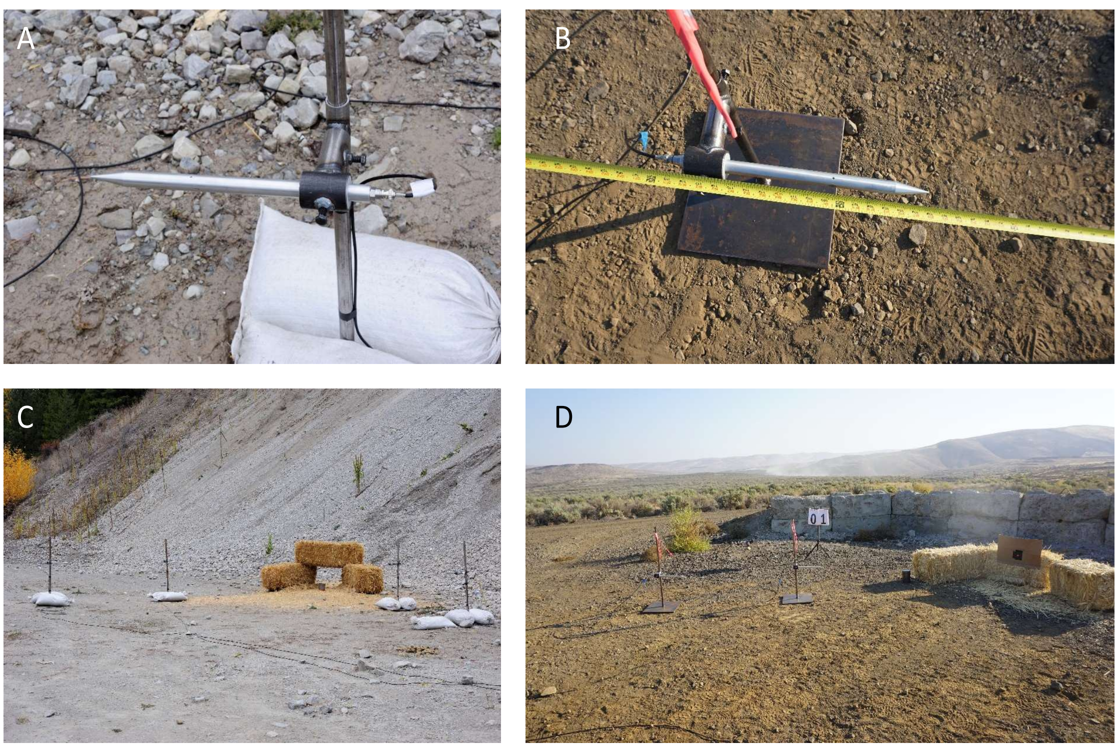

Figure 6—Setup of pressure probes used to measure the blast pressure from the exploding targets for (A) 2015 tests (close-up), (B) 2018 tests (close-up), (C) 2015 tests, and (D) 2018 tests. See also figure 1.

Analysis

Data from the 2018 tests were analyzed by logistic regression (using the glm function in R [2008]) to identify independent experimental variables predictive of ignition occurrence. Variables considered for inclusion in the model were the AL percentage, presence or absence of the pedestal, maximum observed overpressure of the blast wave, and intended degree of mixing. For 2015 and 2018 tests, box plots were constructed (using the boxplot function in R) to explore trends in maximum overpressure from pressure sensor P1 (fig. 1) as a function of mixing, shot placement, target size (mass), and AL percentage. These plots offer a visual interpretation of the central tendencies, as well as the degree of scatter, of the various predictors under the ignition outcomes. Using the Akaike Information Criterion (Sakamoto et al. 1986) statistic, we concluded that the logistic regression best explaining the data included only AL percentage and the presence or absence of the pedestal as predictors of ignition.

Results

Ignition

Tests were conducted on 97 targets. Ignitions of the straw bales were observed in 22 of 51 tests in 2018 (figs. 7, 8) but none in 2015 (Appendix A). Weather conditions and, thus, fuel moisture were very different: warm and dry in 2018 (Appendix B) versus cold and humid in 2015 (Appendix C). Ignition was determined by inspecting the straw bales and blast zone immediately after explosion. Both smoldering and flaming ignitions were classified as successful ignition. Smoldering ignitions were observed in four tests. Ignition probability was modeled by logistic regression from 2018 data and found to be strongly predicted by the characteristics of material used as the target's base (the metal pedestal vs. placing the product directly on the straw bale) as well as the AL concentration (fig. 9). Tannerite was less likely to cause ignition than targets with higher AL concentration because the AL was a relatively low 1.6 percent of the AN weight. Completeness of target mixing was not statistically significant in the model at the $p = 0.05$ level, meaning that ignition likelihood from partially mixed targets and well-mixed targets was not distinguishable from chance.

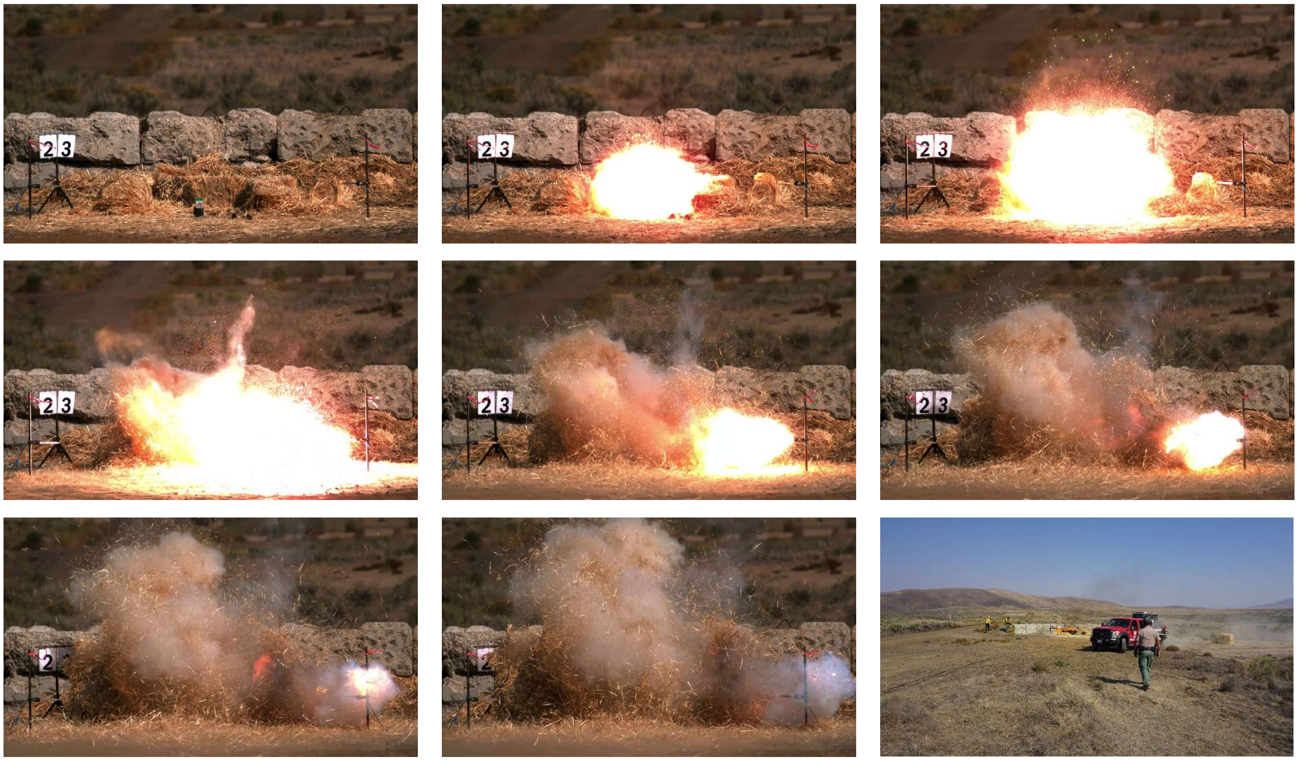

Figure 7—Test 23, 2018, 10 percent aluminum, partially mixed. Series showing explosion, vertical and lateral ejection of burning aluminum, residual combustion within the blast zone, and ignition of straw bales.

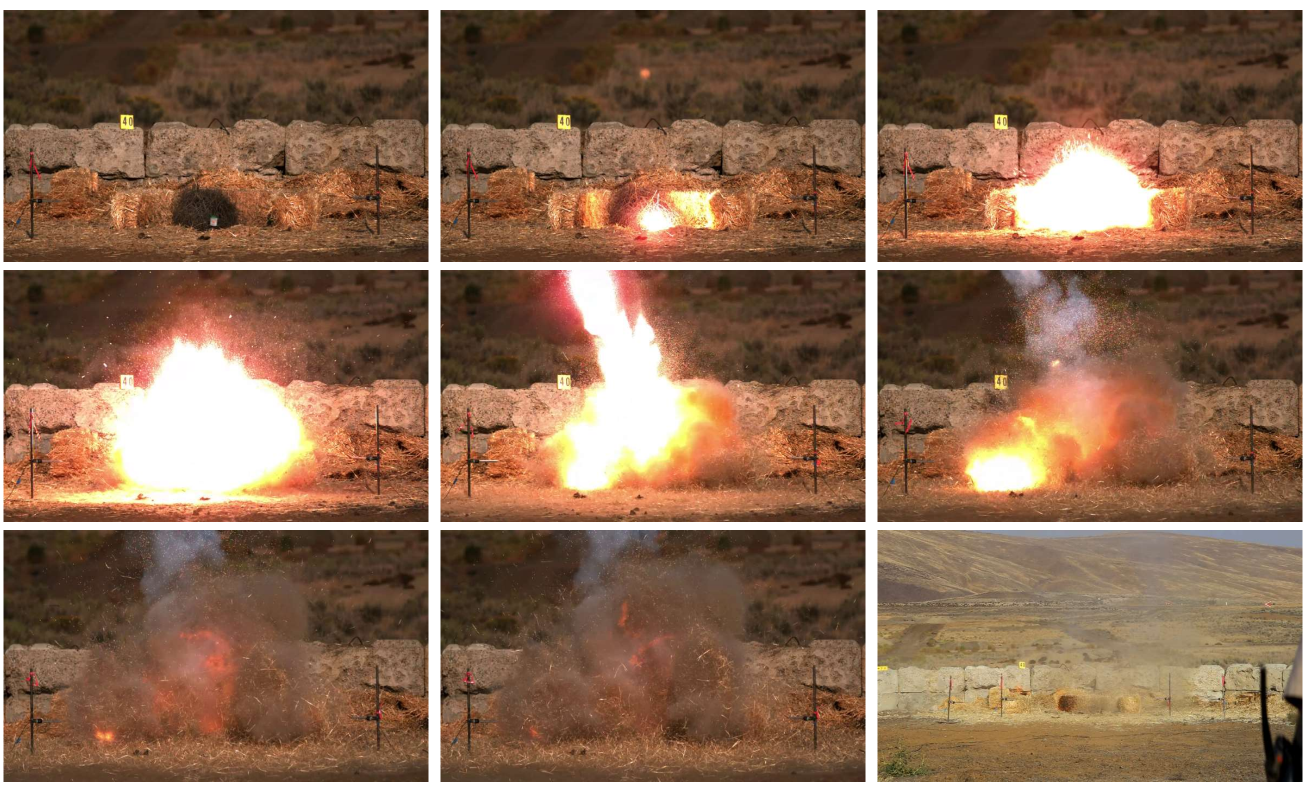

Figure 8—Test 40, 2018, 10 percent aluminum, partially mixed. Series showing explosion, vertical and lateral ejection of burning aluminum, residual combustion within the blast zone, and ignition of straw bales.

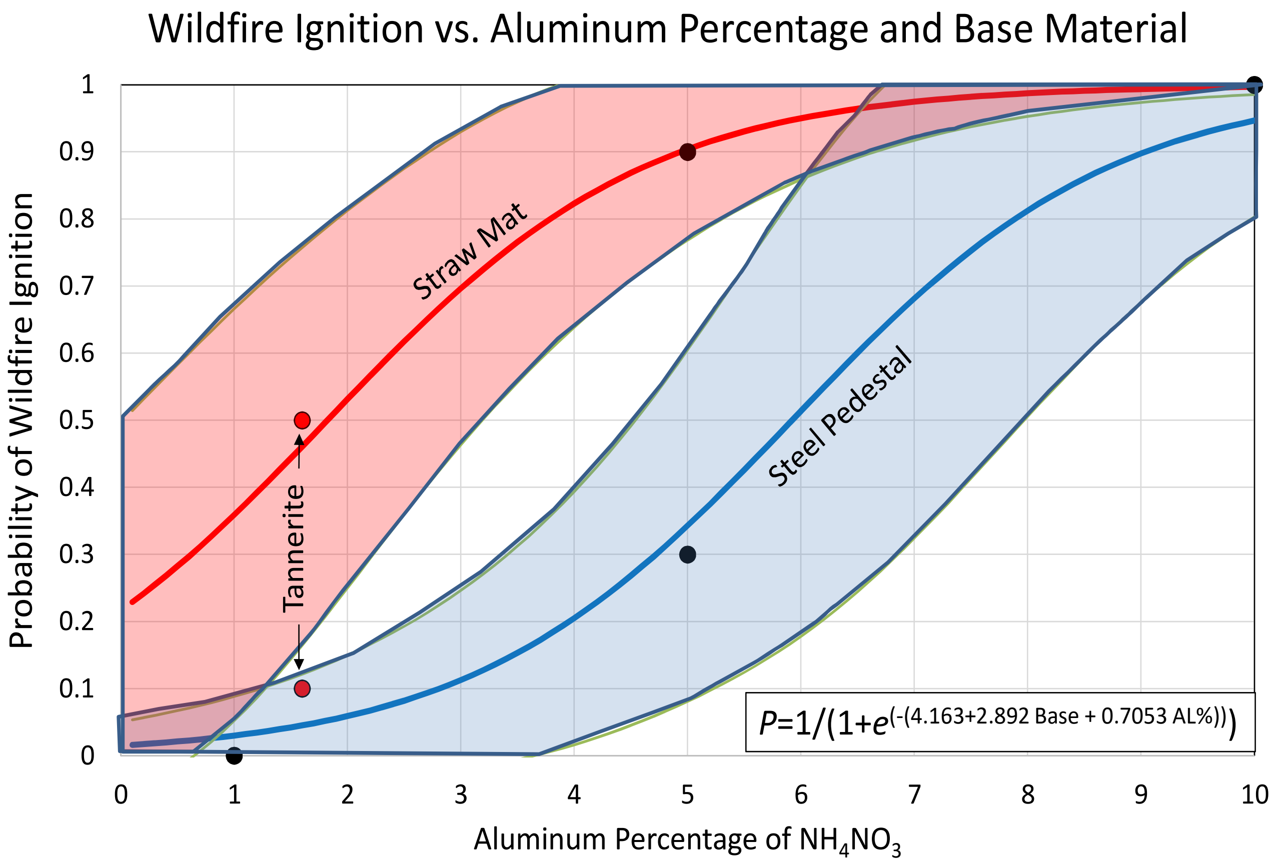

Figure 9—Logistic regression model and 95-percent confidence intervals from the 2018 tests relating the probability of wildfire ignition to the aluminum (AL) percentage of the aluminum-ammonium nitrate mass and the base material supporting the exploding target. Data points are averages of the 2018 data for these combinations. Logistic model uses predictors of base = 0 for pedestal and 1 for straw. Model had residual deviance of 40.31 and Akaike Information Criterion of 46.31.

Video Observations

High speed video revealed behaviors of the explosions that were related to the experimental variables. Partially mixed targets and those with higher AL concentrations appeared to display a larger and brighter fireball that lasted longer with a more coherent burning zone composed of brightly glowing AL particles (figs. 10, 11). Completely mixed targets or those with minimal AL produced a short-lived and small fireball with negligible visible glowing aluminum (figs. 12, 13). High speed video of the explosions suggested that the ejecta were directed upwards and away from potential ground fuels when the target was placed on the steel pedestal rather than the straw mat.

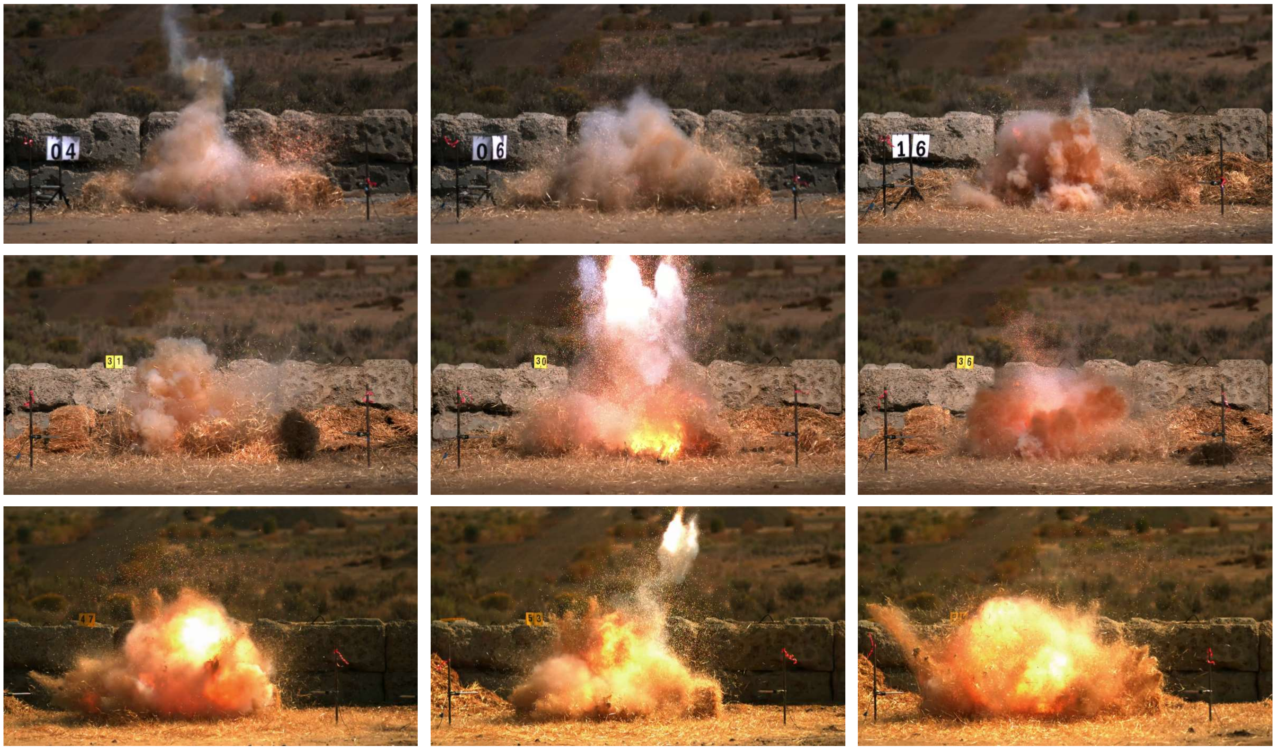

Figure 10—Frames from selected 2018 tests showing ejection of burning aluminum from blast (bright colored sparks) and burning within the blast volume. Number seen in the photograph is the test number corresponding to those in Appendix 2.

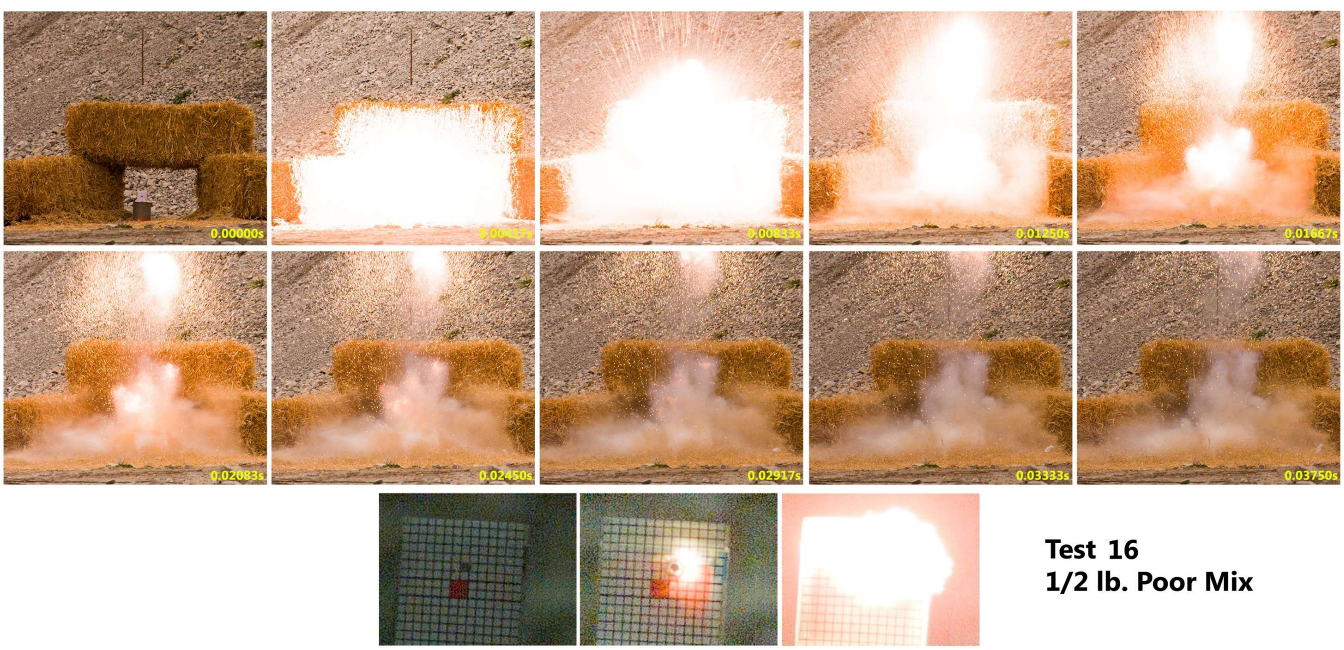

Figure 11—Sequence of images from test 16, 2015, showing large region of luminous burning and bright aluminum ejected from an incompletely mixed target. No ignition resulted.

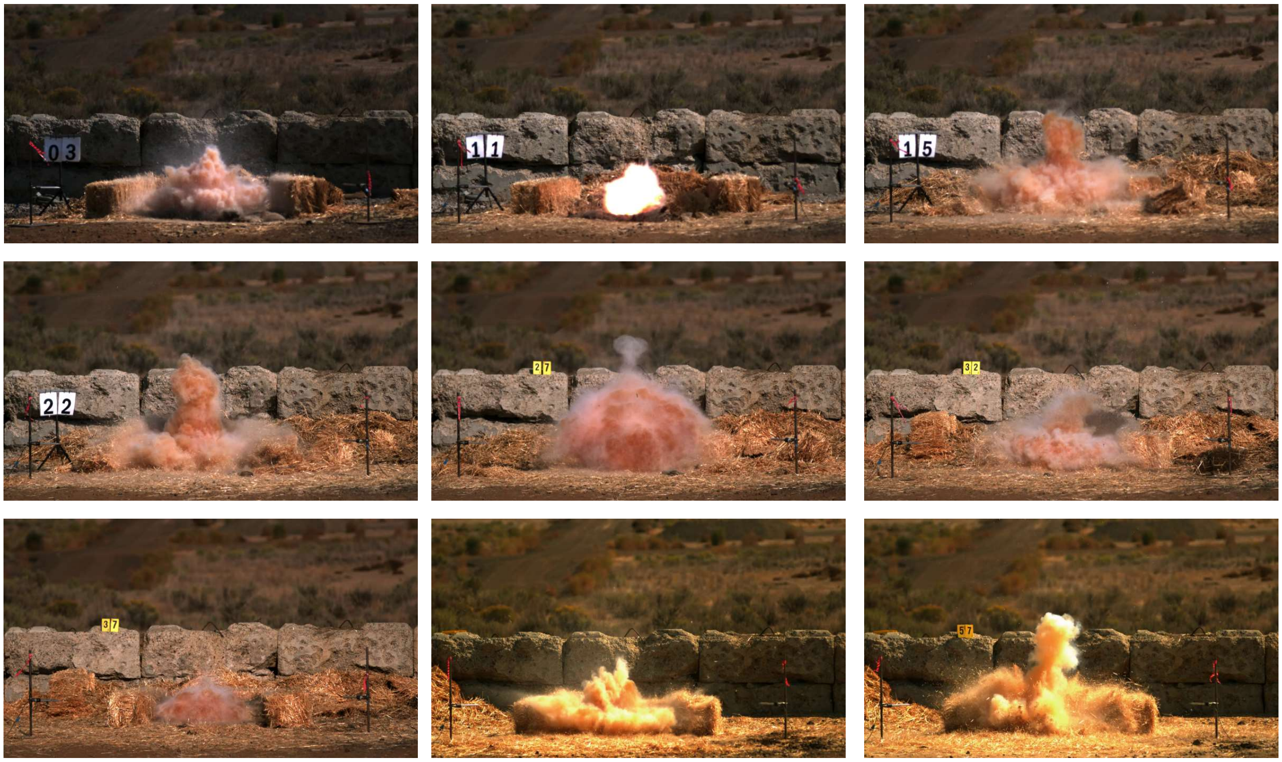

Figure 12—Frames from selected 2018 tests showing smaller explosion envelope with little visible burning within the blast volume or burning aluminum particles. Number seen in the photograph is the test number corresponding to those in Appendix 2.

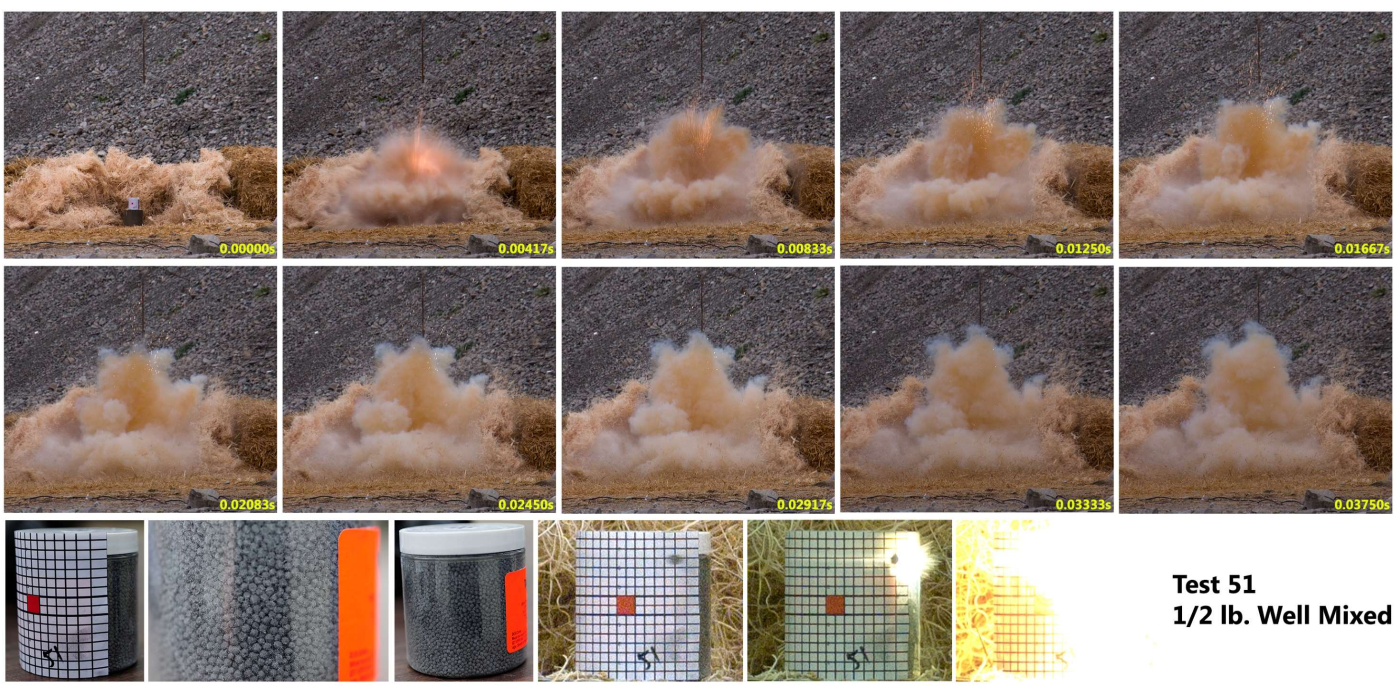

Figure 13—Sequence of images from test 51, 2015, showing side impact on well-mixed 0.5-lb target and minimal amounts of glowing material in the explosion envelope.

Pressure

In both the 2015 and 2018 test series, the average peak overpressure from the explosions (fig. 14) was affected by changes in the experimental variables, particularly the effect of mixing and AL concentration (fig. 15). Trends of maximum overpressure were similar among all four pressure probes, and only sensor P1 (closest left) was summarized for this report. Bullet impact location with the target in 2015 did not significantly affect average peak overpressure (fig. 16), but the box-plots of pressure measurements qualitatively suggested that centered impacts increased average peak overpressure compared to side impacts. Average peak overpressure increased with AL concentration through 5 percent but decreased for the 10 percent tests. The decrease at 10 percent may reflect behavior of a fuel-rich reaction for this particular AN formulation (prills) and aluminum mesh size.

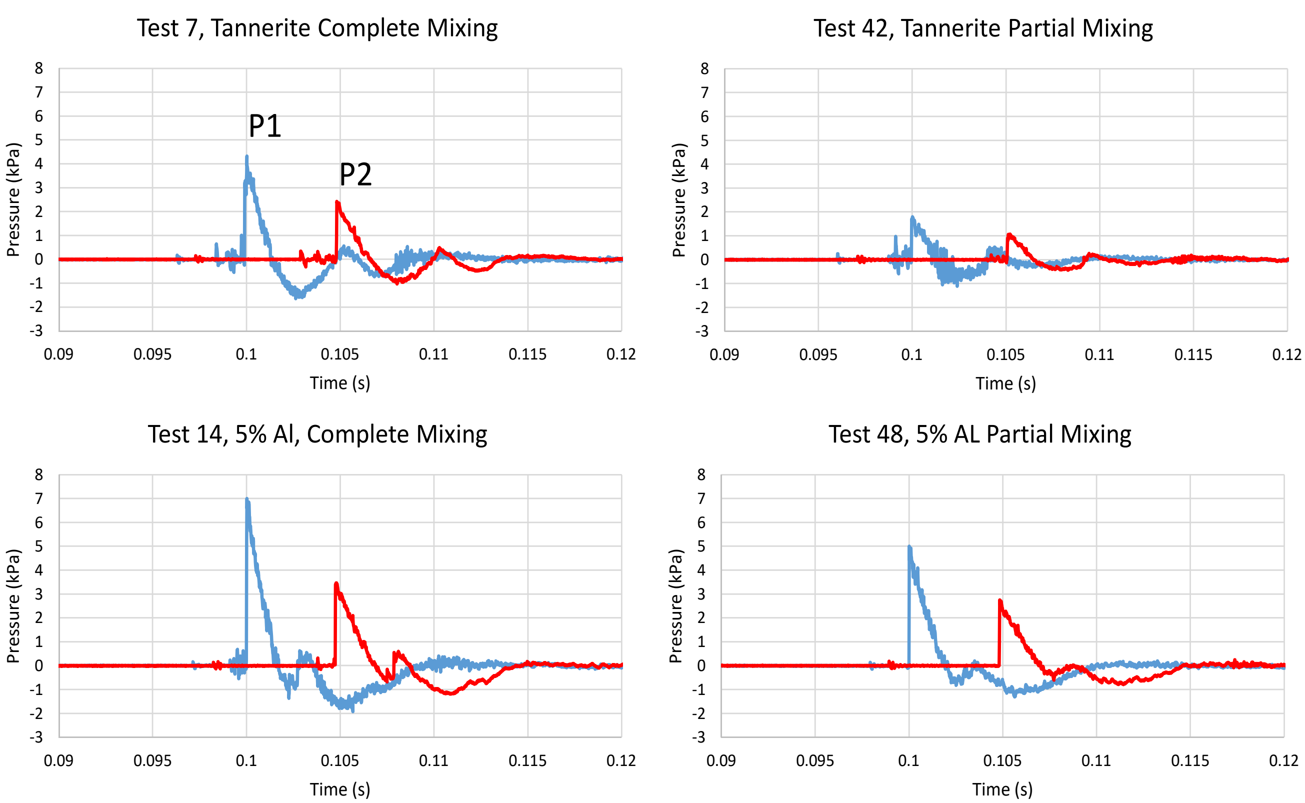

Figure 14—Graphs of air pressure perturbation from selected 2018 tests of exploding targets. All targets are 1 lb. Probe 1 (P1, blue) was 8 ft from the target. Probe 2 (P2, red) was 15 ft from the target (see also figure 1). Higher overpressure occurred with additional aluminum. Partial mixing diminished peak overpressure compared to complete mixing.

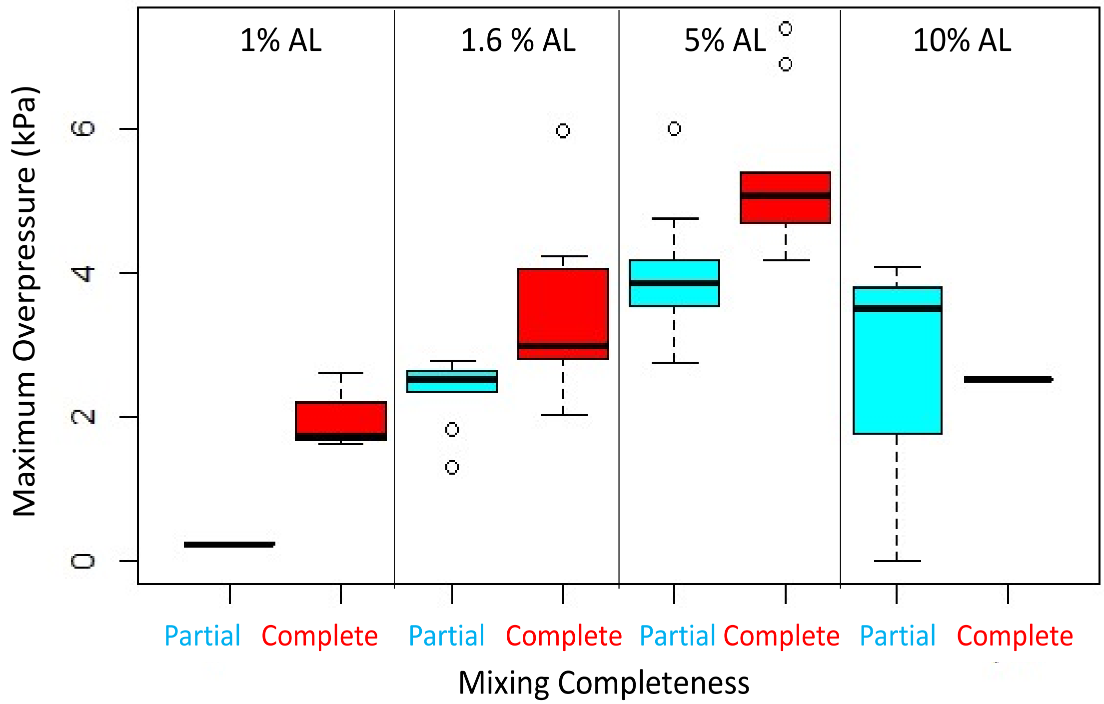

Figure 15—Data on maximum overpressure recorded by probe 1 (see figure 14) in 2018 tests showing variation explained by the completeness of target mixing as well as percentage of aluminum (expressed as percentage of ammonium nitrate mass). All targets contained 1 lb of ammonium nitrate.

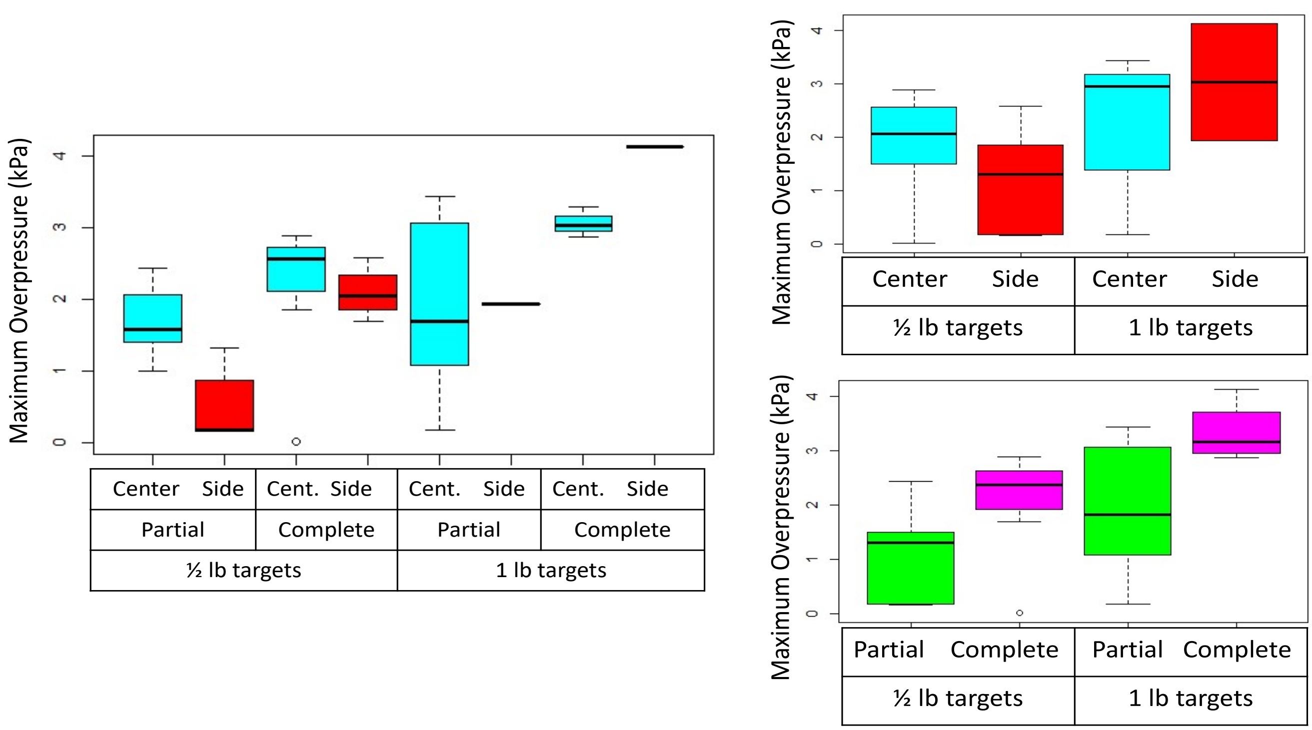

Figure 16—Data from 2015 tests showing maximum overpressure (recorded by probe 1; see figure 14) as a function of target size (0.5 lb or 1 lb), completeness of mixing, and bullet placement (side of target vs. center of target). Bullet placement was recorded by high speed video (see figures 7 and 8).

Discussion

Wildfire ignition from exploding targets was highly variable, but the experimental factors reflecting ANAL formulation and preparation, target placement, and shooting were found to affect both the explosive behaviors and likelihood of wildfire ignition. High speed videography showed more burning within the blast zone and more glowing AL particles for targets with higher AL concentrations and those with incomplete mixing (figs. 10, 11).

These visible differences in explosive characteristics may be related to the amount of AL exceeding the amount consumable by the explosion reaction. Even with thorough mixing, higher global AL concentrations can produce localized mixtures within the target volume that are fuel-rich relative to the amount of AN oxidizer and thus increase temperature of the reaction (Maranda 1990). Increasing the global percentages of AL in target mixtures, even below stoichiometric proportion, does not imply that the AL can react with all of the AN, especially within the interior volume of the spherical AN prills. Obviously, incomplete mixing of the target also creates fuel-rich conditions locally within the AN matrix. In both cases, the explosive reaction may not consume all of the AL fuel, which then remains available for burning. However, not all tests with large visible fireballs started a fire, and this exemplifies the random or uncontrolled nature of processes by which ignition results from characteristics of the explosion. Unconsumed AN prills were visible on a plastic sheet stretched out on the ground at distances of about 30 ft (10 m) from the target, suggesting that this is worthy of continued study to understand the explosive efficiency of ANAL mixtures, perhaps in relation to experimentally controlled factors. Although the role of mixing in wildfire ignition was not statistically significant in the 2018 tests, this is an important area of further investigation because it is perhaps one of the key variables affecting wildfire ignition threat that is not controlled by the manufacturers of exploding targets.

The placement of the target, whether elevated on a steel pedestal or placed on a straw mat, strongly affected wildfire ignition. There may be multiple processes involved. First, it appeared from observations and high speed video that a noticeable portion of the explosion trajectory was directed upward when the target was placed on the steel pedestal. This could be responsible for thrusting a larger quantity of the reaction up and away from vegetation on the ground. Second, targets placed directly on straw could have entrained more straw into the explosion envelope, increasing the amount of ignitable material in contact with burning in the reaction. Some high speed images do suggest the presence of straw floating around within the burning volume. We noted that most ignitions took place on the adjacent intact straw bales themselves rather than on loose material under the target or straw scattered around the blast zone.

This suggests that the trajectory of burning material, aluminum or straw, onto the face of adjacent bales was of considerable influence on ignition response (figs. 7, 8). The bales remained relatively stationary following the explosion and were not fragmented or flung from the blast zone.

Our tests did not directly determine how wildland fuel moisture content or environmental conditions of temperature, humidity, or solar radiation affected ignition. In general, however, dead wildland vegetation will be more likely to ignite at low moisture contents. The 2015 testing produced no ignitions during cool, humid, and cloudy days. The 2018 tests produced ignitions on dry, warm, and sunny days when fuel moisture content varied between about 3 and 9 percent. We are not aware of any prior testing of the commercially available products or whether an increase in aluminum fuel might result in observed ignitions under moist or humid conditions. We are also not aware of any documented testing utilizing naturally occurring dry vegetation and how these fuels might influence the observed ignitions in comparison to straw bales. These are two questions that need to be more fully explored. However, test results are confounded with respect to effects of fuel moisture because all 2015 tests were conducted with a pedestal supporting the target. With the apparent importance of the pedestal in reducing ignition in 2018, it is not clear how ignition rates would have changed if the target had been placed directly on a straw mat or other surface with less density.

Our tests were not conclusive regarding the effect of shot placement on either the completeness of the explosion or consequent ignition of wildfires. The average peak overpressure appeared lower for some targets with oblique impacts (fig. 16), but the sensitivity of the explosion to shot placement is probably much less than sensitivity to the other experimental variables. This factor and mixing are variables related to product usage that are outside the control of manufacturers of exploding targets and could play a role in producing incomplete explosions and wildfire ignitions. There are additional factors that may affect ignition but were not addressed in this study (see table 1). Properties and geometry of AN particles and their moisture content, along with AL particle sizes, could be considerably different among different commercial brands of ANAL targets.

The popularity of these products has led to a wide range of formulations to include more rimfire products that rely on increased metallic fuel content for sensitivity. The testing did show a direct relation between the aluminum content of the products and the prevalence of ignition and visible burning aluminum in the explosion. Wildland fire investigators considering an exploding target hypothesis for a fire start should be aware of the range of products available and how aluminum content, mixing, and other variables might impact the performance of the product and the likelihood of ignition. Tannerite is one of the most common commercial brands of exploding target, but with only approximately 1.6 percent AL, it is among the least likely to cause ignitions compared to brands or formulations with higher AL concentration.

Informal observations during this research suggested that the use of exploding targets may leave evidence in and around the blast seat. The research team observed some shattered pieces of the plastic containers in and around the blast seat following testing. This plastic, which exhibited exposure to high temperatures, appeared to have embedded AN on one side of the plastic. The team also observed unconsumed AN prills on the ground around the blast seat during testing. While this in no way means such evidence is present after all exploding target explosions, fire investigators should be cognizant that potential forensic evidence may be located around the blast seat that should be collected and documented.

Conclusions

Processes and factors affecting wildfire ignition from exploding targets were examined in two series of field tests and suggested that ignition and explosion characteristics were related to each phase of product usage: preparation and formulation, environmental conditions in which the target is used, and possibly shooting or bullet placement. This study was limited in the scope of which factors could be tested to produce statistically significant results, but did show that these products can be a competent ignition source for wildland fires if suitable conditions and fuels are present. More testing would be warranted to encompass different moisture conditions, fuel conditions and types, completeness of mixing, and bullet placement on the target. The wide variety of commercial formulations also suggests that other factors including the qualities and chemistry of different components would influence test results for common usage of exploding targets.

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Appendix A. Results from Field Tests in the Lolo National Forest near Missoula, Montana, 2015

Table A.1—Individual exploding target test results from the 2015 series using Tannerite® commercial targets with an average aluminum concentration of 1.6 percent of the ammonium nitrate component.

Test	Date	Time (MDT)	Size (lb; kg)	Mixing	Aim point	Ignition	Sampling rate (kHz)	Maximum pressure (kPa)
1	11/3/15	11:24	0.5; 0.2	Complete	Center	No	80	2.67
2	11/3/15	11:45	0.5	Partial	Center	No	80	2.44
3	11/3/15	12:00	0.5	Complete	Side	No	80	2.57
4	11/3/15	12:08	0.5	Partial	Side	No	80	0.16
5	11/3/15	12:15	0.5	Complete	Center	No	80	2.90
6	11/3/15	12:25	0.5	Partial	Center	No	80	2.07
7	11/3/15	12:33	0.5	Complete	Side	No	1000	2.09
8	11/3/15	12:46	0.5	Partial	Center	No	1000	2.40
12	11/3/15	13:35	0.5	Partial	Side	No	500	0.45
16	11/3/15	13:40	0.5	Partial	Side	No	250	1.32
18	11/3/15	13:46	0.5	Partial	Center	No	125	1.01
22	11/3/15	13:55	0.5	Partial	Center	No	1000	1.50
24	11/3/15	14:03	0.5	Partial	Side	No	1000	0.17
25	11/3/15	14:10	0.5	Complete	Center	No	1000	2.38
26	11/3/15	14:17	1; 0.4	Partial	Center	No	1000	3.43
29	11/3/15	14:29	1	Complete	Center	No	1000	3.29
30	11/3/15	14:41	1	Partial	Center	No	1000	2.95
31	11/3/15	14:55	1	Complete	Side	No	1000	4.12
34	11/3/15	15:05	1	Partial	Center	Charring	1000	1.09
38	11/3/15	15:15	1	Partial	Center	No	1000	1.70
41	11/3/15	15:25	1	Complete	Center	No	1000	3.03
45	11/3/15	15:35	0.5	Complete	Center	No	1000	1.85
46	11/4/15	10:40	0.5	Partial	Center	No	80	1.66
48	11/4/15	10:46	1	Partial	Side	No	80	1.94
51	11/4/15	10:55	0.5	Complete	Side	No	1000	1.70
52	11/4/15	11:03	0.5	Partial	Side	No	1000	1.30
53	11/4/15	11:12	1	Complete	Center	No	1000	2.87
55	11/4/15	11:21	0.5	Complete	Side	No	1000	2.00
56	11/4/15	11:40	0.5	Partial	Center	No	1000	1.41
57	11/4/15	11:45	0.5	Complete	Center	No	1000	2.56
58	11/4/15	11:51	1	Partial	Center	No	1000	3.07
1000	11/4/15	12:00	0.5	Complete	Center	No	80	2.77

Appendix B. Results from Field Tests at the Yakima Training Center in the State of Washington, 2018.

Table B.1—Individual exploding target test results from the 2018 series. Note that all targets[1] weighed 1 lb (0.4 kg), and sampling rate of 80 kHz was used for all pressure measurements.

Test	Date	Time (MDT)	AL%	Mixing	Base	Air temperature (°F; °C)	Relative humidity (%)	Solar radiation (W/m^2)	Ignition	Maximum pressure (kPa)
1	9/5/18	12:21	5	Partial	Pdstl	79.6; 24.8	17.1	725	Yes	4.57
2	9/5/18	14:23	1.6	Partial	Pdstl	79.3; 26.3	15.8	764	No	3.27
3	9/5/18	12:52	1	Complete	Pdstl	78.3; 25.7	16.2	777	No	3.63
4	9/5/18	14:06	5	Partial	Pdstl	80.1; 26.7	15.2	774	No	5.28
6	9/5/18	14:14	5	Complete	Pdstl	80.4; 26.9	14.9	770	No	6.82
7	9/5/18	14:33	1.6	Complete	Pdstl	80.6; 27.0	15.1	762	No	4.46
8	9/5/18	14:41	1	Complete	Pdstl	80.4; 26.9	15.3	757	No	2.26
10	9/5/18	14:44	1	Partial	Pdstl	80.6; 27.0	15.0	752	No explosion	0.49
10A	9/5/18	14:53	1	Partial	Pdstl	79.9; 26.6	15.5	723	No explosion	0.57
11	9/5/18	15:03	1.6	Partial	Pdstl	79.5; 26.4	15.8	727	No	2.85
13	9/5/18	15:07	5	Partial	Pdstl	79.3; 26.3	15.9	721	No	6.39
14	9/5/18	15:12	5	Complete	Pdstl	81.1; 27.3	15.1	718	Yes	6.86
15	9/5/18	15:34	1.6	Complete	Pdstl	82.6; 28.1	14.4	686	No	3.36
16	9/5/18	15:38	5	Partial	Pdstl	82.0; 27.8	14.4	676	No	5.19
18	9/5/18	15:46	1	Complete	Pdstl	81.5; 27.5	14.7	662	No	3.24
20	9/5/18	15:52	1	Complete	Pdstl	82.2; 27.9	14.8	639	No	2.16
22	9/5/18	15:57	1.6	Complete	Pdstl	82.0; 27.8	15.0	638	No	4.07
23	9/5/18	16:02	10	Partial	Pdstl	81.7; 27.6	14.8	631	Yes	Measurement error
25	9/5/18	16:29	1.6	Complete	Pdstl	81.1; 27.3	15.0	582	Yes	3.12
27	9/5/18	16:38	5	Complete	Pdstl	82.6; 28.1	14.9	562	No	5.80
28	9/5/18	16:44	1.6	Partial	Pdstl	82.8; 28.2	15.8	549	No	2.85
29	9/5/18	16:51	5	Complete	Pdstl	81.9; 27.7	16.2	537	No	5.36
30	9/5/18	17:01	10	Partial	Pdstl	81.5; 27.5	16.2	519	Yes	4.29
31	9/5/18	17:14	5	Partial	Pdstl	82.2; 27.9	16.0	495	No	3.66
32	9/5/18	17:24	1.6	Complete	Pdstl	81.9; 27.7	16.2	469	No	3.85
36	9/5/18	17:32	5	Complete	Pdstl	81.3; 27.4	16.3	444	Yes	5.54

Appendix B cont.

Test	Date	Time (MDT)	AL%	Mixing	Base	Air temperature (°F; °C)	Relative humidity (%)	Solar radiation (W/m^2)	Ignition	Maximum pressure (kPa)
37	9/5/18	17:46	1	Complete	Pdstl	81.9; 27.7	16.4	397	No	2.01
38	9/5/18	17:51	1.6	Partial	Pdstl	82.4; 28.0	16.0	389	No	3.30
39	9/5/18	17:58	1.6	Partial	Pdstl	82.4; 28.0	16.1	368	No	3.43
40	9/5/18	18:02	10	Partial	Pdstl	82.0; 27.8	16.3	353	Yes	5.39
41	9/6/18	10:19	1.6	Complete	Straw	70.9; 21.6	22.8	405	Yes	3.79
42	9/6/18	10:31	1.6	Partial	Straw	72.1; 22.3	21.1	441	Yes	1.77
43	9/6/18	10:37	5	Complete	Straw	72.7; 22.6	21.0	464	Yes	6.90
44	9/6/18	10:51	5	Complete	Straw	74.3; 23.5	19.5	496	Yes	6.94
45	9/6/18	11:03	5	Partial	Straw	75.9; 24.4	18.4	528	Yes	9.16
46	9/6/18	11:07	1.6	Complete	Straw	76.3; 24.6	18.3	538	Yes	2.60
47	9/6/18	11:16	5	Complete	Straw	77.5; 25.3	17.5	559	Yes	7.61
48	9/6/18	11:29	5	Partial	Straw	78.1; 25.6	16.8	584	Yes	4.81
49	9/6/18	11:39	1.6	Partial	Straw	79.2; 26.2	16.4	604	Yes	3.49
50	9/6/18	11:48	1.6	Partial	Straw	79.5; 26.4	15.8	621	Yes	3.74
51	9/6/18	11:57	1.6	Partial	Straw	79.5; 26.4	17.0	637	No	4.41
52	9/6/18	12:04	5	Partial	Straw	80.8; 27.1	15.6	651	Yes	5.16
53	9/6/18	12:12	5	Partial	Straw	80.6; 27.0	15.9	667	Yes	5.02
54	9/6/18	12:19	5	Partial	Straw	80.8; 27.1	16.3	677	No	5.17
55	9/6/18	12:28	1.6	Complete	Straw	81.1; 27.3	16.3	687	No	5.60
56	9/6/18	12:33	1.6	Complete	Straw	81.3; 27.4	16.2	692	No	5.61
57	9/6/18	12:38	1.6	Complete	Straw	81.3; 27.4	16.4	700	No	9.77
58	9/6/18	12:46	1.6	Partial	Straw	81.9; 27.7	16.1	708	No	2.32
59	9/6/18	12:52	5	Complete	Straw	81.9; 27.7	16.1	708	Yes	10.87
60	9/6/18	12:59	5	Complete	Straw	82.2; 27.9	16.0	722	Yes	9.83
61	9/6/18	13:07	10	Complete	Straw	81.7; 27.6	16.1	732	Yes	3.58

[1] Tannerite® commercial targets. Approximate concentration of aluminum powder (AL) was 1.6 percent of the weight of the 1-lb ammonium nitrate component.

[2] Pdstl = 6 in (15 cm) high steel pedestal.

Appendix C. Weather Conditions for Nine Mile, Montana.

Table C.1—Weather conditions recorded at Remote Automated Weather Station (RAWS) NINM8, Nine Mile, Montana, for November 3–4, 2015. RAWS observations[3] (additionally highlighted in yellow) were recorded during exploding target testing conducted on the Lolo National Forest near Missoula, Montana. Station location: Elevation: 3,300 ft (1,000 m); Latitude: 47.071389; Longitude: -114.401389.

Time (MST)	Air Temperature (°F; °C)	Dew-point (°F; °C)	Relative Humidity (%)	Wind Direction	Wind Speed (mph; km/hr)	Fuel Temperature (°F; °C)	Fuel Moisture (%)	Solar Radiation (W/m^2)	Solar % of psbl	Precip 1 Hour (inches; mm)
03 Nov 00:59	31; -0.6	31	98	Calm	0	31	27	0	--	0
03 Nov 01:59	32; 0	31	98	Calm	0	32	27	0	--	0
03 Nov 02:59	31	31	98	Calm	0	32	27	0	--	0
03 Nov 03:59	32	32	99	Calm	0	32	27	0	--	0
03 Nov 04:59	33; 0.6	32	98	Calm	0	33	27	0	--	0
03 Nov 05:59	34; 1.1	33	97	Calm	0	33	27	0	--	0
03 Nov 06:59	33	32	96	Calm	0	32	27	0	--	0
03 Nov 07:59	33	32	98	Calm	0	33	27	6	--	0
03 Nov 08:59	34	33	98	Calm	0	35	27	49	39%	0
03 Nov 09:59[3]	36; 2.2	35	97	Calm	0	37	27	69	21%	0
03 Nov 10:59[3]	39; 3.9	37	91	Calm	0	40	27	109	23%	0
03 Nov 11:59[3]	41; 5.0	38	88	Calm	0	43	27	171	29%	0
03 Nov 12:59[3]	42; 5.6	35	75	SSW	2 (3 km/hr), gusting to (G) 4 (6 km/hr)	43	26	184	29%	0
03 Nov 13:59[3]	43; 6.2	36	75	ESE	2G06 (10 km/hr)	44	25	109	18%	0
03 Nov 14:59[3]	44; 6.7	34	67	WNW	4 (6 km/hr) G10 (16 km/hr)	44	23	142	27%	0
03 Nov 15:59[3]	43	32	64	NW	3 (5 km/hr) G10	42	22	70	18%	0
03 Nov 16:59[3]	42	31	64	NNW	3G08 (13 km/hr)	42	21	49	22%	0
03 Nov 17:59[3]	42	32	67	WNW	2G06	40	20	2	40%	0
03 Nov 18:59	41	32	70	N	3G07 (11 km/hr)	40	20	0	--	0
03 Nov 19:59	40; 4.5	33	76	NW	3G08	39	21	0	--	0

Time (MST)	Air Temperature (°F; °C)	Dew-point (°F; °C)	Relative Humidity (%)	Wind Direction	Wind Speed (mph; km/hr)	Fuel Temperature (°F; °C)	Fuel Moisture (%)	Solar Radiation (W/m^2)	Solar % of psbl	Precip 1 Hour (inches; mm)
03 Nov 20:59	39	33	80	SSW	3G11 (18 km/hr)	38	21	0	--	0
03 Nov 21:59	38; 3.4	34	85	Calm	G04	37	23	0	--	0
03 Nov 22:59	38	35	88	Calm	0	37	23	0	--	0
03 Nov 23:59	37; 2.8	35	94	Calm	G04	37	24	0	--	0
04 Nov 00:59	37	35	92	WSW	1G03	36	25	0	--	0
04 Nov 01:59	36	33	90	SW	3G05 (8 km/hr)	35	26	0	--	**0.01; 2.5**
04 Nov 02:59	35; 1.7	34	98	Calm	G05	33	27	0	--	0
04 Nov 03:59	33	32	95	Calm	0	30	27	0	--	0
04 Nov 04:59	31	30; -1.1	96	Calm	0	30	27	0	--	0
04 Nov 05:59	31	31	98	Calm	0	30	27	0	--	0
04 Nov 06:59	31	30	96	Calm	G05	30	27	0	--	0
04 Nov 07:59[3]	31	30	97	Calm	G06	31	27	3	--	0
04 Nov 08:59[3]	32	31	98	Calm	0	33	27	34	28%	0
04 Nov 09:59[3]	36	35	95	Calm	0	37	27	103	32%	0
04 Nov 10:59[3]	38	35	89	SSW	3G05	40	27	191	40%	0
04 Nov 11:59[3]	41	34	77	SSW	4G05	43	27	241	42%	0
04 Nov 12:59[3]	41	29; -1.7	63	WSW	2G06	42	25	174	28%	0
04 Nov 13:59[3]	46; 7.8	35	66	SW	5G08	50; 10.1	23	267	44%	0

[1]Tannerite® commercial targets. Approximate concentration of aluminum powder (AL) was 1.6 percent of the weight of the 1-lb ammonium nitrate component.

[2]Pdstl = 6 in (15 cm) high steel pedestal.

[3]RAWS observations (additionally highlighted in yellow) were recorded during exploding target testing conducted on the Lolo National Forest near Missoula, Montana.

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