

Considerations for Determining Safe Separation Distances from Mass Fires: a Literature Search

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ABSTRACT

This paper is a brief summary of a comprehensive literature search described in greater detail in a larger Department of Defense Explosives Safety Board (DDESB) Technical Paper. The DDESB Technical Paper includes descriptions and discussion of the following:

- Accidents and incidents
- Experimental studies—small- and large-scale
- Analytical studies
- Why the current weight based approach, $D = kW^{1/3}$, does not adequately address safe separation distances from mass fires
- Recommendations and suggested future work

This paper presents descriptions and discussions of the first three items, while a companion paper, Reference 1, presents the latter two.

ACCIDENTS AND INCIDENTS

A DDESB Technical Paper is being prepared that summarizes reports of accidents and incidents that occurred with the following items:

- Munitions in storage, transportation, and operational situations
- Commercial explosives primarily in transportation situations
- Fireworks primarily in storage situations
- Ingredients such as ammonium perchlorate and ammonium nitrate primarily in manufacture and storage situations

This publication will only present brief summaries of energetic materials in storage.

There are problems associated with using accidents as information sources in an effort to address safe separation distances. One of the major issues is that those who have first-hand experience in witnessing the event are often the first fatalities associated with the event.

Another major problem with using accidents as information sources is illustrated in the simple relationship shown below:

Sample + Stimulus + Environment → Reaction

Sample refers to the energetic material and its associated thermochemistry and other characteristics such as mass burning rate (which is often subject to environment effects). The stimulus refers to the events, or series of events, that start and may sustain the reaction. Environment refers to the

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Sample refers to the energetic material and its associated thermochemistry and other characteristics such as mass burning rate (which is often subject to environment effects). The stimulus refers to the events, or series of events, that start and may sustain the reaction. Environment refers to the surroundings, ranging from the immediate confinement provided by rocket motor casing or casings found in warheads and bombs to confinement provided in storage by structures such as earth-covered magazines. The casings and structures also determine the temperatures and pressures that the energetic material may experience. The reaction is the response that can be observed including no reaction, burning, explosion, or detonation. In research and development studies, the variables in each of these areas are carefully controlled and varied one at a time, and the resulting reaction is carefully observed. Mechanistic understanding comes from having many such observations and determining trends. Unfortunately in accident scenarios an inadvertent, unintended, and usually undesired event occurs, often with fatalities and significant loss of property result, and the accident investigators must “swim upstream” to try to determine the cause(s) and contributors of the accident.

Yet another major problem with using accidents as an information source is that the reaction often destroys much, if not all, of the evidence.

With the above reservations in mind, a review of literature addressing various accidents was performed. One of the primary conclusions is that fire often is the primary cause (stimulus) of the accident, and that fire may burn for significant times before the next reaction. Often an explosion that may in turn cause detonation occurs. The fire can be due to many causes including:

- Decomposition that may lead to auto-ignition. In single-base gun propellants, this is often due to stabilizer depletion. Propellants containing nitrate esters, such as nitrocellulose and nitroglycerine, are particularly prone to auto-ignition. When nitrate esters decompose, they give off oxides of nitrogen that can form nitric acids, which further catalyzes the propellant decomposition. The process can boot-strap and cause auto-ignition of the propellant. Stabilizers such as diphenylamine are added to propellants to react with the oxides of nitrogen and prevent them from catalyzing the decomposition. But, as the stabilizers react with the oxides of nitrogen, the number of reactive sites decreases and eventually the stabilizer becomes depleted and loses its effect leading to auto-ignition. Several of the major accidents have been attributed to auto-ignition of gun propellants.
- Electric malfunctions in the storage area.
- Electrostatic discharge (ESD). Two major accidents, one of a Pershing missile in Germany and one of a Minuteman missile during pulling of the mandrel in Utah, were attributed to ESD. Both of these accidents had fatalities.
- Lightning.
- Fire of adjacent materials such as fuels, boxcar flooring, and grass/vegetation.

A few of the accidents are described in the following paragraphs to illustrate the above points.

PEPCON, Henderson, Nevada, May 1988

In this accident, over 8 million pounds of ammonium perchlorate, the oxidizer used in many solid rocket motors, was stored in plastic drums and aluminum tote bins located in an open area. Inadvertent fire burned 10 to 20 minutes before the first explosions, then at least 8 minutes passed until subsequent explosions and detonations ensued. A crater approximately 15 feet deep and 200 feet long was left in the storage area. There were 2 fatalities, 372 injuries, and over \$1M in damages.

Walden, Ontario, Canada, 1989

A truck carrying 18,000 kg of blasting explosives went off the road and caught fire. The fire burned 35 minutes before explosions occurred. The contents exploded throwing fragments of the truck up to 2,740 meters (5,800 feet). There were no fatalities and two minor injuries.

Hawthorne Army Ammunition Plant, Nevada, August 1989

A fire occurred in one of the arches of a 3-arch earth-covered magazine (Figure 1).



FIGURE 1. Three Arch Earth-Covered Magazine at Hawthorne Army Ammunition Plant.
Fire occurred in unit on the right.

The magazine contained 30,715 pounds of Hazard Division (HD) 1.3 Navy propelling charges. Many of the lots had low stabilizer levels, and Hawthorne had requested permission to dispose of the items by open burning. Unfortunately, the State of Nevada denied their request. Fire occurred and blew open the doors. Flames extended out 100 to 150 feet. The very intense burning continued for about 3 minutes and then decreased significantly. During the period of decreased burning, several “pops” attributed to deflagration occurred, but there was no detonation. The fire was allowed to burn itself out. Cartridge cases, unburned propellant grains, and pieces of cork were expelled through the doors and found scattered on the ground directly in front of the magazine; in addition, several cartridge cases were found several hundred feet from the magazine. The fire was attributed to stabilizer depletion in single-base propelling charges.

Camp Doha, Kuwait, July 1991 (4 months after conclusion of Operation Desert Storm)

A defective heater in a M992 ammunition carrier loaded with 155 mm artillery shells caught on fire. Unit members tried unsuccessfully to fight the fire before being ordered to evacuate the area. The fire burned for approximately 40 minutes before the burning M992 exploded. This set off an hours-long series of fires and explosions that devastated vehicles and equipment and scattered unexploded ordnance and debris over much of the camp as shown in Figure 2. The fires and explosions destroyed over 102 vehicles, including four Abrams M1A1 tanks and seven M109 howitzers. There were no fatalities (although three fatalities occurred during clean-up activities), and 50 U.S. and 6 UK troops were injured.



FIGURE 2. Destroyed M109 Howitzers at Camp Doha, Kuwait.

Magazine at White Oak, Maryland, June 1992

Two explosions destroyed an earth-covered magazine similar to the one shown in Figure 3.



FIGURE 3. Magazine Similar in Design to One Destroyed at White Oak, Maryland, 28 June 1992.

The magazine contained 5,180 pounds of largely HD1.1 materials. Fire was caused by decomposition of experimental energetic material, followed 2 minutes later by detonation of the other energetic materials. The magazine was destroyed. Debris including pieces of concrete 1 to 2 feet in diameter was thrown up to 800 feet. Smaller pieces of debris (concrete pieces up to 4 inches in diameter) were thrown as far as 2,000 feet.

Indian Head, Maryland, August 1994

This accident occurred in a non-standard, above ground, non-barricaded structure similar to the ones shown in Figure 4.

The magazine was sited for storage of 500,000 pounds of HD1.3 materials. At the time of the accident, there were 93,522 pounds of HD1.3 material and 4,609 pounds of HD1.1 material. Most of the materials were bulk powders and propellants for cartridge-activated devices or propellant-activated devices (CAD/PAD). The HD1.1 material in the magazine was pyrotechnic/propellant material for which the hazard classification was in question. Later analysis determined it was HD1.1.

The surmised sequence of events started with auto-ignition of nitrocellulose gun propellant. The fire spread and involved a relatively large quantity of magnesium-teflon-viton flare material, which provided an intense boost to the fire. This in turn led to the first and largest detonation followed by a series of smaller detonations.



FIGURE 4. Magazines Similar in Construction to Magazine 518, Indian Head, Maryland.
The structure after the fires and detonations is shown in Figure 5.



FIGURE 5. Magazine 518 after the Fires and Detonations.

Red River Army Depot, August 1996

The contents of an earth-covered magazine ignited. The resulting fire burned for several days and destroyed the magazine and its contents. The most probable cause of the accident was auto-ignition of single-base M-10 propellant due to stabilizer depletion. Black powder was stored immediately adjacent to the M-10 propellant. There was considerable combustible wood dunnage (pallets and crates). The magazine was approximately two-thirds full. The fire resulted in blowing out the magazine door. Burning and smoldering items (over 300 items) were expelled through the open doorway. The burning continued for several days. After the area was cleared, there was evidence of the initial fire where the M-10 had been stored and a small crater (4 to 5 feet) where the black powder had been stored.

Milan Army Ammunition Plant, October 2004

An accidental explosion occurred at the Milan Army Ammunition Plant, Milan, Tennessee. Two fatalities and one critical injury resulted from the event. Property loss and damage included total destruction of an earth-covered magazine (ECM) P-69 and its contents, total loss of a van-type truck, and severe damage to a crew truck. The rail line that serviced P-69 and several other magazines suffered major damage as did numerous rail cars that were stored in the area. One railcar that was parked in very close proximity to P-69 at the time of the explosion was completely destroyed.

The magazine contained 4,599 pounds of Comp A-5 (98.5-99% RDX and 1.5-1.0% stearic acid), 5,307 pounds of M2 propellant (77.45% nitrocellulose, 19.5% nitroglycerin, 2.15% potassium nitrate, 0.6% ethyl centralite, and 0.3% graphite), and 12,447 pounds of M9 propellant (57.75% nitrocellulose, 40% nitroglycerin, 1.5% potassium nitrate, and 0.75% ethyl centralite). At the time of the accident, a crew was returning three metal drums of M9 propellant to storage. The drums had been taken to the workshop to draw surveillance samples for testing prior to loading into ammunition items.

Witnesses reported hearing two blasts in rapid succession, with the second blast being more powerful than the first. Of particular interest was the size of some of the debris and the distances it was thrown. For example, one fragment was steel reinforced concrete 16 feet in length and 3 to 4 feet in width (Figure 6).



FIGURE 6. Large Fragment that Landed Between Magazines P-70 and P-71.

Figure 7 shows a large fragment that had been part of the headwall found at approximately 1,300 feet.



FIGURE 7. Large Fragment that had Been Part of the Headwall Found at Approximately 1,300 Feet from the Magazine.

The large fragment shown above traveled beyond the 1,250 foot radius for inhabited building distance (IBD) arc. Other large fragments were found significantly further than the 1,250 foot IBD arc. For example, there was significant damage to a tree located 2,100 feet in front of the magazine caused by a large fragment impact. Other debris estimated to have been a 6- by 8-foot section from the head wall significantly damaged a tree 3,100 feet from the magazine.

Subsequent debris mapping was conducted. All of the debris was from the structure of the earth-covered magazine. Four sectors were defined and the debris within each of the sectors was mapped. The four sectors are shown in Figure 8.

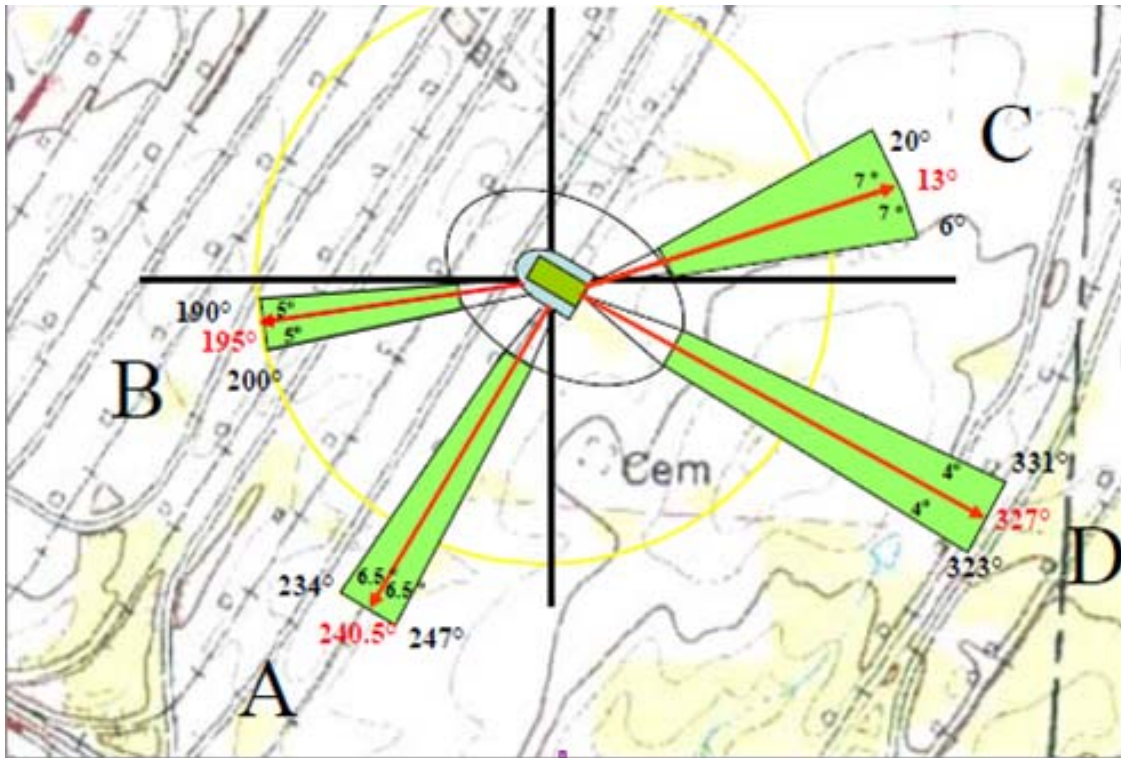


FIGURE 8. Search Sectors, Milan Accident 2004.

Most of the fragments were concrete, rebar, or a combination of both. Emphasis was placed on hazardous fragments having an impact energy of 58 ft-lb or greater and/or a weight greater than 6.17 ounces (175.5 grams). The vast majority of the fragments were hazardous. The fragments were addressed in the following two fashions: one was simply a unit count, each fragment counted as one item, and the other was a weight-equivalent count where each fragment's weight was divided by the minimum weight of a hazardous fragment (6.17 ounce). The results show the following in terms of less than one hazardous fragment per 600 square foot area:

- Sector A. For the unit count method, there is a problem (more than one hazardous fragment/ 600 ft²) from 1,250 to 1,300 foot radius, and no problem out to 1,750 feet. However, for the weight-based count, there is a problem from 1,250 to 1,350 feet and again at about 1,550 feet.
- Sector B. There are essentially no problems for either the unit- or weight-based count from 1,250 to 2,400 feet radius.

- Sector C. There are essentially no problems for the unit count method from 1,250 to 1,841 feet radii, but there are problems with the weight count over this same range of radii with almost a 400 fragment/600 ft² weight count at about 1,600 feet radius.
- Sector D There are no problems in the range of 1,250 to 2,892 foot radii with the unit count method, but there are problems with the weight counts for all but the 2,150 to 2,750 foot radii.

The conclusions from this study are:

- The use of unit count indicates excessive hazardous fragment density beyond the 1,250 IBD arc in one sector (A).
- The use of weight-equivalent count indicates excessive hazardous fragment density beyond the 1,250 IBD arc in three sectors (A, C, and D).

In addition to the sectors described above, the investigators recorded notable fragments outside of the search sectors. These included especially large fragments and/or fragments that traveled unexpectedly long distances. For example, significant debris was found on top of and in front of magazine P-6, which is approximately 2,050 feet away from P-69 (Figure 9).



FIGURE 9 Fragment Found in Close Proximity to ECM P-6,
Approximately 2,050 Feet Away from ECM P-69.

The results of this accident will be discussed later after results of tests are presented.

Forward Operating Base Falcon near Baghdad, Iraq, October 2006

An incoming 82-mm mortar round started a fire at Forward Operating Base Falcon located in a former commercial trucking depot near the southern entrance to Baghdad. There were no injuries reported, but the fire spread and caused fires and explosions in surrounding tank and artillery ordnance and small arms ammunition. The fires and explosions went on for over 12 hours after the original fire. There was significant damage as shown in Figures 10 and 11.



FIGURE 10. Damage at FOB Falcon near Baghdad, Iraq, 10 October 2006.



FIGURE 11. Damage at FOB Falcon near Baghdad, Iraq, 10 October 2006.

Milan Army Ammunition Plant, May 2007

The fire started in an earth-covered magazine and continued for about an hour with smoke continuously coming from the front and the exhaust vent on top of the magazine. All personnel were accounted for after the incident. Post-incident investigation indicated that the front wall and interior of the magazine were destroyed, while the side walls and rear wall appeared to be intact.

At the time of the accident, 51,869 pounds of M-10 propellant (HD1.3) were stored in the magazine. The magazine was sited for 250,000 pounds of HD1.1. The propellant had been turned over to a private contractor to use for fireworks. Magazine N-21 was built circa 1941 and was excess to operational requirements. It was leased to Accurate Arms as part of the Armament Retooling and Manufacture Support (ARMS) Program. The last propellant stability test on this propellant had been conducted in 1999 with the result: Satisfactory.

The post-mortem photographs clearly show that the fire blew out the headwall and scattered debris over an area as shown in Figures 12 through 14.



FIGURE 12. Earth-covered Magazine with Headwall Blown Out.



FIGURE 13. Debris from Magazine and Contents.



FIGURE 14. Debris Expelled from Magazine.

The cause of the accident was likely due to auto-ignition of the M-10 propellant as a result of stabilizer depletion.

LESSONS LEARNED FROM ACCIDENTS

In the draft DDESB Technical Publication, after each of the accidents there is a Lessons Learned discussion. Among the incidents, there were many common lessons regardless of whether the accident involved storage of ingredients (such as ammonium perchlorate), gun propellants, fireworks, or all-up munitions, or transportation of nitrate fertilizer or commercial boosters. The lessons learned from analysis of the accident reports presented in the draft DDESB Technical Paper include the following:

- The initial major reaction in most of the accidents was fire. That is a rather global finding, but it lacks technical detail. For example, what caused the fire, how did it spread, what effect did it have on adjacent energetic material (sensitization), especially given that the adjacent materials were subjected to high temperatures for a significant amount of time, and what happened next?
- Many of the accidents involving single-base gun propellant was due to stabilizer depletion that led to auto-ignition of the gun propellant and subsequent spread of fire.
- Several of the accidents involved single-based gun propellants in storage awaiting demilitarization. In one accident, the facility had repeatedly asked that the materials be destroyed because they represented a safety hazard. Unfortunately, approval was denied.
- In most of the accidents involving fire, the fire burned for many minutes, some for more than an hour, before the next major reaction.
- A fire that had burned for a number of minutes or hours did the following:
 - Consumed some adjacent energetic material. That is, all of the energetic material did not react simultaneously nor instantaneously.
 - Heated, and sensitized, adjacent energetic material.
 - In a heavily confined environment such as an earth-covered magazine, fires may have caused significant over-pressure, forming large pieces of debris, and may have caused these pieces to be thrown significant distances.
- Fires do not have to burn for long periods of time when there is significant confinement before over-pressure causes rupture and debris to be thrown from the structure. This will be addressed in the testing section.
- In several of the accidents, over-pressure blew open the double-doors or even the entire headwall, releasing the over-pressure in the structure.
- The fires often had intense fireballs that extended hundreds of feet from the original fire. In several instances, energetic material was expelled from the structure and burned outside in the plume, not inside. Obviously, the energy release was outside the structure, not inside. Analytical modeling of fires within structures needs to address this. This expulsion of material and burning outside the structure will be discussed in the section on testing.
- Following a fire that may have burned for significant time, the next major reaction was often an explosion, not a detonation.
- The explosion(s) may in turn cause a detonation of the already sensitized energetic material. Post-accident investigations found craters where detonations occurred, but no craters where explosions occurred.
- Several of the accidents involved mixed storage of HD1.1 and 1.3. The HD1.3 material is easier to ignite than HD1.1 and burns well even at atmospheric pressure, while many HD1.1 materials do not burn well at atmospheric pressure. The burning HD1.3 materials can serve as the stimulus for the explosion of HD1.3 materials in confinement and/or explosion or detonation of HD1.1 materials.
- Several of the reviewed accident reports contained the following two common misrepresentations:
 - The assumption was made that HD1.3 materials can be considered as “wooden round,” and that HD1.3 reactions are rather benign.

- o The assumption was made that HD1.1 items are the most sensitive materials. As mentioned above HD1.3 energetic materials, such as ammonium perchlorate-based propellants, especially those with burn rate catalysts, ignite easily and burn readily at one atmosphere. On the other hand, in order to initiate a detonation of HD1.1 military munitions, a mechanical shock on the order of 40 kbars may be required. Such a mechanical shock level is rarely found in storage or transportation conditions.
- Even after the detonation of HD1.1 materials, fires continue to burn for minutes, hours, or even days.
- However, not all fires cause explosions or detonations (this includes fires in heavily confined enclosures, such as earth-covered magazines).
- Evacuation plans and safe separation distances must consider human nature. In several of the accidents that involved a fire burning for a significant amount of time, spectators were attracted to the blaze and perished when explosions or detonations occurred. In one accident, a television crew was filming the blaze when an explosion and detonation occurred, killing the crew. In other accidents, congestion was caused by spectators attracted to the scene and others trying to flee the scene, which produced gridlock and increased fatalities.

A BRIEF REVIEW OF TESTING THAT STARTS WITH FIRE

As mentioned in the section on accidents, burning of energetic material in a confined space causes pressurization in that space, and may result in catastrophic rupture of the structure and debris throw. The critical concern is the race in time between pressurization due to combustion and pressure release due to venting. The pressurization due to combustion involves the loading density of the energetic material in the available volume in the confining structure and the mass conversion rate of the solid to reaction gases and the thermochemistry associated with that conversion. The mass conversion rate (dm/dt) of solid to gases is usually described by the following:

$$dm/dt = \rho r A_b$$

Where:

ρ = density of the solid

r = surface regression rate of the energetic material

A_b = burning surface area of the energetic material

The other major consideration has to do with the venting and whether flow through the vent is un-choked or choked flow. Choked flow occurs when the velocity of gases flowing from the chamber to the outside reaches sonic velocity through the exit. This occurs when the chamber pressure is equal to or greater than $[(k + 1)/2]^{k/(k-1)}$ times the outside pressure, where k is the ratio of specific heats of the gases. Since the k for most gases ranges from 1.1 to 1.67, the values of $[(k + 1)/2]^{k/(k-1)}$ ranges from 1.7 to approximately 2.1. While the velocity cannot go above sonic, the mass flow rate can increase as the pressure and temperature increase within the chamber; however, once the flow is choked, the pressure inside the chamber will quickly rise and continue to rise until either rupture of the confining structure occurs or the energetic material burns itself out. As a rough rule of thumb, choked flow occurs when the chamber pressure is about 1.7 to 1.9 times the outside pressure.

Tests Where the Vent Area and Loading Density Resulted in Un-choked Flow

Several tests were run where the vent area was large enough that un-choked flow resulted. These studies included those by Herrera and Vargas (References 2 and 3), Tozer (Reference 4), Allain (Reference 5), and Joachim (Reference 6). In these tests, unburned propellant and partially reacted gases were expelled and burned outside the chamber. In some instances, unburned propellant was found out to

70 to 80 meters from the exit. In these un-choked flow tests, there was no rupture of the chamber, and the primary hazard was direct exposure to fireballs and radiation exposure.

In the test described by Joachim (Reference 6), the plume distance from subscale tests depended on the loading density of propellant to available volume of chamber, and vent area to chamber volume. Joachim had a single container of 1.4 by 1.9 by 1.9 meters with a 35.6-cm-diameter vent tube. The reinforced concrete walls, roof, and floor were 30 cm thick. Single perf M-1 gun propellant was placed in the container in varying amounts to provide loading densities of 2, 5, 20, 50, and 100 kg/m³. The bunker, vent pipe, and sample location are shown in Figure 15.

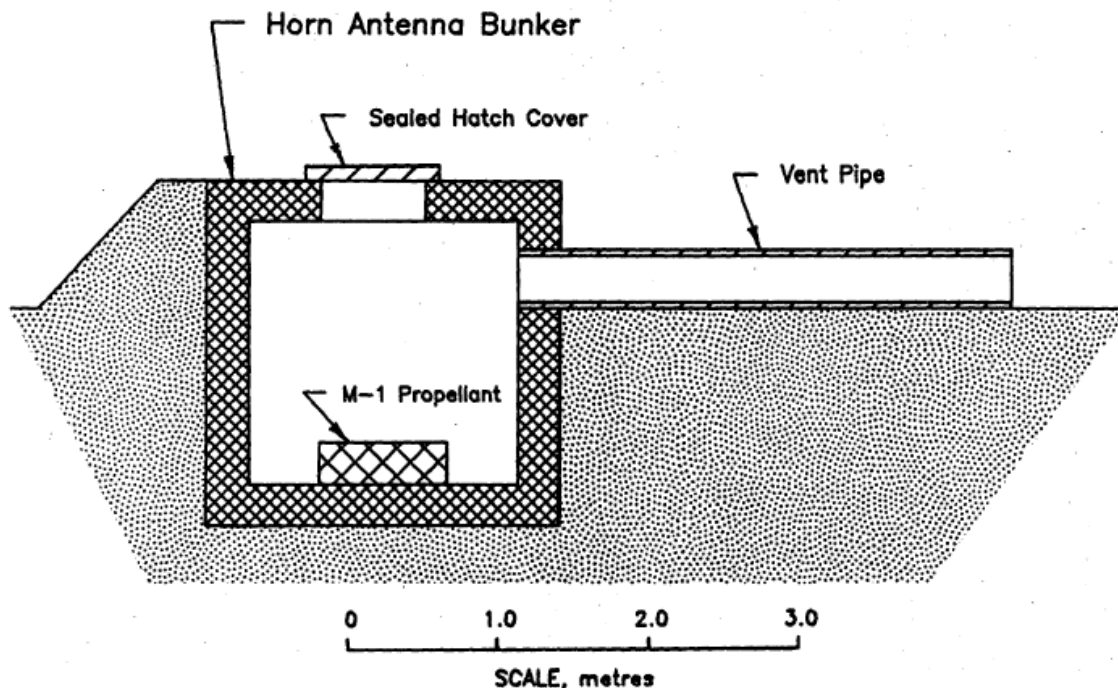


FIGURE 15. Schematic of Bunker, Vent Pipe, and Sample Location.

Test C-1 was 10 kg of M-1 propellant in the 5 m³ chamber giving a 2 kg/m³ loading density. Initially black smoke was observed coming out the end of the vent pipe. The smoke quickly changed to flame and, by 4 seconds after assumed initiation, the flame extended approximately 5 meters from the end of the pipe. The total duration of the external flame was about 11 seconds. The initial gas flow out the end of the pipe was 3.47 m/sec. The pressures beyond the vent pipe were higher than the chamber pressures indicating that unburned gas and propellant were carried outside the chamber and burning was occurring in the vented gas plume. The video recorded a pulsating flame in the gas plume. Heat flux measured within the tube reached 30 cal/cm² sec (1256 kW/m²) with the average heat flux being about 25 cal/cm² sec (1047 kW/m²).

Test C-2 had 25 kg of M-1 propellant (5 kg/m³ loading density). Initially a glowing plume was observed to extend about 3 meters beyond the end of the vent pipe within approximately 1 second after ignition. The plume of smoke and flame quickly extended to a length of 10 meters after approximately 10 seconds. Although it burned violently, the length of the plume decreased after 10 seconds, retreating to the end of the pipe. The total duration of the external plume was about 18 seconds. The results still indicated that unburned gas and propellant were propelled outside, and then burned outside the chamber.

Once again, the plume appeared to be pulsing. The heat flux measured in the pipe was about 30 cal/cm² sec.

Test C-3 had 100 kg of M-1 propellant in the chamber (20 kg/m³). Initially a smoke plume was observed to extend 1.5 meters beyond the end of the pipe at approximately 0.2 seconds. The plume extended 16 meters in approximately 6 seconds. The initial plume velocity was 5.58 m/sec. After about 6 seconds, the plume retreated towards the end of the pipe. At approximately 11 seconds, a violent gas jet with a velocity of about 29.5 m/sec was noted with a duration of about 1 second. The total duration of the plume was about 12 seconds. The results again indicated that unburned gases and propellant were propelled outside and then burned outside of the chamber. Again, the plume had a pulsating flame. The heat flux measured in the vent pipe was about 30 cal/cm² sec.

Test C-4 had choked flow and the chamber was ruptured. This will be discussed later in the section on results of experiments having choked flow.

Herrera and Vargas presented work on various gun propellants in a vented cube (8 feet per side) and 1/10th-scale igloos (References 2 and 3). Tests described in Reference 2 showed the following:

- Below a critical loading density of propellant within the cubicle, much unburned propellant is carried outside the cubicle in the exhaust plume and reacts outside the cubicle. The temperatures were more than twice as high in the exhaust plume than in the cubicle.
- The tests within the 1/10th-scale igloo were conducted using only gun propellant (IMR-5010, IMR-8208, and M1) in scaled shipping containers. Ejection of large amounts of unburned propellant with subsequent burning outside the structure was again observed.

Herrera and Vargas continued the testing of various gun propellants and flares in the 1/10th scale igloo with pressure and temperature sensors shown in Figure 16. In the tests, the energetic material type and quantity and the vent size were varied. The vents were square, so a 12-inch vent was 12 inches by 12 inches. A 12-inch vent would correspond to an igloo with double doors and multiple vents (vent area ratio of 0.1234), a 9-inch vent would correspond to an earth-covered magazine with double door (vent area ratio of 0.07), and a 6-inch vent would correspond to an earth-covered igloo with single door (vent area ratio of 0.03).

The results are shown in Table I.

The report showed plots of velocities for the various test conditions. As the vent size went down from 12 inches to 9 inches, the velocities went up; but, when further reduced to 6 inches, the velocities went down. The drop in velocity is indicative of the plume flow becoming choked at the door. This was evidenced in the video that showed the hottest portion of the plume separated from the igloo, pulsating back and forth outside the igloo, thus indicating a choked or near-choked flow.

Temperature data also showed interesting behavior. The data showed that the maximum temperatures outside of the igloo were hotter as compared to the maximum temperatures inside of the igloo. This strongly indicates that unburned propellant is carried outside of the igloo and burns out in the plume.

Reference 3 presented predicted scaling effects in going from 1/10th scale to full scale. They predicted that the 25 foot plume obtained with the 1/10th scale and 10 pounds of propellants would be approximately 250 feet of plume with a velocity of 1500 fps for full scale igloo and 10,000 pounds of propellant.

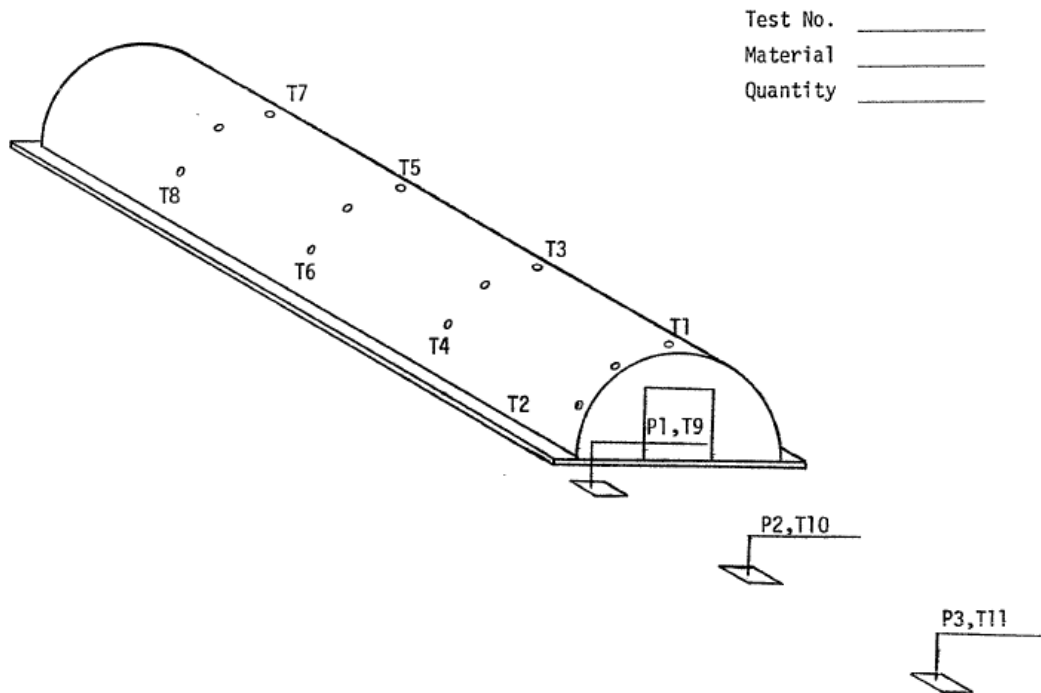


FIGURE 16. Schematic of 1/10th Scale Igloo with Sensor Locations.

TABLE I. Igloo Confinement Test Results.

Test	Material	Quantity (lb)	Vent Size (in.)	Plume Length (ft)	
				Max	Hot
8	IMR 8208	2	12	10	4
9	IMR 8208	4	12	15	9
10	IMR 8208	6	12	15	12
11	M1	1	12	9	5
12	M1	5	12	17	13
13	IMR 8208	1	12	5	5
14	IMR 8208	5	12	16	14
15	IMR 8208	10	12	25	18
16	M1	10	12	25	15
17 (Repeat 12)	M1	5	12	12	9
24 (Repeat 16)	M1	10	12	25	14
18	IMR 8208	5	9	20	17
19	M1	5	9	15	10
20 (Repeat 18)	IMR 8208	5	9	10	8
21	IMR 8208	1	9	6	5
22	M1	1	9	8	7
23	M1	10	9	25	14
31	IMR 8208	10	9	20	12
25	M1	1	6	8	6
26	IMR 8208	1	6	4	-
27	M1	5	6	20	15
28	IMR 8208	5	6	20	17
32	M1	10	6	13	9
33	IMR 8208	10	6	18	15
39	M1	10	6	18	14
29	ALA 17	1/2	12	10	5
30	ALA 17	1	12	10	5
34	ALA 17	1	9	10	8
35	ALA 17	1	6	10	8
36	ALA 17	2	12	15	12
37	ALA 17	2	9	15	10
38	ALA 17	2	6	25	15

The tests for 6 inch vent and 10 pounds of IMR 8208 propellant showed choked flow behavior and will be discussed in a later section.

Tozer (Reference 4) presented data on two single-base gun propellants in M2 containers that were arranged in various configurations and loaded in an ISO container that was then placed over a fuel fire.

In the first test series, four M2 cans were initiated individually by a remotely activated match head igniter inserted into a bag of black-powder. The first can was fired with the lid off and burned for about 45 seconds. The other cans were fired with the lids clamped on and the lids were blown off, and the propellant was consumed in 30 seconds. In all cases, the reaction was fire; there were no explosions or detonation.

In the second series of tests, M2 cans of both propellants were suspended over liquid fuel fires. Each can contained 55 kg of powder. In all instances the cans ruptured instead of blowing off their lids. There was no explosion or detonation. Both propellants behaved in similar manner.

In test series 3, both propellants were subject to tests with a two-tiered pallet load. The lower tier had thirteen M2 cans of propellant (about 700 kg total) with the upper tier having thirteen cans of sand/sawdust mixture. The pallet load was suspended over a liquid fuel fire. Similar cook-off times (13 to 23 seconds) were recorded for both propellants and the severity of reaction was also similar. When a can, or cans, ignited rapid pulsing burning similar to a roman candle was observed. The cans were ruptured, and some were thrown from the pallet. Again, there was no explosion or detonation.

Test series 4 was the major trial with pallets of M2 cans containing gun powder loaded into an ISO container. A 20-tonne steel ISO container was packed with 12 pallets of cans with a total of nine tonnes of gun propellant that was placed over a liquid fuel fire. After the fuel was ignited there was no evidence of propellant burning until 1 minute 5 seconds after ignition. Vigorous burning commenced about three minutes after ignition, reaching a peak at 3 minutes 25 seconds when the ISO container doors burst open and the container was displaced longitudinally about three meters. The ensuing fireball extended to a radius of about thirty meters. Cans were propelled from the open end of the container for a distance of about eighty meters and the propellant was totally consumed within four minutes. Again there was no detonation.

Allain (Reference 5) presents the results of four 1/3rd scale igloo tests. The first three tests used three different structures with approximately 2.22 metric tons of LB 7 T 72 (0,8) propellant. This gun propellant is similar to M-1. In the tests, over-pressure gauges and flux-meters were placed in locations shown in Figure 17.

The first test was of an earth-covered (about 30 cm) metal arch placed on the ground with no headwall. Simultaneously, with development of the plume (approximately 40 meters from the igloo), the rear part of the igloo lifted and then ruptured, creating a second plume at 45 degree angle. The burn duration was about 15 seconds. The following shows average flux at the various points:

Firing 1, Values in W/cm ² .		
Lateral distance	15 meters	25 meters
at 2 meters	8.5	5
at 7 meters	11	5.5
at 12 meters	12.5	5.7

Unburned propellant was found 45 meters from the igloo.

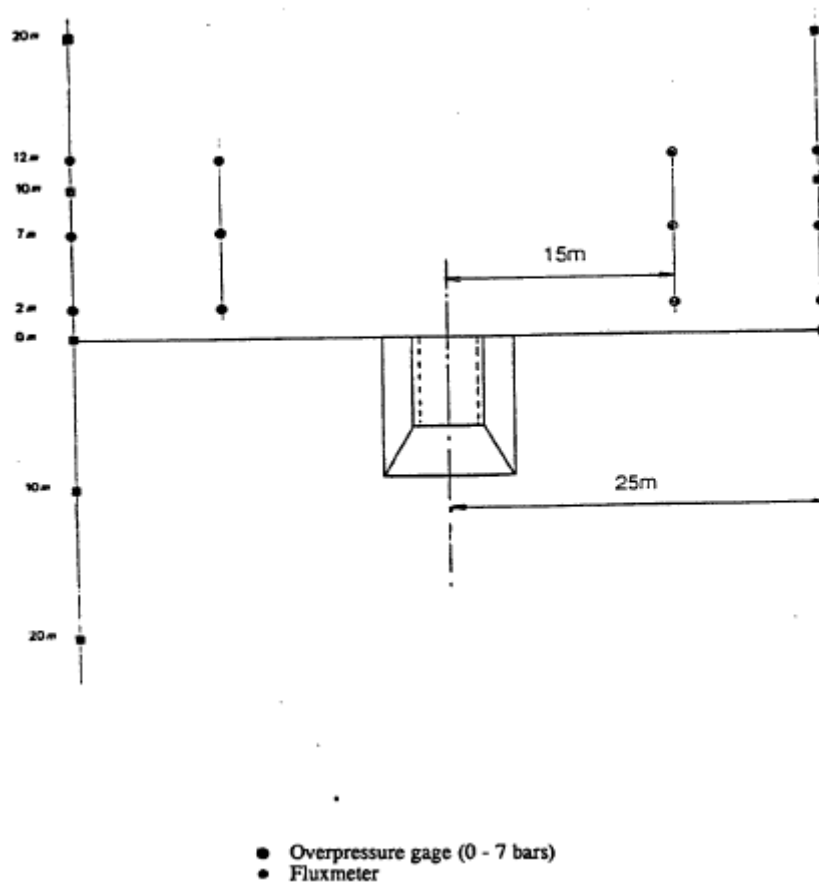


FIGURE 17. Location of Flux Sensors and Overpressure Gauges.

The second test used an earth-covered (about 30 cm) arch placed on the ground with a 0.5-cm-thick metal front wall and a 0.96 by 1.1 meter opening(vent). On ignition, the entire igloo lifted approximately 1m off the ground but remained intact. The plume extent was 40 meters long, and the burning duration was 15 seconds. The following shows the average flux at the various points:

Firing 2, Flux Values in W/cm^2 .			
Lateral distance	15 meters	25 meters	
at 2 meters	5.2	3.6	
at 7 meters	10.3	4.3	
at 12 meters	12.8	5.8	

Unburned gun propellant was found 45 meters from the igloo.

Tests 3 and 4 involved explosions, but not detonations, and will be discussed in the section on choked flow.

In addition to the tests described above, Henderson (Reference 7) presented results of various energetic materials subjected to a liquid fuel fire in a storehouse. The storehouses were constructed of internal block work with external brick-work and a reinforced concrete roof. The results of these tests

showed rather benign results, even in the instance where 120 mm propelling charges were simultaneously initiated. In this latter test, the front wall failed by being pushed out and falling over.

Tests Where the Vent Area and Loading Density Resulted in Choked Flow

Test C-4, in the series of tests described by Joachim (Reference 6), had 250 kg of M-1 propellant (50 kg/m^3) in the chamber shown previously in Figure 15. Initially a smoke plume was observed to extend 1.3 meter past the end of the pipe within approximately 0.3 seconds. The plume quickly extended from the vent and filled the entire video field of view (greater than 25 meters) in approximately 5.3 seconds. Shortly after, the structure failed at approximately 6 seconds, releasing all pressure. The remaining propellant then burned rapidly in the air outside. The chamber failed from excessive internal pressure. Post-test observation showed that the concrete bond to the rebar had failed and the rebar pulled out of the concrete. At the time of the failure, the hatch cover and roof section were hurled high into the air at an average velocity of about 33 m/sec (hatch) and 11 m/sec (roof). The peak pressure on the side wall was about 10^3 kPa . This test indicated that over-pressure caused the failure, not a transition to detonation.

In the tests described by Herrera and Vargas (Reference 3) involving the 6- by 6-inch vent and 10 pounds of IMR 8208 propellant in the $1/10^{\text{th}}$ scale igloo, choked flow did occur. The 12- and 9-inch vents showed higher temperatures outside the igloo than inside indicating un-choked flow, but the temperatures for the 6-inch vent showed that the temperatures were higher inside the igloo than outside. This indicates that the majority of burning was occurring inside the igloo. With the choked flow and more of the burning occurring inside the igloo, the pressures would have risen and led to an increase in the burning rate, causing further pressurization.

In the $1/3^{\text{rd}}$ -scale igloo test series described by Allain (Reference 5), the third test involved a “reinforced earth-covered (about 30 cm) metal arch, fixed on ground with concrete front wall.” The plume rapidly spread out. After 2 or 3 seconds of burning, the igloo exploded. No blast overpressure was recorded by any of the blast pressure gauges indicating the rupture of the igloo was not due to detonation of the propellant. Unburned gun propellant was found 70 meters from igloo.

The fourth test differed from the previous tests in that a different magazine design was used and a different stacking of the cartridge bags. Figure 18 shows the magazine shape for Test 4.

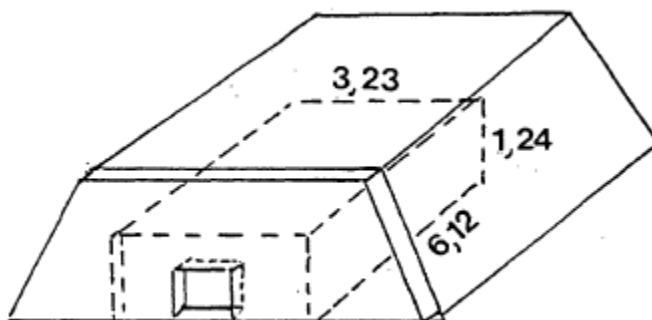


FIGURE 18. Igloo Shape for Test 4.

The construction of the igloo consisted of earth covering (0.4 m on top and extending 2 m at the base of the sides and over 4 m at the base of the rear) the concrete box structure that had an internal metal liner, all mounted on a concrete base. The vent opening was 0.33 m^2 .

In order to keep the same loading density as the previous tests, the amount of gun powder and the loading configuration were changed. The new quantity was 2.037 metric tons and 334 cartridge bags, configured as shown in Figure 19.

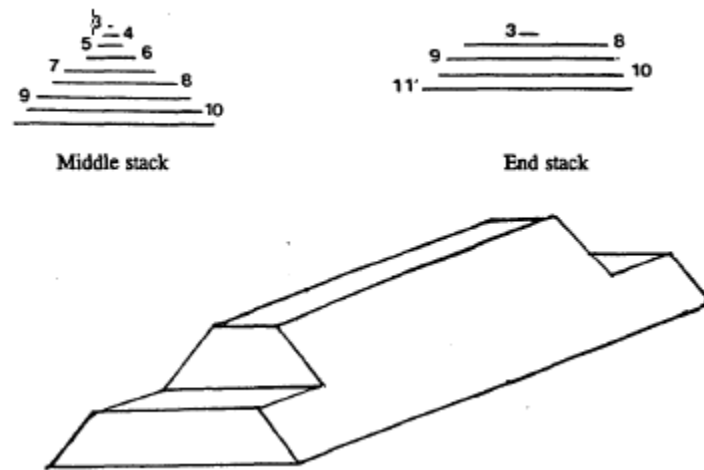


FIGURE 19. Charge Configuration for Test 4.

The volume of the igloo was 24.5 m^3 and the opening area was 0.33 m^2 , giving a volume of charge to volume of chamber of 0.11 and ventilation coefficient of 0.013.

In Test 4, instrumentation was simply two rows of three overpressure gauges at 25 meters on both sides of igloo axis, as indicated in Figure 20.

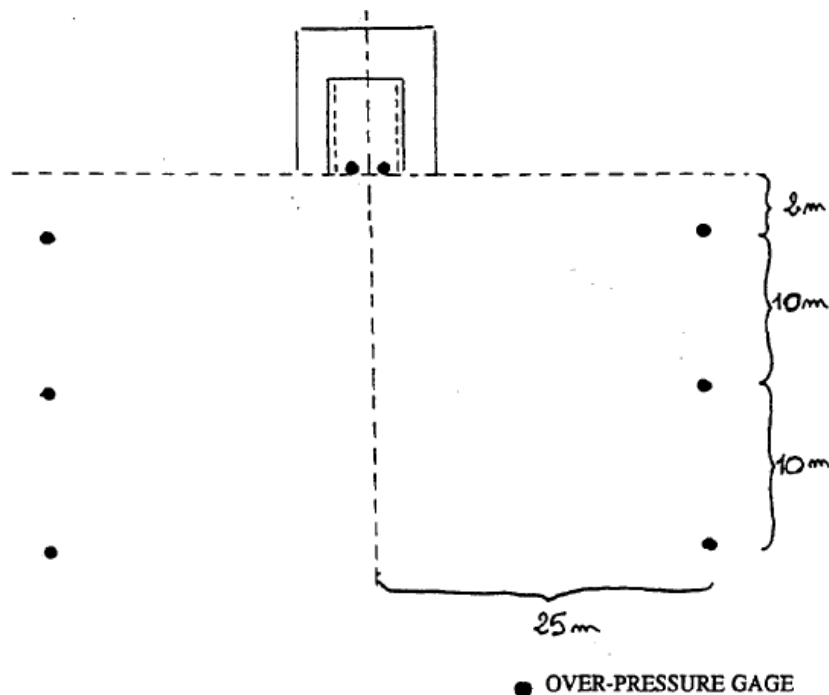


FIGURE 20. Location of Over-pressure Gauges Relative to Magazine in Test 4.

Test 4 resulted in the igloo bursting 1 second after ignition, releasing a fireball. At ground level, no trace of a plume was observed. The igloo separated along its structural lines or corners. It separated into five main parts, each comprising two pieces—one concrete and one steel as shown in Figure 21.

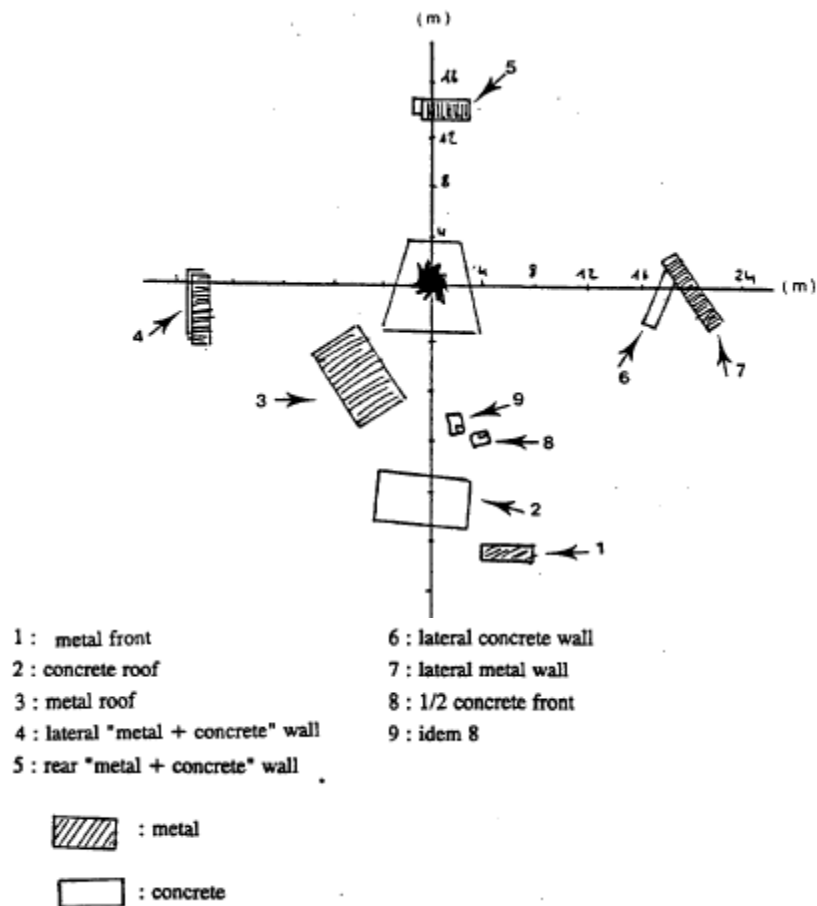


FIGURE 21. Location of Debris.

Figure 22 shows the igloo before the tests and the post-event photograph.

Interestingly, none of the overpressure gauges recorded any signal, nor was any crater formed, indicating neither a strong explosion nor a detonation occurred (Figure 22b). One of the internal overpressure gauges recorded an overpressure of 7 bars before saturating. The authors estimated that the maximum internal overpressure before rupture at 10 to 12 bars.



(a)



(b)

FIGURE 22. Captieux Trial Shot 4 (a) Before and (b) After.

LESSONS LEARNED FROM TESTING

- What happens when an energetic material burns in a vented enclosure is a race between how fast the pressure increases in the structure due to the burning of the energetic material versus how fast pressure can be released through venting. The pressurization due to combustion involves the loading density of the energetic material in the available volume in the confining structure and the mass conversion rate of the solid to reaction gases and the thermochemistry associated with that conversion. The other major consideration has to do with the venting and whether flow through the vent is un-choked or choked flow.
- Flow becomes choked when the pressure inside the chamber exceeds the outside pressure by 1.7 to 1.9 times.

- If there is minimal vent area available, as in an earth-covered magazine with the doors closed, combustion will pressurize the magazine and may result in doors blowing open, thereby providing additional vent area. Then the consideration is whether the increased vent area results in un-choked or choked flow.
- If the flow through the vent is un-choked, unburned energetic material is often expelled through the vent/door and burns outside. So some of the energy release during the event is outside the chamber.
- The burning of the energetic material outside the chamber provides a significant plume with heat fluxes on the order of 125 kW/m² (Allain) and fluxes in the vent pipe of 1200 kW/m² (Joachim). Fatalities will occur if personnel are in direct contact with the plume and if the radiant heat flux and exposure time are sufficient to cause extensive second degree burns.
- If the flow through the vent is choked, the energetic material burns inside the chamber and can quickly increase the pressure within the chamber, to the point of rupturing the structure. In Test 4 of the 1/3rd-scale tests described by Allain, the rupture occurred 1 second after ignition. The pieces produced by the rupture were huge. In Test 4, the pieces were the 3 walls, the roof, and the headwall. (There were actually 10 large fragments, which included the concrete and metal liner pieces for the walls, roof, and headwall.) The pressures on the walls were estimated to be on the order of 10 to 12 bars at rupture.
- From the stand-point of hazard reduction, it is desirable to have vents large enough to ensure un-choked flow, or have building construction that will self vent if the flow becomes choked (i.e., frangible walls and roof panels).

SUMMARY AND CONCLUSIONS

This paper is a summary of a much larger literature search. The larger literature search will be published as a DDESB Technical Paper. The following conclusions have been taken from the lessons learned from accidents and testing. The companion paper, Reference 1, will make recommendations based on the following conclusions.

1. The initial major reaction in most of the accidents was fire.
2. Many of the accidents involving single-base gun propellant were due to stabilizer depletion followed by auto-ignition.
3. In most of the accidents involving fire, the fire burned for many minutes, and in some instances for more than an hour, before the next major reaction.
4. Following the fire that may have burned for a significant amount time, the next major reaction for a structure containing only HD1.3 material was often an explosion or a pressure rupture of the confining structure, not a detonation.
5. An explosion may cause a detonation, and a detonation may also be the result of cook-off of HD1.1 energetic material or ordnance.
6. Fire that had burned for some minutes or hours:
 - Consumed some adjacent energetic material. That is, all of the energetic material did not react simultaneously nor instantaneously.
 - Heated, and sensitized, adjacent energetic material.

- In a heavily confined environment such as an earth-covered magazine, fires may have caused significant over-pressure that caused formation of large pieces of debris and may have caused these large pieces of debris to be thrown significant distances.

7. When an energetic material burns in a vented enclosure, there is a race occurs between how fast the pressure increases due to the burning of the energetic material versus how fast pressure can be released through venting. The pressurization due to combustion involves the loading density of the energetic material in the available volume in the confining structure and the mass conversion rate of the solid to reaction gases and the thermochemistry associated with that conversion. The other major consideration has to do with the venting and whether flow through the vent is un-choked flow or choked flow.

8. Flow becomes choked when the pressure inside the chamber exceeds the outside pressure by 1.7 to 1.9 times.

9. If the flow through the vent is un-choked, unburned energetic material is often expelled through the vent/door and burns outside. So some of the energy release is outside the chamber. Several of the accidents displayed this behavior of energetic material being expelled and burning outside the magazine, in many instances with fireballs extending hundreds of feet from the original structure. The burning of the energetic material outside the chamber provides a significant plume with heat fluxes on the order of 125 kW/m^2 (Allain) and fluxes in the vent pipe of 1200 kW/m^2 (Joachim). Fatalities will occur if personnel are in direct contact with the plume and if the radiant heat flux and exposure time are sufficient to cause extensive second degree burns.

10. If the flow through the vent is choked, the energetic material burns inside the chamber and can quickly increase the pressure within the chamber to the point of rupture of the structure. In Test 4 of the $1/3^{\text{rd}}$ -scale tests described by Allain (Reference 5), the rupture occurred 1 second after ignition. The pieces produced by the rupture were huge. In Test 4, the pieces were the three walls, the roof, and the headwall. (There were actually 11 large fragments which included the concrete and metal liner pieces for the walls, roof, and headwall.) The pressures on the walls were estimated to be on the order of 10 to 12 bars at rupture.

11. Several of the accidents involved mixed storage of HD1.1 and 1.3. The HD1.3 material is easier to ignite than HD1.1 and burns well even at atmospheric pressure, while many HD1.1 materials do not burn well at atmospheric pressure. The burning HD1.3 materials can serve as the stimulus for the explosion of HD1.3 materials in confinement and/or explosion or detonation of HD1.1 materials.

12. Several of the reviewed accident reports contained two common misrepresentations:

- The assumption that HD1.3 materials can be considered as “wooden rounds” and that HD1.3 is rather benign.
- The assumption that HD1.1 items are the most sensitive material.

As mentioned above, HD1.3 energetic materials, such as ammonium perchlorate-based propellants (especially those with burn rate catalysts), ignite easily and burn readily at one atmosphere. On the other hand, in order to initiate a detonation of HD1.1 military munitions, a

mechanical shock on the order of 40 kbars may be required. Such a mechanical shock level is rarely found in storage or transportation conditions.

13. From the stand-point of hazard reduction, it is desirable to have vents large enough to ensure un-choked flow, or have building construction that will quickly self vent if the flow becomes choked (i.e., frangible walls and roof panels).

14. Evacuation plans and safe separation distances must consider human nature. In several of the accidents that involved fire burning for significant time, spectators were attracted to the blaze and perished when explosions or detonations occurred. In one accident, a television crew was filming the blaze when the explosion and follow-on detonation occurred, killing the crew. In other accidents, congestion caused by spectators being attracted to the scene, and others trying to flee the scene, caused gridlock and increased fatalities.

ACKNOWLEDGMENTS

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Considerations for Determining Safe Separation Distances from Mass Fires: a Literature Search



2010 DDESB Seminar

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Jacobs Naval Systems Group**

**Dr. Josephine Covino
Department of Defense Explosives Safety Board**

Approved for Public Release: Distribution Unlimited





Literature Search

Work in Progress

Will be published as a DDESB Technical Paper

Includes:

- Accidents and incidents
- Experimental studies-small and large scale
- Analytical studies-small and large scale
- Current weight based approach, $D = kW^{1/3}$, does not adequately address safe separation distance from mass fires
- Recommendations & suggested future work





Literature Search

- **This presentation will focus on lessons learned from**
 - Accidents and Incidents
 - Test results
- **The second presentation, presented by Dr. Covino, will build on the lessons learned and present Recommendations and Suggested Future Work**





Accidents

- **Munitions**
 - Storage
 - Transportation
 - Operations
- **Commercial explosives**
 - Primarily transportation
- **Fireworks**
 - Primarily storage
- **Ingredients (e.g. ammonium perchlorate, ammonium nitrate)**
 - Primarily manufacture and storage

Time and space precludes discussing all accidents from report, Will just present some as examples





Accidents

There are problems with using accidents as information sources

- **Witnesses to events are often the first fatalities**
- **Sample + stimulus + environment → reaction**
 - In an R&D experiment: carefully control variables (usually vary one at a time) and observe resulting reaction
 - In an accident: have an unintended, undesired result and must “swim upstream” to try to determine cause(s)
- **Often the reaction destroys the evidence**





Accidents: Lessons Learned

- **Fire often is primary cause**
 - Decomposition /stabilizer depletion/auto-ignition
 - Electrical
 - ESD
 - Lightning
 - Fire of adjacent material
 - ✓ Fuel
 - ✓ Flight deck
 - ✓ Boxcar
 - ✓ Grass/vegetation
- **Fire burns for significant time before next reaction, often explosion that may in turn cause detonation**





Fire First Reaction in Many Accidents and Burns a Significant Time before next Reaction

- **PEPCON, Henderson, Nevada 1988**

- Over 8 million pounds of ammonium perchlorate stored in open in plastic drums and aluminum tote bins
- Fire burned 10 to 20 minutes before first explosions
- And at least 8 minutes until subsequent explosions/detonation
- 2 fatalities, 372 injuries, over \$1M in damages

- **Red River Army Depot, 1996**

- Fire started in M-10 gun propellant most likely due to stabilizer depletion → auto-ignition
- Adjacent black powder detonated, magazine still intact
- Fire burned for several days
- Energetic materials expelled and burned outside





Fire First Reaction in Many Accidents and Burns a Significant Time before next Reaction

- **Hawthorne Army Ammunition Plant, Nevada, 1989**
 - Fire in magazine intensely burned for several minutes
 - Plume 100 to 150 feet out the doors
 - Allowed to burn itself out
 - No detonation
- **Camp Doha, Kuwait, 1991**
 - Fire burned for ~ 40 minutes before first explosion
 - Subsequent fire and explosions for hours





Fire First Reaction in Many Accidents and Burns a Significant Time before next Reaction

- **Fireworks Factory, Enschede, the Netherlands, 2000**
 - Fire burned 30 minutes before first explosion
 - 22 deaths, 1000 injured, 500 million Euros damage
- **Fireworks Factory, Kolding, Denmark, 2004**
 - Fire burned ~ 90 minutes before first explosion
 - Fire and explosions/detonations for ~ 3 ½ days
 - 1 fatality, 3 serious injuries, 100 million euros in damages





Fire First Reaction in Many Accidents and Burns a Significant Time before next Reaction

- **Milan Army Ammunition Plant, May 2007**
 - Fire probably started from stabilizer depletion/auto-ignition
 - Over-pressure from fire blew out front wall of magazine
 - Unburned energetic material expelled and burned outside
 - Extensive fire plume out front of magazine
 - Fire continued to burn for ~ 1 hour
 - No detonation





Milan 2007





Other accidents involving fire

- **Four aircraft carriers**

- USS Oriskany 1966
- USS Forrestal 1967
- USS Enterprise 1969
- USS Nimitz 1981

220 fatalities, 702 injured, \$394.6M

- **Trains**

- Roseville, California 1973
- Benson, Arizona 1973





Experiments/Tests





- **Some of you may wonder why I didn't include Milan Army Ammunition Plant, October 2004**
- **We're going to come back to it in a few minutes**





Tests

Critical Issue

- **Race in time between pressurization due to combustion in confinement and pressure release due to venting**
 - $p(t) = f(\text{mass burning rate, thermochemistry, ..})$
 $dm/dt = \rho r A_b$
 - Venting
 - ✓ Un-choked flow if vent(s) big enough
 - ✓ Choked flow if vents too small
 - ✓ Choking when $p_i / p_o > 1.7-1.9$



Tests, Un-choked flow



- **Several studies**
 - Herrera & Vargas
 - Tozer
 - Allain
 - Joachim
- **Partially burned gases & propellant expelled from chamber**
- **Unburned propellant found out to 70-80 m**
- **Propellant burns outside chamber**
- **No rupture of chamber**





Plumes Associated with Un-choked Flow

- **Plume size**

- 8 m from 1.4 x 1.9 x 1.9 m chamber
- 7.6 m from 1/10th scale igloo → 76 m for igloo with 10,000 #
- 40 m from 1/3rd scale igloo tests
- 80 m

- **Flux**

- ~5024 kW/m² in vent pipe
- 94 kW/m² for propellant burning in open
- 125-128 kW/m² @ 15 m from center line
58 kW/m² @ 25 m from center line





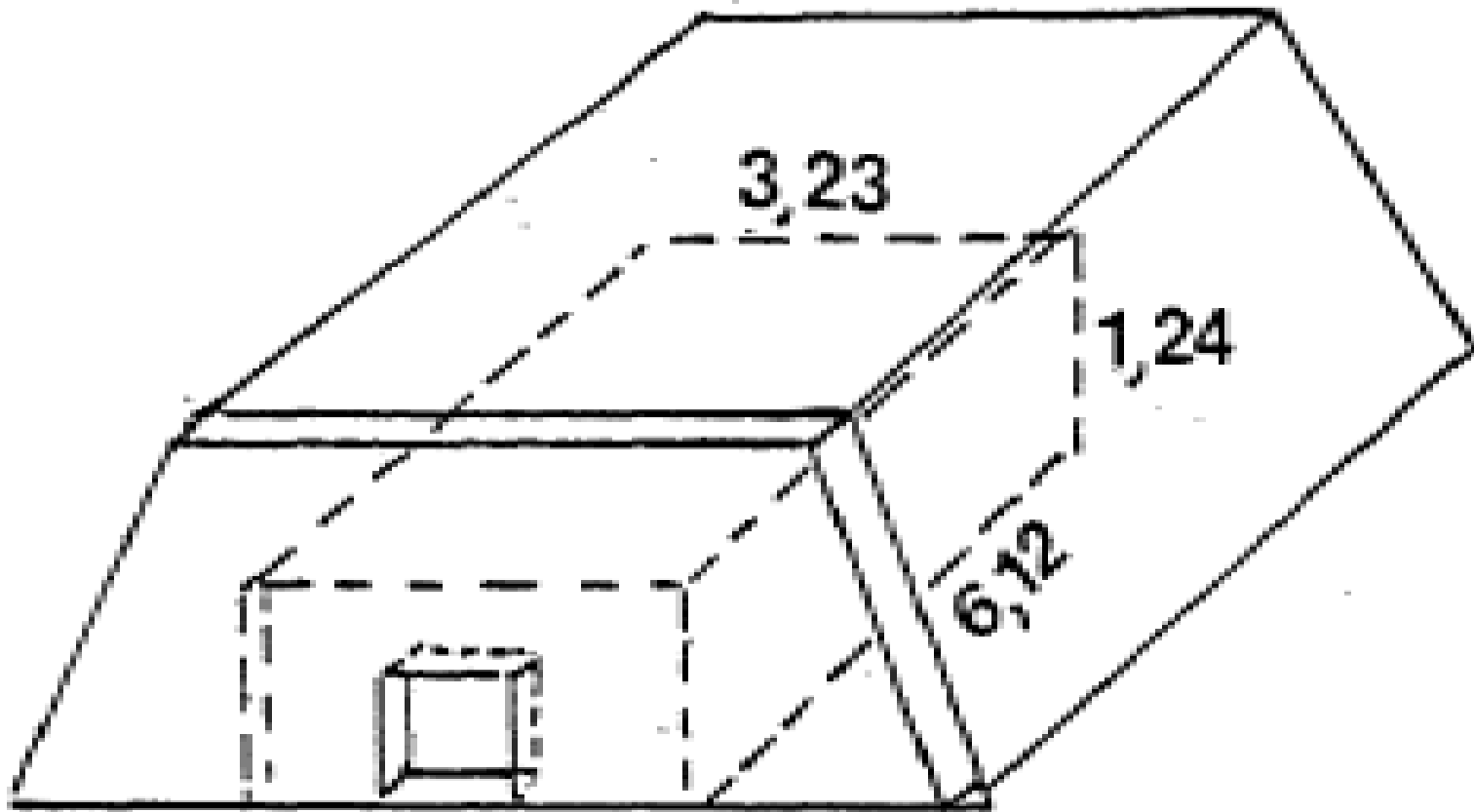
Choked flow

- **Joachim 1.4m x 1.9m x 1.9m chamber, 50kg/m³**
 - Structure failed from internal pressure @ ~6 s
 - No detonation
 - Peak pressure on wall ~103 kPa (10 bar)
- **Allain 1/3rd scale igloos**
 - Test 3 Igloo ruptured after 2-3 second burn
 - No blast over-pressure
 - Unburned propellant at 70 m
 - Test 4 Same loading density as 3 but smaller vent to volume
 - Ruptured after burning 1 second
 - 6 big concrete fragments—roof, 3 walls and front out to 20 m
 - No over-pressure, no crater
 - Pressure on wall --
 - » 7 bar measured before gauge saturated
 - » 10-12 bar estimated at rupture





Allain Test 4





Allain Test 4

BEFORE

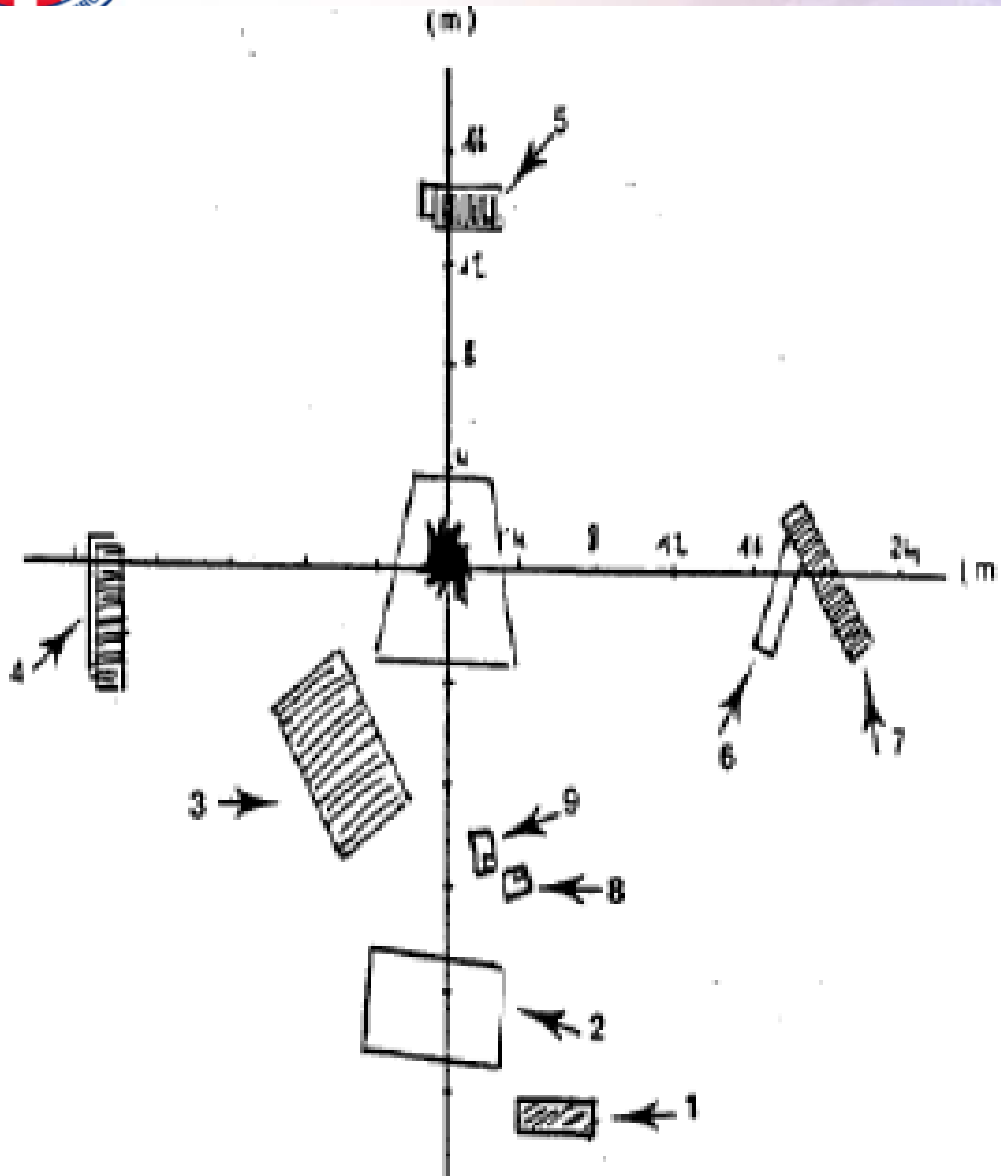


AFTER





Allain Test 4



- 1 metal front
- 2 concrete roof
- 3 metal roof
- 4 lateral metal + concrete wall
- 5 rear metal + concrete wall
- 6 lateral concrete wall
- 7 lateral metal wall
- 8 1/2 concrete front
- 9 1/2 concrete front





Combustion of HD 1.3

- **Un-choked flow**

- Energetic material often expelled from structure and burns outside not inside
- Plume hundreds of feet outside

- **Choked flow**

- Pressure rapidly builds
- May cause rupture of structure
- Can occur in 1 second after ignition
- Can throw large pieces of structure debris considerable distances





Milan 2004

- **Contents of earth covered magazine**
 - 4,599 pounds Comp A-5
 - 5,307 pounds of M2 propellant
 - 12,447 pounds of M9 propellant
- **Crew returning 3 metal drums of M9**
- **2 fatalities, 1 critical injury**

“... significant fragments traveling distances significantly greater than the 1250 foot radius IBD arc. For example, there was significant damage to a tree located 2100 feet in front of ECM-69...”

“Other debris estimated to have been a 6’ by 8’ section of the head wall significantly damaged a tree 3,100 feet from ECM-69..”



Milan 2004





Milan 2004





Milan 2004

Tree at 3100' from magazine impacted by 6' x 8' piece of headwall that shattered on impact with tree





Milan 2004



Tree at 2100' impacted by large piece of headwall. Piece of hinge found at base of tree. Rebar and angle iron also found at base of tree. Concrete shattered on impact, concrete debris found beyond tree.



Milan 2004



Fragment found 2050 feet from magazine





Milan 2004

- **Two “explosions” heard within ~ 1 second**
- **First was softer, more muffled. Second was louder, more brisant than first**
- **Could this have been due to: Combustion of M9 propellant**
- **Pressure build-up and rupture of magazine into large pieces**
- **Followed almost instantly by detonation that helped accelerate large pieces to distances greater than IBD**





Summary & Conclusions

- **Fire is often first reaction**
- **Fire can burn significant time before next reaction**
- **Mass fire may, or may not, transition to mass explosion/detonation**
- **Consequence of mass fire dependent on whether un-choked or choked flow**

