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Less-than-lethal “Flashbang” Diversionary Device

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Abstract

Diversionary devices such as flashbang grenades are used in a wide variety of military and law-enforcement operations. They function to distract and/or incapacitate adversaries in scenarios ranging from hostage rescue to covert strategic paralysis operations. There are a number of disadvantages associated with currently available diversionary devices. Serious injuries and fatalities have resulted from their use both operationally and in training. Because safety is of paramount importance, desired improvements to these devices include protection against inadvertent initiation, the elimination of the production of high-velocity fragments, less damaging decibel output and increased light output. Sandia National Laboratories has developed a next-generation diversionary flash-bang device that will provide the end user with these enhanced safety features.

Acknowledgements

The authors would like to acknowledge the work of Mark C. Grubelich, also of Sandia National Laboratories in Org. 16000. The Sandia fuel-air Less-than-lethal Diversionary Device was invented by Mark, and patented through Sandia National Laboratories (U.S. Patent Number 6,253,680).

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Introduction

The “traditional” flashbang design, used in varying configurations, features a fuze cast out of zinc alloy, similar to delay fuzes used on grenades. After a delay, of typically one second, the fuze output charge fires into a volume filled with a fuel-oxidizer mixture of aluminum and potassium perchlorate, which is commonly called “flash powder”. In some cases, aluminum in the flash powder is replaced with magnesium. The flash powder is sensitive to accidental initiation by friction, electrostatic discharge, and impact. The combustion of flash powder travels faster than the speed of sound in the unreacted material, meeting the definition for a detonating explosive. The flash powder charge is typically contained in a strong cylindrical cardboard body, and in the more advanced Mk 141 design, in a hard urethane foam body. Other advances in the Mk 141 included a fuze that ejects from the foam body at low velocity, to prevent the fuze from becoming a high-velocity fragment hazard when the main explosive charge functions. Other solutions to the fragment hazard issue included using a flashbang device body with ports, and allowing the combustion products and high-pressure gases of the device to vent through the symmetrically located body ports. Despite the advances, the device still contains explosive flash powder, and also generates dangerous acoustic pressures close to the flashbang body during functioning.

Problems associated with many currently used diversionary devices include occasional flashthroughs in the fuze assembly (leading to "instantaneous" functioning), fuze function failures, the ejection of the fuze at potentially lethal velocities ranging from 24 meters/sec to 55 meters/sec, fires as a result of smoldering cardboard body fragments, and permanent damage caused by acoustic and optical output.¹ These devices are also susceptible to sympathetic detonation and/or initiation by bullet impact. As a result of the law enforcement safety requirements for an improved operational device, Sandia National Laboratories was asked to design a device addressing these problems. The following paper addresses internal pressure, audio and optic performance measurements of this device.

Based on recent research, coupled with the desire for an improvement in safety, a safer and more versatile diversionary device has been developed using the combustion of a fuel delivered by the device and the oxygen present in the ambient air (U.S. Patent Number 6,253,680). This flashbang diversionary device ejects a powdered fuel that mixes with ambient air and then ignites from hot particles. This process is similar to the ignition of propellant gases in guns resulting in a "muzzle flash" event. The operation of this device produces a fuel-air combustion reaction. Since a fuel-air combustion process is more spatially and temporally diffuse than the detonation of a condensed explosive, a longer pressure pulse with a slower rise to the peak pressure results.

Work was conducted to take the current prototype of Sandia’s flashbang device and obtain design information needed to convert the concept model into a producible design. The first phase involved redesigning the device body to be smaller and lighter. For the redesign, the internal pressure with a normal load of propellant was used (combined with safety factors) as a guide to allow decreasing of the existing dimensions

and weight (Figure 1). The second phase involved proof testing the redesigned flashbang device, and obtaining performance data (optical and acoustic output) to validate the design and, where possible, to compare it to commercial devices.



Figure 1: Redesigned flashbang device. Prototype design is on the left, while the redesigned body is on the right. While the redesigned body is smaller in diameter and shorter in length, the internal volume and dimensions are preserved.

Background Theory of Fuel-Air Explosions

The explosion of a mixture of vapor or finely divided solid fuel and air, exhibits marked differences from an explosion of a condensed phase liquid or solid explosive.

- The cloud of fuel and air fills a much larger volume than an equivalent mass of condensed phase explosive.
- The fuel-air cloud acts as a diffuse source, which does not generate the very high near-field pressures of a condensed-phase explosive.
- The fuel-air explosion pressures seldom exceed 20 atm, or 300 psi.^{2,3}
- The pressure pulse from a fuel-air explosion has a much longer timescale than a condensed-phase event.
- Because of the long pressure pulse, the impulse generated by a fuel-air event is comparatively large.^{2,3}
- The fuel-air event more effectively couples through air blast to certain targets such as structures and human adversaries.
- While near-field pressures generated by fuel-air events may be lower, the pressures are still close to the in-cloud pressure even at distances on the order of several cloud diameters away from the edge of the fuel-air cloud, due to the long timescale of the pressure profile.^{2,3}

In the Sandia flashbang device design, the acoustic output is generated by the dispersal event, with some contribution from the cloud of burning aluminum powder. In general, the Sandia Flashbang diversionary device also exhibits the other characteristic properties of fuel-air explosion events. This is beneficial because, with the long pressure duration, the acoustic output at longer distances can be comparable to flash powder or other high explosives. This allows similar acoustic performance while the pressures close to the Sandia flashbang device body are much lower than those close to a charge of flash powder or other high explosive.

Prototype Flashbang Diversionary Device Design

The prototype was designed with the features necessary to disperse and ignite the aluminum powder fuel. These features include the threads necessary for fitting the hand grenade time fuse assembly, and a chamber under the grenade fuze to hold the black powder propellant, shown in red (Figure 2). The propellant chamber is sealed with aluminum foil tape, to exclude ambient moisture during storage and handling. The dark grey cap assembly with black powder and time fuse is in turn threaded into the body, depicted in light grey. The main body holds the aluminum powder fuel charge, shown in green. The ports, through which the aluminum is dispersed into the surrounding air, are sealed with Kapton tape, to prevent the fuel charge from leaking out. To initiate the device, the grenade pin is pulled, and the spoon released, which fires a percussion primer, in turn igniting a delay column. The delay column then ignites the output charge of the fuze, which fires into the black powder propellant chamber, igniting the 3.0-gram charge of 4Fg black powder propellant. The grenade fuze output and black powder propellant combustion together, rupture the foil tape seal and apply pressure to the Eckart 5413H aluminum powder fuel charge. The tape sealing the vent ports ruptures, and the aluminum powder is dispersed out of the case, along with the high temperature propellant combustion products. The aluminum powder ignites in the presence of the hot combustion products and ambient air. The burning fuel-air cloud forms the desired luminous output from both the burning aluminum and high temperature aluminum oxide products. The acoustic output is due to the pressurized dispersal event and to some extent is sustained by burning aluminum.

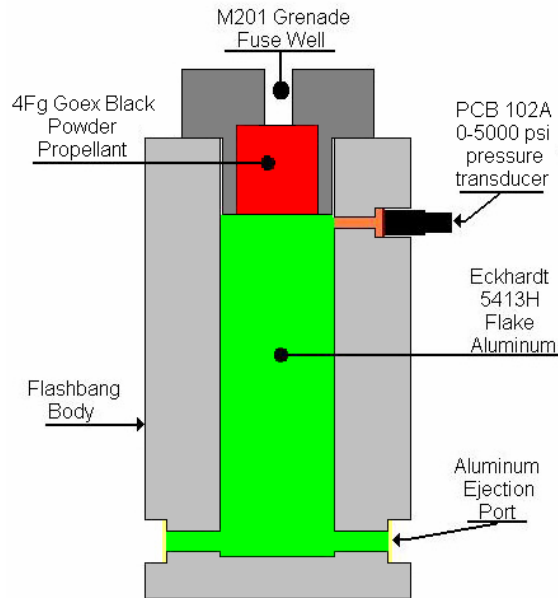


Figure 2: Diagram (not to scale) depicting the prototype Flashbang diversionary device body, showing mounting location of pressure transducer. Note transducer is immediately under powder cavity (in red) where pressure is highest.

The black powder propellant chamber was originally designed to hold up to 6 grams of black powder, while the final propellant load was limited to 3.0 grams. The cross-sectional area of the fuel chamber is exactly 1 in², which equals the area all of the individual vent port areas summed. This was calculated to impede as little as possible the flow of fluidized aluminum fuel out through the vents. The outside dimension of the case was designed to be the same as that of a standard soft drink can. While this created a design that was natural to hold, and that was strong enough for repeated use and testing, the weight of the resultant thick walled case was found to be unacceptable. The acoustic performance of the original design was found to be satisfactory however, so a redesign was undertaken that held constant the original interior dimensions and performance, but which trimmed away excess weight. An additional safety feature was incorporated into the redesign, which involved reducing the propellant cavity dimensions, to allow only a 3.0-gram charge of black powder to be loaded. Figure 1 shows the prototype design and the final flashbang diversionary device canister design.

Experimental Testing

Internal Pressure Measurements

In order to design the flashbang body and perform a stress analysis on the design, internal pressure measurements were necessary. A total of 12 separate experiments were conducted. Internal pressure measurements were taken using a PCB Piezotronics 102A transducer with an operational range of 0-5000 psi. The pressure transducer was

mounted into the prototype flashbang body (Figure 2). The transducer was protected from thermal loading by coating the outside of the diaphragm with a layer of Room Temperature Vulcanizing (RTV) silicone and by filling the mounting well with silicone grease.

Three internal pressure measurements were taken using the standard amount of 3.0 grams of 4Fg Goex black powder. The values of these measurements ranged from 500 to 700 psi (Table 1). To ascertain the relative risk of blowing the M201 fuze out of the Flashbang diversionary device body, a second series of tests was conducted by doubling the black powder propellant load from 3.0 grams to 6.0 grams. With this overload of 6.0 g, the internal pressure was measured to be between 3000 and 4000 psi (Table 1). In nine overload tests performed, the fuze was not ejected from the device.

Table 1: Internal Pressure Measured as a Function of Gas Generator Load

Goex 4Fg Black Powder Load	Pressure Range
3.0 g (standard load)	500-700 psi
6.0 g (double overload)	3000-4000 psi

The redesign of the flashbang made it lighter (445 grams loaded) while keeping the internal volume, the internal dimensions, and the ejection ports the same. The material used for the device construction is T6061 aluminum alloy. The dimensions of the black powder cavity were changed to hold exactly 3.0 grams of propellant to prevent overloading the black powder charge. The internal pressure measurements used for the final body design are seen in Figure 3.

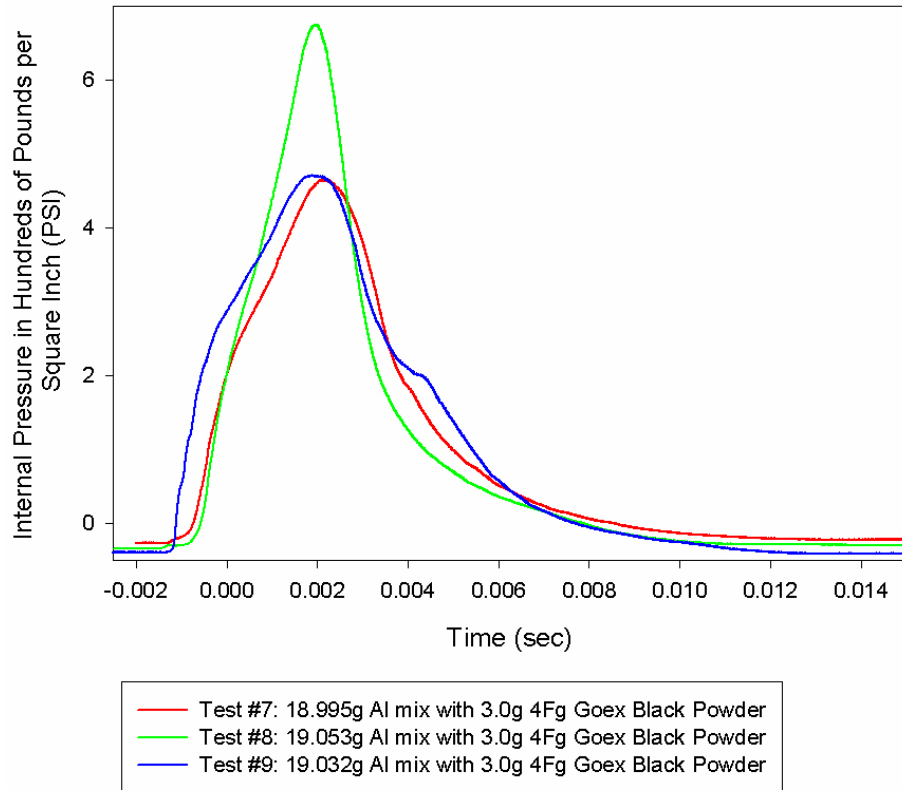


Figure 3: Internal Pressure plotted as a function of time. On the Y-axis is the internal pressure measured, in hundreds of pounds per square inch (psi). Also demonstrated here is the variability in internal pressure due to variations in propellant load, fuze output, and aluminum powder packing.

Using thick cylinder theory,⁴ the stresses were calculated at the internal surface of the aluminum cavity where stresses would be highest. Applying the calculated stresses and the yield strength of the material, the thickness of the body was determined to ensure that the overall factor of pressure safety remained approximately a factor of five times. Figure 4 shows the weakest areas in red where the safety factor is below five, but still above the yield strength of the material. Figure 5 shows a detailed view of the safety factors calculated around the exit holes, which is the weakest area. The blue contour represents a safety factor of five; green represents a safety factor of four.

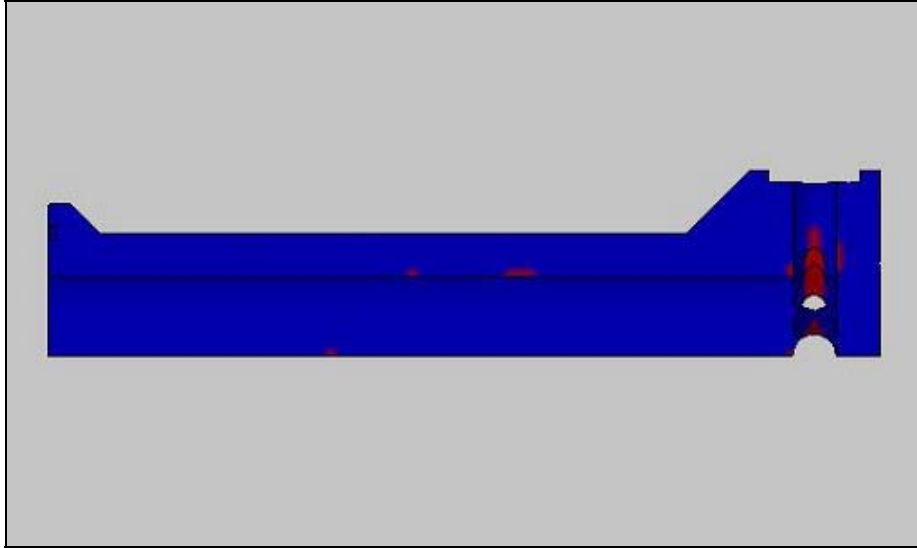


Figure 4: Modeling of safety factors on a quarter cross-section. Red areas correspond to a safety factor less than 5.

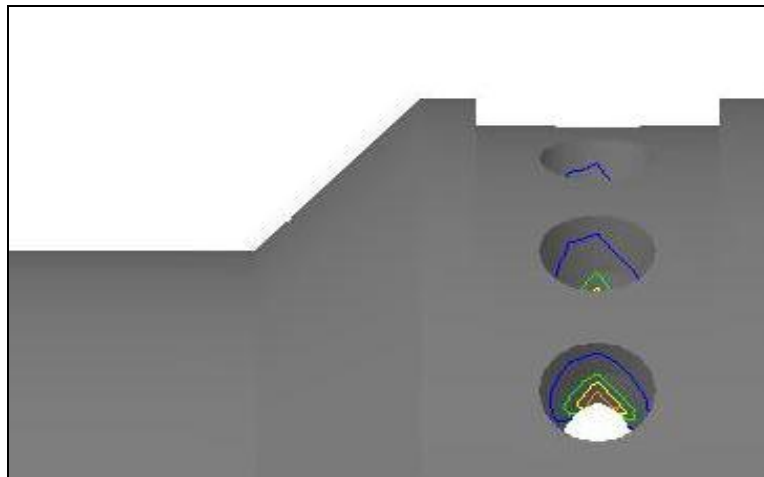


Figure 5: Detailed view of safety factors calculated around exit holes.

One of the customer requirements was that the flashbang device be reusable up to ten cycles for training purposes. In order to investigate cyclic effects on the device body, a series of tests using strain gages were completed. A modified flashbang body was used during the strain gage tests to simulate a worst-case scenario. Approximately one-third of the ejection ports were not machined on one side of the body. This configuration would simulate the device being thrown into a thick carpet or dirt, potentially blocking some of the ejection ports.

Strain was measured on the flashbang body in three areas: two on the side (circumferential and longitudinal) and one on the bottom (Figure 6). Micromasurements' general-purpose CEA series foil gages were used. To protect the

gages from the product cloud during device firing, a layer of RTV silicone was placed over the gages. Strain data were collected from the modified Flashbang diversionary device body for twenty cycles. There was no significant increase in strain or material deformation at the three gage locations over the twenty cycle testing. The circumferential strain average was 206 units of microstrain with a standard deviation of 56.4 microstrain. On the side of the device, the longitudinal average value was 187 microstrain with a standard deviation of 57.3. The strain on the bottom had an average value of 362 microstrain with a standard deviation of 120.7. All the average values of microstrain would correspond to deformations of material on the order of 10 micrometers.

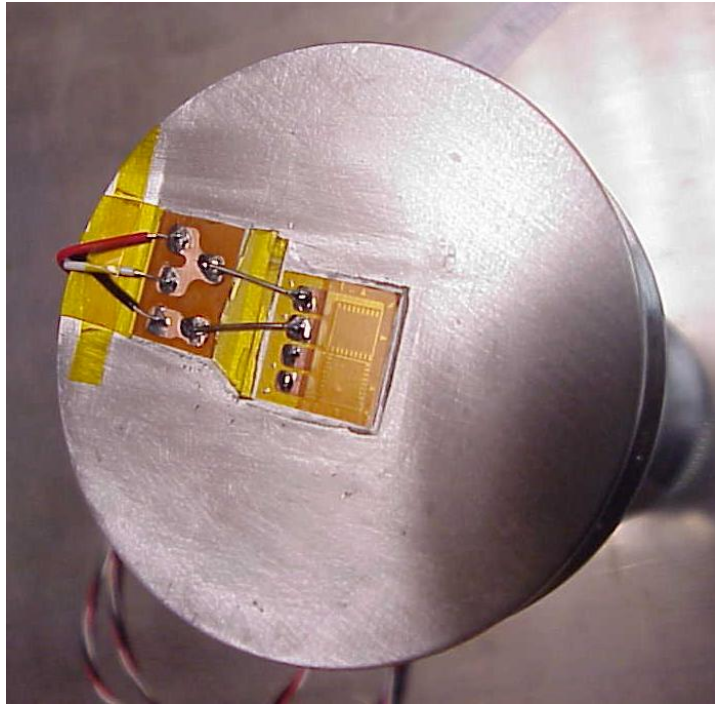
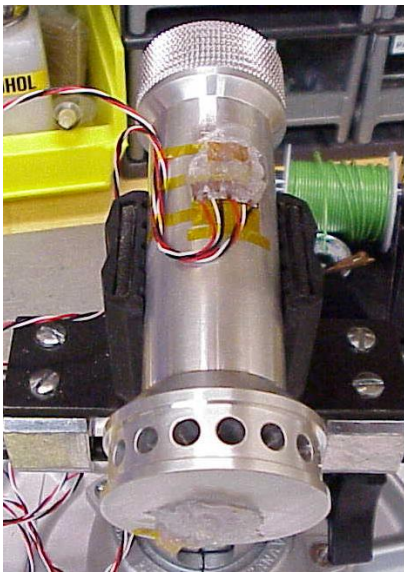
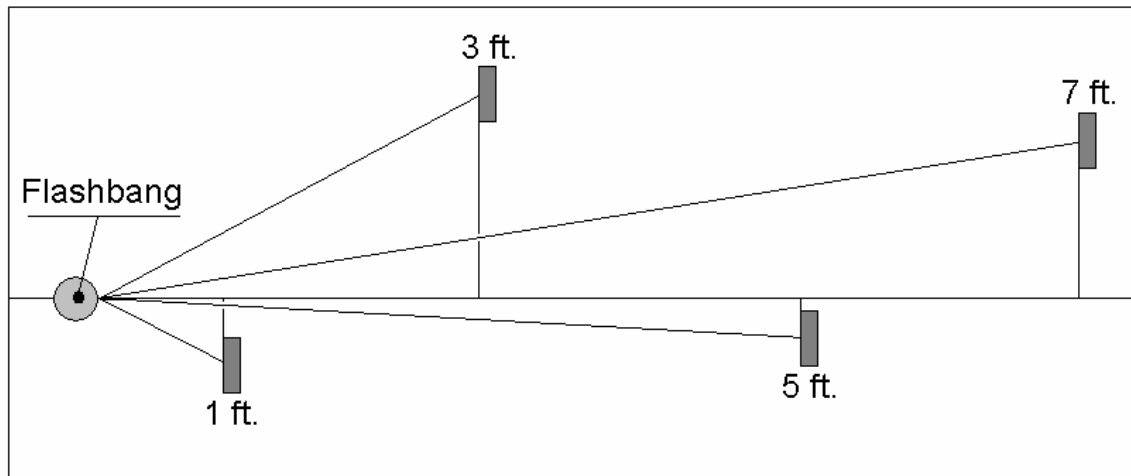


Figure 6: Strain gage placement on the side and bottom of the modified flashbang.

Acoustic and Optical Output Performance Testing and Results

Instrumental Setup

Instruments were arranged to measure the acoustic and optical intensity performance simultaneously. The measurement stations were arranged such that closer detectors would not shadow detectors farther away from the source (shown in Figure 7). The arrangement of detectors and transducers at each station is shown in Figures 8 and 9 (front and back). The four measurement stations were positioned at 1, 3, 5 and 7 feet away from the Flashbang diversionary device. The measurement stations were elevated to a point roughly halfway between the floor and ceiling, 5 feet above the floor, and six feet from the ceiling. The measurement stations were placed approximately in the middle of the firing pad. The Flashbang diversionary device was elevated to the same point in the pad and above the floor, to avoid reinforcement of the acoustic output from a hard reflecting surface. Black fabric was installed on the surrounding walls to reduce reflective reinforcement of the light output. At each station, there was a PCB 102A15 pressure transducer and a Thorlabs PDA-55 silicon optical detector. The pressure transducer range was 0 to 200 psi.



Station	Along Centerline	Offset from Centerline
1 foot	11 inches	down 5 inches
3 foot	36.5 inches	up 10.5 inches
5 foot	58.5 inches	down 12 inches
7 foot	82 inches	up 5.5 inches

Figure 7: Instrument layout. Note that instrumented stations do not “shadow” each other, but have a direct line-of-sight to the Flashbang diversionary device source.



Figure 8: Flashbang diversionary device's point of view looking toward the detectors.

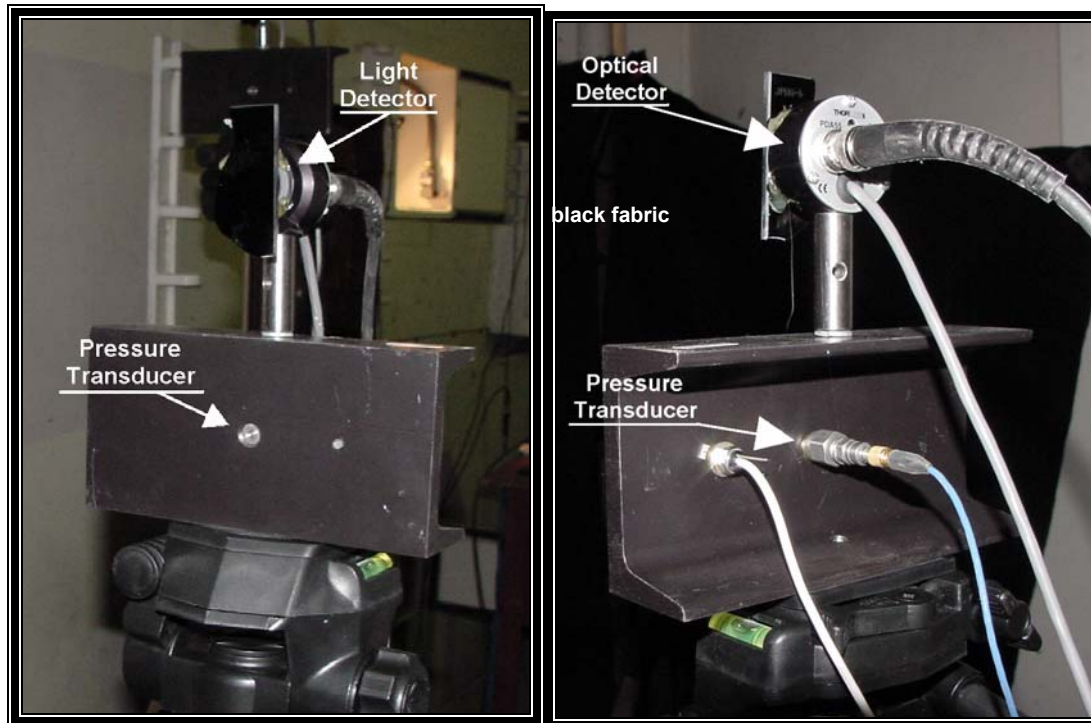


Figure 9: Arrangement of detectors and transducers at each measurement location (front and back).

Optical Intensity Output Measurements

The optical measurements were performed during the collection of acoustic data to quantify performance of the device, as well as to allow the estimation of the effectiveness of the Flashbang diversionary device for temporary visual disruption.

The Thorlabs PDA-55 silicon optical detectors were operated at 10 MHz bandwidth. The optical measurement range of these detectors is 350 to 1400 nanometers, which covers the visible range of light. Sections of welding lens were used in front of the detectors to decrease the light intensity below the point at which the detectors would be saturated. Initial results of these tests indicated a non-linear attenuation by the welding filters. The two most probable causes of the sporadic results were short wavelength light that is not uniformly attenuated with the longer visible and infrared radiation, and static electric coupling from the rapidly exiting aluminum powder from the flash-bang device. To resolve these problems, neutral density metallic attenuating filters were purchased and inserted in place of the welding filters. This configuration yielded excellent results, and repeatability from shot-to-shot. To ensure reliable and accurate measurements, the detectors and filters were calibrated by Sandia National Laboratories' primary standards laboratory. The detectors were subjected to multiple wavelengths from a calibrated photonic source, then compared to their specifications data sheet for validation. The specifications and measured sensitivities compared to within 5% of each other.

Once calibrations and emission data were acceptable, measurements were taken to correlate luminous emission vs. distance. In a perfect point source radiation device, the luminous intensity should be reduced by the inverse square of the distance. Figure 10 illustrates the non-point source nature of the flashbang device. The intensities measured at 1, 3, 5, and 7 feet from the source would decay according to the inverse-square-of-distance-law if the device were a perfect point source. However, rather than a point source, the flashbang device produces a cloud source of large diameter. This makes a true candela (formerly called candlepower in the optics field) intensity measurement difficult, due to the "sphere" shaped ring of light that is produced by the burning aluminum powder.

Intensity of Flashbang

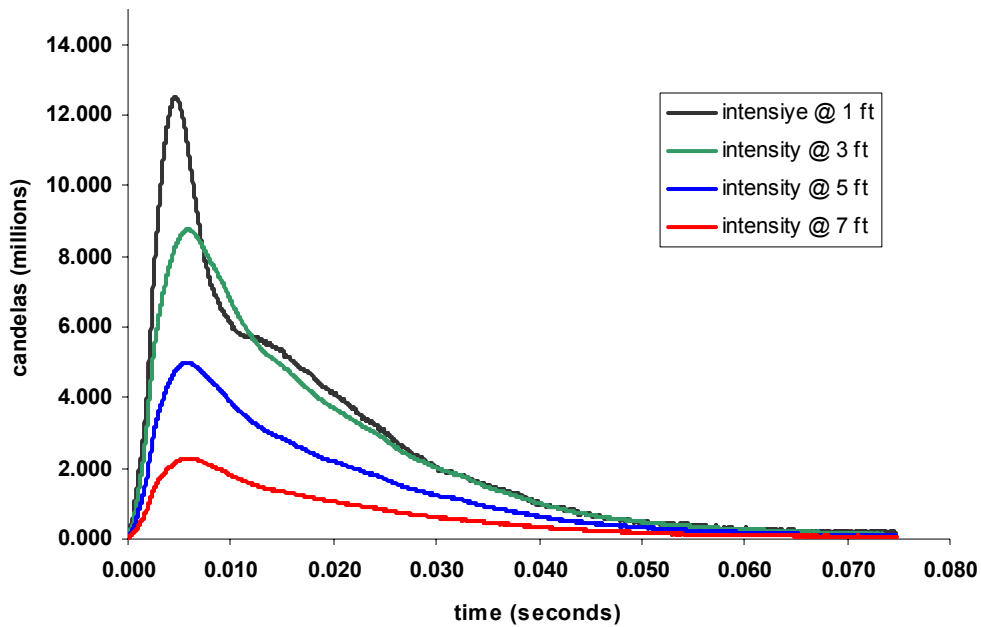


Figure 10. Relative amplitude intensity of four tests using the Sandia device. Note the lack of perfect fit of amplitudes to the inverse-square-of-distance intensity decay law.

An image from a typical test, recorded through an attenuation lens, is shown in Figure 11. Note the pattern of light formed by the individual jets of burning aluminum. The diameter of the luminous plume is estimated to reach approximately nine to twelve feet. The flashbang diversionary device is located at the center of the luminous plume, with all detectors oriented towards the base of the device with the luminous plume orthogonal to the direction of measurement.

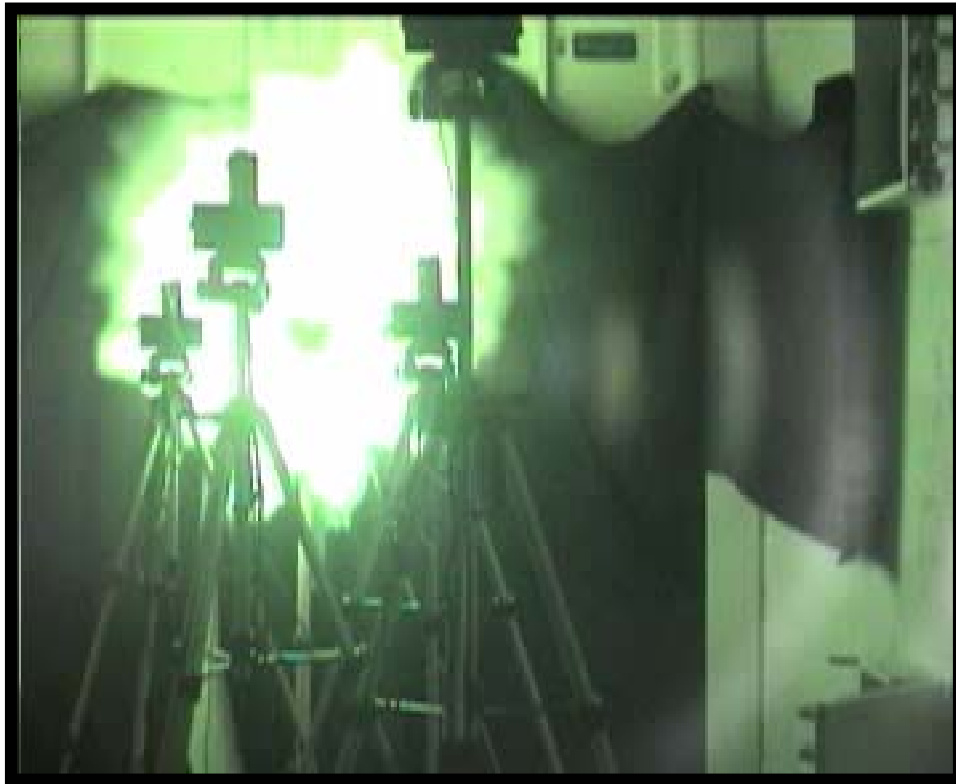


Figure 11: Radial light intensity distribution measurement test.

Luminous Intensity (Candela) Calculations

Candela measurements are, by definition, at a single wavelength (555 nanometers) and correlate to the human eye's photopic peak response. The candela is defined as the luminous intensity in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hertz. The radiant intensity is 1/683 Watt per steradian. Candela measurement requires a distance-from-source calculation. The approximate center of the flashbang diversionary device must be known. Light emission from the Sandia device is a ring shape that is continually enlarging as the device ignites the aluminum powder. A better approximation for this particular device would be to use an illuminance (Lux) value, which is the measurement of radiance onto a surface (the eye in this case). However, numerous pseudo-extended source flashbang devices made by commercial vendors have their performance rating in peak candlepower. In order to compare the Sandia device to the commercial devices, candelas will be used. Additionally, the commercial flashbang devices are typically rated at a distance of 7' from the detector, which is the distance also used to evaluate the Sandia diversionary device for comparison purposes.

The active areas of the detectors are 13mm^2 , and throughput values of the attenuating filters and 555 nanometer band pass filters are taken into account for the final

measurement value. Figure 12 illustrates the total illumination value of the commercial versus Sandia Flashbang diversionary device. Note that the peak intensities are similar but the duration of the Sandia Flashbang diversionary device is substantially longer.

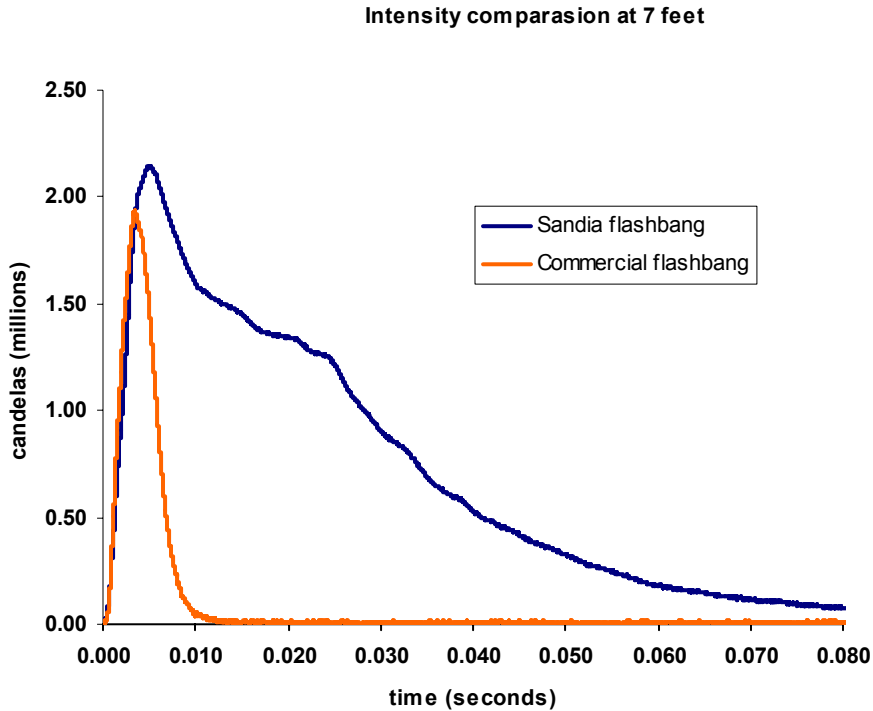


Figure 12: Optical output intensity of Sandia versus commercial Flashbang diversionary device at 7 feet from devices. The commercial device is the sharp peak drawn in red, while the Sandia Flashbang diversionary device is the longer duration peak drawn in blue. Note intensity duration difference between the two devices.

Since the optical output data plot is markedly different between commercial and the Sandia Flashbang diversionary device, comparisons between the devices can only be best approximations. Generally speaking, the Sandia Flashbang diversionary device will produce more light in a given confined area due to its large (about 9-12') diameter ring of burning aluminum. The larger diameter ring is beneficial in use due to the higher total intensity optical output but is safer than a compressed source device due to the inability of the eye to focus a large ring of light onto a small spot on the retina. The longer duration output of the Sandia Flashbang diversionary device will also aid in providing longer temporary flash-blindness that is advantageous in field use. The light output of the device has duration of about 60 milliseconds, and an intensity of about 2.2 million candelas at one foot.

Acoustic Output Performance Results

The acoustic output performance data were recorded for nine separate experiments. A typical trace of the pressure transducer output is shown in Figure 14. The first transducer to be excited by the pressure pulse from the device is the transducer at the 1-foot distance, which recorded the large first signal, shown as the tall blue peak, the first peak from the left. The pressure pulse then swept past the second measurement station at 3 feet, shown in yellow, past the third measurement station, shown in purple, and finally past the 4th measurement station at 7 feet, shown in green.

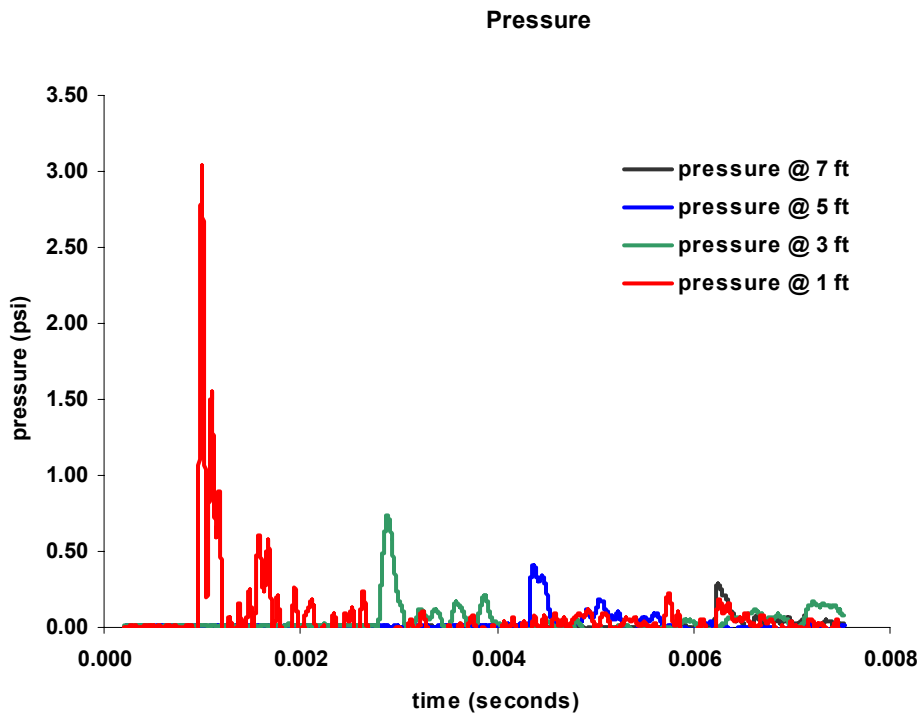


Figure 13: Pressure traces from the four-transducer locations. The highest peak also corresponds to the first red signal from a station 1 foot away, followed by green at 3 feet, blue at 5 feet, and black at 7 feet.

The additional peaks are due to echoes in the chamber from the reflective walls and surfaces, which then strike the transducers repeatedly, at all four measurement stations. The greatest acoustic intensity was recorded at the first station, one foot from the device. The signal recorded at the one-foot station averaged about 178 dB (Decibels). According to literature, eardrum rupture occurs at 185 dB. The acoustic data gathered are listed in Table 2. Some early experiments are not included in the table, as the optical collectors were being optimized during those runs, and in a few cases, the data collection scopes did not trigger correctly.

Table 2: Acoustic Measurement Results

Test #	1 Foot Away	3 Feet Away	5 Feet Away	7 Feet Away
6	175.5 dB	166.3 dB	162.5 dB	156.1 dB
9	180.2	170.0	165.7	161.1
10	181.3	168.2	164.8	159.4
12	178.7	164.7	164.0	156.0
13	177.0	167.1	163.1	No Data
14	178.7	167.9	163.5	No Data
15	176.1	166.8	162.5	156.4
16	174.8	166.8	161.3	156.8
17	179.0	169.1	165.5	160.8
Average	177.9	167.5	163.7	158.1
Std Deviation	2.2	1.6	1.5	2.3
95% Confidence Interval	177.9 ± 1.8	167.5 ± 1.3	163.7 ± 1.2	158.1 ± 2.3

Conclusion

There are many advantages of this new Flashbang diversionary device device.

- Due to the reduced near-field peak overpressure, the possibility of permanent damage to subjects exposed to the near-field pressure wave is greatly reduced.
- The acceleration of any near-field objects produced by the overpressure should be less pronounced, making serious injury due to secondary high-velocity fragments much less likely.
- The measured acoustic output of 178 decibel and light intensity of 2.2 million candlas at one foot, do not appear to be high enough for permanent injury, while both remain high enough for effective diversion. According to literature,⁵ eardrum rupture begins to occur at 185 dB. In order to establish medical thresholds for both permanent hearing and visual damage, extensive human testing would be necessary.
- The non-explosive nature of the powdered-metal fill would allow the devices to be stored and shipped with fewer restrictions than currently available Flashbang diversionary device devices. The restrictions in shipping, handling, and storage, would be only those of the fuzes and black powder propellant charge.

There are, however, a few disadvantages. Mainly, because the burning plume of aluminum powder has a larger radius and longer duration than the fireball from a traditional device that uses flash-powder, the probability of starting fires and burning subjects or users may be increased.

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