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Realistic Safe-Separation Distance Determination for Mass Fire Hazards

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FOREWORD

This document might be seen as a natural progression of many years of research and study. The authors have been involved in various programs dealing with the hazards associated with propellants and explosives and munitions incorporating these energetic materials. In 2005 and 2006, the NASA Engineering and Safety Center (NESC) assembled a team to review a test plan to update propellant safety siting methodology for application to the Vehicle Assembly Building (VAB) at the Kennedy Space Center (KSC). The team included members from National Aeronautics and Space Administration (NASA), Department of Defense (DOD), the Department of Defense Explosive Safety Board (DDESB), and industry. One of the recommendations was that NASA fund an effort to develop alternate methods to determine safe separation distance based on fire hazards. The NESC was funded to assemble a team of experts to develop these alternate methods. The team developed the methodology and applied it to determining the safe separation distances from the VAB. The results of that effort were published in Reference 69 of this document. One of the primary conclusions was that the safe separation distance calculated using the heat flux based method for 11.6 million pounds of Hazard Division (HD) 1.3 propellant in the VAB was a circle centered in the VAB and extending out to 400 meters (1,312 feet). This was very close to the weight-based quantity–distance arc determined for the 4.44 million pounds of the same HD 1.3 propellant for the Space Shuttle Program. If the weight-based approach had been used for the 11.6 million pounds, the arc would have encompassed 236 acres as compared to the 125 acres required using the heat-flux-exposure time method.

Dr. Jerry Ward and Dr. Josephine Covino, both from DDESB, and Thomas Boggs, New Directions Technology, Inc./Jacobs Naval Systems Group, were part of the NESC teams and were interested in applying the heat flux–exposure time methodology to determine safe separation distances for siting DOD facilities. DDESB funded an effort at the Naval Air Warfare Center Weapons Division, China Lake, California, to provide research to help enable the determination of safe separation distances from mass fire events. Part of that effort has been to perform a literature search and to make recommendations. This document is the product of that effort.

The authors would like to thank the following people who reviewed portions of the document. Their comments and suggestions have been gratefully received and incorporated into the document. Our thanks go out to Alice Atwood, Ronald Derr, Kenneth Graham, Michael Sharp, and Michael Swisdak. We also want to thank Rhonda Capron, Naval Air Warfare Center Weapons Division, for her excellent editorial contributions and her patience.

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14. ABSTRACT

(U) Propellants and explosives are energetic materials found in missile motors, bombs, and warheads, as well as bulk powder and fill in gun cartridges and projectiles. The materials can burn, explode, and/or detonate either on purpose or by inadvertent accident. These accidents can occur during manufacture, transportation, storage, and operational use. One way to protect personnel and facilities from the risk and consequences of accidents caused by inadvertent reaction of these energetic materials is to provide safe-separation distances between possible explosive sources and exposed sites whether they are inhabited buildings, public roadways, or processing buildings.

(U) This report presents an overview of how safe-separation distances are currently determined for various hazard divisions (HDs), with emphasis on HD 1.1 and HD 1.3. It reviews accidents and incidents involving munitions in manufacture, storage, transportation, and operational situations; commercial explosives primarily in transportation situations; fireworks primarily in storage situations; and energetic ingredients such as ammonium perchlorate (AP) and ammonium nitrate (AN) primarily in manufacture, transportation, and storage situations; experimental test results, and analytical models. This report will discuss how to determine safe-separation distances to prevent fatalities from mass fire events.

15. SUBJECT TERMS
Ammonium Nitrate, Ammonium Perchlorate, AN, AP, Detonation, Energetic Ingredients, Explosion, Fire, Fireworks, Hazard Division, HD 1.1, HD 1.3, Q-D, Quantity-Distance, Safe-Separation Distance

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ACRONYMS

2NDPA	2-nitrodiphenylamine
AAP	Army Ammunition Plant
ABL	Allegany Ballistics Laboratory
AEDC	Arnold Engineering Development Center
AFB	Air Force Base
AGM	above ground magazine
AN	ammonium nitrate
ANFO	ammonium nitrate and fuel oil
AP	ammonium perchlorate
APFSDS	armor-piercing fin-stabilized discarding sabot
ARMS	armament retooling and manufacture support
ASAP-X	automated safety assessment protocol–explosives
ATK	Alliant Technical Systems
AZF	AZote Fertilisant
BAM	Bundesanstalt fur Materialforschung und-prufung
BARPI	Bureau d´ Analyse des Risques et des Pollutions Industrielles
BASF	baden aniline and soda-fabrik
BSM	Blue Streak Merchandise
CAD	cartridge-actuated device
CAD	computer-aided design
CFD	computational fluid dynamics
CHAF	Control of the Hazards Associated with the Transport and Bulk Storage of Fireworks [program]
CO_2	carbon dioxide
CoRA	certificates of risk acceptance
CST	Central Standard Time
CxP	constellation program
DDESB	Department of Defense Explosives Safety Board
DISAM	Defense Institute of Security Assistance Management
DLAR	defense logistics agency regulation
DNA	deoxyribonucleic acid
DOD	Department of Defense
DODM	Department of Defense Manual
DODX	Department of Defense-owned railcars

DPPR	Department of Prevention of Pollution and Risks
DREF	Disaster Relief Emergency Fund
ECM	earth-covered magazine
EES	electric engine starter
EMERCOM	Emergency Situations Ministry
EOD	explosive ordnance disposal
ERW	explosive remnants of war
ES	exposed site
ESD	electrostatic discharge
ESMAM	explosives safety mishap analysis module
EST	Eastern Standard Time
EU	European Union
FaAA	Failure Analysis Associates
FARDC	Forces Armées de la République Démocratique du Congo
FDS	fire dynamics simulator
FLACS	Flame Acceleration Simulator
FOB	forward operating base
ft	feet
ft^2	square feet
ft^3	cubic feet
ft-lb	foot-pound
ft/sec	feet per second
g/cc	gram per cubic centimeter
GMT	Greenwich Mean Time
HCl	hydrochloric acid
HD	Hazard Division
HDPE	high density polyethylene
HESH	high explosive squash head
HMX	high melting explosives
HSL	health and safety laboratory
HTPB	hydroxyl-terminated polybutadiene
IAAP	Iowa Army Ammunition Plant
IB	inhabited building
IBD	inhabited building distance [arc]
I.D.	inside diameter
IED	improvised explosive device
ILD	intraline distance
IMD	adjacent magazine
I_s	specific impulse
ISO	International Standards Organization

K	Kelvin
kbar	kilobars
kg/m^3	kilograms per cubic meter
kJ/m^2	kilojoules per square meter
km/sec	kilometers per second
kPa	kilopascal
KSC	Kennedy Space Center
KSO_4	Potassium Sulfate
lb/s	pound per second
lbs	pounds
LNG	liquefied natural gas
m/s	meters per second
m^2/ton	square meters per ton
m^3	cubic meter
m^3/ton	cubic meters per ton
MAG	Mines Advisory Group
MAPO	methylaziridinly phosphine oxide
M-K-T	Missouri-Kansas-Texas Railroad Company
MLP	mobile launch platform
mm	millimeter
mm/μsec	millimeters per microsecond
MPa	megapaschal
mph	miles per hour
MSIAC	Munitions Safety Information Analysis Center
MTV	magnesium-teflon-viton
MX	Missile X
NaDDC	sodium dichloro-isocyanurate
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVSEAINST	NAVSEA Instruction
NAWCWD	Naval Air Warfare Center Weapons Division
NEQ	net explosive quantity
NESC	NASA Engineering and Safety Center
NEW	net explosives weight
NFPA	National Fire Protection Association
NIMIC	NATO Insensitive Munitions Information Center
NO_x	nitrogen oxide
NPK	nitrogen, phosphorus, potassium
O.D.	outside diameter
PAD	propellant-actuated device

PBD	process building
PEPCON	Pacific Engineering Production Company of Nevada
PES	potential explosive site
PML	Prins Maurits Laboratory
psf	pounds per square foot
psi	pounds per square inch
PSM	process safety management
p-t	pressure–time
PTRD	public transportation route
Q-D	quantity-distance
RDX	hexahydro-trinitro-triazine
Rs	rupees (Indian Currency)
SAFER	safety assessment for explosives risk
SDW	substantial dividing wall
SEESAC	Southeastern and Eastern Europe Clearinghouse for the Control of Small Arms and Light Weapons
SFPE	Society of Fire Protection Engineers
SSD	self sustained decomposition
SSP	Space Shuttle Program
tc	combustion time, thermocouple
THIMUN	The Hague International Model United Nations
TNO	Netherlands Organisation for Applied Scientific Research
TNT	2.4.6-trinitrotoluene (CAS number 118-96-7; explosive)
U.S.	United States
UK	United Kingdom
UN	United Nations
UNDAC	United Nations Disaster Assessment and Coordination
USD	United States dollar
UXO	unexploded explosive ordnance
VAB	vehicle assembly building
WP	work package

PREFACE

This document is the result of a project sponsored by the Department of Defense Explosives Safety Board (DDESB). The goals and objectives of the project were as follows:

- Review methods for determining safe-separation distances for the various hazard divisions of energetic materials and ordnance, with emphasis on 1.3 (mass fire) and 1.4 (moderate fire).
- A massive literature search was performed, collecting information in the following areas:
    - Accidents associated with
        - Storage of ordnance
        - Transportation of ordnance and explosives
        - Storage of fireworks
        - Storage and transportation of energetic ingredients such as ammonium nitrate and ammonium perchlorate

      Effort was made to determine the cause of the accident. Often reports simply listed "undetermined cause" or "unknown cause." Some the reports listed the cause as "human error." Unfortunately, while "human error" contributes to the accident, it does not address the reactions and associated chemistry and physics of the cause of the accident. We spent much time collecting as many documents describing an accident as we could find in an attempt to determine the cause of the accident. Over 80% of the accidents started with fire.
    - Tests that were initiated by fire.
    - Analytical modeling.
- The literature search resulted in lessons learned from accidents, testing, and analytical modeling.
- Recommendations were made based on the lessons learned.

The document contains two sets of references:

- General references found at the end of the document. These are in the typical citation form.
- Because much of the literature was obtained via electronic means, links to the World Wide Web are provided. The links for each accident are found with the description of each of the accidents. Unfortunately, some of the links are no

longer available. The links are still listed, but with the annotation [No longer available] because information that was contained in those links was used, and hard copies of those files have been retained by the authors.

At the outset of the project, a decision was made that in order to maximize the impact and usefulness of the document, it needed to have an unlimited distribution. No restricted or classified materials are contained in the report. Some of the old photographs indicate a restricted distribution, but we made sure that they are no longer restricted. In fact, many are now available on historical websites.

Many of the lessons learned were "paid for" with injuries and loss of lives. We hope these lessons do not have to be re-learned with further injury and loss of life.

EXECUTIVE SUMMARY

This report presents the following information:

- An overview of how safe-separation distances, sometimes referred to as quantity-distance (Q-D), are currently determined for various hazard divisions (HDs), with emphasis on HD 1.1 and HD 1.3. A weight based approach, $D = kW^{1/3}$, is used for the various hazard divisions with different values of k for different hazard divisions and different scenarios within HD 1.1.
- A review of accidents and incidents involving the following:
    - Munitions in manufacture, storage, transportation, and operational situations.
    - Commercial explosives primarily in transportation situations.
    - Fireworks primarily in storage situations. While fireworks are not one of the major emphases of the Department of Defense (DOD), lessons can be learned from the many accidents involving fireworks.
    - Energetic ingredients such as ammonium perchlorate (AP) and ammonium nitrate (AN) primarily in manufacture, transportation, and storage situations.

One of the major conclusions from this extensive review of accidents is that most of the accidents started with fire as the first major reaction, not explosions or detonations. Often the fires burned for a significant time before either burning itself out, or transitioning to an explosion or detonation.

- Results of experimental studies that showed that even when a mass fire did not transition to an explosion or detonation, if confined in a robust structure such as an earth-covered magazine, and if there was insufficient venting, pressure inside the structure could rapidly build and cause rupture of the structure. The pressure induced rupture can throw large pieces of structural debris significant distances without evidence of a blast over-pressure or cratering. These experimental studies also show that even when the structure does not catastrophically rupture, plumes from mass fires can extend several hundred feet from the structure. Any personnel in the path of the plume are likely to perish, and personnel can also perish if exposed to radiation from the plume if the heat flux-exposure time are sufficient to cause second- and third-degree burns.
- Review of analytical studies.
- Based on the lessons learned from accidents, incidents, experimental studies, and analytical studies, it was concluded that the current weight-based methods for determining safe-separation distances may be applicable for HD 1.1 materials

where the threat is blast and fragments. The current weight-based methods for determining safe-separation distances are not applicable for HD 1.3 and 1.4 materials where the threat is direct impingement of hot plumes and exposure to heat flux from the plumes, and structural debris if a pressure rupture of the confining structure occurs.

- Discussion of an alternate approach to determining safe-separation distances that considers the risks and consequences of mass fire reactions is presented—an approach based on human response to fires and radiation from the fires. This approach considers the radiation levels and exposure times and uses a criterion to prevent second-degree burns and associated fatalities.
- Recommendation that the Department of Defense Explosives Safety Board (DDESB) consider a consequence/risk based approach for determining safe-separation distances from mass fire events that would prevent fatalities resulting from direct exposure to fireballs and exhaust plumes and radiation to distance from these fireballs and plumes. The ultimate goal is to incorporate these methods into DOD 6055.09.
- Recommendation that DDESB establish a plan to address needed additional tests and analytical studies to provide necessary input and validation data.

One of the major conclusions from this extensive review of accidents is that most of the accidents started with fire as the first major reaction and not explosions or detonations. Often, the fires burn for a significant time before transitioning to an explosion or detonation, if it transitions at all. Obviously if the fires are prevented, or ameliorated, the explosion or detonation could be prevented.

BACKGROUND

Propellants and explosives are energetic materials found in missile motors, bombs, and warheads, as well as bulk powder and fill in gun cartridges and projectiles. The materials can burn, explode, and/or detonate either on purpose or by accident. These accidents can occur during manufacture, transportation, storage, and operational use. One way to protect personnel and facilities from the risk and consequences of accidents caused by inadvertent reaction of these energetic materials is to provide safe-separation distances between possible explosive sources and exposed sites whether they are inhabited buildings, public roadways, or processing buildings.

Within the Department of Defense (DOD), the methods for determining safe-separation distances are contained in DOD Ammunition and Explosive Safety Standards, DOD 6055.09-M (Reference 1). This document presents various hazard division (HD) classifications and the methods for determining the safe-separation distances for each HD and/or mixed storage involving multiple HD classifications.

The HDs include the following:

- HD 1.1—Mass detonation and mass explosion where the major hazards are blast and fragments.
- HD 1.2—While a single item can detonate or explode, the multiple stores do not mass detonate or explode when a single item is initiated. Instead the reactions take place over time and progress in severity. Fragments, firebrands, and unexploded items may be projected from the site. Blast effects are limited to the immediate vicinity and are not a primary hazard.
- HD 1.3—Includes items that burn vigorously with little or no possibility of extinguishment in storage situations. Explosions normally are confined to pressure ruptures of containers, will not produce propagating shock waves or blast overpressure, and have minor fragments.

  [Note: As will be discussed later, burning HD 1.3 materials in a confined volume can result in pressure increase within the volume. If there is not sufficient venting, the pressure can cause catastrophic rupture of the confining structure and projection of secondary fragments significant distances.]
- HD 1.4—Has moderate fire but with no significant blast or fragments.
- HD 1.5—Includes very insensitive explosive substances (with a mass explosion hazard).

- HD 1.6—Includes extremely insensitive explosive articles (no mass explosion hazard).

The tests and protocols to determine which HD an item would be in are defined in TB 700-2 (Army), Naval Sea Systems Command (NAVSEA) instruction (NAVSEAINST) 8020.8B (Navy), TO 11A-1-47 (Air Force), Defense Logistics Agency Regulation (DLAR) 8220.2 (Reference 2). Once an item has been classified into its HD, DOD 6055.09-STD (Reference 1) is used to determine safe-separation distances. Much of the following discussion will be centered around HD 1.1 and 1.3, because most of the items containing energetic material are in these two HDs. Most of the discussion will address the need for risk/consequence based determination of safe-separation distances from mass fires associated with HD 1.2, 1.3, and 1.4 materials.

The methods (predominantly tables and equations) presented in DOD 6055.09-M are largely based on a

$D = kW^{1/3}$ relationship

where

D = distance in feet
k = a factor that depends on HD and other considerations that will be discussed later
W = weight of energetic material in pounds

D is often referred to as the Quantity-Distance (Q-D) for the given weight (quantity) of energetic material.

In this report, the term safe-separation distance will be used rather than Q-D. The reason for this is that Q-D is a subset of safe-separation distance and is usually used for mass explosion/mass detonation. The term quantity usually refers to weight (or net explosives weight (NEW) that factors in the explosive output, often referred to in terms of 2, 4, 6-trinitrotoluene (CAS Number 118-96-7; explosive (TNT)) equivalence). Safe-separation distance on the other hand considers how far away from a given situation (e.g., storage of energetic materials and components, operations involving energetic materials) personnel must be to avoid unwanted consequences (serious injuries or fatalities). This report will discuss how to determine safe-separation distances to prevent fatalities from mass fire events.

Before discussing safe separation distances from reactions of propellants and explosives, a brief description of reactions of propellants and explosives is presented in the next several paragraphs.

Military munitions utilize rocket/missile motors for propulsion and warheads/bombs to produce fragments and blast. The reactions range from combustion to detonation. Obviously you want the device to perform its function when desired and not inadvertently react during manufacture, storage, or transportation. Should a munition inadvertently react, you want the reaction to be as benign as possible. The following sections briefly discuss the various types of reaction ranging from combustion to explosion to detonation. The purpose in presenting the following paragraphs is simply to provide a brief introduction before presenting discussions of accidents, testing and analytical modeling. There are many text books that discuss combustion and detonation in much greater detail.

The simplest and perhaps the most familiar reaction is combustion, ranging from a very slow reaction like burning firewood in a fireplace to the rapid combustion associated with missile motors. Unlike the fire burning in the fireplace, which has a solid fuel, wood, and an ambient oxidizer, air; a missile motor carries its own fuel and oxidizer. In a solid propellant, the oxidizer and fuel are intimately mixed and the resultant propellant can burn in an inert atmosphere and even under water. The rate of combustion is a function of several variables, with the most important being the surface area available, the surface regression rate (burn rate), and the thermochemistry of the propellant.

Gun propellants are often small cylindrical grains of propellant giving them a relatively high surface area (often enhanced by perforations within the grains). In contrast the solid propellant in a missile motor is often a monolithic grain with a center perforation. Ignition occurs in this center perforation and burns back radially. In a very large motor, such as the Space Shuttle boosters, the motor may be several large motor segments, again with a central perforation, stacked one atop another with connections and seals. The bottom segment has the nozzle(s), and the top segment is the end cap.

The surface regression rate of the solid propellant is a function of pressure, usually given by an expression:

$$r = cp^n$$

where
- r = surface regression rate
- c = constant
- p = pressure
- n = pressure exponent, usually less than one

Propellants are relatively easy to ignite. The combustion converts the solid propellant to hot reaction gases and produces pressure in the motor or gun. The pressure produced and the pressurization rate is determined by the density of the propellant, the surface regression rate, the burning surface area and the thermochemistry of the reaction, and by the volume of the gun breech and change in volume as the gases push a projectile down the gun barrel or by the volume of the motor and the diameter of the nozzle throat in the rocket motor. This description is obviously a simplification. There are many textbooks that present much more detailed descriptions.

Gun propellants are classified as single base (primarily nitrocellulose), double base (primarily nitrocellulose and nitroglycerine), and triple base (often nitrocellulose, nitroglycerine and nitroguanide). Rocket/missile propellants are often various combinations of ammonium perchlorate/hydrocarbon binder/aluminum powder like the propellant in a Space Shuttle booster motor. Most of the gun propellants and missile propellants/motors are HD 1.3; however, there are missile propellants/motors that are HD 1.1. These systems usually have propellants consisting of nitramines and energetic binders and aluminum powder.

Propellants are obviously designed to burn, but if the reaction gases are contained an explosion can occur, and in some instances propellant can detonate. However the main hazards associated with propellants are mass fires. A pressure burst or explosion can occur when the gas production rate from combustion exceeds the gas exhaust rate from the containment, resulting in increasing pressure within the container. If the mass burning is contained in structures without proper venting, internal pressurization can cause the enclosure to violently rupture as is discussed in several sections of the paper. The debris can be rather large pieces that are propelled significant distances. This will be discussed in more detail in the sections on Accidents, Test Results, and Analytical Modeling in this document.

Propellants and explosives can explode, and the explosions can set off detonation reactions especially if there is mixed storage of materials having different hazard classifications.

A mass detonation of munitions is truly an awesome event, and an inadvertent detonation of munitions during manufacture, storage, or transportation operations is to be prevented.

A detonation of energetic material is a reaction that converts the energetic material to final products, usually gases, that occurs at supersonic rate. Sonic velocity in a solid explosive or propellant is on the order of 2 mm/µsec (6,560 ft/sec). So a detonation reaction has to exceed this sonic velocity. Typical detonation velocities of explosives are on the order 7.6 to 8.8 km/sec. (24,936 to 28,873 ft/sec). Obviously a detonation reaction rapidly converts the solid explosive to reaction products very, very quickly, and releases tremendous amount of energy. Often, the detonation destroys the building(s) and the only evidence is a hole in the ground (crater).

Military explosives are often formulated and designed to be hard to initiate to a detonation. Again, you want it to detonate when you want, but not react inadvertently. For example, it may take a mechanical shock of 40 kilobars (600,000 psi) to initiate a detonation. So while munitions designed to detonate produce tremendous output that results in fragments and blast, the probability of inadvertent detonation is extremely low in storage or transportation scenarios. A study showed that impact at 60 mph into concrete abutments only produced a few kilobars shock loading, well below that required for initiation (Reference 3).

The probability of initiation to detonation increases with damage to the material, age, exposure to fire (cookoff) (Reference 4).

Before considering safe-separation distances from mass fire reactions, a review of accidents and incidents, experimental test results, and analytical models is appropriate.

ACCIDENTS AND INCIDENTS

Reference 5 presents a table that lists 81 accidents associated with solid propellants and the consequences of these accidents. The accidents spanned the time frame from 1940 through 1999 and resulted in 486 fatalities and 1,381 injured.

In addition to the descriptions of accidents presented in Reference 5, this section will summarize reports of accidents and incidents that occurred with the following items:

- Munitions in manufacture, storage, transportation, and operational situations.
- Commercial explosives primarily in transportation situations.
- Fireworks primarily in storage situations.
- Ingredients such as ammonium perchlorate (AP) and ammonium nitrate (AN), primarily in manufacture and storage situations, but also in transportation.

Subsequent sections will focus on these areas. Some of the accidents could be placed in several sections. To avoid unnecessary duplication and repetition, each accident will only be discussed in one section, even though it may overlap another section.

Because some of the sections discuss hundreds of accidents, each of the sections begins with a summary table that lists the accidents that are discussed in that section. The summary table is followed by some discussion of similarities/differences between the accidents and any general highlights presented in that section. This is then followed by brief discussions of each of the individual accidents in that area.

Before presenting the individual sections, some general comments about accidents are given below.

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 firsthand 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:

$$\text{Sample} + \text{Stimulus} + \text{Environment} \rightarrow \text{Reaction}$$

Sample refers to the energetic material or device containing energetic material and its associated thermochemistry and other characteristics (such as mass burning rate, which is often subject to environmental effects such as confinement of gases). The stimulus refers to the events, or series of events, that start and may sustain the reaction. For example, a stimulus might be high temperatures that cause a decomposition that can lead to combustion, a radiant heat flux that causes a sample to ignite, or a high intensity shock wave that causes a sample to detonate. 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 (ECMs). 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 and the accident investigators must "swim upstream" to try to determine the cause(s) of and contributors to 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.

There are many excellent compilations of accidents including those shown in Table 1.

In addition, the North Atlantic Treaty Organization (NATO) Munitions Safety Information Analysis Center (MSIAC), which was formerly the NATO Insensitive Munitions Information Center (NIMIC), publishes a newsletter on a quarterly basis. These newsletters usually contain a section on accidents dealing with energetic materials. MSIAC/NIMIC have published the newsletter since 2000. It can be accessed at the following web address: http://www.msiac.nato.int

TABLE 1. Documents That Contain Lists of Accidents Involving Munitions in Production, Storage, and Transportation Aspects.

Geneva International Centre for Humanitarian Demining, *Explosive Remnants of War (ERW), Undesired Explosive Events in Ammunition Storage Areas,* Geneva, November 2002, ISBN 2-88487-006-7, pp. 248-253.
Greene, O., Holt, S., and Wilkinson, A., *Ammunition Stocks: Promoting Safe and Secure Storage and Disposal—Briefing 18 Biting the Bullet,* February 2005, ISBN 1898702-63-2, pp. 16-17.
http://www.seesac.org/uploads/studyrep/BTB18.pdf
Wilkinson, A., *Targeting Ammunition: A Primer, Chapter 8 Stockpile Management of Ammunition,* Third Draft, 8 February 2006 Annex A Explosive Events in Ammunition Depots (1997-2005), pp. 18-22.
South Eastern and Eastern Europe Clearinghouse for the Control of Small Arms and Light Weapons (SEESAC), *Explosive Ordnance Disposal* (EOD) C*learance of Ammunition Storage Area Explosions,* RMDA/G 05.55, 4th Edition, 2006-07-20, Annex C Summary of explosive events in ammunition storage locations (2001-2006), pp. 13-16.
International Committee of the Red Cross, *Book I: Weapon Contamination Environment,* August 2007, pp. 27-28.
Parliamentary Forum on Small Arms and Light Weapons, *Conventional Ammunition Stockpiles Parliamentary Handbook 2008,* ISBN 978-91-633-3524-2, Annex A Ammunition Depot Explosions, pp. 6-10.
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Unfortunately, many of these presentations simply list the location, date, number of fatalities, number of injuries, and a few words to indicate a cause. Often, the cause is simply listed as human error or carelessness as opposed to identifying the stimulus that caused the accident or the series of events that allowed the reactions to build in severity. This latter problem is that the tables often list explosion or detonation as the reaction when the first reaction was fire and often the fire burned for a significant time before the next reaction, whether it was an explosion or a detonation, occurred. In the following descriptions, effort was taken to describe the series of reactions that occurred. In many instances, this involved extensive research to find as many descriptions of an accident as possible. The first descriptions were often a simple listing of the worst reaction that occurred (e.g., detonation) without considering that if some of the earlier occurring reactions had been prevented, the catastrophic event might not have occurred. In many of the accidents, if the initial fire was put out, the subsequent explosions or detonations would not have occurred.

Yet another problem is that articles are often written by journalists who do not have a background in energetic materials and the reactions of these materials, or the journalist is quoting someone who does not have the background knowledge. For example, an accident at the Milan Army Ammunition Plant (AAP), 16 May 2007, occurred in an ECM. The front wall was blown out. The remaining portion of the ECM was relatively intact as shown in the pictures. There was no evidence of cratering to indicate that a detonation occurred. This is in direct contrast to the description in the MSIAC accident report that had a base spokesperson saying, "At approximately 5:00 a.m., one of our storage magazines internally detonated. Something happened that caused the detonation to result in a fire." Again, there was no detonation. The fire was likely due to auto-ignition of the M-10 propellant that was stored in the magazine. The fire resulted in pressurization of the magazine. Fortunately, the pressure blew out the front wall resulting in un-choked flow. The un-choked flow resulted in some material being dispersed outside the magazine and burning outside as indicated in the photographs.

> [Note: Choked and un-choked flow and why it is so important will be discussed in the Testing Section.]

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

- Decomposition that may lead to auto-ignition. This will be more thoroughly discussed in following sections.
- Electric malfunctions in the storage area.

- Electrostatic discharge (ESD). Two major accidents, one of a Pershing missile in Germany and one of a Missile X (MX) Peacekeeper 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.

The accidents described in the following paragraphs illustrate the above points.

ACCIDENTS INVOLVING STORAGE OF ENERGETIC MATERIALS AND MUNITIONS

There have been many inadvertent explosions of energetic materials and munitions. For example, Wikipedia has published a list of 117 explosions (Reference 6), ranging from the Halifax, Nova Scotia, explosion that resulted in 1,950 fatalities, to the metropolitan store, Windsor, Ontario, Canada, explosion that resulted in 10 fatalities. While not all of the 117 explosions involved munitions, many of them did. Often, the accidents started with fires that may then have led to explosions that in turn may have led to detonations. The following accidents involved storage of energetic materials and munitions. Table 2 is a summary of the accidents involving storage of energetic materials and munitions.

TABLE 2. Accidents Involving Storage of Energetic Materials and Munitions.

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost, not adjusted for inflation
15 Feb 1898	Cuba	USS *Maine*	266	0	Fire	Explosion	
11 Sep 05	Japan	Battleship *Mikasa*	339	300	Fire	Explosion	
12 Mar 07	France	Battleship *Iena*	120	0	Fire	Explosion	
10 Jul 10	USA	Lake Denmark, NJ	21	51	Lightning	Explosion, detonations	$84,000,000
25 Sep 11	France	Battleship *Liberte*	300	0	Fire	Explosion	
20 Oct 16	Sevastopol	Ship *Imperatrista*	228	0	Fire	Explosion	
9 Jul 17	Scotland, Scapa Flow	*HMS Vanguard*	843	2	Fire	Explosion	
18 May 18	USA	Aetna Chem., PA	241	400	Fire	Explosion	
16 Oct 26	China, Kiukiang	Ship *Kuang Yuang*	1,200	0	Fire	Explosion	
12 Sep 40	USA	Hercules, Kenvil, NJ	51	200	?	Explosions	
8 Jun 43	Japan	Battleship *Mutsu*, at anchor	1,121	0	?	Explosion	
10 Nov 44	Admiralty Islands	USS *Mount Hood*	432	371	?	Explosion, detonation	
13 Jul 44	USA	Port Chicago	320	390	?	Detonations	$124,000,000
13 Feb 47	Philippines	Batangas	0	0	Grass fire	Detonations	
26 Apr 60	USA	Radford, VA	0	0	Lightning	Deflagration	
22 May 61	USA	ABL, WV	9	26		Explosion	
16 May 65	Vietnam	Bien Hoa AFB	27	100	Fuse	Fires, exp, det	
11 Aug 81	USA	ABL, WV	2	0	?	Detonations	
17 May 84	Russia	Severomorsk	0	0	Fire, cigarette	Explosions, 5 days	
28 May 84	Czechoslovakia	Semtin	5	200	Fire	Explosion	
11 Jan 85	Germany	Waldheide Pershing	3	7	ESD, fire	Motor ignition	
23 Nov 85	USA	AEDC, TN	0	0	Motor press. burst	Deflagration	
29 Dec 87	USA	Morton Thiokol, UT	5	0	ESD, friction	Motor ignition	

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
9 May 89	India	Pulgaon	0	0	Grass fire	Fire	$5,500,000 + $59,000
9 Aug 89	USA	Hawthorn, NV	0	0	Fire	Rapid deflagration	igloo $23,910
11 Jul 91	Kuwait	Camp Doha	0	56	Fire	Explosion	
9 Apr 92	Armenia	Abovian Military Depot	0	0	Fire	Missile propulsion, explosion	
14 May 92	Russia	Vladivostok	1	6	?	Explosion, fires	
28 Jun 92	USA	White Oak, MD	0	0	Cookoff	Detonations	
19 May 94	Russia	Novonezhino	0	84	Fire	Explosions	
1 Aug 94	USA	Indian Head, MD	0	0	Fire	Detonations	
20 Oct 94	Russia	76th Paratrooper Division	3	7	?	Fire, explosion	
21 Aug 96	USA	Red River Depot, TX	0	0	Fire	Detonation, fire	
27 Apr 97	Russia	Bira	0	0	Fire	Explosion	
21 Feb 98	Russia	Volgograd	0	0	Fire	Explosion	
19 Jun 98	Russia	Sverdlovsk, Ural Mtn	14	17	Lightning	Explosions	
1 Dec 98	Philippines	Tarlac City	0	0	Fire	Explosions	
4 Dec 98	Russia	Yekaterinburg, Ural	3	0	Fire	Explosions	
19 Jul 99	Finland	Undisclosed	0	0	Fire	Explosions	
12 Jun 99	Russia	Volgograd	3	0	Fire	Explosion	
14 Apr 00	Congo	Kinshasa	101	200	Short circuit fire	Explosions	
28 Apr 00	India	Bharatpur	5	10	Grass fire	Explosions, fires	
3 May 00	India	Pune	0	0	Grass fire	No ignition of munitions	$77,000,000 + $2,600,000
28 Apr 01	India	Pathankot	0	5	Fire	Explosions	
24 May 01	India	Birdhwal Depot	1	5	Fire	Explosions	$5,400,000
21 Jul 01	Russia	Buryatia, Siberia	3	4	Lightning	Fires	$74,000,000
16 Aug 01	India	Tamil Nadu	26	2	Fire	Detonations	
25 Oct 01	Thailand	Pak Chong Arsenal	20	90	Fire	Massive explosions	

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
11 Jan 02	India	Bikaner, Rajasthan	2	12	Electric spark, fire		
27 Jan 02	Nigeria	Lagos Armory	1,100	5,000	Fire in adjacent mkt	Massive explosions	
7 Mar 02	Afghanistan	Kandahar	0	0	Grass fire	Explosions	$12,000,000 in ammunition
25 Apr 02	India	Pune	6	1	Fire	Explosions	
28 Jun 02	Afghanistan	Spin Boldak	32	70	?	Explosions	
10 Jul 02	Russia	Buryatia, Siberia	3	11	Lightning, fire	Explosions	
10 Aug 02	Afghanistan	Jalalabad	26	90	Fire	Explosions	
16 Oct 02	Russia	Vladivostok	0	26	Fire	Explosions	
30 Oct 02	Mozambique	Beira Arms Depot	6	50	Lightning	Explosion	
12 Nov 02	Germany	Lubben, Brandenburg	4	0		Explosion	
12 Nov 02	Nicaragua	Managua	5	5	Explosion	Fires, explosions	
20 Nov 02	Ecuador	Riobamba	7	274	Fire cookoff	Explosions	
23 Jan 03	Peru	Tumbes	7	98	High temperatures?	Detonations	$80,000,000
23 Mar 03	Ecuador	Guayaquil	0	95	?	Explosion	
26 Apr 03	Iraq	Zafaraniyah	14	50	Fire	Detonations	
5 May 03	Vietnam	Thai Nguyen	2	31	Fire	Explosions	
1 Jun 03	India	Jodhpur	0	0	Fire	Explosion	
9 Jun 03	Iraq	Ad Diwaniyah	3	2	Fire	Explosion	
9 Jun 03	Iraq	Karbala	0	0	Fire	Explosions	
22 Jun 03	Iraq	Najaf	40	0	Fire	Explosions	
22 Jun 03	Iraq	Haditha	30	6	?	Explosions	
12 Jul 03	Russia	Vladivostok	0	13	Firecracker	Explosions	
16 Jul 03	Angola	Menongue	2	15	Fire	Explosions	
7 Aug 03	USA	San Jose, CA	0	0	Ignition	Explosion	
14 Aug 03	Russia	Babstovo	2	0	Spilled fuel fire	Explosions	
17 Aug 03	Iraq	Tikrit	12	0	?	Explosion	
12 Sep 03	USA	San Jose, CA	1	0	Cutting vac line	Explosion	
10 Oct 03	Ukraine	Artemovsk	0	2	Fire started by welding, explosions		
19 Feb 04	India	Amritsar	0	30	Fire	Explosion	

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
23 Feb 04	India	Nellore	6	3	Fire from propellant		
25 Feb 04	Philippines	Quezon City	0	4	Fire caused by spark, explosions		
6 May 04	Ukraine	Novobogdanovka	5	20	Fire	Explosions	
2 Jun 04	Iraq	Kirkuk Air Base	0	0	Fire caused by rocket attack, explosions, detonation		$700,000,000
9 Jul 04	India	Madhya Pradesh	0	2	Fire		
26 Aug 04	India	Orissa	0	0	Fire		
13 Oct 04	USA	Milan, TN	2	1	Fire, explosion, detonation		
23 Feb 05	Sudan	Juba	31	150	Fire due to high temp	Explosions	
23 Feb 05	Nigeria	Kaduna	4	44	Fire	Explosions	
31 Mar 05	Cambodia	Andong Chen	6	20	High temperatures?	Explosions, detonations	
2 May 05	Afghanistan	Bajgah	28	70	?	Explosions	
18 Jun 05	Guatemala	Guatemala City	0	0	Fire	Explosions	
23 Jul 05	Ukraine	Novobogdanovka	0	0	Fire	Explosions	
30 Sep 05	Russia	Kamchatka Peninsula	0	1	Fire	Explosions	
25 Nov 05	Dem Rep of Congo	Nord-Kivu	6	0	Lightning		
23 Mar 06	Afghanistan	Jabal Saraj	2	60	Fire due to WP?	Explosions	
19 May 06	Sudan	Juba	2	10	Fire	Explosions	
12 Jun 06	USA	Iowa AAP, IA	2	2	Explosion		
5 Jul 06	USA	Wyoming Co., WV	0	0	Fire	Explosions	
15 Jul 06	USA	Camp Minden, LA	0	0	Grass fire	Explosions	
19 Aug 06	Ukraine	Novobogdanovka	0	4	Grass fire, fire	Explosions	
24 Aug 06	USA	Camp Minden, LA	0	0	Fire, explosions, detonation	Detonations	$118,000
6 Sep 06	Aden	Khour Maksar	3	7	Friction heating	Explosions	

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
7 Sep 06	Finland	Niinisalo	0	0	Fire	Explosions	
10 Oct 06	Iraq	FOB Falcon	0	0	Fire by 82-mm round	Fires, explosions	€ 1,000,000
19 Oct 06	Serbia	Paracin	0	20	Fire	Explosions	
21 Feb 07	So. Korea	Taebaek	2	9	Fire	Explosion	
2 Mar 07	Slovakia	Novaky	8	45	?	Explosion, Detonation	
22 Mar 07	Mozambique	Malhuxine	104	492	Fire due to hi temp	Explosions	
16 May 07	USA	Milan AAP, TN	0	0	Fire	Blew out front wall	
17 May 07	India	Dehra Dun	5	5	Fire	Explosions	
18 May 07	Ukraine	Novobogdanovka	2	0	?	Explosion	
18 May 07	Israel	Israel Military Indus	0	0	Fire	Explosions	
18 May 07	Dem Rep of Congo	Mbandaka	3	100	?	Explosion, fires, explosions	
23 Jun 07	Mozambique	Malhuxine	5	11	Clean up of unexploded explosive ordnance		
29 Jun 07	India	Bhadrawati Ordnance Factory	0	0	Fire	Explosions	
26 Jul 07	Syria	Aleppo	15	50	Fire from high temp	Explosions	$4,900.00
11 Aug 07	India	Khandroo, S. Kashmir	30	40	Fire	Explosions	
20 Sep 07	Romania	Romarm SA Mija	0	4	Fire	Explosions	
20 Sep 07	Viet Nam	Minh Son	3	4	Ammo deterioration explosions		
25 Sep 07	Chile	Talagante	0	4	Fire	Explosions	
29 Dec 07	Colombia	Medellin	6	10	Grenade detonated	Explosions	
15 Mar 08	Albania	Gerdec	27	300	Fire	Explosions, detonations	
23 Mar 08	Russia	Lodeinopolsky	0	0	Fire	Missiles propulsive	
7 Jun 08	Taiwan	Kinmen	0	0	Fire		$30,000,000

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
3 Jul 08	Bulgaria	Chelopechene	0	3	Fire	Explosions	
9 Jul 08	Uzbekistan	Kagan	3	21	Fire		
27 Aug 08	Ukraine	Lozovaya	0	2	Forest fire spread	Fires, explosions	
17 Sep 08	USA	East Camden, AR	1	0	Inadvertent ignition of motor		
30 Sep 08	Russia	Fokino	0	0	Lightning, fires	Explosions	
25 Oct 08	Russia	Kazan	4	5	?	Explosions	
4 Dec 08	India	Gandhidham	2	6	Fire	Explosion	
5 Dec 08	India	Jawahar Nagar	4	2	?	Explosion	
6 Jan 09	Albania	Polican	1	0	Fire	Explosion	
20 Mar 09	Kazakhstan	Arys	4	16	Fire	Explosions	
29 Apr 09	Tanzania	Dar Es Salaam	26	1,000	?	Explosions	
24 May 09	USA	Owensville, OH	0	0	Fire	Explosions	
6 Jun 09	Sri Lanka	Jaffna	0	0	Fire		
8 Jun 09	Sri Lanka	Vavuniya	0	0	Fire	Explosions	
9 Jun 09	Kazakhstan	Almaty	1	0	Fire	Explosion, fire	
28 Jun 09	Cambodia	Tuol Kraisaing Camp	0	2	Fire	Rockets flew, no detonations	
14 Sep 09	Russia	Karabash	1	2	Fire	Explosions, detonation	
30 Sep 09	India	Pune	0	0	Explosion blew out frangible roof		
13 Nov 09	Russia	Ulyanovsk	2	60	Fire	Explosions, fires	
23 Nov 09	Russia	Ulyanovsk	8	2	Unexploded explosive ordnance from previous fires, explosions		60 million rubles
3 Feb 10	Bulgaria	Gorni Lom	0	4	Fire	Explosions	
13 Mar 10	Ukraine	Hruzevytsya	0	1	Fire	Detonation	
26 Mar 10	India	Panagarh, W. Bengal	0	0	Fire		
4 May 10	USA	Milan AAP, TN	0	2	?	Explosion	
24 May 10	USA	ABL, WV	0	2	?	Explosion	

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
1 Jul 10	Russia	Ulyanovsk	0	2		Explosion	
3 Jul 10	Russia	Biysk Unit 30654	6	0		Explosion	
5 Jul 10	Russia	Saratov Base	1	1	Fire	Explosion	
13 Jul 10	USA	Redstone Arsenal	0	0	Fire		
23 Aug 10	Dem Rep of Congo	Camp Bokala	0	0	Rocket inadvertently launched		
24 Aug 10	Russia	Bashkortostan	1	0		Detonation	
7 Sep 10	Belgium	Seneffe	0	0	Fire	Explosions	
14 Sep 10	USA	Toone, TN	0	6	Flash fire		
20 Nov 10	India	Binnaguri	0	0	Fire	?	
25 Nov 10	India	Tamil Nadu	5	12	Mixing operation	Explosion	
27 Dec 10	Serbia	Cacak	0	0	Fire	Explosion, detonations	
5 Jan 11	USA	Oakland, TN	1	1	Fire	Explosion	€ 10,000,000
30 Jan 11	Venezuela	Maracay	1	0	Fire	Explosions	
16 Feb 11	Tunisia	Dar Es Salaam	27	500	Fire	Explosions	
20 Feb 11	UK	Over Wallop, Hampshire	0	0	Fire lasted 3 seconds		
8 Mar 11	USA	Lake City AAP, MO	0	6	?		
6 Apr 11	Russia	Lipetsk	3	2	"Spontaneous ignition" of gunpowder		
13 Apr 11	USA	Toone, TN	0	3	Workers burned mixing chemicals		
20 Apr 11	Czechoslovakia	Semtin	4	7	Reaction of NG	Explosion	
26 May 11	Russia	Bashkortostan	0	12	Fire	Explosions, fires	
2 Jun 11	Russia	Pugachyovo	3	100	Fire	Explosions, fires	
7 Jun 11	USA	Camp Minden, LA	0	0	?	Explosion of black powder	
7 Jul 11	Turkmenistan	Abadan	0	0		Fires, explosions	

TABLE 2. (Contd.)

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
11 Jul 11	Cyprus	Evangelos Florakis	13	62	Fire	Explosions, detonations	
23 Aug 11	Russia	Ashuluk range	7	11	Inadvertent ignition of motor, detonation		
4 Mar 12	Republic of Congo	Brazzaville	316+	1,500	Fire, faulty wiring	Explosions, detonations	
			346	1,697			
		Totals	7,769	13,261			

As a summary, Table 2 lists accidents involving ordnance over the time span from the turn of the twentieth century to March 2012. For each of the 173 accidents listed, the date, country, location, number of fatalities and injuries, the first reaction and ensuing reactions, and cost are presented if given. The fatalities listed totaled 7,769 and 13,261 were reported injured. Of the 173 accidents listed, 141 identified initial reactions. Of the 141, in 106 (75%) the first reaction listed was fire. Table 3 lists the number of times a given first reaction was cited.

TABLE 3. Initial Reaction Cited in the 141 Accidents
Where an Initial Reaction was Given.

Initial Reaction Cited	Number	% Relative to 141
Fire	106	75
Other, includes explosion	13	9
Lightning often followed by fire	8	6
High temperature followed by fire	6	5
Electric followed by fire	4	3
Cookoff	2	1
Electrostatic discharge followed by fire	2	1

It should be noted that the initial reactions listed in Table 3 were those given by the authors of the various reports referenced in the text. Many of the reactions listed as fire were with gun propellants and probably the first reaction was depletion of stabilizer that led to accelerated decomposition reactions that led to ignition and fire. Some of the items listed under fire were due to fire of vegetation in the surrounding areas. On the other hand, several of the other reactions listed in Table 3 also had “followed by fire” as part of the listing. The real take-away from Tables 2 and 3 is that fire was the prevalent initial reaction, and that if the fire could have been prevented then the ensuing reactions, often explosions and detonations, could have been prevented as well.

Another caveat is that many of the accidents occurred near “ammo dumps” where the conditions of storage were primitive at best. One could argue that the number of accidents that occurred at locations where conditions were tightly controlled are significantly less than the number of accidents where controls were lax. For example, several of the fires were attributed to smoking of cigarettes and careless discarding of cigarette butts. Many of the accidents with high rates of fatalities were associated with ammo dumps with primitive conditions, with some of these ammo dumps in relatively close proximity to areas of high population density.

Reference 7 also presents tables of accidents that occurred during storage and transportation. In the area of storage, the table lists 59 accidents that occurred under a category labeled as general, 18 in the category of lightning related, and 9 in the vegetation fire category. It also gives brief descriptions of the accidents that occurred at Lake

Denmark, New Jersey, on 10 July 1926; Batangas, Philippines, on 13 February 1947; and Radford, Virginia, on 26 April 1960.

We start with a description of the sinking of the USS *Maine*, because it was the first in a series of accidents involving storage of gunpowder in battleships around the turn of the century. Some of the accidents involved the new at that time smokeless powders. The auto-ignition of these powders would also occur in future accidents not only on board ship but also in storage magazines on land.

USS *MAINE*, HAVANA HARBOR, CUBA, 15 FEBRUARY 1898

The experimental second class battleship USS *Maine*, of about 6,000 tons, is shown in Figure 1. She was commissioned 17 September 1895.

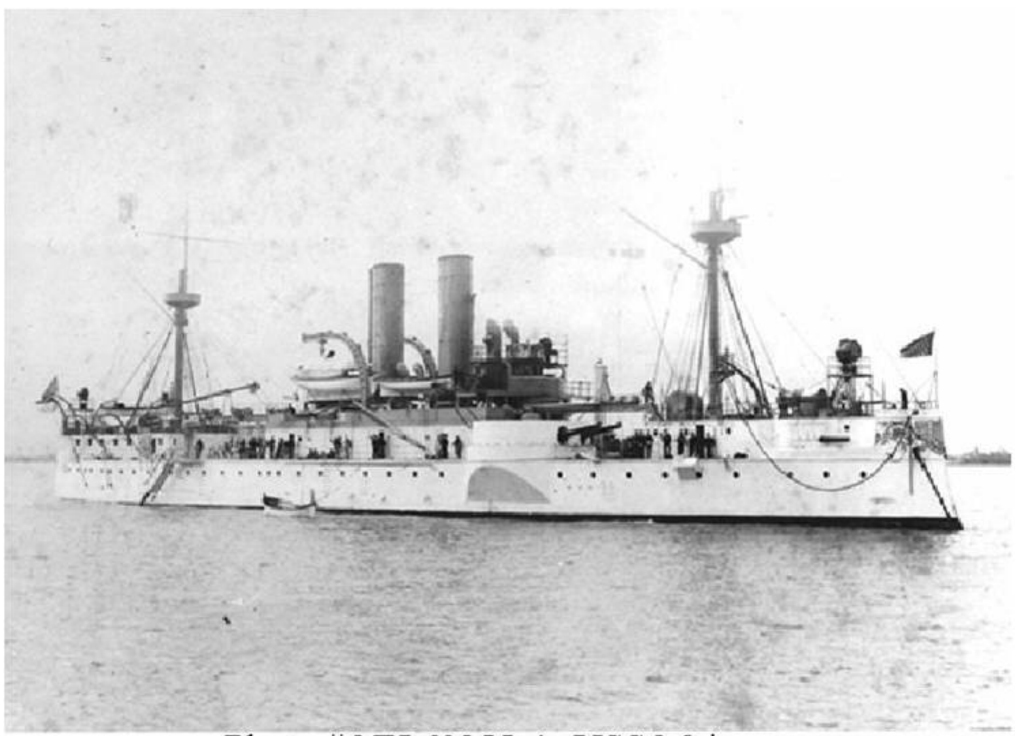


Photo # NH 60255-A USS Maine

FIGURE 1. USS *Maine*.

At 9:40 p.m. on 15 February 1898, a terrible explosion shattered the stillness in Havana Harbor. While the incident is often remembered as a catalyst in the start of the Spanish-American War, subsequent investigations revealed that more than 5 tons of powder charges for the vessel's 6- and 10-inch guns caught fire. The subsequent explosion obliterated the forward third of the ship. Fatalities numbered 266 men.

How the propellants caught fire is still unknown, although there is much conjecture. The original investigations suggested that the explosions were caused by the *Maine* striking a mine in the harbor. However, technical experts at the time disagreed with this finding. The technical experts believed that the explosions were due to fires, and that the fires were due to coal in bunkers adjacent to the magazines spontaneously igniting and then setting off the gunpowder. Other incidents occurred where coal in bunkers aboard ship spontaneously ignited. In 1976, Admiral Hyman Rickover became interested in the subject and called upon two experts. The conclusion was that damage to the *Maine* was inconsistent with the external explosion of a mine. The experts speculated that the most likely cause was spontaneous combustion of coal in the bunker that then spread to the magazine.

While accounts in following sections describe auto-ignition of nitrocellulose powder in the magazines of battleships, it appears that the *Maine* did not have nitrocellulose-based gunpowder, but rather had the old brown and black powders that were not as much prone to auto-ignition. While the actual cause of the fires in the gunpowder is unknown, this material is presented on the *Maine* to serve as a contrast to the battleship disasters occurring only a few years later that were attributed to auto-ignition of nitrocellulose gun propellant. By the turn of the century, nitrocellulose propellant had replaced brown and black powder because of increased performance, its smokeless products of combustion, and non-hygroscopicity. For example, the United States Navy manufactured single-based (nitrocellulose) tubular powder for naval artillery at Indian Head, Maryland, beginning in 1900. These naval disasters preceded a series of accidents involving gunpowders stored in magazines on land in the 1984 to 2007 time frame that are described later in this volume.

The material above was largely based on the Naval History and Heritage Command document, "The Destruction of USS *Maine*." http://www.history.navy.mil/faqs/faq71-1.htm

Several of the accidents described below were caused by stabilizer depletion and auto-ignition. Propellants containing nitrate esters, such as nitrocellulose and nitroglycerine, are particularly prone to auto-ignition. Gun propellants are often referred to as single-based powder, double-based powder, and triple-based powder. Single-based powders are based on nitrocellulose alone (typically an ether-alcohol colloid of nitrocellulose). Double-based powders have both nitrocellulose and nitroglycerine in the formulation. Triple-based propellants have nitrocellulose, nitroglycerine, and nitroguanidine. When nitrate esters decompose, they give off oxides of nitrogen, potentially forming nitric acid, which further catalyzes the propellant decomposition. This process can boot-strap and cause auto-ignition of the propellant.

Stabilizers such as diphenylamine for single-base powders and ethyl centralite and 2-nitrodiphenylamine (2NDPA) for double- and triple-base powders are added to the propellants, because the stabilizers react with the nitrogen oxide (NO_x) and prevent them from catalyzing the decomposition. But, as the stabilizers react with the NO_x, the number of reactive sites on the stabilizer molecule decreases, and eventually the stabilizer becomes depleted. As the stabilizer becomes depleted, the decomposition with its associated exothermicity becomes more and more prevalent. If the heat release from the decomposition exceeds the heat loss rate, the propellant auto-ignites. Initially, the stabilizer is added at the 1 to 2% level. When the stabilizer has been depleted to below the 0.2% level, the propellant is usually removed from storage and should be disposed of. Several of the accidents described below were caused by propellants having less than 0.2%. In fact, several of the accidents were caused by propellants awaiting demilitarization, because they had low stabilizer content.

These accidents, due to auto-ignition, have occurred at storage sites on land and aboard ships as indicated in the following accidents. It is interesting that many of the early accidents were onboard ship. As mentioned above, smokeless powder was a great advantage in fighting naval battles, but as seen in the accidents below it also had its disadvantages too.

For a short history of nitrocellulose-based propellants and the need for propellant stabilizers, please refer to Reference 8.

JAPANESE BATTLESHIP, *MIKASA*, SASEBO HARBOR, JAPAN, SEPTEMBER 1905

The Japanese battleship *Mikasa* is shown in Figure 2. She served as the flagship of Admiral Togo Heihachiro during the Battle of the Yellow Sea on 10 August 1904, and the Battle of Tsushima on 27 May 1905 during the Russo-Japanese war. Currently, she is preserved as a museum at Yokosuka.

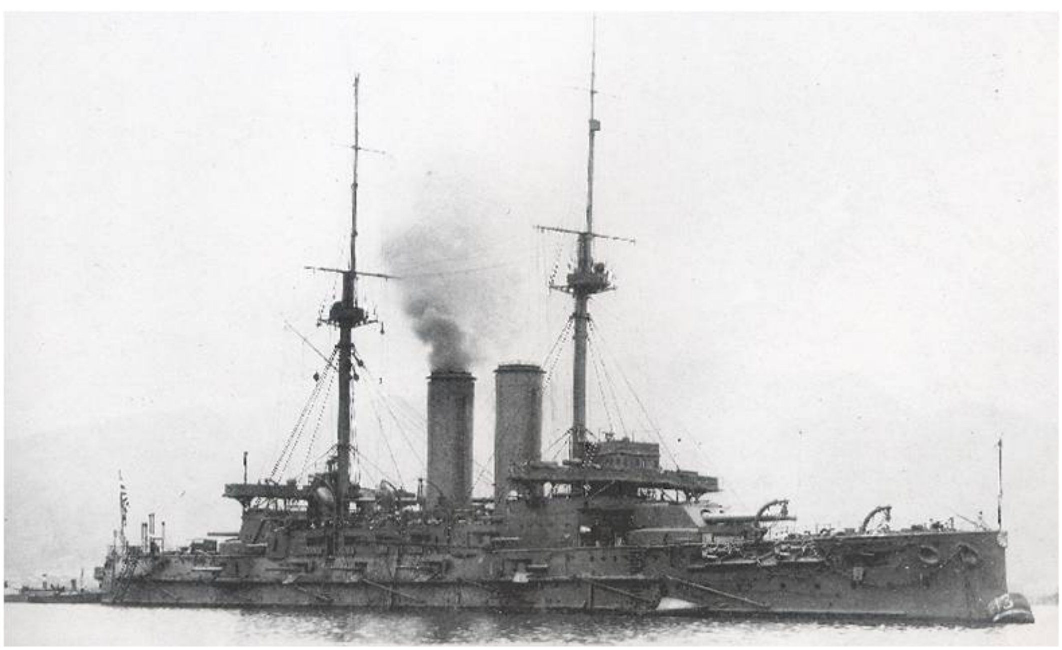


FIGURE 2. Japanese Battleship *Mikasa*, 1905.

On 11 September 1905, while in Sasebo harbor, the *Mikasa* experienced a fire and subsequent explosion in a magazine. The explosion took out a section of the hull and the ship sank. There were 339 fatalities and an additional 300 injuries. At this time many of the battleships of the world used nitrocellulose-based gun propellants that were subject to auto-ignition as the nitrocellulose decomposed.

http://en.wikipedia.org/wiki/Japanese_battleship_Mikasa

FRENCH BATTLESHIP *IENA*, TOULON DRY-DOCK 2, FRANCE, MARCH 1907

Figure 3 shows the *Iena* in March 1907. On 4 March 1907, *Iena* was moved into dry-dock No. 2 at Toulon. Eight days later, fire, beginning at 1:35 a.m. and continuing until 2:45 a.m., occurred in the No. 5 magazine. The multiple explosions gutted the superstructure between the main mast and the rear funnel and collapsed the superstructure surrounding the main mast. The ship's side was ripped open down to the lower edge of the armor belt, and all of the machinery in this area was destroyed.

FIGURE 3. French Battleship *Iena*, March 1904.

The origin of the first explosion was traced to well-aged Powder B, a nitrocellulose-based gun propellant that became unstable and auto-ignited. It was estimated that 80% of the contents of the ship's magazines were Powder B at the time of the accident. The explosion resulted in 120 fatalities, including two civilians who were killed by fragments in the suburb of Pont-Las.

http://en.wikipedia.org/wiki/French_battleship_I%C3%A9na_(1898)

LAKE DENMARK NAVAL AMMUNITION STORAGE DEPOT, NEW JERSEY, U.S., JULY 1910

On 10 July 1910, a lightning strike hit one of the storage units containing TNT at the Navy's storage depot at Lake Denmark and started a fire. Reference 9 states: "It could have been contained but the officer in charge had been assured that the protective system in place would prevent damage from any lightning strike. The result was that the little fire mushroomed quickly into a catastrophe. The lightning-arresting system, which had been installed for just such an event, for some reason failed." After the firefighters arrived and started spraying the building with water, three detonations occurred within minutes of one another. The three detonations (temporary magazines 8 and 9 and shell house 22) were triggered within 30 minutes of the lightning strike. The first explosion occurred at 5:20 p.m. The damages included the following:

- 3.2 million pounds of explosives burned or detonated with approximately 2.4 million pounds of explosives detonated.
- 21 people killed. Reference 10 lists 44 fatalities. Reference 11 lists 21 fatalities. Reference 9 lists 30 fatalities.
- 51 people injured (Reference 9 lists 200 injuries).
- All 500 buildings damaged (Reference 11). Reference 9 lists 164 buildings destroyed at the arsenal.
- $84 million in damages (1926 dollars) (Reference 11). Reference 9 lists over $150 million in damages.
- Several craters approximately 35 feet deep (Reference 11). Munitions expelled up to one mile around ground zero (Reference 11).

As an outgrowth of the Lake Denmark event and the public uproar, the Seventieth Congress directed the establishment of a board of U.S. Officers that would provide oversight for explosives safety (Reference 12) that, in turn, became the Armed Forces Explosives Safety Board (the predecessor of the Department of Defense Explosives Safety Board [DDESB]).

FRENCH BATTLESHIP *LIBERTE*, TOULON HARBOR, FRANCE, SEPTEMBER 1911

Figure 4 shows the *Liberte* on a visit to the U.S. shortly after her commissioning in 1908.

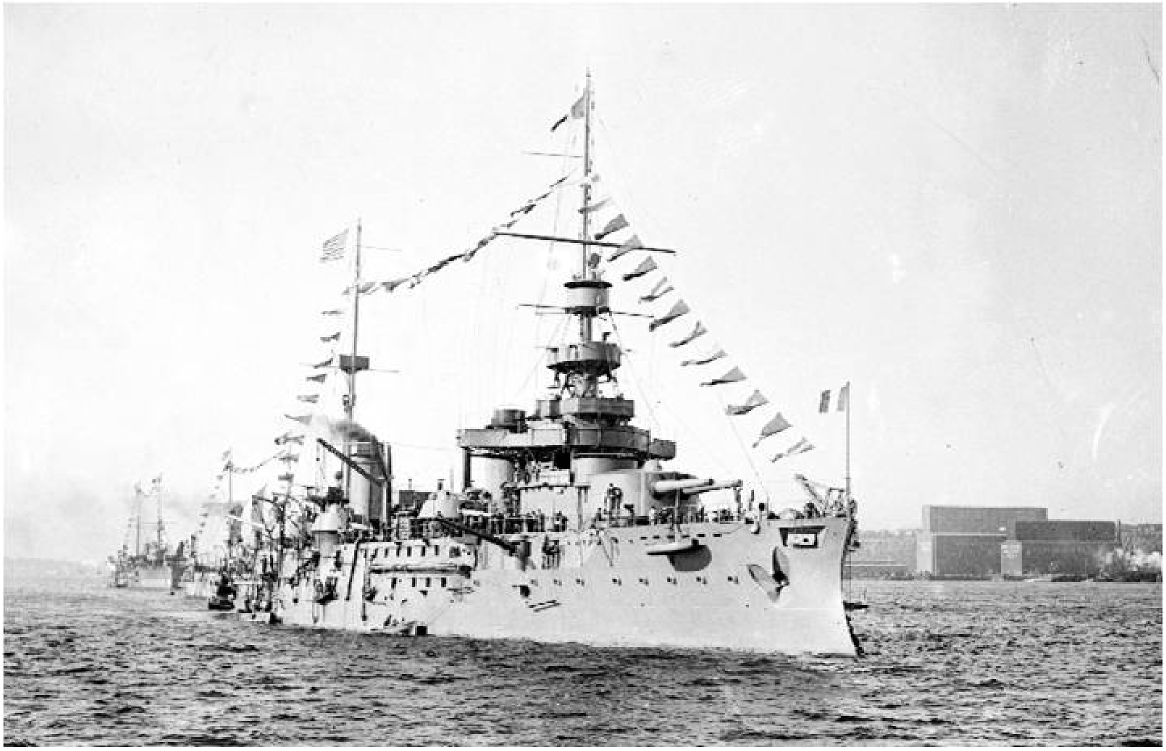


FIGURE 4. French Battleship *Liberte* in 1908.

On 25 September 1911 while in the Toulon harbor, the magazines of the *Liberte* exploded. The chain reaction explosions of the magazine followed frantic firefighting after auto-ignition of the nitrocellulose gun propellant in a forward magazine. The violence of the explosion amidships tossed the upper decks back, curled and flattened like a banana peel as indicated in Figure 5.

Sections of the *Liberte* were hurled outward with great force. Figure 6 shows a large piece of the *Liberte* embedded in the *Republique*, which was anchored nearby.

As a result of the explosions, the *Liberte* suffered 200 fatalities, and an additional 100 fatalities of French sailors occurred on neighboring ships.

http://www.cityofart.net/bship/liberte_disaster.html

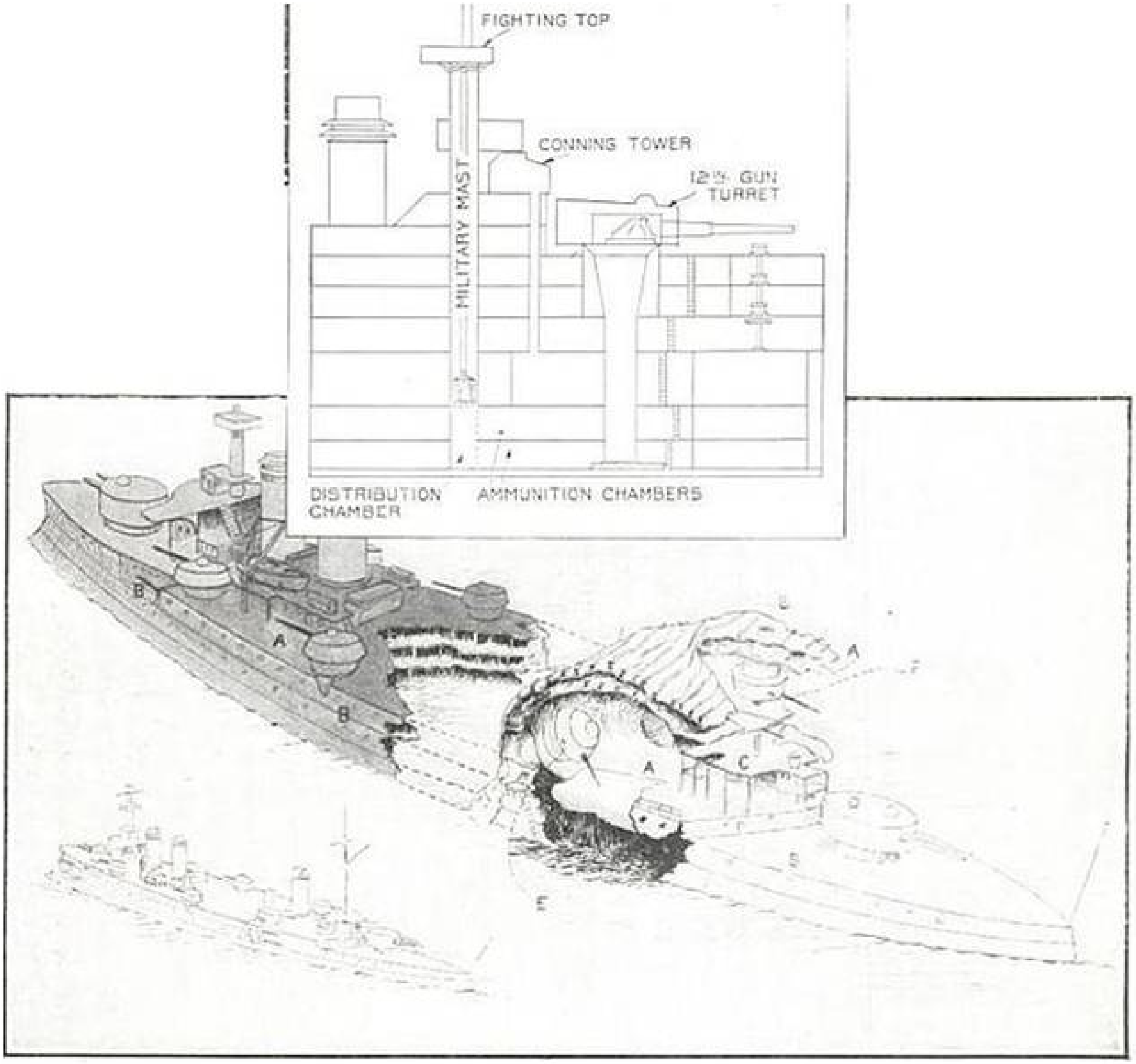


FIGURE 5. Result of the Explosion Aboard the *Liberte*, 25 September 1911.

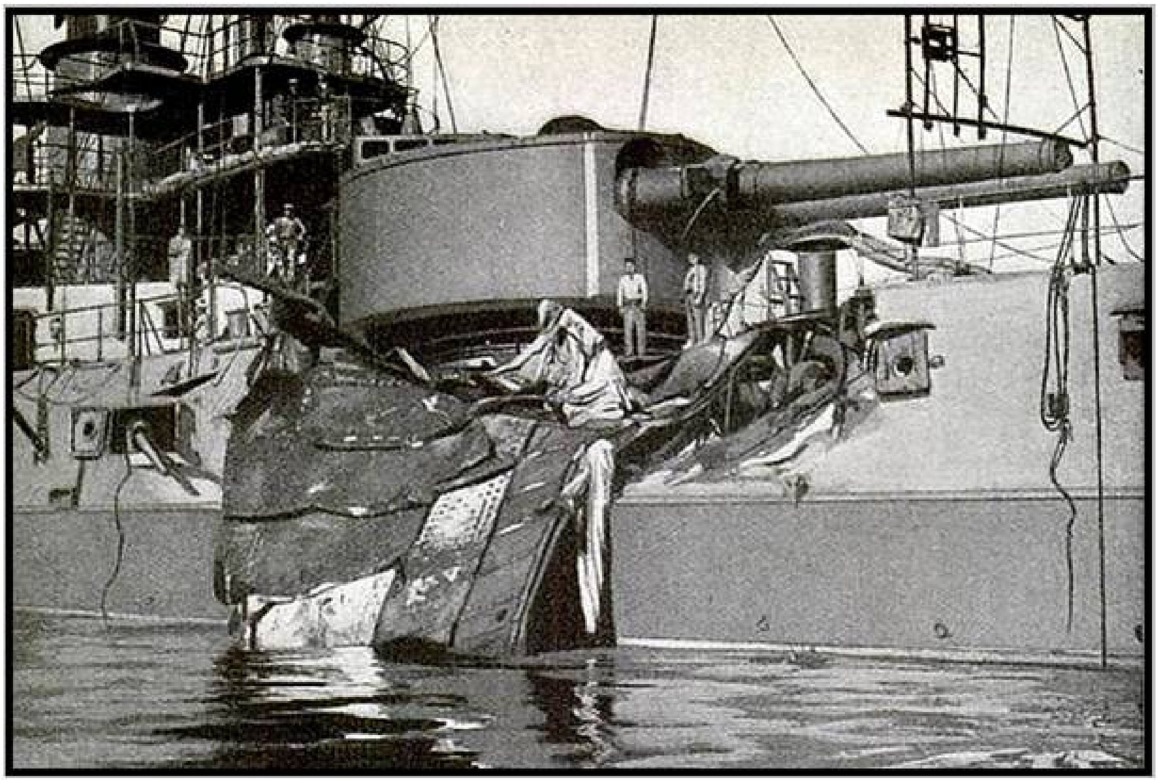


FIGURE 6. Sections of the *Liberte's* Armor Plate Embedded in the *Republique*, Which was Anchored Nearby.

RUSSIAN BATTLESHIP *IMPERATRITSA MARIYA*, AT ANCHOR IN SEVASTOPOL, OCTOBER 1916

Figure 7 shows the *Imperatritsa Mariya* at anchor in Sevastopol.

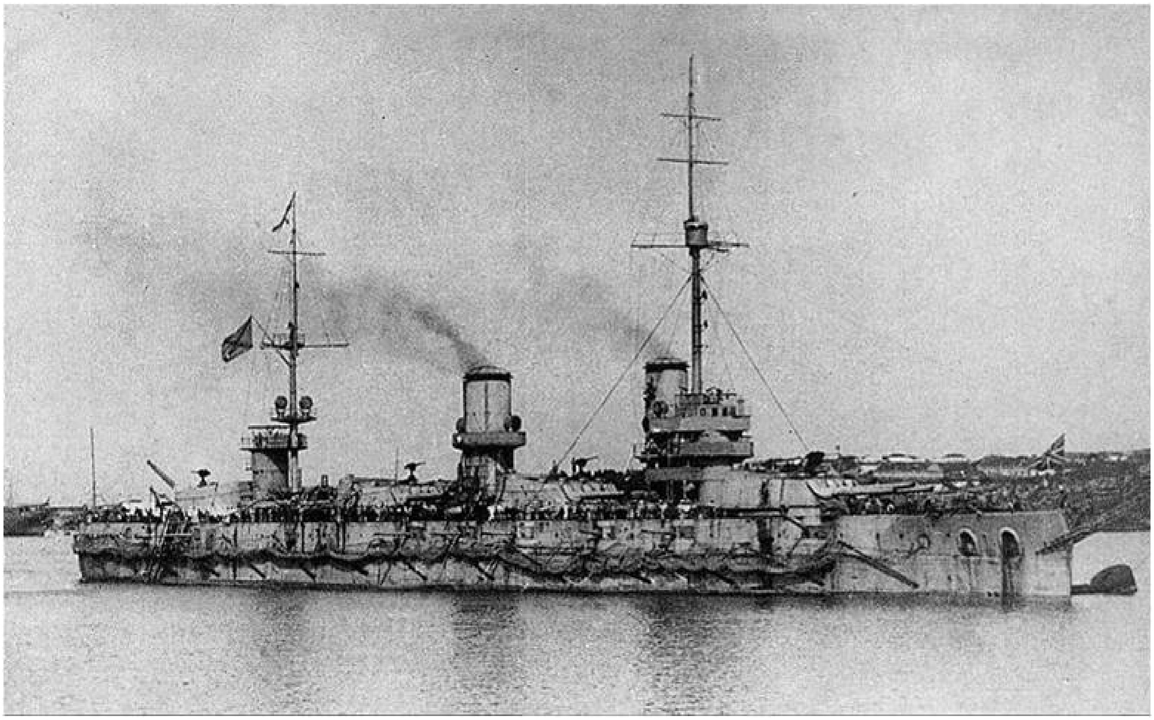


FIGURE 7. *Imperatritsa Mariya* at Anchor in Sevastopol.

The Russian battleship *Imperatritsa Mariya* sunk at anchor in Sevastopol due to a magazine explosion on 20 October 1916. The cause of the explosion was a fire in the forward powder magazine. The subsequent investigation determined that the fire was due to auto-ignition of the nitrocellulose gun propellant. When the ship capsized, 228 sailors went with her.

The above series of accidents involved auto-ignition of nitrocellulose gunpowder, resulting in fires in high confinement environments allowing significant pressurization leading to explosions. [Magazines below the waterline with associated confinement of the waterline armor belt (see, for example, the armor plate from the *Liberte* embedded in the adjacent *Republique* shown in Figure 6). The waterline armor belt of the *Republique* held up, but the unprotected upper deck crumpled.]

http://en.wikipedia.org/wiki/Russian_battleship_Imperatritsa_Mariya

UK BATTLESHIP *HMS VANGUARD*, SCAPA FLOW, NORTH SCOTLAND, 9 JULY 1917

Just before midnight on 9 July 1917, the *HMS Vanguard*, shown in Figure 8, suffered an explosion and sank almost immediately, resulting in 804 fatalities (although research in 2002 placed the loss at 843). There were only two survivors.

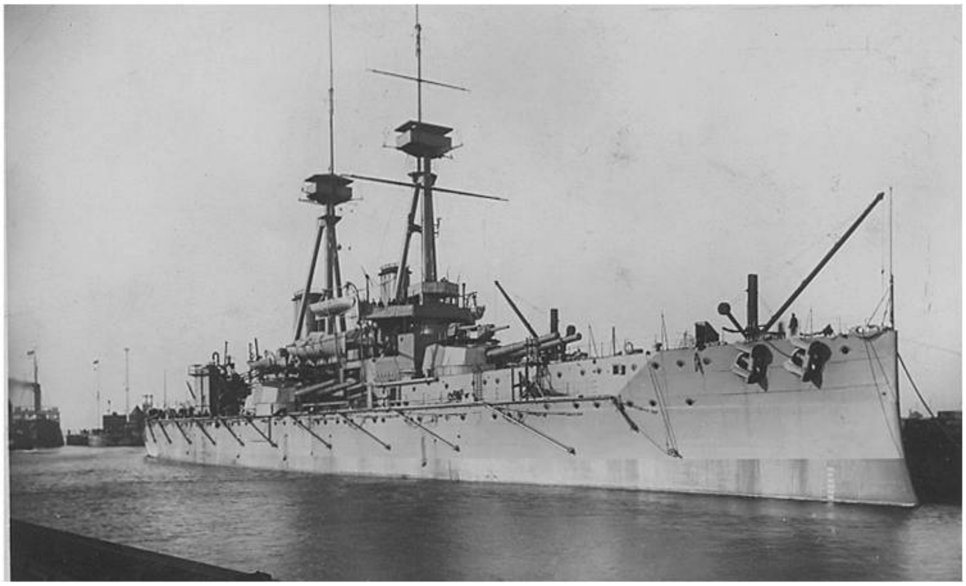


FIGURE 8. *HMS Vanguard* Sank Almost Instantly
After an Explosion on 9 July 1917.

The explosion occurred in one of two magazines that served the “P” and “Q” gun turrets that were located mid-ship. Although no formal cause for the cordite explosion was ever found by the Court of Inquiry, the most likely explanation given was that a fire started in a 4-inch magazine, probably due to fire in a coal bunker that smoldered long enough to heat the cordite causing an explosion, that in turn spread to one or the other main magazines which then exploded. It was found that some of the cordite on board had been temporally off-loaded in December 1916 and was cataloged at that time, and was past its stated safe life. The explosions resulted in large amounts of debris that landed on nearby ships. A 5- by 6-foot section of plating was found on the *HMS Bellerophon* [separation between *Vanguard* and *Bellerophon* not given].

http://www.orcadian.co.uk/features/articles/vanguard.htm [no longer available]
http://www.absoluteastronomy.com/topics/HMS_Vanguard_(1909)
http://www.gwpda.org/naval/vanguard.htm
http://en.wikipedia.org/wiki/HMS_Vanguard_(1909)

AETNA CHEMICAL COMPANY, PITTSBURGH, PENNSYLVANIA, U.S., MAY 1918

An accident occurred on 18 May 1918 in a suburb of Pittsburgh in a plant that manufactured TNT. The accident was triggered by an error in the part of the factory where various chemical components of TNT were being mixed. Low popping sounds were followed seconds later by explosions. “Fires and explosions continued like a series of gigantic firecrackers until, within a few minutes, the whole neighborhood was wrecked” (Reference 9). There were 241 fatalities and approximately 400 injured.

CHINESE TROOP SHIP *KUANG YUANG*, ANCHORED AT KIUKIANG, YANGTZE RIVER, CHINA, 16 OCTOBER 1926

On 16 October 1926, fire broke out on the Chinese troop ship *Kuang Yuang* that was anchored at Kiukiang on the Yangtze River, China. The flames triggered an explosion of ammunition and munitions that killed an estimated 1,200 soldiers, some by drowning.

http://recollectionbooks.com/bleed/1016.htm
http://en.wikipedia.org/wiki/List_of_accidents_and_disasters_by_death_toll

HERCULES POWDER PLANT, KENVIL, NEW JERSEY, U.S., 12 SEPTEMBER 1940

At 1:30 p.m. on 12 September 1940, over 297,000 pounds of gunpowder blew up in a series of explosions and fires, leveling over 20 buildings. The explosions were felt as far away as Poughkeepsie, NY, and recorded on the seismograph at Fordham University in New York City. There were 51 fatalities and over 200 injured and burned. Cause of the explosions was never determined.

http://www.roxburynewjersey.com/hercules.htm
http://www.safetyxchange.or/uncategorized/september-12-1940-hercules-munitions-plant-.
http://trove.nla.gov.au/ndp/del/printArticleJpg/25823888/3?print=y

JAPANESE BATTLESHIP *MUTSU*, HASHIRAJIMA ANCHORAGE, JAPAN, 8 JUNE 1943

Around noontime on 8 June 1943, while moored at the Battleship Division 2 flagship buoy number 2 in the Hashirajima anchorage, Japan, the Japanese Nagato class battleship *Mutsu* (Figures 9 and 10), was rocked by a violent explosion that blew the ship in two. The 535-foot forward section rolled over to starboard and sank immediately. The 147-foot aft section upended and remained floating with the stern pointing skyward, sinking 14 hours later. There were 1,121 fatalities, while 353 crewmembers survived. Some witnesses claimed to see smoke near the number 3 gun turret just before the explosion. Initially it was speculated that special incendiary shells that were on board caused the fires, but subsequent experiments were unable to cause these shells to explode. The final report indicated the cause to be “human interference.” It must be remembered that this was during the war at a time when Japan had experienced some setbacks and were worried about damage to morale.

http://www.bobhenneman.info/mutsuwrk.htm
http://en.wikipedia.org/wiki/Japanese_battleship_Mutsu

FIGURE 9. *Mutsu* at Anchor.

FIGURE 10. *Mutsu* at Anchor Before the War.

PORT CHICAGO, CALIFORNIA, U.S., JULY 1944

The Liberty ship *SS E.A. Bryan* docked at the single pier at the Port Chicago Naval Magazine on 13 July 1944 and commenced loading munitions to be shipped across the Pacific Ocean. By the evening of 17 July, the ship was approximately 40% full (approximately 4,606 tons of munitions). At 10:00 p.m., 98 men were loading 1,000-pound bombs into hold 3, 40-millimeter (mm) shells into hold 5, and fragmentation cluster bombs into hold 4. Live incendiary bombs were being loaded into hold 1. Mk 47 airborne anti-submarine depth charges armed with 252 pounds of torpex (more sensitive than TNT) were being loaded into hold 2. On the pier were 16 railcars containing about 430 tons of explosives. In all, the munitions on the pier and in the ship contained approximately the equivalent of 2,000 tons of TNT.

At the same time, 102 men were busy rigging the Victory ship *SS Quinault Victory* in preparation for loading of explosives that was to commence at midnight.

At 10:18 p.m., a witness reported hearing a noise described as “a metallic sound and rendering timbers, such as made by a falling boom.” Immediately afterward, an explosion occurred on the pier and a fire started. Five to seven seconds later, a more powerful explosion took place as the majority of ordnance within and near the *SS E.A. Bryan* detonated in a huge fireball some 3 miles (4.8 kilometers) in diameter. Chunks of glowing hot metal and burning ordnance were flung over 12,000 feet (3,660 meters) into the air. The *E.A. Bryan* was completely destroyed and the *Quinault* was blown out of the water, torn into sections and thrown in several directions: the stern landed upside down in the water 500 feet (150 meters) away. The U.S. Coast Guard fire boat CG-60014-F was thrown 600 feet (180 meters) upriver, where it sank. The pier, along with its boxcars, locomotive, rails, cargo, and men, was blasted to pieces. Nearby boxcars, waiting within their revetments to be unloaded at midnight, were bent inward and crumpled by the force of the shock. The port’s barracks and other buildings and much of the surrounding town were severely damaged. Shattering glass and a rain of jagged metal and undetonated munitions caused many additional injuries among both military and civilian populations, although no one outside the immediate pier area was killed. Nearly $9.9 million worth of damage ($124 million in current [2010] value) was caused to U.S. government property. Seismographs at the University of California, Berkeley, sensed the two shock waves traveling through the ground, determining the second, larger event to be equivalent to an earthquake measuring 3.4 on the Richter scale.

All 320 of the men on duty at the pier died instantly, and 390 civilians and military personnel were injured, many seriously.

The report from the Naval Board of Inquiry stated that the cause of explosion could not be determined.

While mass detonations occurred that resulted in tremendous loss of lives and property, it was preceded by lesser explosion and fire. The extent of damage is shown in

Figures 11 through 13. [Note: These photographs have been released and are available on several websites. e.g. http://www.history.navy.mil/photos/pl-usa/pl-ca/pt-chgo.htm]

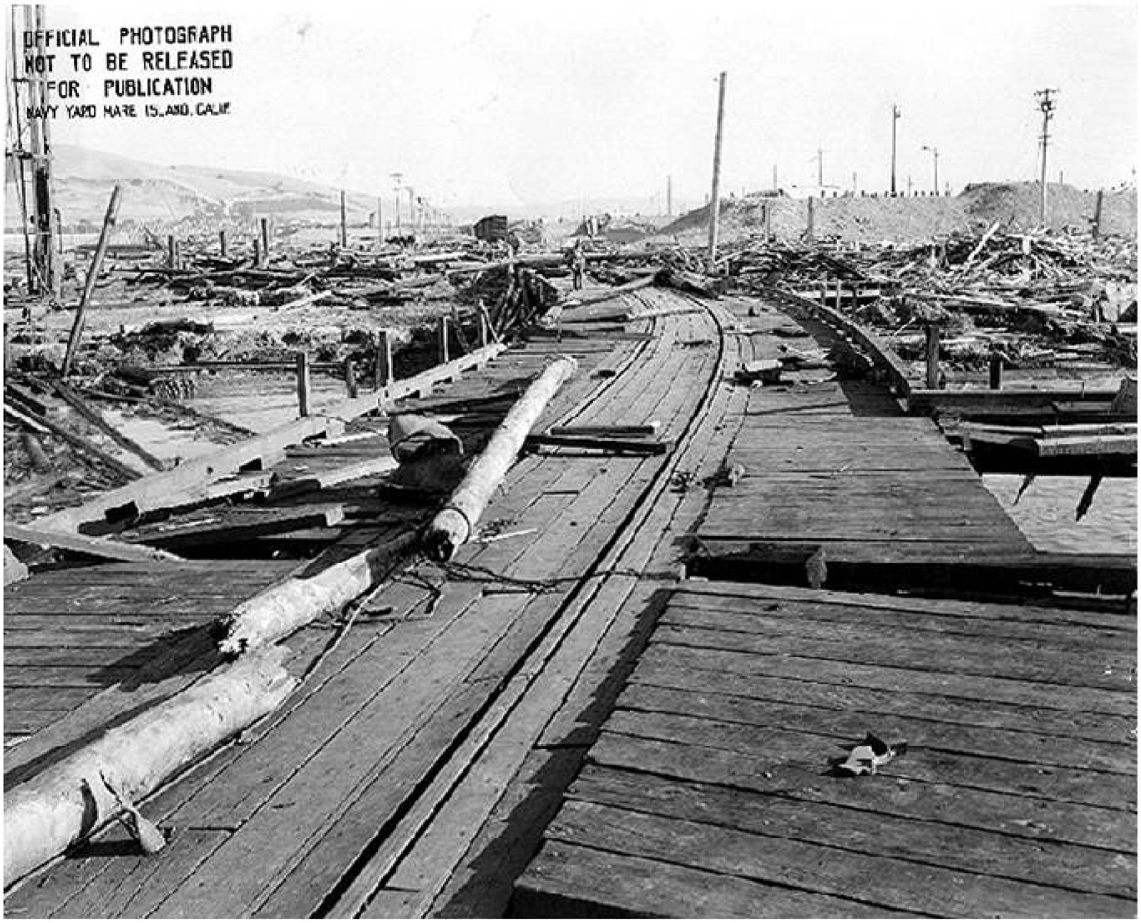
s 

FIGURE 11. Damage at Port Chicago, CA.
View looking south from ship pier.

Photo # NH 96822 Damage at Port Chicago, Ca. View looking north from BM138.

FIGURE 12. Damage to Railcars in Revetments That Were Waiting to be Unloaded.

FIGURE 13. Damage at Port Chicago, CA.
View looking north toward pier.

Additional pictures of the pier before and after and the wreckage of the *Quinault* can be found at the following web addresses:

http://www.usmm.org/portchicago.html
http://en.wikipedia.org/wiki/Port_Chicago_disaster
http://www.history.navy.mil/faqs/faq80-1.htm

USS *MOUNT HOOD*, SEEADLER HARBOR, ADMIRALTY ISLANDS, 10 NOVEMBER 1944

The ammunition ship USS *Mount Hood*, anchored in about 35 feet of water at Seeadler Harbor with about 3,800 tons of ordnance on board, exploded in the morning of 10 November 1944. Eighteen members of her crew had left the ship and were on shore. While walking on the beach, the crew saw a flash from the harbor followed by two quick explosions. The initial explosion caused flame and smoke to shoot up midship to more than mast high. Within seconds, the bulk of her cargo detonated with smoke rising to about 7,000 feet. *Mount Hood's* previous position was revealed by a trench in the sea floor 1,000 feet long, 200 feet wide, and 30 to 40 feet deep. The largest piece of debris was found in the trench and measured no bigger than 16 by 10 feet. Other fragments struck other ships in the harbor. All 350 men aboard the ship perished without leaving any human remains. In addition, 82 of the crew of the repair ship *Mindanao,* which had been moored alongside *Mount Hood,* also died. A total of 371 sailors on board the other ships in the harbor were injured. The cause of the explosion and detonation was not determined.

http://en.wikipedia.org/wiki/USS_Mount_Hood_(AE-11)

BATANGAS, PHILIPPINES, 13 FEBRUARY 1947

The Batangas accident occurred on 13 February 1947 and was initiated by a grass fire in the storage area. As crews approached the fire the contents of the compound began to detonate. Two hours after the first detonation, fire was noticed in another area. The fire caused rocket motors to detonate. Then two buildings containing photoflash bombs detonated within the next 3 hours (Reference 7).

RADFORD, VIRGINIA, U.S., 26 APRIL 1960

On 26 April 1960, an accident occurred at Radford, Virginia. It was caused by lightning that, in turn, caused rocket motor fires. Three ruptures caused by deflagrations were heard 25 minutes after the smoke was initially noted (Reference 7).

ALLEGANY BALLISTICS LABORATORY (ABL), ROCKET CENTER, WEST VIRGINIA, U.S., 22 MAY 1961

An explosion occurred at 8:30 a.m. on 22 May 1961 at ABL and resulted in nine fatalities, 26 injured, three buildings destroyed, and one building damaged.

http://www3.gendisasters.com/node/13003
Cumberland Evening Times, 24 May 1961

BIEN HOA AIR FORCE BASE (AFB), SOUTH VIETNAM, MAY 1965

On Sunday morning, 16 May 1965, Bien Hoa AFB, South Vietnam, was rocked by explosions coming from the B-57 parking ramp area. A fuse functioned inadvertently and detonated a bomb. The ensuing fire caused the bomb laden aircraft that were parked almost wing-tip to wing-tip to explode like a string of firecrackers. Five 50,000-gallon bladders of JP-4 fuel provided additional fire. The video referenced at the end of this section shows movement of the many A-1E Skyraiders with their associated ordnance being moved out of harm's way. When the fire and explosions finally ceased, 27 men had been killed and over 100 injured. Aircraft destroyed included 10 B-57s, one Navy F-8 Crusader, and 15 A-1Es. Figures 14 and 15 present pictures of the conflagration.

The Conflagration/Fire Accident Investigation Board concluded that the accidental explosion of a bomb on a parked B-57 triggered a series of blasts. The aircraft and ammunition were stored too close together, which allowed the fires and explosions to propagate. Once again, fire was a major contributor in allowing spread of reactions and resulted in explosions.

http://en.wikipedia.org/wiki/Bien_Hoa_Air_Base
http://wapedia.mobi/en/Bien_Hoa_AB

Video coverage can be found at the following web address:
http://www.youtube.com/watch?v=teHsjwXTrcU

FIGURE 14. Conflagration at Bien Hoa AFB, South Vietnam,
16 May 1965, as Seen From the Ground.

FIGURE 15. Conflagration at Bien Hoa AFB, South Vietnam,
16 May 1965, as Seen From the Air.

[This photograph has been marked as being in the public domain.]

ABL, ROCKET CENTER, WEST VIRGINIA, U.S., 11 AUGUST 1981

Two workers perished in a blast that occurred late on 11 August 1981 at ABL. A large crater was left where the wooden laboratory had stood. Debris was scattered over an area of 1,000 feet in radius. The blast was felt 7 miles away.

http://www.nytimes.com/1981/08/12/us/around-the-nation-two-missing-after-blast-of-rocket-propellant.html

OKOLNAYA, AMMUNITION STORAGE BASE, SEVEROMORSK, RUSSIA NORTHERN FLEET, 17 MAY 1984

Toward the end of the work day on 17 May 1984, a sailor's cigarette butt started fires that destroyed $^{1}/_{3}$ to $^{1}/_{2}$ of the Russian Northern Fleet's supply of surface-to-air missiles, other missiles, munitions, torpedoes, and mines. Missiles flew above the bay in many and varied directions. There were two submarines with strategic missiles and 7th squadron ships moored at the adjacent Kola Bay facility. Judging from the size of the blast and the mushroom cloud rising from the facility, it was first thought that a nuclear weapon might be involved. Fortunately, the explosions did not include nuclear weapons. The fires and explosions lasted for 5 days. This accident occurred during the Cold War and details were, and still are, hard to get. For example, several articles mentioned casualties but do not give numbers.

http://www.ocnus.net/artman2/publish/Defence_Arms_13/Scattered-Powder-Kegs_printe.
http://rusnavy.com/news/column/prisoners.htm.
http://redbannernorthernfleet.blogspot.com/2008/05/soviet-naval-disaster-of-day.html
http://www.globalsecurity.org/military/world/russia/severomorsk.htm
http://www.time.com/time/magazine/article/0,9171,926658,00.html
http://www.fas.org/nuke/guide/russia/mf-north.htm

EXPLOSIA FACTORY, SEMTIN, CZECHOSLOVAKIA, 28 MAY 1984

On 28 May 1984, gunpowder in storage ignited when a truck scraped against a loading ramp causing sparks. The burning gun propellant exploded killing five people and injuring almost 200 people. The detonation left a large crater where the storage warehouse had been located. Nearby buildings were damaged and the blast wave broke windows up to 20 kilometers away.

http://www.firedirect.net/index.php/2011/04/plant-explosion-4-missing-7-injured/

WALDHEIDE PERSHING 2 BASE, GERMANY, 11 JANUARY 1985

An accident occurred while unloading the first stage motor of a Pershing 2 missile system at Waldheide, Germany. The motor was being removed from the shipping container on a cold, dry winter day. For some reason it was lifted and then reset and lifted again. This allowed static electricity to build up, and it ignited the propellant. The motor burned in place on the launcher/transporter. There was no explosion, nor detonation. Three soldiers were killed; two burned to death almost instantly from exposure to the missile exhaust plume and the other died en route to the hospital. Seven were injured. An exhaustive research effort ensued and it was found that some configurations of propellants having AP/hydroxyl-terminated polybutadiene (HTPB) binder/aluminum were susceptible to ignition due to ESD.

http://articles.latimes.com/print/1985-01-12/news/mn-9508_1_unarmed-missile
http://articles.sun-sentinel.com/1985-01-12/news/8501020134_1_nuclear-weapons-pershing-missile-transporter
http://www.miamisburg.org/pershing_missile_56th_field_artillery_command.htm
http://articles.latimes.com/print/1985-01-13/news/mn-8758_1_missiles

ARNOLD ENGINEERING DEVELOPMENT CENTER (AEDC), ARNOLD AFB, TENNESSEE, U.S., 23 NOVEMBER 1985

On 23 November 1985, during qualification testing of HD 1.1 large rocket motor containing 16,000 pounds of propellant at the J-5 test site, an accident occurred. The pressure inside the motor was about 600 psi just before failure occurred. It was estimated that approximately 1,100 pounds of the original 16,000 pounds of propellant remained in the motor when the failure occurred. The debris recovered included relatively large pieces of motor casing, pieces of unburned propellant, and a few very large sized pieces of the test cell, and indicated that even though the motor was HD 1.1 it did not fully detonate, if at all. The authors of Reference 13 mentioned the difference between a deflagration and detonation, as it pertained to the J-5 accident, was that a pressure pulse for a deflagration would be characterized by a lower peak pressure, and a longer duration than for a detonation. However, the impulsive load on the test cell and the structural members of the enclosure could be just as great [or greater]. It was coincidental that the authors were performing an analysis of what might happen if a large HD 1.1 motor with TNT equivalents of 20,000 and 30,000 pounds were to detonate in the J-5 test cell when the accident mentioned above actually occurred (Reference 14).

It is interesting that while the analytical study provided an outstanding prediction of the quadrants where the fragment might be found, it slightly underpredicted the distances where some of the large structural debris fragments from the accident were found.

MORTON THIOKOL, NEAR BRIGHAM CITY, UTAH, U.S., 29 DECEMBER 1987

A massive fire involving almost 100,000 pounds of propellant at 6:26 a.m. resulted in four fatalities. A fifth employee died 10 hours later from third-degree burns that covered 95% of his body. The accident occurred when the operators were pulling a 20-foot-long Teflon-coated mandrel from the center of the MX (Peacekeeper) first stage motor. The accident investigation concluded that the cause of the fire was either sparked by ESD or friction. The operation was to be performed remotely but the investigation determined that the workers had entered the facility. Two of the bodies were found inside of the building and three, including the man who survived for 10 hours, were outside. The missile propellant burns at about 5,000°F (slightly less than 2,800°C). Direct exposure to those plumes result in instant fatalities. Hours after the accident, a section of the missile motor was still burning, and pieces of debris were still smoldering. The building that was 60 feet wide, 70 feet long, and approximately 35 feet high was completely destroyed by the fire.

http://www.nytimes.com/1987/12/30/us/fire-destroys-part-of-mx-missile-plant-and-kills-4.html
http://alb.merlinone.net/mweb/wmsql.wm.request?oneimage&imageid=5443728
http://www.chron.com/CDA/archives/archive.mpl/1987_512897/five-die-in explosion-fire-thiokol-missile-sect.html

http://www.chron.com/CDA/archives/archive.mpl/1988_531307/air-force-raps-thiokol-in-probe-of-deadly-fire-at.html
http://www.newspaperarchive.com/SiteMap/FreePdfPreview.aspx?img=109405615

CENTRAL AMMUNITION DEPOT, PULGAON, INDIA, 9 MAY 1989

On 9 May 1989, a major fire destroyed ammunition worth rupees (Rs) 280 million (5.5 million United States dollars (USD)) in the 7,200-acre Central Ammunition Depot, Pulgaon. Infrastructure of Rs 3 million (59,000 USD) was also destroyed. Cause of the fire was a fire that started in uncut grass in an adjacent area.

http://undergroundmines.blogspot.com/2010/05/list-of-major-fires-explosions-in.html [no longer available]

HAWTHORNE AAP, NEVADA, U.S., AUGUST 1989

A magazine fire involving 30,715 pounds of Navy propelling charges occurred in Magazine 116-14-E at the Hawthorne AAP on 9 August 1989. The fire occurred in a Navy triple-arch magazine that was built in the 1943 to 1945 timeframe. The facility consisted of three separate earth-covered igloos that shared a common head wall and loading dock. Each igloo was concrete and arched on its long axis. It was 80 feet long x 25 feet wide and 12 feet high at the top of the arch. Each igloo was separated from the adjacent igloo by 13 feet of earth to a height of 6 feet above the floor level. It then decreased to no less than 2 feet of earth cover over the igloo roof. Each igloo had 4-foot wide double doors that opened onto a 6-foot-wide concrete loading dock. The doors were wood covered with 22-gauge steel. Each door had a 12- by 18-inch vent in the lower portion of the door. There was also a rear stack ventilator 15 inches in diameter that extended 30 inches above the level of the earth cover. The ventilator was capped with a vent cap weighing 195 pounds and made of glazed ceramic, metal, and screening. It set on top of the stack but was not fastened. Figure 16 shows the three earth-covered igloos (A, C, and E) making up the Magazine 116-14 after the accident. The fire occurred in unit E. Figure 17 shows the door to Magazine 116-14-E after the accident. There were no fatalities involved in this accident.

FIGURE 16. Magazine 116-14 With Igloos A, C, and E (Left to Right) After the Accident. Notice the burned sagebrush in front of E.

FIGURE 17. Door to Magazine 116-14-E After the Accident.

At the time of the accident, magazine 116-14-E contained 30,715 pounds of HD 1.3 energetic material in the B-5A account (most condition code H) awaiting disposition. It consisted of the following:

- 81-mm mortar increment bags, quantity 237,084 with 7,113 pounds NEW stored in wooden boxes.
- 5-inch, 54-caliber propelling charge (cased with plug), quantity 5 with 93 pounds NEW stored in metal shipping containers.
- 5-inch, 54-caliber propelling charge (cased with plugs), quantity 125 with 2,625 pounds NEW stored in metal shipping containers.
- 6-inch, 47-caliber propelling charge, quantity 4 with 136 pounds NEW stored in metal shipping containers.
- 8-inch, 55-caliber propelling charge (bagged), quantity 433 with 19,658 pounds NEW stored in metal shipping containers.
- 8-inch, 55-caliber propelling charge (bagged), quantity 15 with 681 pounds NEW stored in metal shipping containers.
- 8-inch, 55-caliber propelling charge (bagged), quantity 9 with 409 pounds NEW stored in metal shipping containers.

Most items were stored on Navy metal pallets with a few items stored on wooden pallets. There was also a small quantity of wood used for blocking and bracing.

The magazine contained 42 different lots of the propellant. Of the 42 lots, seven lots had low stabilizer levels ranging from 0.04 to 0.16%. Levels below 0.20% generally are considered unsafe. Hawthorne had requested permission from the State of Nevada to treat (dispose of) much of the material in the magazine by open burn; unfortunately, the State had denied their request.

Fire was first observed by a work crew working on an adjacent magazine dock at approximately 9:30 a.m. on 9 August 1989 when they saw smoke coming out of the vent stack. The crew said they then heard the “sound of air rushing out and the doors blew.” The doors were forced open by the pressure buildup caused by the burning propellant followed by a large jet of flame that extended 100 to 150 feet from the door. The very intense burning continued for approximately 3 minutes and then decreased significantly. During the period of decreased burning, several loud “bangs” were heard. The fire was allowed to burn itself out. The next morning, EOD personnel entered the magazine and observed that all of the propellant in the magazine had been consumed, with the exception of some cartridge cases. Unburned propellant grains and pieces of cork that were expelled through the doors were found scattered on the ground directly in front of the magazine.

The post accident investigation indicated that the reaction was a rapid deflagration but there was no detonation. The 195-pound vent cover was found 65 feet from the magazine (Figure 18).

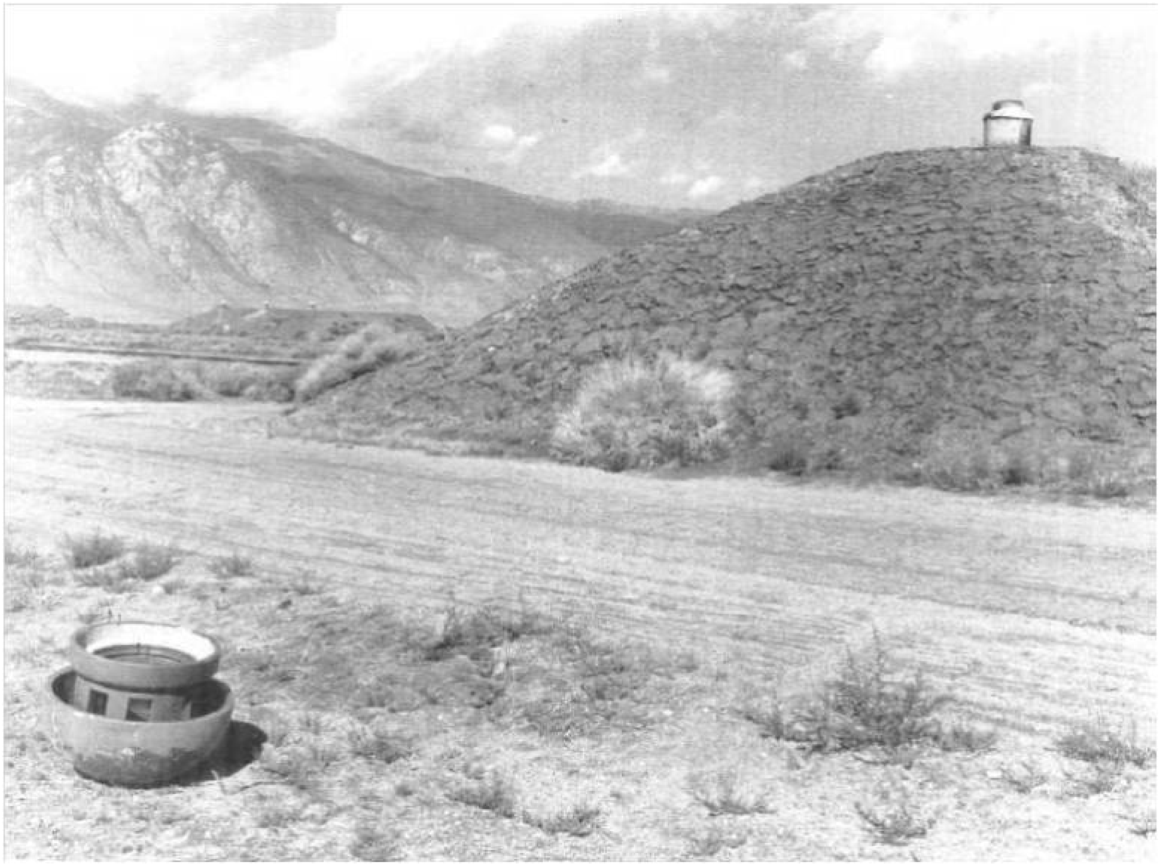


FIGURE 18. 195-Pound Vent Cap Found 65 Feet
From the Magazine After the Accident.

The most intense heat was at the front portion of the magazine as evidenced by slag that had been molten metal from the metal shipping containers (Figure 19). Since the shipping containers were aluminum, this indicates that the containers were exposed to temperatures of over 660°C (1,220°F) sufficiently long to cause melting.

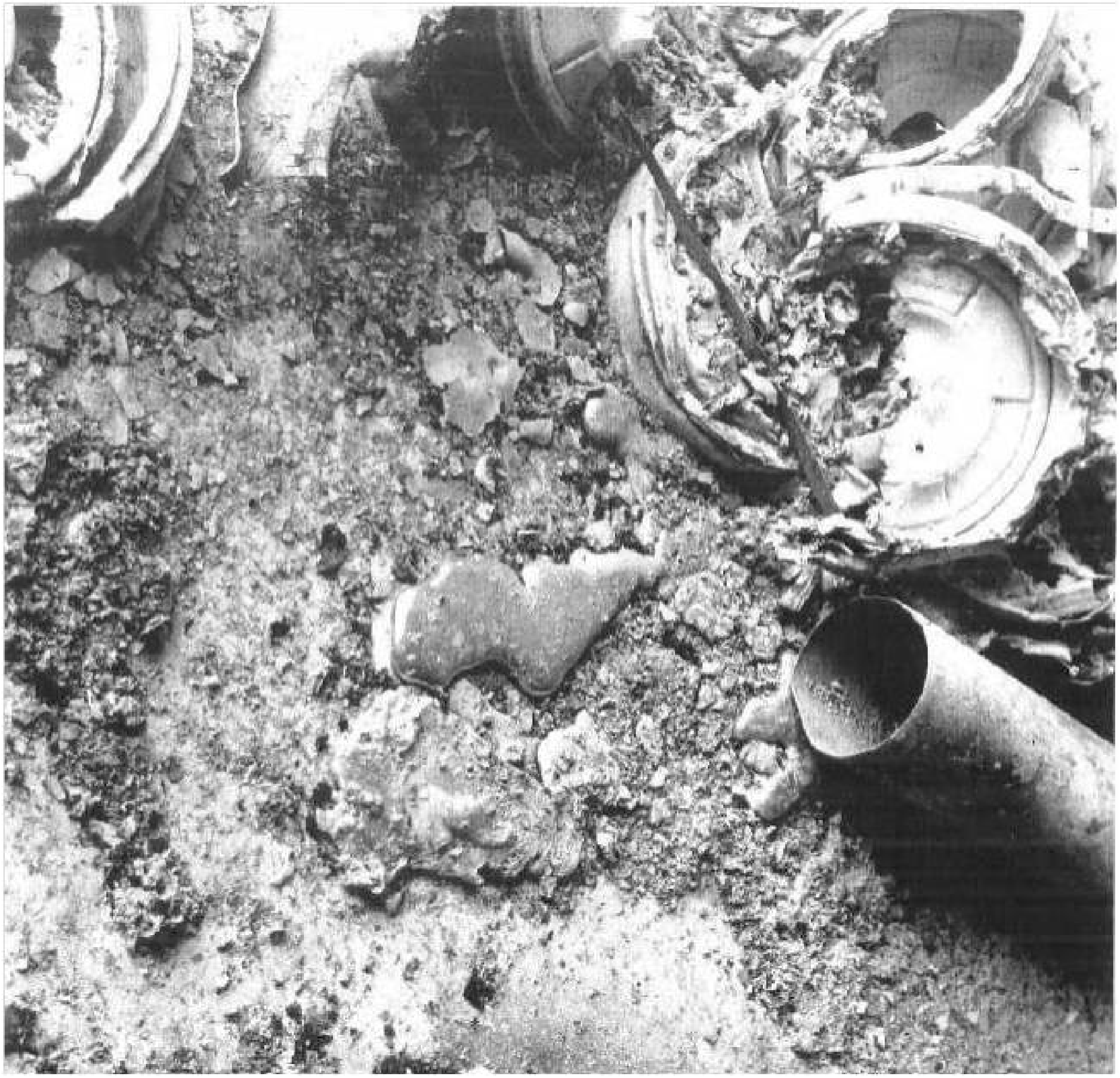


FIGURE 19. Debris on Floor of Magazine Showing
Slag That was Molten Aluminum.

There was heavy smoke residue and spalling in various locations within the magazine. There was evidence that a 6-inch, 47-caliber case propelling charge impacted the front wall near a side wall. There was an indentation approximately 1-inch deep on the inside wall, and severe spalling on the outside of the wall opposite the impact that was about 2 feet by 2 feet and several inches deep (Figure 20). The steel rebar was exposed and concrete fragments were thrown across the entire width of the loading dock.

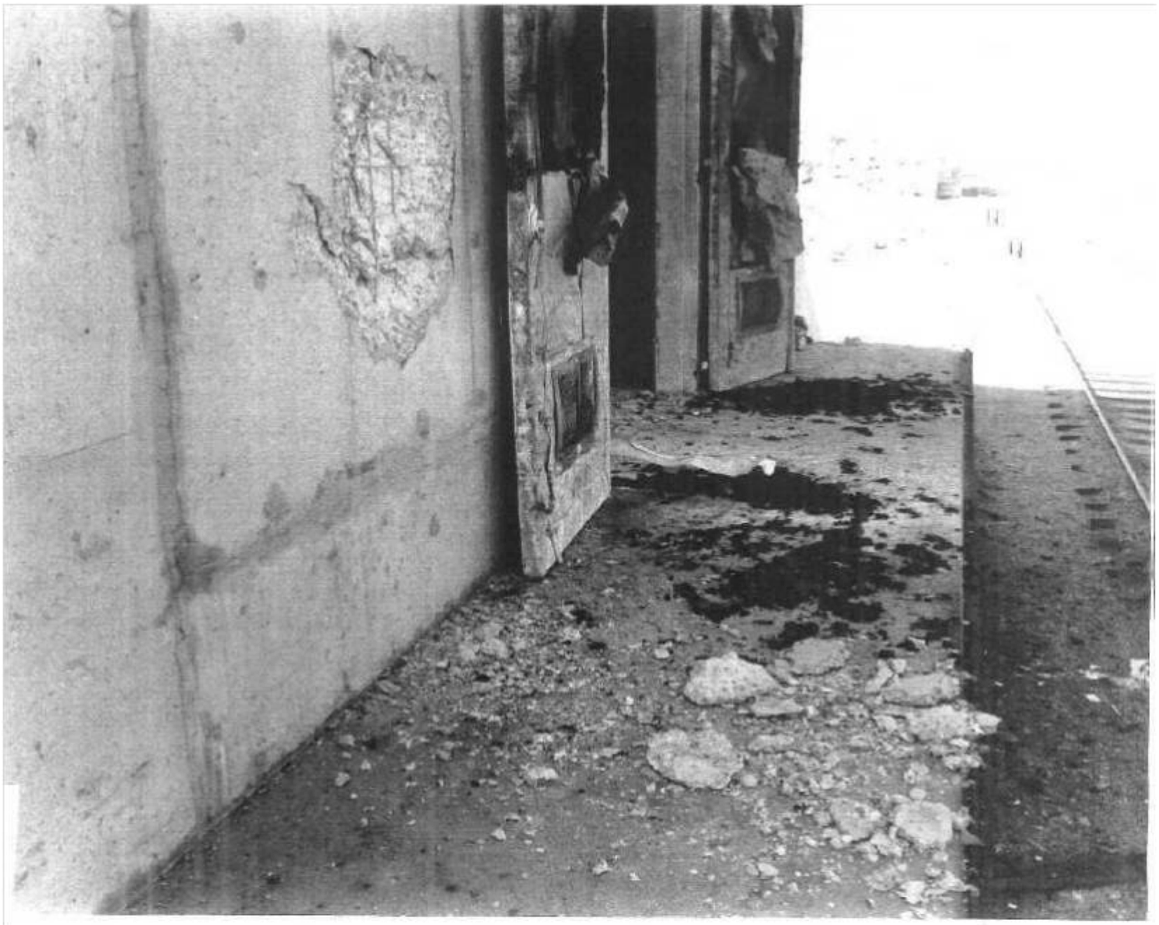


FIGURE 20. Damage to Front of Head Wall of Magazine 116-14-E Caused by Impact of 6-Inch, 47-Caliber Case Propelling Charge That Impacted the Rear of the Head Wall (Inside the Magazine).

The railroad tracks directly in front of the magazine were damaged and numerous railroad ties were severely charred attesting to the intensity of the plume exiting the doors (Figure 21).

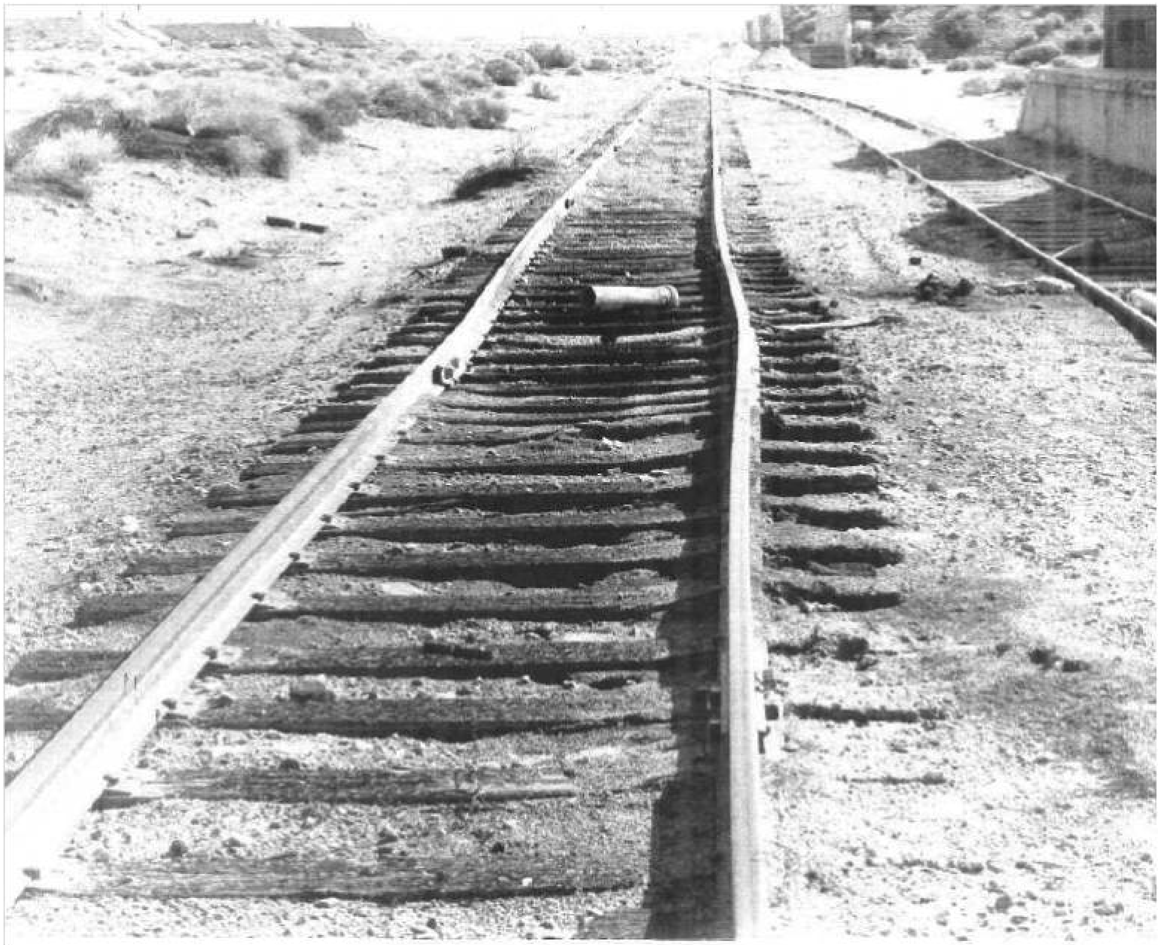


FIGURE 21. Damage to Rails and Charred Rail Ties in Front of Magazine 116-14-E.

There was no cratering or significant damage to the floor of the magazine, and there was no rupture of the magazine walls or displacement of the earth cover. The damage to the E igloo was estimated to have been $23,910. The other two igloos were relatively unaffected. A recording thermometer in 116-14-A showed that there was almost no temperature increase in that igloo.

Sagebrush in front of the magazine was burned out to a distance of approximately 135 feet from the door. Several cartridge cases were found several hundred feet from the magazine.

The sequence of events was postulated as follows:

- The fires appear to have started in the 8-inch, 55-caliber bagged propelling charges. Earlier it was mentioned that 7 lots had low stabilizer levels (0.04 to 0.16%). All of these lots were 8-inch, 55-caliber bagged charges. The propellant in the 8-inch charges was a single-based nitrocellulose propellant with diphenylamine stabilizer. The auto-ignition of this material caused smoke and sparks to come out of door vents and rear ventilator. The fires then spread to the 81-mm mortar increments and the remaining 8-inch, 55-caliber bag charges. The burning propellant caused pressurization within the igloo causing the doors to blow open and the ventilator cap to pop off. This venting allowed the large plume of flame out the vent and doors observed by the witnesses. The 5-inch, 54-caliber and 6-inch, 47-caliber cased propelling charges cooked off during the fireball and continued after the fireball had subsided.

Lessons learned included:

- Single-base nitrocellulose propellants experience stabilizer depletion. When the stabilizer level gets low enough it can result in decomposition of the nitrocellulose and subsequent auto-ignition of the propellant. That appears to have been the "match" that caused the ensuing fire.
- The burning propellant pressurized the interior of the magazine resulting in bursting the doors and popping the ventilator cap, with significant plume of flame out the doors and the ventilator.
- While the reactions were intense, the overall reactions were deflagration not detonations. Burning in magazines does not always transit to a more violent reaction.
- This accident could have been avoided if Hawthorne AAP had been allowed to treat (dispose) of the unsafe propellants as requested.

The Board of Investigation report is Reference 15.

CAMP DOHA, KUWAIT, JULY 1991 (4 MONTHS AFTER CONCLUSION OF OPERATION DESERT STORM)

At approximately 10:20 a.m., 11 July 1991, a defective heater in a M992 ammunition carrier loaded with 155-mm artillery shells caught on fire at Camp Doha, Kuwait. Unit members tried unsuccessfully to extinguish the fire before being ordered to evacuate the North Compound (Figure 22).

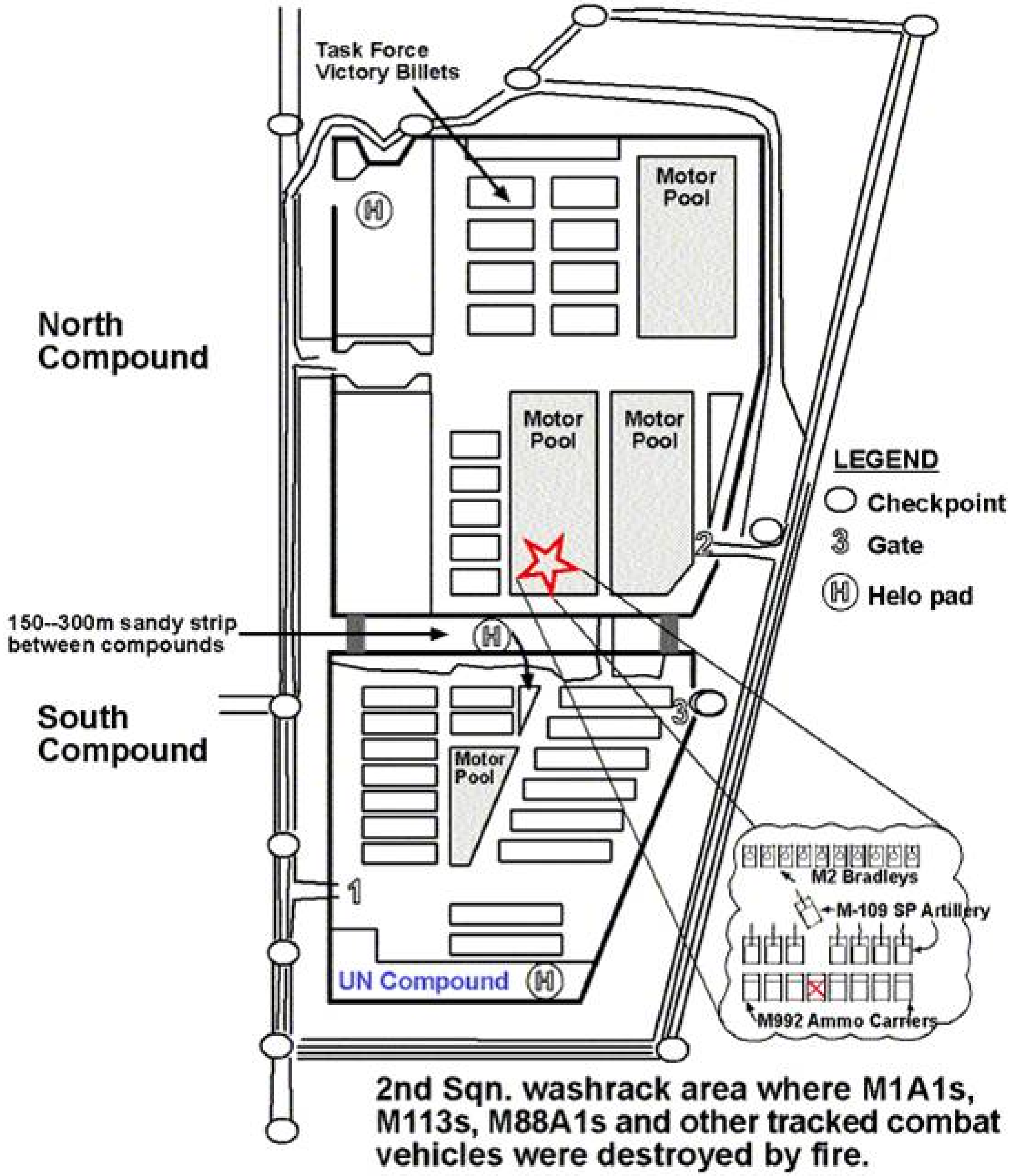


FIGURE 22. Diagram of Camp Doha.

The evacuation was still underway when the burning M992 exploded at 11:00 a.m. (40 minutes after the first fire). The explosion scattered artillery submunitions over nearby combat-loaded vehicles and equipment in the North Compound. This set off hours-long series of fires and blasts that devastated vehicles and equipment in the North Compound and scattered unexploded ordnance and debris over much of the camp. There were no fatalities (although 3 fatalities occurred during cleanup activities) and injuries to 50 U.S.

and 6 UK troops. Most of the injuries were relatively minor, such as those suffered when troops climbed over the 15-foot-high perimeter wall (Figure 23), but there were two serious injuries. However, destruction to the camp and equipment was extensive, as shown in Figures 23 through 28.

FIGURE 23. Troops Evacuating Camp Doha's North Compound.

FIGURE 24. Burned-Out M1A1 Abrams Tank at Camp Doha, July 1991.

FIGURE 25. Aftermath of Doha Motor Pool Fire (View of Wash Rack Area) Showing Armor Hulks and Unexploded Explosive Ordnance (UXO).

FIGURE 26. Aftermath of Camp Doha Motor Pool Fire.

FIGURE 27. Unexploded Ordnance in Camp Doha North Compound.

FIGURE 28. Destroyed M109 Howitzers at Camp Doha, Kuwait.

A total of 102 vehicles were destroyed, including four M1A1 Abrams tanks, and seven M109 Howitzers.

Lessons learned included:

- Fire in combat-loaded vehicles burned for almost 40 minutes before the first explosion. Obviously fire was the initial stimulus.
- Fires and blasts persisted for hours. Obviously, all the ordnance did not react instantaneously or simultaneously.

http://www.gulflink.osd.mil/du_ii/du_ii_tabi.htm
http://www.eaglehorse.org/3_home_station/doha/doha.htm
http://articles.latimes.com/print/2000/apr/15/news/mn-19784
http://news.bbc.co.uk/1/hi/world/africa/716625.stm

ABOVIAN MILITARY DEPOT, NEAR YEREVAN, ARMENIA, 9 APRIL 1992

A fire at the Abovian Military Depot about 18 kilometers from the center of Yerevan, Armenia, at 12:30 a.m. on 9 April 1992, caused hundreds of missiles and rockets to shoot into the sky and some to explode. Explosions occurred at a rate of about 20 a minute. The fires blazed for two days. Three hundred thousand people fled into the night, most with coats hastily thrown over pajamas and nightgowns, some pushing children in strollers down the dark streets to designated shelters. Fortunately, there were few injuries and no fatalities.

http://www.agbu.org/publications/article.asp?A_ID=538
www.chron.com/CDA/archives/archive.mpl/1992_1055367/tens-of-thousands-flee-arsenal-blasts-in-russian-p.html
http://articles.latimes.com/print/1992-05-15/news/mn-2255_1_port-city

VLADIVOSTOK, RUSSIA, 14 MAY 1992

A blast at the old Soviet Pacific Fleet facility triggered thousands of additional explosions over several hours and forced evacuation of more than 50,000 out of the city's 700,000 residents from their homes. The first blast started a fire that spread to other stocks. By 4:00 a.m. the next day, the explosions had stopped but fires continued to rage. The city's entire military garrison was fighting the fires. Windows were knocked out of homes and factories nearby, and the ground shook as if from earthquakes. The equivalent of 1,300 railway cars of artillery shells exploded. Unexploded shells were spread over the neighborhood. Four soldiers were injured fighting the fires but no other injuries were reported. Another report lists 1 fatality and 6 people wounded. The cause of the first explosion was unknown.

http://articles.latimes.com/print/1992-05-15/news/mn-2255_1_port-city
Lukin, A., *Environmental Security of the Russian Far East: Domestic, Transnational, and Regional Dimensions*, found at http://r-cube.ritsumei.ac.jp/handle/10367/951

MAGAZINE AT WHITE OAK, MARYLAND, U.S., 28 JUNE 1992

On Sunday, 28 June 1992, an accident occurred at the White Oak Detachment of the Naval Surface Warfare Center. As described in Reference 16, two explosions destroyed ECM 355. The first, believed to have been a cookoff due to exothermic reaction of experimental formulations, occurred at 1:00 p.m. eastern daylight time. Witnesses to this first event, some as near as 800 feet, observed a dark plume rising from the direction of the magazine and heard firecracker-like popping sounds, but did not observe any flying debris. It was followed approximately two minutes later by a significantly more violent event that produced a heavy shower of debris, and a dark grayish-brown cloud ascended approximately 500 feet into the air.

Magazine 355 was a reinforced ECM constructed in 1951. Figure 29 is a photograph of a similar magazine.

FIGURE 29. Magazine Very Similar to Magazine 355, White Oak, Maryland.

At the time of the accident, the magazine was sited for 7,000 pounds of HD 1.1 material. It was located in the magazine area at White Oak, and it had an inhabited building distance (IBD) arc of 1,250 feet. At the time of the accident, there were 5,180 pounds of largely HD 1.1 materials, primarily consisting of detonation cord, large-scale and expanded large-scale gap test tubes, and test charges for various experimental programs in the magazine.

As mentioned above, Magazine 355 was destroyed. Debris and unexploded ordnance was scattered by the explosion and landed throughout the White Oak facility, resulting in several brush fires. Large debris (pieces of concrete 1 to 2 feet in diameter and various lengths of reinforcing bar) 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. Windows were reported broken out beyond 2,000 feet. Figure 30 presents two photographs that show the damaged area around the site of the previous magazine.

The explosions removed all of the earth covering the magazine and the structure down to the floor slab. The floor slab was broken into several pieces. Some of these pieces were driven several feet into the earth below their original location. Large portions of the floor slab were missing entirely. The average radius of the crater was 32.4 feet and no depth was given in the report.

FIGURE 30. Damage Around Where Magazine 355 Had Been Located.

Lessons learned included:

- Exothermic reactions from a decomposing experimental formulation stored in the magazine may have led to a cookoff reaction. This cookoff reaction produced an audible blast but did not produce fragments/debris.
- This first reaction produced additional heat, fire, and firecracker-like popping sounds; and may have also sensitized other materials in the magazine. Two minutes later, a second, much more violent, reaction occurred that produced a heavy shower of debris and a gray-brown plume approximately 500 feet in the air.
- During the two-minute delay between the two explosions, the magazine was subjected to heat and fire that may have conditioned the structure and its contents for the final blast.
- Once again, the reactions occurred over a period of time; all of the material did not react simultaneously.

AVIATION AMMUNITION STORAGE DEPOT, NOVONEZHINO, NEAR VLADIVOSTOK, RUSSIA, 14 MAY 1994

An off-duty guard was dismantling an electrical component from a rocket with a knife on 14 May 1994. It caught fire and the guard threw it onto the grass. The resulting fire led to explosions of nearly 1,600 tons of ammunition. Debris from shells and rockets fell on the town of Bolshoi Kamen, a few kilometers away. The explosions prompted the evacuation of 3,000 people from Novonezhino. The blast could be felt in Vladivostok 100 kilometers away. Several dozens of people were injured.

http://www.themoscowtimes.com/news/article/guard-linked-to-fire/212810.html
http://dlib.eastview.com/browse/doc/2854822

INDIAN HEAD, MARYLAND, U.S., 1 AUGUST 1994

On Monday, 1 August 1994 at 10:25 p.m. eastern daylight time, an explosive accident occurred at the Indian Head Division of the Naval Surface Warhead Center. In this accident, Magazine 518, a masonry structure described below, was destroyed by explosion and fire. As described in Reference 16, five separate events occurred:

1. Rumble/thunder/large fire
2. Fireworks/thunder/rocks hitting metal
3. Explosion/sharp crack
4. Small explosion/rumbling thunder
5. Major fire

Events 1 and 2 lasted about 30 seconds. Events 3 and 4 lasted an additional 30 seconds. The entire process lasted approximately 15 to 30 minutes. Several witnesses reported seeing extremely bright light that illuminated the area "like daytime."

Magazine 518 was a non-standard, above ground, non-barricaded structure 52 feet wide and 102 feet long. Constructed in 1942, it had walls of four courses of brick, a transite roof (a mixture of 1 to 40% asbestos in Portland cement) supported by a steel truss frame, and a reinforced concrete floor (approximately 5 inches thick) over compacted dirt. Figure 31 shows other magazines having this same construction.

FIGURE 31. Magazines Similar in Construction to Magazine 518.

The magazine was sited for storage of 500,000 pounds of HD 1.3 with an IBD of 600 feet. At the time of the accident there were 93,522 pounds of HD 1.3 materials and 4,609 pounds of HD 1.1 material in the magazine. Most of the materials were bulk powders and propellants for cartridge-actuated devices (CADs) or propellant-actuated devices (PADs). The HD 1.1 material in the magazine was pyrotechnic/propellant material for which the hazard classification was in question. It was later determined that the proper hazard classification was HD 1.1.

The magazine was damaged beyond economic repair but was not completely destroyed. As shown in Figure 32, the south wall was completely destroyed as was approximately two-thirds of the west wall and one-third of the east wall (the portions that were adjacent to the south wall).

In addition, the foundation on the south was bowed out as much as 8 inches, had spalling over about 8- to 10-foot-diameter with cracks radiating from the center of the spall. At the southeast corner the two walls were separated. At the northeast corner the east wall was bulged out 2 to 3 inches, while the north wall was pushed outward 4 to 6 inches. One of the roof trusses was thrown approximately 250 feet.

An oblong crater, approximately 7 feet east-to-west and 4 feet north-to south and 3 feet deep at the center, was formed at the southeast corner of the building. In addition, there were smaller craters along the entire width of the south wall. The floor was depressed along the entire width of the south wall.

Structural damage beyond the magazine consisted of damaged roofs, siding, and broken windows out to approximately 1,000 feet. Six buildings had broken windows, with the furthest at approximately 1,500 feet.

(a)

(b)

FIGURE 32. Magazine 518 After the Accident of 1 August 1994.

The sequence of events described in Reference 16 started with auto-ignition of nitrocellulose gun propellant. The fire spread and involved a relatively large quantity of magnesium-teflon-viton (MTV) flare material, which provided an intense boost to the fire. This, in turn, led to the first and largest detonation near the southeast corner of the magazine, followed by a series of smaller detonations along the south wall. The remaining materials burned until consumed. As stated earlier the entire sequence took between 15 and 30 minutes and involved five separate events occurred:

1. Rumble/thunder/large fire
2. Fireworks/thunder/rocks hitting metal
3. Explosion/sharp crack
4. Small explosion/rumbling thunder
5. Major fire

Events 1 and 2 lasted about 30 seconds. Events 3 and 4 lasted an additional 30 seconds. One might ask the time interval between first ignition of propellant and event 1 rumble/thunder/large fire.

From the crater depth, it was inferred that between 200 and 2,000 pounds of HD 1.1 detonated.

Lessons learned included:

- It appears that the nitrocellulose propellant lost stabilizer until the material auto-ignited. Nitrocellulose materials should be in surveillance program to analyze for stabilizer concentration.
- Mixed storage of HD 1.3 and HD 1.1 resulted in the ignition of the HD 1.3 materials, and the combustion in turn resulted in the detonation of the HD 1.1 materials.
- Even if the HD 1.1 material had not been present in the magazine, the intense fire from the HD 1.3 materials would have destroyed the building.
- Even after the detonation of the HD 1.1 materials, the HD 1.3 materials continued to burn for several minutes, and was intense enough to light up the night sky as if it were daylight.
- Once again, the materials reacted over a period of time; they all did not react simultaneously.
- The asbestos-containing roof presented some environmental cleanup issues.

76TH PSKOV PARATROOPER DIVISION, RUSSIA, 20 OCTOBER 1994

A fire started at the 76th paratrooper division facility due to explosion of an Ural-4320 truck. The fire spread to 11 adjacent ammunition storage areas. Three people were killed and seven were injured. The cause of the original explosion was unknown.

http://dlib.eastview.com/browse/doc/2854822

RED RIVER ARMY DEPOT, U.S., 21 AUGUST 1996

On 21 August 1996, the contents of magazine A-7-7 at Red River Army Depot ignited. The resulting fire burned for several days and destroyed the ECM and its contents. The most probable cause of the fire was self-ignition of M-10 propellant due to stabilizer depletion to a low level. M-10 is a single-base propellant with 98% nitrocellulose, 1% KSO_4 flash suppressant, and 1% diphenylamine stabilizer. Some of the M-10 propellant was packaged in fiber drums. In addition to the M-10 propellant, M-9 propellant (57.75% nitrocellulose, 40% nitroglycerin, 1.5% potassium nitrate, and 0.75% ethyl centralite) and 5,681 105-mm cartridges containing M-1 propellant (85% nitrocellulose, 10% dinitrotoluene, 5% dibutylphtalate, and 1% diphenylamine) were in the magazine. Black powder was stored immediately adjacent to the M-10. There was also considerable combustible wood dunnage (pallets and crates). The magazine was approximately two-thirds full.

The sequence of events appears to have been as follows. The M-10 propellant self-ignited due to stabilizer depletion, and spread to the adjacent M-10. The fire propagated to the black powder causing it to explode/detonate with enough force to blow the door from its mounting. This allowed the door to bow and land face down on the apron without any fragment damage and the lock still securely fastened in place. The blast also scattered burning and smoldering items out the now open door. The blast also caused a low oxygen level within the magazine that in turn caused the wood dunnage to smolder producing large amounts of smoke. As air entered the magazine through the door opening, the fire became more intense and another blast occurred.

This blast expelled over 300 items (most burning) across the access road and the apron, and again deprived the smoldering wood in the magazine oxygen needed for combustion. The "breathing" combustion behavior continued for some time (someone mentioned 4 to 5 hours). At some time the walls failed and the roof collapsed. 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 (4 to 5 feet) crater in the floor where the black powder had been stored.

Lessons learned from this accident include:

- Gun propellants such as M-10 can self-ignite due to stabilizer depletion. There have been other instances where M-10 has self-ignited.
- Mixed storage of HD 1.1 and HD 1.3 can have fire leading to detonation of the HD 1.1 material and then continued fire. In this accident, HD 1.2 materials were in the magazine. These materials cooked-off in "popcorn" fashion with some of the materials simply exploding, while some of the items may have undergone full detonation reactions. It appears that less than 1% of the total amount of HD 1.2 ammunition reacted (Reference 17).
- The fire can last for days—all of the energetic material is not reacted instantaneously or simultaneously.
- The reactions of the energetic materials and the confinement/venting of the structure interact.

The Board of Investigations report is Reference 18.

A telephone conference took place on 25 January 2010 between Jimmy Langley, Joe Cambrum, Jo Covino, Eric Wilson, Alice Atwood, Kevin Ford, Thom Boggs, Ephraim Washburn, Matt Gross, and Nathaniel Davis. A fax from Jo Covino, DDESB, was distributed to Alice Atwood, Thom Boggs, Kevin Ford, and Eric Wilson on 26 January 2010 detailing the timeline of events.

BIRA, RUSSIA, 27 APRIL 1997

Neglect of fire safety rules resulted in ammunition explosions at an army storage area near Bira, Russia, on 27 April 1997. The blaze damaged sections of the Trans-Siberian railroad and a high-voltage power line. The overall damage was approximately 300 billion rubles.

http://dlib.eastview.com/browse/doc/2854822

VOLGOGRAD, RUSSIA, 21 FEBRUARY 1998

A fire broke out at an army storage area where tank shells were stored in Volgograd on 21 February 1998. The fire resulted in explosion of about 1,600 shells.

http://dlib.eastview.com/browse/doc/2854822

**SVERDLOVSK REGION, URAL MOUNTAINS,
RUSSIA, 19 JUNE 1998**

Lightning struck an ammunition storage area in the Ural Mountains in Russia on 19 June 1998. The ensuing series of explosions resulted in at least 14 deaths. Thirteen soldiers and one policeman were confirmed killed. A total of 4 people were missing, and 17 other servicemen were injured in fighting the fires. The depot was storing 240 tons of ammunition.

http://articles.orlandosentinel.com/keyword/hit-by-lightning
http://www.scoop.co.nz/stories/wo0808/s00069.htm
http://www.albca.com/aclis/modules.php?name=news&file=print&sid=1465 [no longer available]

**CAMP SERVILLANO AQUINO, TARLAC CITY,
PHILIPPINES, 1 DECEMBER 1998**

A fire triggered two hours of explosions before dawn on 1 December 1998 at the Philippines largest ammunition depot. At least a dozen buildings were destroyed, and windows were shattered one kilometer away. Fortunately there were no fatalities or injuries. An official said "the building where the explosions originated vanished, the whole building." In its place was a 10 meters wide by 6 meters deep crater. Arson investigators said that the fire started at the room of a retired soldier living in the Nolcom's Veterans Corps building. From there the fire spread to the ammunition depot and other structures nearby. About 1,000 rockets used by helicopter gunships, as well as bullets, old grenades, and other explosives were at the depot.

http://www.newsflash.org/199812/ht/ht000602.htm

**YEKATERINBURG, URALS MILITARY DISTRICT,
RUSSIA, 4 DECEMBER 1998**

Negligent handling of a heater resulted in a fire at the engineering storage area in Yekaterinburg, Urals military district, Russia, on 4 December 1998. The resulting explosions killed three people.

http://dlib.eastview.com/browse/doc/2854822

FINNISH AMMUNITION DEPOT (LOCATION UNDISCLOSED), 19 JULY 1999

An accident that occurred just after 7:00 p.m. on 19 July 1999 completely destroyed a magazine and resulted in ordnance and energetic material being spread over a wide area. The net explosive content of the magazine was approximately 28,000 kilograms. A guard heard a noise that sounded like a shotgun discharge and the sound continued every few seconds, but after about one minute changed to a more metallic sound. The guard sounded an alarm and within 5 minutes had climbed a watchtower about 300 meters from the magazine. By this time the explosions were louder and more regular. The large explosions continued for about 90 minutes and were followed by smaller explosions. Some single events occurred several days after the initial events. It took more than 4 days for helicopters and aircraft to extinguish the fire using water. Fortunately, no personnel were injured.

The investigation revealed that the unheated and unventilated storage facility contained several types of 1.2 hazard classification ammunition awaiting disposal. It also included double- and single-based propellants. The official accident investigation board concluded that the accident resulted from auto-ignition of propellant. The magazine was of lightweight construction with a timber clad frame and sheet metal roof. For the preceding six weeks the temperature in this area of Finland had been relatively high with 30°C being recorded. Temperatures in a comparable facility were found to be as high as 60°C.

> [Note: the experiences described in this paper may shed some light on the accident in Maputo, Mozambique described later.]

More than 12,000 debris items were recorded with more than 99% were found within 100 meters of the former magazine.

As a result of the accident several studies of stabilizer depletion were undertaken and are described in the paper.

I. Tuukkanen and K. Makinen. "Major Accident Involving Hazard Classification 1.2 Ammunition," 2010 DDESB Seminar, July 2010, Portland, Oregon.

KOLUMBAN, NEAR VOLGOGRAD, RUSSIA, 12 JUNE 1999

A fire caused an explosion at an artillery storage area in Kolumban, Russia, on 12 June 1999. Three people were killed.

http://dlib.eastview.com/browse/doc/2854822

ARMY MUNITIONS DEPOT AND AIRPORT, KINSHASA, CONGO, 14 APRIL 2000

A short circuit caused a fire at the army munitions depot at Kinasha on 14 April 2000, triggering a series of explosions that shattered the windows in the adjacent airport. Several buildings were set ablaze. Secondary explosions lasted for more than 2 hours as ammunition blew up, showering the area with shrapnel (References 19 and 20). Reference 21 lists 101 fatalities and over 200 injured. Of the injured, there were about 80 listed as critical condition. Many of the fatalities and injuries occurred when a hangar at the airport collapsed.

http://articles.latimes.com/print/2000/apr/15/news/mn-19784
http://www.independent.co.uk/news/world/africa/hospital-fills-with-casualties-after-kinshasa [no longer available]
http://news.bbc.co.uk/1/hi/world/africa/716625.stm
http://www.deseretnews.com/article/755493/Kinshasa-airport-death-toll-rises to 101.html

BHARATPUR ORDNANCE DEPOT, INDIA, 28 APRIL 2000

On 28 April 2000, a fire broke out in dry elephant grass outside the perimeter of the Bharatpur ordnance depot. A guard tried to put out the fire, but it spread rapidly due to high temperatures and prevailing winds reaching open plinths where ammunition was stored. The fire spread so rapidly that the computerized fire alarm system caught fire before it could raise an alarm. Additional fires led to explosions and spread the fire. The depot was spread over 300 to 400 acres and had more than 30,000 metric tons of operational ammunition and missiles stored in it. The munitions were stored in 20 open plinths and 9 conditioned buildings. The fires continued into the night and the next day with the last explosions at about 5:30 p.m. The loss totaled about 12,111 tonnes (metric tons) of munitions worth about Rs 393 crore (77 million USD) (another report estimated Rs 376 crore, 74 million USD). Missiles lost included Igla, SAM-6, and SAM-7. Ammunition for the 155-mm Bofors gun and the 130-mm, 122-mm, and 105-mm guns was also lost. Damage to infrastructure totaled about Rs 13 crore (2.6 million USD). There were five fatalities and about ten injured. Extensive damage occurred in 20 surrounding villages.

http://www.outlookindia.com/printarticle.aspx?209394
http://www.hinduonnet.com/thehindu/2000/04/29/stories/01290003.htm [no longer available]
http://www.tribuneindia.com/2000/20000503/main1.htm
http://.www.hinduonnet.com/thehindu/2000/05/01/stories/01010002.htm [no longer available]
http://undergroundmines.blogspot.com/2010/05/list-of-major-fires-explosions-in.html [no longer available]
http://www.irinnews.org/report.aspx?reportid=94384

DEHU ROAD AMMUNITION DEPORT, PUNE, INDIA, 3 MAY 2000

Just days after the fires and explosion that occurred at Bharatpur, fires broke out in dry elephant grass at the Dehu road ammunition depot. Fortunately, the fire was controlled before it could cause ignition of any of the ammunition at the depot. It took 12 fire engines 3 hours to control the fire.

http://www.hinduonnet.com/thehindu/2000/05/04/stories/01040006.htm [no longer available]
http://undergroundmines.blogspot.com/2010/05/list-of-major-fires-explosions-in.html [no longer available]

MAMOON AMMUNITION DEPOT, PATHANKOT, INDIA, 29 APRIL 2001

Fire occurred in the ammunition depot near Mamoon exactly one year after the massive fires and explosions at Bharatpur destroyed over 10,000 tonnes of ammunition worth Rs 376 crore (74 million USD) and resulted in five fatalities and about ten injured. Fortunately, the fires at Mamoon that started at about 9:30 p.m., resulted in no fatalities and few injuries. However, 427 tonnes of ammunition, mostly 122-mm tank and 30-mm anti-aircraft shells worth over Rs 27.39 crore (5.4 million USD) were destroyed in the fires that authorities said were "caused by spontaneous combustion triggered by high day temperatures." The Mamoon fires continued to smolder with occasional blasts the following day.

http://www.tribuneindia.com/2001/20010501/main1.htm
http://undergroundmines.blogspot.com/2010/05/list-of-major-fires-explosions-in.html [no longer available]

BIRDHWAL AMMUNITION DEPOT, SURATGARH, INDIA, 24 MAY 2001

A fire broke out at about 11:00 a.m. at the Birdwahl ammunition depot that stored heavy and medium ammunition, including rockets, missiles, tank shells, 130-mm and 155-mm artillery rounds and assorted mines. Hundreds of villagers were evacuated and the army sealed off a 20-kilometer area. The cause of the fire was attributed to "spontaneous combustion" of munitions that were stored in the open with temperatures reaching 49°C. Explosions were set off by the fires. Window panes were shattered in houses. Loss was estimated to be Rs 378 crore (88.3 million USD). There was one fatality and five injuries.

http://www.hinduonnet.com2001/05/25/stories/01250007.htm [No longer available]
http://www.tribuneindia.com/2001/20010525/main1.htm
http://www.globalsecurity.org/military/world/india/army-fac.htm

BURYATIA, SIBERIA, RUSSIA, 21 JULY 2001

Three people were killed and four others injured in a blaze at the army ammunition depot in the Buryat region of eastern Siberia on 21 July 2001. The accident was said to have been caused by lightning.

http://news.bbc.co.uk/2/hi/1494204.stm

TAMIL NADU INDUSTRIAL EXPLOSIVES LTD., INDIA, 16 AUGUST 2001

> [Note: While this accident occurred in a government-run dynamite factory, it was listed in the U.S. Department of State publication, *Dangerous Depots: the Growing Humanitarian Problem Posed by Aging and Poorly Maintained Munition Storage Sites,* 19 May 2010, page 6, as an explosion in a munitions depot. The accident is also listed in several of the other compilations of accidents. It is included in this publication because lessons can be learned that are applicable to munitions.]

At 9:25 a.m. on 16 August 2001, at least 25 people were killed and 3 people in an adjacent building were seriously injured, with one succumbing due to the injuries. The explosion occurred in a building where detonators were fabricated, and evidently occurred during a crimping operation. The 200- by 100-foot building was flattened by the blast. Several of the articles reviewed mentioned that the work was being performed by "casual workers" that were supervised by a "trainee supervisor." The combination of untrained workers and untrained supervisor may have contributed to the accident. One report said that several workers had reported "sparks from detonators." "The workers are reported to have expressed their fears to the trainee supervisor." Another report said that an official said the blast was "caused by the 'accidental ignition' of explosives stored in one of the factory's holding units." About 20,000 detonators and fuses had been gathered into a stack near one of the two entrances to the building. "A crater near the spot where the live detonators were gathered also lent credence to the theory that the first stage of the accident happened near the stack." Workers in the factory described the initial sound as being like a firecracker, followed by a big bang, and then a final bang. The last bang was attributed to the collapse of the building. Fires continued to burn after the blasts.

http://news.bbc.co.uk/2/hi/1493849.stm
http://news.bbc.co.uk/2/hi/1494204.stm
http://www.hindu.com/businessline/2001/08/17/stories/14171802.htm
http://www.hindu.com/thehindu/2001/08/17/stories/01170003.htm
http://www.telegraph.co.uk/news/1337623/Blast-at-Indian-explosives-factory-kills-27.html
http://www.frontlineonnet.com/f11818/18181260.htm [No longer available]

KORAT, PAK CHONG ARSENAL,
THAILAND, 25 OCTOBER 2001

Massive explosions at 9:00 a.m. on 25 October 2001 at the Pak Chong arsenal, Thailand's army's largest weapons depot, caused bombs, rockets, and artillery shells to be spread over a 4-kilometer area. Seven of the magazines were completely destroyed. There were 20 fatalities and about 90 people injured, many by flying glass. About 5,000 people were evacuated from the area. The cause of the initial fires was auto-ignition of obsolete ammunition from the Cambodian war era. The blasts that were felt several kilometers away destroyed 385 houses in Pak Chong and damaged 111 others. A fire broke out in a textile factory 2 kilometers from the depot after it was hit by exploding ammunition. Thousands of bombs and hundreds of thousands of bullets were believed to have been strewn across the district. There were 400 bomb-disposal officers and 500 rescue crew workers in the area. By the end of October, some 21,000 explosive items had been retrieved.

http://www.geocities.ws/chainat_prov/4411/thai-ammoaccident.html
http://articles.cnn.com/2001-10-25/world/thailand.explosion_1_huge-explosion-thai-ammunition?_s=PM:asiapcf
http://news.bbc.co.uk/2/hi/asia-pacific/1618955.stm
http://articles.cnn.com/leyword/ammunition [No longer available]
NIMIC (now MSIAC), *NIMIC Newsletter 4th Quarter 2001*, page 7.

BIKANER, RAJASTHAN, INDIA,
11 JANUARY 2002

Nearly 70 explosives-laden trucks with about 1,000 tons of ammunition caught fire near Bikaner, India on 11 January 2002. Shells, rockets, and fragments landed in civilian areas in an 8-kilometer radius. The cause was attributed to an electric spark in one of the trucks that then spread to the other trucks in the parked convoy. There were two fatalities and 12 injured.

NIMIC (now MSIAC), *NIMIC Newsletter 1st Quarter 2002,* page 6.

IKEJA AMMUNITION DEPOT, LAGOS,
NIGERIA, 27 JANUARY 2002

On 27 January 2002, a fire broke out in a street market adjacent to the Ikeja military cantonment in the city of Lagos. At approximately 6:00 p.m., the fire spread to the base's main munitions store that, in turn, lead to a massive explosion. [Note: One article reported: "The blast was officially blamed on a nearby fire, but unofficially the cause was put as the deterioration of ammunition stocks." In either case the initial reaction was fire that led to explosion.] The fires created by the debris from this explosion burned down a large portion of northern Lagos and caused a panic that spread to other areas. The blast also expelled many munitions that, in turn, spread the destruction. While the initial explosions killed many of the base staff, many more people were killed in the ensuing panic. Many people were killed in the stampede, and many more were killed when panicking people fell into a canal. The surge of people caused those on the bottom to drown. At least 600 people were killed in the canal, many of them children. The final death toll was estimated to be more than 1,100 with at least 5,000 injured, and displaced 20,000 people from their homes. It was estimated that over $12 million worth of ammunition was destroyed.

http://en.wikipedia.org/wiki/Lagos_armoury_explosion
http://www.irinnews.org/report/94384/
NIMIC (now MSIAC), *NIMIC Newsletter 1st Quarter 2002,* pp. 6-7.

AMMUNITION DEPOT NEAR KANDAHAR, AFGHANISTAN, 7 MARCH 2002

Afghan soldiers gathering firewood set off a booby trap resulting in fire at about 10:00 a.m. The fire quickly spread through the surrounding grass due to high winds and extremely dry conditions to a nearby ammunition depot close to the Kandahar base. There were explosions every few seconds for more than an hour. The last explosion occurred about 6:00 p.m. The fire burned for more than a day, and was still smoldering the next day.

NIMIC (now MSIAC), *NIMIC Newsletter 2nd Quarter 2002*, page 5.

HIGH ENERGY MATERIALS RESEARCH LABORATORY, PUNE, INDIA, 25 APRIL 2002

A fire broke out in the High Energy Materials Research Laboratory in Pune, India, on 25 April 2002. The fire caused an explosion in the propellant processing building that resulted in six fatalities and one injured.

NIMIC (Now MSIAC), *NIMIC Newsletter 2nd Quarter 2002,* page 5.

SPIN BOLDAK, AFGHANISTAN, 28 JUNE 2002

Explosions at a weapons depot in Spin Boldak, Afghanistan, resulted in 32 fatalities and 70 injured, and munitions spread “all over town.” The cause of the explosions is unknown, but several references have listed “sabotage.”

http://www.news.bbc.co.uk/1/hi/world/south_asia/2073985.stm [No longer available]
http://www.afghanistannewscenter.com/news/2002/june/jun302002.html
NIMIC (Now MSIAC), *NIMIC Newsletter 3rd Quarter 2002*, page 7.

AMMUNITION DEPOT BURYATIA REPUBLIC, SIBERIA, RUSSIA, 10 JULY 2002

Lightning started a fire at an artillery ammunition depot in Buryatia Republic, Siberia, Russia, on 10 July 2002. The ammunition depot contained firearms, ammunition, artillery shells, and mortar rounds. The fire destroyed a warehouse full of flare rockets. At least 3 people were killed and 11 injured. Flying glass rained down on nearby homes. At least seven homes in the nearby town of Gusinoye Ozero were destroyed. Firefighters fought fires into the next day while missiles in the depot continued to explode.

NIMIC (Now MSIAC), *NIMIC Newsletter 3rd Quarter 2002*, page 6.

JALALABAD, AFGHANISTAN, 10 AUGUST 2002

An accidental explosion at the Afghan Construction and Logistics Unit construction compound in Jalalabad resulted in 26 fatalities and 90 injuries. A total of 50 houses were destroyed and another 500 damaged. The explosion of 35 boxes, each containing about 25 kilograms of dynamite stored in a metal freight container in a warehouse, was due to "the scorching summer heat or by some electrical fault." Villagers say they saw smoke rise from the warehouse for a few minutes before the explosion. A crater more than 2 meters deep and 12 meters wide was evidenced where the metal freight container had been.

http://www.reliefweb.int/node/107064
http://www.afghanistannewscenter.com/news/2002/august/aug112002.html
NIMIC (now MSIAC), *NIMIC Newsletter 3rd Quarter 2002*, page 7.

VLADIVOSTOK, RUSSIA, 16 OCTOBER 2002

A fire broke out in a naval arsenal of the Russian Pacific Fleet in Vladivostok, Russia, on 16 October 2002. The fire caused numerous uncontrolled explosions of ammunition supplies. Three engineers were destroying 500 old 30-mm munitions when the fire spread to an open storage area. The fire caused the explosion of 12 railroad cars of old artillery shells. Police evacuated residents from the area. No injuries were reported. [Note: Wilkinson reported 26 injuries.]

NIMIC (Now MSIAC), *NIMIC Newsletter 4th Quarter 2002*, page 9.

BEIRA ARMS DEPOT, MOZAMBIQUE, 30 OCTOBER 2002

Lightning on 30 October 2002 set off an explosion at the Beria arms depot that resulted in 3 deaths [A. Wilkinson lists 6 deaths and 50 injured] and destroying 130 homes.

There is some conflict between various reports on this incident as shown in Table 4. There was the original accident and a later accident involving UXO generated from the original accident.

TABLE 4. Various Accounts of the Beira, Mozambique, Accident.

	Banjo	Wilkinson (a)	Wilkinson (b)	Berman
Date of original accident	2003	30 October 02	30 October 02	24 October 02
Number of fatalities	3	6	6	?
Number of injuries	Not given	50	50+	Not given
Homes destroyed	130	Not given	Not given	Not given
Cause of accident	Lightning	Lightning	Not known	Not given
Date of UXO accident	January 2007	NA	23 November 06	Not mentioned
Number of fatalities UXO	5	NA	5	Not mentioned

Banjo, A., *Reflections on the Military Armoury Disaster in Mozambique, March 2007,* Journal of Military and Strategic Studies, Volume 12, Issue 2, Winter 2010 ISSN:1488-559x.

Wilkinson (a), A., *Parliamentary Oversight of Conventional Ammunition Supplies,* Nicosi, Cyprus, 18 February 2011.

Wilkinson (b), A., *Conventional Ammunition Stockpiles Policy Brief, Draft Edition 1, Ammunition Depot Explosion,* page 7.

Berman, E. G., *Illicit Trafficking of Small Arms in Africa: Increasingly a Home-Grown Problem,* GTZ-OECD-UNECA Expert Consultation of the Africa Partnership Forum Support Unit, 14 March 2007, Addis Ababa, Ethiopia.

Five years after the explosion, in 2007, 5 people were killed by unexploded ordnance ejected during this accident in 2002.

http://www.irinnews.org/Report/94384

LUBBEN, BRANDENBURG, GERMANY,
12 NOVEMBER 2002

An explosion in a bunker at a plant destroying munitions at Lubben, Brandenburg, Germany, resulted in four fatalities on 12 November 2002. The earth-covered concrete bunker was completely destroyed by the explosion with debris scattered up to 500 meters. The workers were defusing 500-pound bombs. Nine bombs were stored inside the bunker and at least two of them detonated.

NIMIC (Now MSIAC), *NIMIC Newsletter 4th Quarter 2002,* page 9.

MANAGUA, NICARAGUA, 12 NOVEMBER 2002

A group of soldiers were carrying gunpowder from a warehouse in Managua, Nicaragua, on 12 November 2002. One of the boxes exploded inside the warehouse killing five soldiers and wounding five others. The first explosion triggered fires and subsequent explosions.

NIMIC (Now MSIAC), *NIMIC Newsletter 4th Quarter 2002,* page 9.

RIOBAMBA, ECUADOR, 20 NOVEMBER 2002

A fire resulted in cookoff of weapons at a depot within Ecuador's largest military base at Riobamba, Ecuador, on 20 November 2002. A total of seven people were killed and 274 injured (74 to 155 seriously, depending on source). The first explosion caused a second larger reaction. Buildings within a radius of 300 meters were severely damaged and windows were broken within a radius of 2 kilometers. Munitions were scattered within and outside the depot. Estimated damages were $80 million.

NIMIC (Now MSIAC), *NIMIC Newsletter 4th Quarter 2002,* page 9.

TUMBES, PERU, 23 JANUARY 2003

A major explosion resulted in the death of seven soldiers and injured 98 people (15 soldiers and 83 civilians outside the military area) at an army base near Tumbes, Peru. The cause of the accident was unknown (one suggested cause was high temperatures). The facility was a recently built (late 1980s) depot with partially buried magazines with IBD and inter-magazines distance in accordance with international standards. The explosion crater was 5 meters deep and 15 meters in diameter.

NIMIC, NIMIC *Newsletter 1st Quarter 2003*, page 7.

SOUTHERN NAVY BASE, GUAYAQUIL, ECUADOR, 23 MARCH 2003

A dozen people were seriously hurt and several dozen were treated for minor injuries following an explosion that occurred on 23 March 2003 at the southern navy base at Guayaquil, Ecuador, on 23 March 2003. Buildings close to the base were damaged by the blast and falling debris, with destroyed roofs, walls, and shattered windows.

NIMIC, *NIMIC Newsletter 2nd Quarter 2003,* page 12.

AMMUNITION DUMP, ZAFARANIYAH, IRAQ, 26 APRIL 2003

Fires were caused by insurgents firing flares into an ammunition storage area at the ammunition dump in Zafaraniyah, Iraq, on 26 April 2003. The flares started fires that soldiers tried to suppress but the blaze spread and resulted in detonations of confiscated weapons. The confiscated weapons included rocket-powered grenades, and large missiles. The weapons were being held behind a tall earth ridge 500 meters from the residential area. Between 8:00 a.m. and 11:00 a.m., Hai Al-Muallimin was subjected to a rain of twisted blackened metal from a series of massive explosions. The series of blasts resulted in rockets raining down on a nearby residential area, flattening a house, and burying the victims in rubble. A Soviet made FROG-7 missile exploded, demolishing two houses, and leaving a large crater in the street. Its front yard was transformed into a large water-filled crater about 10 feet deep and 25 feet across. Reported casualties vary between sources from 6 to 14 Iraqi citizens killed and more than 50 injured.

NIMIC, *NIMIC Newsletter 2nd Quarter 2003,* page 12.

THAI NGUYEN, VIETNAM, 5 MAY 2003

A huge fire erupted at the z115 military depot and ammunition factory located at Thai Nguyen, Vietnam, on 5 May 2003. About 40 minutes later there was a very loud explosion, and four other explosions followed lasting about an hour. Most of the estimated 700 houses within a 1.5-kilometer radius were leveled or damaged by the blasts. The cause of the fire was believed to be extreme outside temperatures. Two people were killed and 31 people were injured.

NIMIC, *NIMIC Newsletter2nd Quarter 2003,* page 13.

JODHPUR, INDIA, 1 JUNE 2003

A fire started in the arms depot at Jodhpur, India, on 1 June 2003. The fire destroyed ammunition and mines. An initial explosion occurred in one of the four magazines. There were no fatalities or injuries. Preliminary reports give the cause of fire as high temperatures, and mention that at least 16 fires have broken out at ammunition depots across India in the previous 3 years.

NIMIC, *NIMIC Newsletter, 2nd Quarter 2003,* page 13.

AD DIWANIYAH, IRAQ, 9 JUNE 2003

An explosion at an Iraqi ammunition supply facility killed three Iraqis and injured two on the morning of 9 June 2003. MSIAC said that the cause of the explosion was unknown; however, Wilkinson listed the cause as fire.

NIMIC, *NIMIC Newsletter 2nd Quarter 2003,* page 13.
Wilkinson, A., *Oversight of Conventional Ammunition Stockpiles,* Nicosia, Cyprus, 18 February 2011, page 4.

KARBALA, IRAQ, 9 JUNE 2003

A fire caused a series of explosions at a coalition ammunition supply point on 9 June 2003. There were no reported casualties and the fire was localized. The area was evacuated and a 4-kilometer buffer zone was established.

NIMIC, *NIMIC Newsletter 2nd Quarter 2003,* page 13.

NAJAF, IRAQ, 22 JUNE 2003

A total of 40 people perished when looters accidently started a fire in an ammunition depot at Najaf, Iraq, on 22 June 2003. The looters were trying to steal large quantities of brass shell casings. As the shells were being emptied, an explosion set the whole depot on fire.

http://www.patriotfiles.com/index.php?name=Section&req=viewarticle&artid=8250&pag
[No longer available]
NIMIC, *NIMIC Newsletter 3rd Quarter 2003,* page 4.

HADITHA, IRAQ, 22 JUNE 2003

On 22 June 2003 another ammunition dump, this one at Haditha, Iraq, blew up as looters were trying to steal large quantities of brass shell casings. Between 25 and 30 people were killed and 6 were injured.

NIMIC, *NIMIC Newsletter 3rd Quarter 2003,* page 4.

NAVAL ARSENAL NEAR VLADIVOSTOK, RUSSIA, 12 JULY 2003

Several violent explosions occurred at the naval arsenal near Vladivostok, Russia on 12 July 2003. The explosions were caused when a firecracker used to celebrate Fisherman's Day, flew through a ventilator at one of the arsenal's storage buildings. The resulting explosions injured 13 people. Most of the injuries occurred due to the explosions shattering windows and damaged walls of nearby houses. More than 1,000 people were evacuated from nearby villages.

NIMIC, *NIMIC Newsletter 3rd Quarter 2003,* page 4.

NATIONAL AIR FORCE HANGAR, MENONGUE, ANGOLA, 16 JULY 2003

A fire started near the National Air Force hangar at Menongue, Angola on 16 July 2003. When the fire reached the area where bombs were stored, an explosion occurred. The explosion killed two, injured 15, and destroyed the hangar and vehicles. A second explosion occurred when mines around the area were initiated 4 hours after the main explosion.

NIMIC, *NIMIC Newsletter 3rd Quarter 2003,* page 4.

PRATT & WHITNEY SPACE PROPULSION PLANT, SAN JOSE, CALIFORNIA, U.S., 7 AUGUST 2003

An explosion demolished a mix facility at the Pratt & Whitney Space Propulsion Plant in the rural hills south of San Jose, California, on 7 August 2003. Only the metal skeleton was left of the three story mix facility. The accident occurred shortly before 6:00 p.m. The fire burned approximately 37 acres of grassland. The explosion was caused by ignition of the several thousand pounds of an AP composite propellant that was being mixed in the 600-gallon mixer in the mix facility (Building 0582). The ignition, which occurred as the aluminum powder was being added to the AP/binder mix, was attributed to a foreign object entrained between the mixer blades and the mixer metal bowl. This was based on scrape marks on the bottom of the mixing bowl. There were no fatalities or injuries because the operation was being performed remotely with the five technicians in a control bunker about ¼ to ½ mile away from the mix building, and because the day shift had ended and most of the 700 employees were no longer at work. Reference 22 is the report of the senior investigator.

http://articles.latimes.com/print/2003/aug/09/local/me-sanjose9
http://articles.sfgate.com/2003-09-13/bay-area/17509509_1_rocket-fuel-fuel-storage-grass-fire

http://www.firehouse.com/forums/showthread.php?t=51947
http://articles.sfgate.com/2003-08-08/news/17502239_1_rocket-fuel-whitney-space-propulsion-division-pratt-whitney

BABSTOVO, PRIMORSKII KRAI, RUSSIA,
14 AUGUST 2003

A fire started at a military base at Babstovo, Russia, on 14 August 2003. The fire started due to negligence of soldiers who had spilled fuel while refilling a vehicle. The spilled fuel ignited and the fire spread to open ground adjacent to the hangar where four Ural trucks loaded with shells were parked. As soon as the blaze reached the trucks, the 120-mm shells exploded producing fragments. The blaze then spread to the supply depot triggering further explosions. Two officers tried to drive the trucks away from the hangar but were killed by the blasts. Fragments from the shells were scattered over a radius of 500 meters. It took rescue teams 5 hours to bring the fire under control and a further 3 hours before the fires were fully extinguished.

NIMIC, *NIMIC Newsletter 3rd Quarter 2003,* page 5.

TIKRIT, IRAQ, 17 AUGUST 2003

An ammunition dump near Tikrit blew up while looters were trying to steal brass shell casings on 17 August 2003 resulting in 12 fatalities.

NIMIC, *NIMIC Newsletter 3rd Quarter 2003,* page 5.

PRATT & WHITNEY SPACE PROPULSION PLANT,
SAN JOSE, CALIFORNIA, U.S., 12 SEPTEMBER 2003

The plant had been in stand-down mode following the 7 August 2003 accident described previously. On 12 September 2003 at approximately 11:15 a.m., an employee of a sub-contractor working for Pratt & Whitney Space Propulsion was killed. He was killed while using a portable band saw to cut a 2-inch stainless-steel vacuum line that was used to pull air from the 400-gallon propellant mixing bowl in Building 0571. The employee had cut partially through the line when it exploded. The subsequent accident investigation revealed that the vacuum line was contaminated with AP and cyclotetramethylenetetranitramine (sometimes referred to as high melting explosive [HMX]) that evidently initiated when the saw blade had cut through and into the tube. Cause of death was multiple and extensive fatal fragmentation injuries due to the impact of the metal fragments from the stainless-steel pipe to the body of the deceased.

Byrne, M. L., *Report of Investigation Senior Investigator Michael L. Byrne*, State of California Department of Industrial Relations, San Francisco, California, Report Number N1110-062-03, 19 July 2004.

ARTEMOVSK, UKRAINE, 10 OCTOBER 2003

On 10 October 2003, a powerful blast destroyed 10 out of 17 magazines at an ammunition depot in Artemovsk, Ukraine. The depot contained shells, mines, and other munitions. The blasts shattered windows in several apartment blocks. Several thousand people were evacuated from their homes. The blast was caused by a fire that started from a welding torch. Casualties were limited to two injured.

http://www.highbeam.com/doc/1P1-85607653.html
http://www.highbeam.com/doc/1P1-85646870.html
http://www.sott.net/signs/signs277.htm
NIMIC, *NIMIC Newsletter 4th Quarter 2003,* page 37.

POLICE ARMORY, AMRITSAR, INDIA, 19 FEBRUARY 2004

Fire led to a major explosion at the police armory at Amritsar, India on 19 February 2004. The explosion injured 30 people (at least two seriously), destroyed or damaged more than 50 shops, and badly damaged 100 parked cars.

NIMIC, *NIMIC Newsletter 1st Quarter 2004,* page 5.

SATISH DHAWAN SPACE CENTER, NELLORE, INDIA, 23 FEBRUARY 2004

> [Note: Several articles described the accidents. Unfortunately, several conflicting accounts were reported, and several of the articles were written by authors who have no background in missile propulsion or missile motor production. The following account is the senior author's best interpretation of what happened based on the conflicting accounts.]

The accident occurred in the Cast-Cure facility at the Space Center at about 3:15 p.m. on 23 February 2004. Six people were killed and three were severely burned. The people had been removing the mandrel from a large (14.5 tons of solid propellant) motor segment. The propellant was an AP/aluminum powder/HTPB composite propellant. [See also the accident that occurred at Morton Thiokol, Utah on 30 December 1987 previously described. In that accident, a fire occurred while the mandrel was being pulled from a large MX Peacekeeper motor. In that accident, five people were killed.] One article said that workers had successfully removed the mandrel and were attending to the removal of the bottom plate of the casting assembly. In any case, the propellant ignited and caused severe damage to the building and the people inside. One article said that six people died almost instantly, while another said that three people died almost instantly and another three died while on the way to the hospital.

http://www.universe-galaxies-stars.com/archive_1393_print.html
http://www.telegraphindia.com/1040224/asp/others/print.html
http://articles.timesofindia.indiatimes.com/2004-02-24/hyderabad/28331547_1_sriharikota-shar-huge-electrical
http://articles.timesofindia.indiatimes.com/keyword/sriharikota/recent/5
NIMIC (now MSIAC), *NIMIC Newsletter 1st Quarter 2004,* page 5.

NATIONAL POLICE LOGISTIC SUPPORT SERVICE, QUEZON CITY, PHILIPPINES, 25 FEBRUARY 2004

A fire and several small blasts preceded an explosion at the arsenal of the National Police Logistic Support Service, Quezon City, Philippines, on 25 February 2004. The fire was caused by a spark from a loose wire. Three firemen and a policeman were injured in the explosions that involved recovered explosives and ammunition. Grenade shells and ammunition casings were scattered around on the ground.

NIMIC, *NIMIC Newsletter 1st Quarter 2004,* page 5.

275TH AMMUNITION BASE, NOVOBOGDANOVKA, UKRAINE, 6 MAY 2004

At approximately 12:40 p.m. on 6 May 2004, a fire started during disposal work at the ammunition base located near Novobogdanovka in the southern part of the Ukraine. The base was built in 1953 and was designed to accommodate 4,000 carloads of munitions, with a standard carload accounting for approximately 20 tons of ammunition. At the time of the accident there were 4,808 carloads with about 1,526 carloads of artillery and mortar projectiles, about 1,275 carloads of missiles, 849 carloads of tank ammunition, and smaller amounts of other munitions. There were 107 storage units comprised of 18 reinforced concrete magazines, 18 brick magazines, and 71 open ground sites. The accident was attributed to exceeding the authorized storage capacity, non-observance of the safety and protective measures, and human error. The fires were not fully extinguished until 19 May. Three soldiers at the base were arrested and charged with smoking while handling live ammunition.

The schematic of the base and the storage locations are shown in Figure 33.

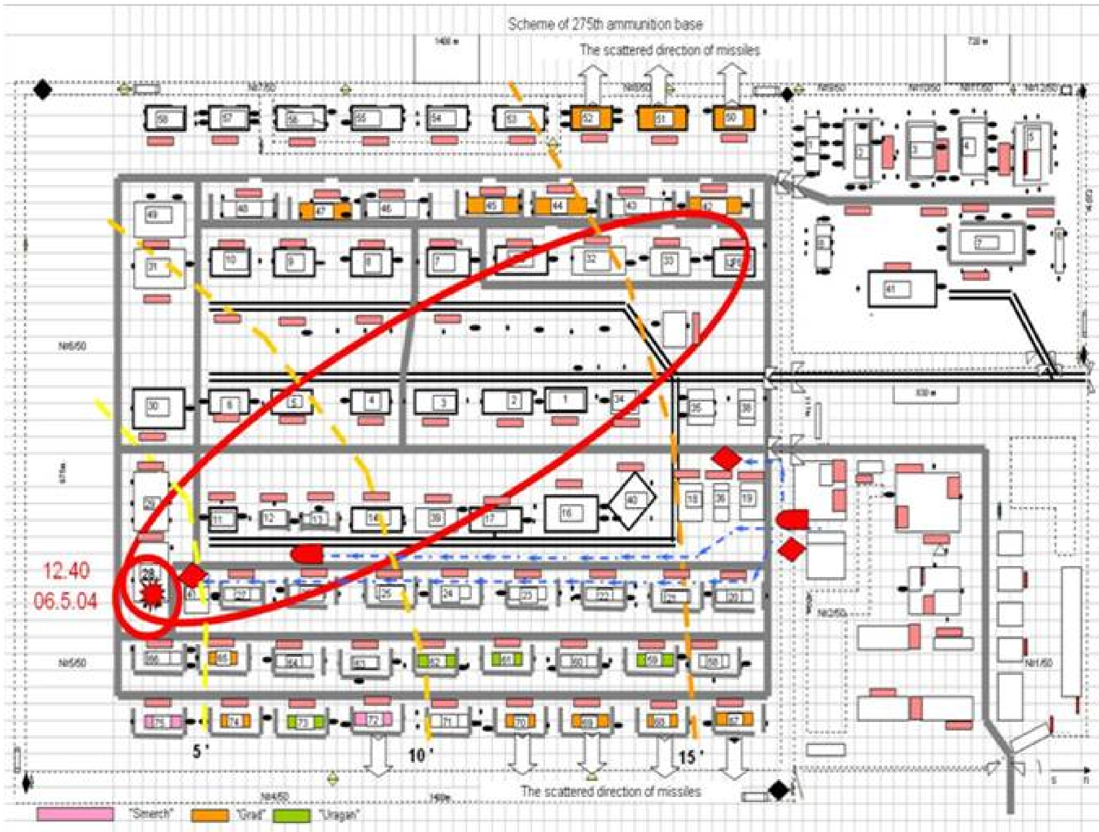


FIGURE 33. Schematic of the 275th Ammunition Base Showing the Storage Locations and the Weapon Types Stored in the Various Areas. The fire started in storage area 28, an area for demilitarization operations.

Figure 33 shows the storage locations and the weapons stored in the various locations. The fire started in storage area 28. The “Smerch” refers to 300-mm caliber multiple launcher rocket system having a range of between 20 and 70 kilometers. The “Grad” refers to a 122-mm caliber multiple-launch rocket system having a range between 1.6 and 20.4 kilometers. The “Uragan” refers to a 220-mm caliber multiple-launch rocket system having a range between 8 and 35.8 kilometers.

The accident resulted in 5 fatalities (3 of the dead were elderly people who died of heart failure), 20 injuries, 900 carloads (approximately 20,000 tons) of ammunitions scattered over an area of 300 square kilometers, and 30,000 inhabitants from 15 villages were evacuated. The estimated damages were more than $700 million. Figures 34 and 35 show before and after views. Figures 36 and 37 show some of the devastation, while Figures 38 through 41 show some of the dispersal of munitions and debris.

FIGURE 34. Novobogdanovka, Ukraine, Before May 2004 Accident.

FIGURE 35. Novobogdanovka, Ukraine, After May 2004 Accident.

FIGURE 36. Devastation of Facilities and Equipment at the 275th Ammunition Base, Novobogdanovka, Ukraine.

FIGURE 37. Aerial View Showing Some of the Devastation at the 275th Ammunition Base, Novobogdanovka, Ukraine.

FIGURE 38. View of Devastation and Dispersion of Munitions and Debris at the 275th Ammunition Base, Novobogdanovka, Ukraine.

FIGURE 39. View of Devastation and Dispersion of Munitions and Debris at the 275th Ammunition Base, Novobogdanovka, Ukraine.

FIGURE 40. Aerial View of Devastation and Dispersion of Munitions and Debris at the 275th Ammunition Base, Novobogdanovka, Ukraine.

FIGURE 41. Aerial View of Devastation and Dispersion of Munitions and Debris at the 275th Ammunition Base, Novobogdanovka, Ukraine.

Presentation "Novobogdanovka accident (May 2004)" presented at the NATO AC/326 meeting, 16-17 June 2005, and from http://www.artukraine.com/parced/military depot blast latest.php?gallary+ [No longer available]
NIMIC, *NIMIC newsletter 2nd quarter 2004*, page 6, also MSIAC, *MSIAC newsletter 3rd quarter 2005*, page 9.

See also
http://news.bbc.co.uk/2/hi/europe/3690779.stm
http://www.independent.co.uk/news/world/europe/more-than-5000-blasts-an-hour-shake-up [No longer available]
http://Nuclearno.com/text.asp?8275
http://www.highbeam.com/doc/1P2-16585200.html [No longer available]
http://www.highbeam.com/doc/1P2-16567876.html [No longer available]
…*Aging Stocks of Ammunition and SALW in Ukraine: Risks and Challenges*, National Security and Defence, No. 2 (62) 2005, published by the Ukrainian Centre for Economic and Political Studies.
Brown, Mitch, *Environmental Update from Ukraine*, Bucharest, May 2004.

KIRKUK AIRBASE, IRAQ, 2 JUNE 2004

At about 9:00 p.m., a rocket attack caused fires near the ammunition dump at the U.S. air base at Kirkuk, Iraq. The fires spread and caused several explosions over the next few hours. The fires were finally put out at approximately 5:00 a.m. The following morning, there were no casualties on base, but the explosions caused damage over a wide area, including shattered windows and damaged cars. Debris was found 1.5 kilometers from where the munitions were stored. Figure 42 shows the conflagration.

Video from a handheld unit can be found at the following web addresses:
http://www.youtube.com/watch?v=iIzzJCKlVR4
http://www.youtube.com/watch?v=N7xauXUksic
http://www.strategypage.com/military_videos/military_photos_200573122.aspx

The video shows mass fires and several intermittent explosions. Local residents said explosions continued every 10 to 15 minutes for almost 2 hours after the first blast. Unfortunately, the video is not of the highest quality. It was shot from a distance, was handheld, and it was a dark night with dark smoke obscuring some of the flames. Never the less, it is interesting to watch. The sound track includes "guy talk" comments from the man filming the events as well as his companions, sirens from the base, and the sounds of the explosions. Figures 43 and 44 show the extent of the damage to the ammunition dump.

NIMIC, *NIMIC Newsletter 2nd Quarter 2004,* page 7.

FIGURE 42. Conflagration at Kirkuk U.S. Airbase, Iraq, 2 June 2004.

FIGURE 43. Damage to the Kirkuk Airbase After the
Fire and Explosions of 2 June 2004.

FIGURE 44. Crater Evidence of the Violence of Reactions
Occurring at Kirkuk Airbase, 2 June 2004.

AMLANAGAR, MADHYA PRADESH, INDIA, 9 JULY 2004

A large quantity of ammunition and explosives were destroyed in a major fire. Indian Air Force firefighters extinguished the blaze after 2 hours. There was no loss of life, but two Indian Air Force personnel were injured during debris clearance operations.

NIMIC, *NIMIC Newsletter 3rd Quarter 2004,* page 5.

INDIAN AIR FORCE AVIATION RESEARCH CENTRE, CHOWDAR, ORISSA, INDIA, 26 AUGUST 2004

A fire partially destroyed the ammunition depot at the Indian Air Force Aviation Research Centre on 26 August 2004. The blaze destroyed a section where small arms munitions were stored; however, a section containing heavy weaponry was spared. Nearly 5,000 people were evacuated from a nearby village.

NIMIC, *NIMIC Newsletter 3rd Quarter 2004,* page 5.

MILAN AAP, MILAN, TENNESSEE, U.S., 13 OCTOBER 2004

On 13 October 2004, an accidental explosion occurred at Milan AAP, Milan, Tennessee. Two fatalities and one critical injury resulted from the event. Property loss and damage included total destruction of 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 railcars 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 to 99% hexahydro-trinitro-triazine (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, 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.

When the crew was returning the drums into the magazine, one drum tipped, which resulted in the securing cam latch opening that then released the drum lid. This allowed M-9 propellant to spill from the drum. The spilled propellant ignited and the fire spread to the propellant in the drum. What happened next is subject to conjecture, and will be discussed later after a review of tests. Again, as was mentioned earlier, the closest witnesses to an accident are often the first fatalities.

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 45).

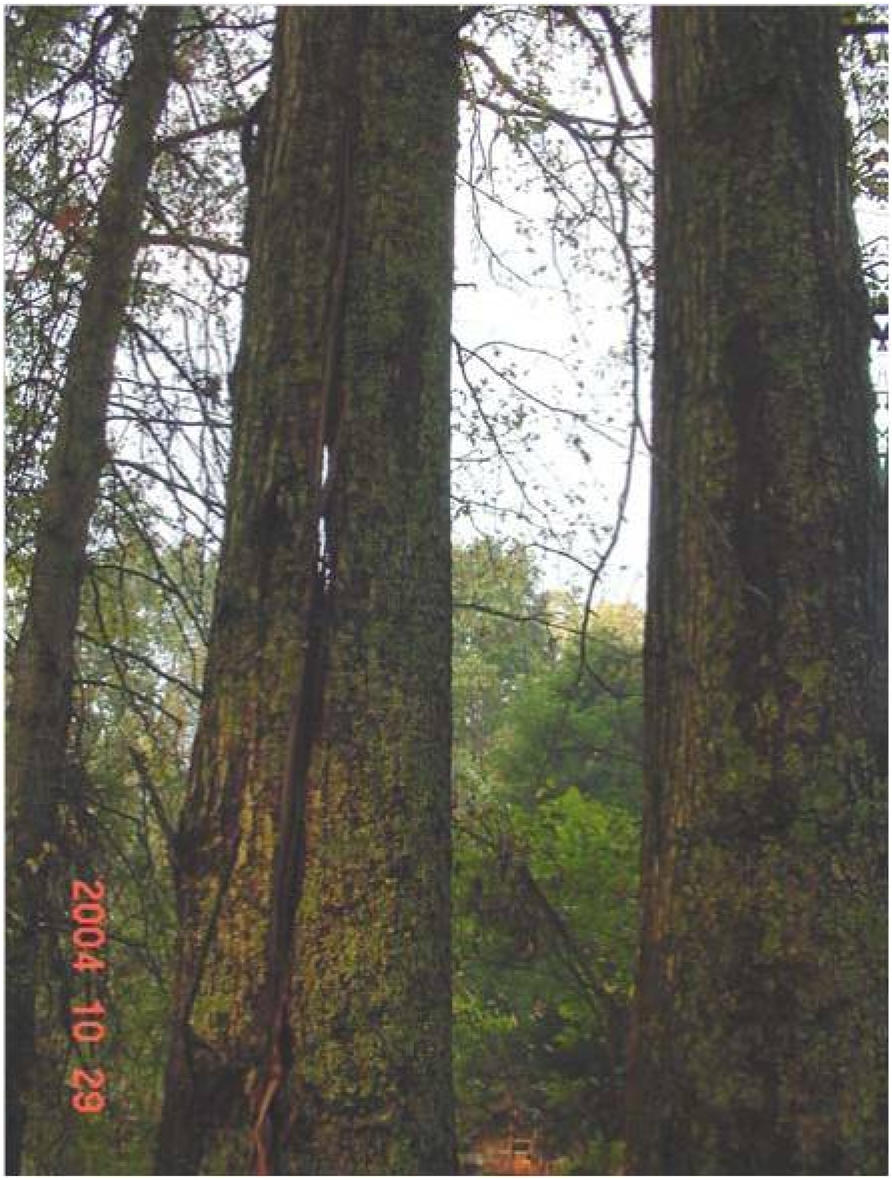
FIGURE 45. Large Fragment That Landed Between Magazines P-70 and P-71.

Some of the debris resulted from large fragments breaking up into smaller fragments on impact. There was also evidence of significant fragments traveling distances significantly greater than the 1,250-foot radius IBD arc (Figure 46). For example, there was significant damage to a tree located 2,100 feet in front of ECM-69, as shown in Figure 47 that presents photographs of the tree and the debris found at the base of the tree.

FIGURE 46. Large Fragment That Had Been Part of the Head Wall.
It was found approximately 1,300 feet from the magazine.

(a) Tree impacted by debris shown in (c).

FIGURE 47. Tree Impacted by Debris.



(b) Another view of the tree showing damage.

FIGURE 47. (Contd.)

(c) Debris that caused the damage to tree
located 2,100 feet to the front of ECM P-69.

FIGURE 47. (Contd.)

Other debris estimated to have been a 6- by 8-foot section from the head wall significantly damaged a tree 3,100 feet from ECM-69 shown in Figure 48. Obviously, this is well beyond the 1,250-foot IBD arc.

FIGURE 48. Tree Approximately 3,100 Feet From P-69 That was Impacted by an Estimated 6- by 8-Foot Section From the Head Wall of P-69.

In addition to fragments from ECM-69, there was also damage to railcars. The railcar pictured in Figure 49 was located on the rail line that serviced ECM P-69. As shown in Figure 49, there was significant damage to the railcar and many large steel fragments were torn from it and projected long distances.

FIGURE 49. Railcar That Had Been Located on Rail Line That Serviced ECM P-69.

Obviously, many large fragments were found at distances greater than the 1,250-foot IBD arc for magazine ECM-69.

The U.S. Army Technical Center for Explosives Safety initiated an effort to study the debris fields and dispersion of fragments (Reference 23). Four sectors were defined and fragments were mapped and weighed within the sectors. The sectors were an 8-degree wide sector extended from the center of the front of the magazine (Sector D), a 13-degree wide sector from the side of the magazine (Sector A), a 10-degree wide sector about midway between the side and back of the magazine (Sector B), and a 14-degree wide sector midway between the front and opposite side of the magazine (Sector C) as illustrated in Figure 50.

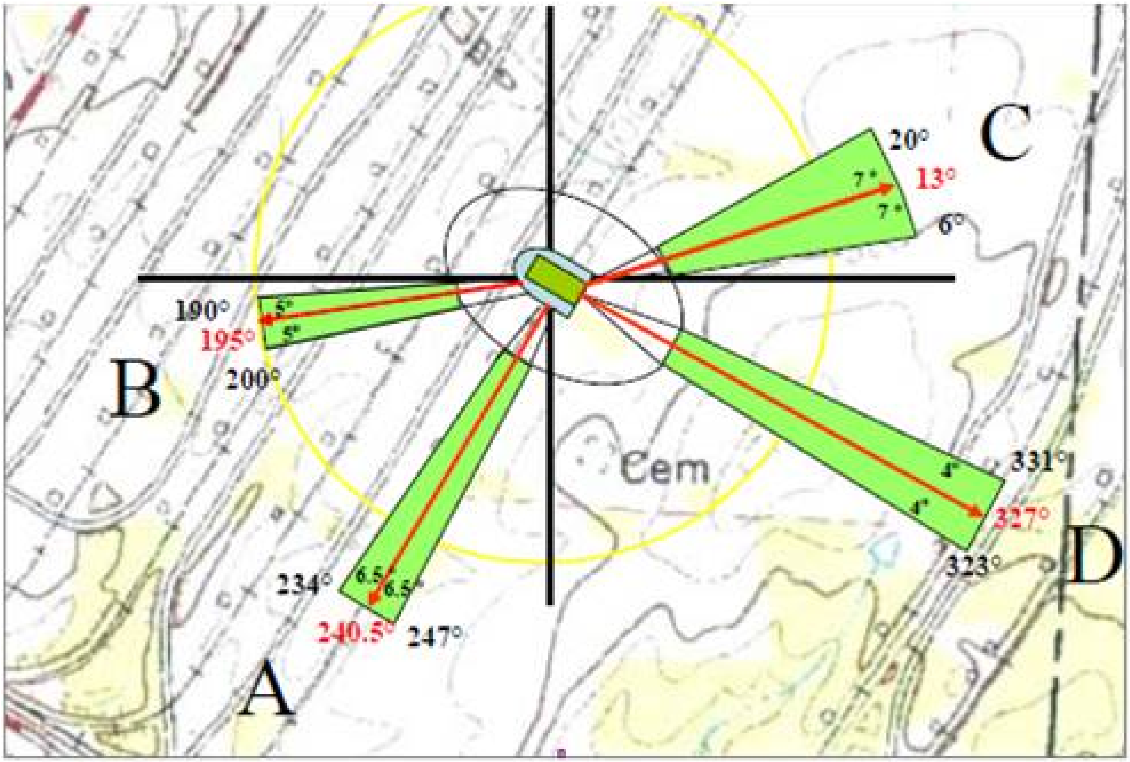


FIGURE 50. Search Sectors.

All fragments were secondary fragments originating from the structural elements of the ECM. No primary fragments (fragments from the HD 1.1 materials) were recovered. Most of the fragments were concrete, rebar, or a combination of both. Emphasis was placed on hazardous fragments having an impact energy of 58 foot-pounds (ft-lb) or greater and/or a weight greater than 6.17 ounces or 175.5 grams. The vast majority of the fragments were hazardous. The fragments were addressed in two fashions: one was simply a unit count, each fragment counted as one item regardless of size and weight, 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 ounces). 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 square feet) from 1,250- to 1,300-foot radius, and then 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 then again at about 1,550 feet.
- Sector B. There are essentially no problems for either the unit or weight-based count within a 1,250- to 2,400-foot radius.
- Sector C. There are essentially no problems for the unit count method within the 1,250- to 1,841-foot radius, but there are problems with the weight count over this

same range of radii, with almost a 400 fragment/600 square foot weight count at about 1,600-foot 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-foot IBD arc in one sector (A).
- The use of weight-equivalent count indicates excessive hazardous fragment density beyond the 1,250-foot IBD arc in three sectors (A, C, and D).

In addition to the sectors previously described, 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 51).

FIGURE 51. Fragment Found in Close Proximity to ECM P-6, Approximately 2,050 Feet Away From ECM P-69.

Lessons learned from the Milan October 2004 accident include:

- An accident that starts with a fire can very quickly spread especially when powder or granular material is present. As will be discussed in the testing section, a fire with gunpowder can build to 10 bars internal pressure in a second, and quickly rupture an ECM.
- The minimum IBD for storage of more than 500 pounds and less than 50,000 pounds of HD 1.1 in an ECM is 1,250 feet. The total amount of energetic materials stored in P-69 was 22,353 pounds (4,599 pounds of Composition A-5, 5,307 pounds of M-2, and 12,447 pounds of M-9 propellant). ECM P-69 was sited for 1,250-foot IBD. Yet the fragment recovery effort showed that significant numbers of hazardous fragments (hazardous fragment density greater than 1 hazardous fragment/600 square feet) were projected to distances significantly greater than 1,250 feet. For example, many fragments were documented at distances greater than 2,700 feet.
- Many very large fragments were produced and traveled significant distances.
- The current tables for safe-separation (Q-D) may need to be re-examined in light of the large number of hazardous fragments, and the high hazardous fragment density (greater than 1 hazardous fragment/600 square feet), that occurred outside the 1,250-foot IBD arc.
- In tests and trials, the explosive materials are often initiated so that they react simultaneously (explosives are simultaneously boosted so that all the material quickly detonates). In accidents, the reaction may start with an inadvertent fire that may result in an explosion, or perhaps a deflagration-to-detonation transition that in turn may result in mass detonation. Perhaps some trials need to be performed where some material is ignited and the reactions must then propagate to adjacent stores. This will be more fully discussed in later sections after testing has been discussed.

Williams, K., "Army Class A Accident, Earth Covered Magazine on 13 October 2004," presented at 2006 DDESB Seminar.
Personal communication between Lyn Little, Josephine Covino, and Thom Boggs.
Defense Group, Inc., "Milan AAP Explosion Hazardous Fragment Density Analysis" vugraph presentation, 10 October 2005.
Defense Group Inc., "Milan Army Ammunition Plant Earth-Covered Magazine Explosion (13 October 2004) Hazardous Fragment Density Analysis" 1 December 2005.
Vesely, Todd, "Milan Fragment Report 1" pdf file, 2.45mb.
http://www.armyproperty.com?Resources/Countermeasure-Magazine
Logistics Management Specialist, U.S. Army Technical Center for Explosives Safety, McAlester, OK.

JUBA, SUDAN, 23 FEBRUARY 2005

On 23 February 2005, explosions at a military depot in Juba, southern Sudan killed 31 (another source lists 80 fatalities) and injured an additional 150 people while a number remained unaccounted for. An official statement from the Government of South Sudan said that the cause of the explosions was due to high temperatures. One report (MSIAC) reported evacuation by soldiers 10 minutes before the first explosion, indicating fire and/or smoke before first explosion. The blasts scattered shells and mortar shells over a radius of 2 kilometers into residential and market areas. The explosion and ensuing fire extensively damaged and burned 900 local housing units in a nearby residential area. Approximately 660 households were affected and over 3,000 people were homeless after losing their housing. The Customs Market, the second largest market in the area, was also completely gutted, disrupting the livelihoods of thousands of people who depended on the market.

http://news.bbc.co.uk/2/hi/africa/4294287.stm
http://reliefweb.int/node/168820/pdf
Disaster Relief Emergency Fund, *Sudan: Explosion in Juba, Final Report,* 05ME014, 27 October 2006.
United Nations Mine Action Office, Sudan, *Newsletter, December 2006.*
MSIAC, *MSIAC Newsletter 2nd Quarter 2005,* page 8.

KADUNA, NIGERIA, 23 FEBRUARY 2005

Fires and blasts occurred at the Dallett Barracks, home to Nigeria's 1 Mechanized Division, in Kaduna, Nigeria, at about 5:00 p.m. on 23 February 2005. The fires and blasts lasted until approximately 7:00 p.m. Two different causes were reported. One said that it was due to burning of brush adjacent to the arsenal that then spread to the arsenal triggering at least six consecutive blasts (e.g., MSIAC report). The other reported cause was due to a prolonged power outage that resulted in loss of cooling in the storage area causing aged bombs to explode. There were four fatalities and 44 injured.

http://news.biafranigeriaworld.com/archive/2005/02/24/index.php
http://allafrica.com/stories/200502240413.html
http://allafrica.com/stories/200502250375.html
http://allafrica.com/stories/200502280152.html
MSIAC, *MSIAC Newsletter 2nd Quarter 2005*, page 8.

ANDONG CHEN, CAMBODIA, 31 MARCH 2005

Several reports that listed accidents had an entry of an accident that occurred at Andong Chen, Cambodia on 31 March 2005. All the reports listed six fatalities and 20 injuries, and listed the probable cause as high temperatures. The MSIAC report lists overheating and the storage of aging artillery shells and TNT powder as probable causes.

Police said that the explosion projected shrapnel and rockets through the air with some of them landing up to 4 kilometers away. The magazine stored 50 tonnes of ammunition that were destroyed in the blast, with subsequent detonations scattering more than 1,300 artillery shells.

Parliamentary Forum on Small Arms and Light Weapons, *Conventional Ammunition Stockpiles Parliamentary Handbook 2008*, page 8.
The Hague International Model United Nations 2010/XLII Annual Session, page 13.
Red Cross, *Book I: Weapon Contamination Environment,* page 28.
Wilkinson, A., Explosive *Remnants of War (ERW), Undesired Explosive Events in Ammunition Storage Areas,* Geneva International Centre for Humanitarian Demining, page 253.
MSIAC, *MSIAC Newsletter, 2nd Quarter 2005*, page 8.

BAJGAH, AFGHANISTAN, 2 MAY 2005

An explosion on 2 May 2005 resulted in 28 fatalities (mostly women and children), at least 13 injured (another report listed 30 fatalities and 70 injuries) and leveled 25 houses and damaged 20 others in Bajgah, in the northern part of Afghanistan. The explosion was at an illegal munitions storage compound. The ammunition included artillery and tank shells, rocket-propelled grenades, and smaller ammunition. The munitions belonged to a former militia commander, Jalal Bajgah, who had said that he had disarmed. Much of the munitions were from the Russian occupation. Bajgah had contacted Dutch NATO peacekeeping troops about moving the old weapons to safety. The cause of initiation is unknown.

http://news.bbc.co.uk/2/hi/south_asia/4508801.stm
http://www.afghanistannewscenter.com/news/2005/may/may62005.html
http://www.irinnews.org/PrintReport.aspx?ReportID=285832
http://hinduvoice.net/cgi-bin/dada/mail.cgi?flavor+archive;list=NL;id=20050505205743
http://reliefweb.int/node/172907

GUATEMALA CITY, GUATEMALA, 18 JUNE 2005

Two ammunition warehouses caught fire resulting in explosions at a military base near Guatemala City on 18 June 2005. No serious injuries were reported.

MSIAC, *MSIAC Newsletter 2nd Quarter 2005*, page 8.

NOVOBOGDANOVKA, UKRAINE, 23 JULY 2005

A fire caused an explosion at the Novobogdanovka military base on 23 July 2005 and resulted in criminal charges being filed on 25 July 2005. Although there were no casualties, the fire brought the Moscow-Simferopol railroad line to a standstill, delaying trains for more than 24 hours and redirecting them through Kiev.

MSIAC, *MSIAC Newsletter 3rd Quarter 2005,* page 9.

PACIFIC FLEET AMMUNITION DEPOT, KAMCHATKA PENINSULA, RUSSIA, 30 SEPTEMBER 2005

The arsenal, covering 75 hectares with 27 open-air ammunition storage areas, near the town of Yuzhnye Koriaki in the Russian Far East caught fire around 6:00 p.m. (Moscow time) on 30 September 2005. It burned for several days. Much of the materiel was ammunition designated for disposal. While there were no fatalities and only one injury, about 7,500 residents from five villages were evacuated. The ensuing explosions resulted in munitions projected out to distances on the order of 4 to 8 kilometers. One shell hit a residence 2 kilometers from the depot.

http://dlib.eastview.com/browse/doc/8355877
http://www.irinnews.org/report.aspx?reportid=94384
Valkov, Valery, *Prisoners of Arsenals,* RusNavy.com article lists many of the accidents at Russian depots.

WALIKALE, NORD-KIVU, DEMOCRATIC REPUBLIC OF CONGO, 25 NOVEMBER 2005

Six persons were killed when a military arms depot of the Eighty-fourth Brigade was struck by lightning on 25 November 2005. The victims were four soldiers and two civilians.

MSIAC, *MSIAC Newsletter 4th Quarter 2005,* page 10.

JABAL SARAJ, AFGHANISTAN, 23 MARCH 2006

Two people were killed and 60 were injured in a huge blast at a store of confiscated weapons in the northern Afghan province of Parwan. The fire broke out at about 7:30 p.m. on 23 March 2006 at the Afghan National Army headquarters in the Tapa Sorkh area of the Jabal Saraj district. The weapons were collected under the Disarmament of Illegal Armed Groups Program sponsored by the United Nations Development Program. There was speculation that leaking white phosphorus munitions may have started the fires that, in turn, lead to the explosions.

http://www.highbeam.com/doc/1P2-16009472.html
http://www.rferl.org/articleprintview/1067041.html
Bureau of Political-Military Affairs, *Dangerous Depots: The Growing Humanitarian Problem Posed by Aging and Poorly Maintained Munitions Storage Sites Around the World, The DISAM Journal, March 2009,* pp. 65-69.

JUBA, SUDAN, 19 MAY 2006

A fire at a munitions dump sparked a series of explosions on 19 May 2006. The fire caused intermittent explosions for about 90 minutes, and resulted in the death of two Sudanese soldiers and injured at least 10 people, including a United Nations (UN) monitor.

MSIAC, *MSIAC Newsletter 2nd Quarter 2006,* page 10.

IOWA ARMY AMMUNITION PLANT (IAAP), MIDDLETOWN, IOWA, U.S., 12 JUNE 2006

An explosion at the IAAP left two American Ordnance workers missing and presumed dead on 12 June 2006. Two other workers received minor injuries. The explosion occurred on line 1 at IAAP. The explosion caused major damage to two buildings. The two missing were the only people scheduled to be working in that part of the plant at that time.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2006,* page 11.

TALON MANUFACTURING, WYOMING COUNTY, WEST VIRGINIA, U.S., 5 JULY 2006

An explosion occurred at the Talon Manufacturing storage facility on 5 July 2006. Firefighters quickly put out the fire, but the State Fire Marshalls evacuated everyone from the area because Talon manufactured and stored ammunition. No injuries were reported. On 6 July it was reported that four cargo containers filled with small arms powder had exploded. The containers were sitting in a fenced parking lot when the explosion occurred.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2006,* page 9.

CAMP MINDEN, LOUISIANA, U.S., 15 JULY 2006

Fire caused an explosion in a Goex, Inc. black powder plant at Camp Minden (formerly the old Louisiana AAP) on 15 July 2006. The explosion caused extensive damage to the plant, destroying one building. The fire apparently started as a grass fire that spread. No one was hurt.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2006,* page 9.

NOVOBOGDANOVKA, UKRAINE, 19 AUGUST 2006

A large fire broke out at the military base A2985 in Novobogdanovka for the second time in three years, mid-afternoon on 19 August 2006. The fire started in dry grass and spread to an area storing shells due for demilitarization and triggered explosions. The explosions in rapid succession continued into the night, hurling shells up to about 300 meters into the air. More than 86,000 pieces of unexploded ammunition were collected. There were no fatalities, but four people were injured. About 1,500 residents had been evacuated from Novobogdanovka, and a further 4,000 had been taken temporally to special shelters. The base held approximately 20,000 tons of ammunition (some reports listed 35,000 tonnes). The fires covered an area of about three hectares (7.5 acres). Damages were estimated to be 596,000 hryvnias ($118,000). Train traffic between Kiev and the Crimean peninsula was severely disrupted.

http://news.kievukraine.info/2006/08/arms-depot-blasts-in-ukraine-injure-4.html
http://groups.yahoo.com/group/PanamaVets/message/25611
http://news.oneindia.in/2006/08/20/fire-triggers-blasts-at-ukraine-arms-depot-4-hurt-1156113207.html
http://dlib.eastview.com/browse/doc/9932293
www.rferl.org/content/article/1070697.html

**EXPLO SYSTEMS, CAMP MINDEN, LOUISIANA,
U.S., 24 AUGUST 2006**

Several explosions occurred at the old Louisiana AAP on 24 August 2006. Officials closed U.S. Highway 80 and Interstate 20 for several hours, evacuated Doyline, and closed two local schools. The sheriff's investigator said that a melting pot, where munitions were rendered down, appeared to be where the first explosions occurred not long after a fire was reported. Residents were allowed to return to their homes on 25 August. The Sheriff said that the fire and blasts left "total devastation," including many craters, the largest 60 feet wide in the middle of what had once been a large concrete building. The Sheriff also said that weapons, including 750-pound bombs, were strewn around the area but did not have detonators.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2006,* page 11.

HADEED MOUNTAIN, KHOUR MAKSAR, ADEN, 6 SEPTEMBER 2006

Explosions, "after friction caused it to heat," killed three people and injured several more. One report said that the explosions continued for about 45 minutes. Two houses caught fire, and several buildings had their windows blown out. The three fatalities occurred when their bus was hit by shrapnel. A senior military official said that the warehouse was used to store old, unusable weapons. The mountain facility stores many military weapons including rockets, guns, and bombs, and those weapons were exploding and launching up to 5 kilometers in all directions for nearly 5 hours.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2006,* page 11.

NIINISALO, FINLAND, 7 SEPTEMBER 2006

A fire broke out in a building reserved for testing munitions in the Niinisalo garrison on 7 September 2006. The building contained six artillery rounds and hundreds of kilograms of gunpowder. The fire resulted in explosions. No one was injured in the fire, but the financial losses could be up to a million euro, since the destroyed testing facility was the only one in Finland.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2006,* page 11.

FORWARD OPERATING BASE FALCON NEAR BAGHDAD, IRAQ, 10 OCTOBER 2006

A fire started by an 82-mm mortar round fired by insurgents occurred at Forward Operating Base (FOB) Falcon near Baghdad at around 10:40 p.m. on 10 October 2006. Falcon is located in a former commercial trucking depot in a sprawling industrial area at 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 arm ammunition. These fires and explosions went on for 12 hours after the original fire. The flames, smoke, and flashes from the explosions could be seen in central Baghdad, which was several miles away. There was significant damage as shown in Figures 52 and 53.

FIGURE 52. Damage at FOB Falcon Near Baghdad, Iraq, 10 October 2006.

FIGURE 53. Damage at FOB Falcon, Near Baghdad, Iraq, 10 October 2006.

Lessons learned include the following:

- Just as was experienced at Camp Doha, Kuwait, in 1991,
  - Fire (in this case caused by the 82-mm mortar round) was the initial stimulus
  - The tank and artillery ordnance and small arms ammunition burned with sporadic explosions for 12 hours. Obviously, the reactions did not occur instantly or simultaneously.

Williams, K. L., "Certificates of Risk Acceptance (CoRAs)," viewgraph presentation, slide 8.
Untitled viewgraph presentation, "FOB Falcon," 5 viewgraphs.
DDESB ESMAM query.
http://www3.dac.army.mil?esidb/login/esmam/query/default.asp?id=20061010I018/14/2007 1:48:19
http://www.globalresearch.ca/index.php?context=viewArticle&code=20061022&articleId=3566
http://www.foxnews.com/printer_friendly_story/0,3566,219422,00.html

PARACIN, SERBIA, 19 OCTOBER 2006

A series of explosions rocked a Serbian army ammunition depot near Paracin, Serbia, injuring about 20 people on 19 October 2006. The first explosion occurred at approximately 3:45 a.m., with the second explosion occurring around 6:00 a.m. The second explosion was the stronger of the two. The warehouse contained 3.5 tons of explosives including mines, high explosives, and ammunition. The explosions were preceded by fire caused by auto-ignition in the 1,200,000 bullets earmarked for destruction.

International Federation of Red Cross and Red Crescent, *Serbia: Explosion in Military Warehouse,* On Formation Bulletin number 1/2006, 19 October 2006.
http://www.ccmr-bg.org/cms/view.php?id=2290
http://fufor.twoday.net/stories/2843760/
http://www.ccmr-bg.org/cms/view.php?id=2410
MSIAC, *MSIAC Newsletter, 4th Quarter 2006,* page 4.

TAEBAEK, S. KOREA, 21 FEBRUARY 2007

An explosion at a gunpowder manufacturing factory killed two workers and injured nine others on 21 February 2007. The explosion occurred at 10:02 a.m. at a waste gunpowder processing facility in the factory where workers were burning defective explosives.

MSIAC, *MSIAC Newsletter, 1st Quarter 2007,* page 7

**MILITARY REPAIR COMPANY, NOVAKY, SLOVAKIA,
2 MARCH 2007**

An explosion in an ammunition factory killed at least three people, left five missing and injured 45 on 2 March 2007. The accident occurred in a factory run by the ministry where military equipment is repaired. The explosion occurred in a building where old ammunition was destroyed. The victims were not soldiers. The explosion leveled the building and several other buildings in the factory complex also collapsed. Three explosions were heard around 4:30 p.m. and a column of flame shot 300 meters in the air. The fire was extinguished after several hours. The explosion resulted in a crater 20 meters in diameter and flattened the hall in which the five missing persons had been working.

MSIAC, *MSIAC Newsletter, 1st Quarter 2007,* pp. 7-8.

**MAPUTO ARMS DEPOT, MALHUXINE, MOZAMBIQUE,
22 MARCH 2007**

On 22 March 2007, an arms depot containing obsolete munitions and materiel that had not been used since the country's civil war experienced a series of explosions occurring over 2 ½ hours that killed 104 people and injured more than 492. Most of the casualties were soldiers working at the depot or residents of the neighborhood surrounding the building. The building was in a residential neighborhood near the international airport. Approximately 64 houses were completely destroyed, seriously affecting 320 people. The Defense Ministry blamed the explosions on fires caused by the high temperatures around 35°C (93°F) that existed for much of the summer. It is likely that the extended high temperatures may have caused depletion of stabilizer in some of the materials and led to auto-ignition of the energetic material.

> [Note: See the accident that occurred in Finland, 1999. It was concluded that that accident was caused by auto-ignition of propellant during periods of high ambient temperatures.]

Resulting fires may have led to the explosions. The deaths and injuries continued after the explosions because munitions had been hurled into the densely populated neighborhood and exploded days and months after the accident.

http://en.wikipedia.org/wiki/2007_Maputo_arms_depot_explosion
http://www.irinnews.org/report.aspx?reortid=94384
MSIAC, *MSIAC Newsletter, 1st Quarter 2007,* page 9.

MILAN AAP, 16 MAY 2007

At 5:05 a.m. Eastern Standard Time (EST) on 16 May 2007, guards at Milan AAP heard a loud noise resembling thunder coming from the direction of the Area N storage area. The Milan Fire Department responded and found extensive flames coming from ECM N-21. The fire 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. 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 (HD 1.3) were stored in the magazine. The magazine was sited for 250,000 pounds of HD 1.1. 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 cause of the accident was likely due to auto-ignition of the M-10 propellant as a result of stabilizer depletion. The ensuing fire pressurized the ECM and blew out the head wall and scattered debris out through the enlarged opening.

The postmortem photographs clearly show that the fire blew out the head wall and scattered debris over an area as shown in Figures 54 through 56. The remaining portion of the ECM was relatively intact as shown in the pictures. There was no evidence of cratering to indicate a detonation occurred. This is in direct contrast to description in the MSIAC accident report that had a base spokesperson saying, "At approximately 5:00 a.m., one of our storage magazines internally detonated. Something happened that caused the detonation to result in a fire." Again, there was no detonation. The fire was likely due to auto-ignition of the M-10 propellant. The fire resulted in pressurization of the magazine. Fortunately, the pressure blew out the front wall resulting in un-choked flow. The un-choked flow resulted in some material dispersed outside the magazine and burning outside as indicated in the photographs.

> [Note: Choked and un-choked flow and why it is so important will be discussed in the section on Testing.]

FIGURE 54. ECM With Head Wall Blown Out and Debris Scattered.

FIGURE 55. ECM With Head Wall Blown Out.

FIGURE 56. Debris Thrown From Magazine Toward Fence.

Evidently, the Army set a value of $2,000 on the destroyed magazine. Since there were no injuries and the value of the magazine falls below the threshold established by DODI 6055.7, reports were not filed with DDESB.

Lessons learned included:

- Once again, M-10 appeared to auto-ignite, probably due to stabilizer depletion.
- As the propellant burned, the pressures within the magazine rose until sufficient to blow out the front wall and expel considerable burning debris.
- The fire continued for approximately 1 hour. Again, reactions occurred over time; the reactions were not instantaneous or simultaneous.

Unfortunately, mapping of debris location and type does not appear to have been performed. This, and the lack of report in the DDESB explosive safety mishap analysis module (ESMAM) database, is regrettable.

An e-mail was sent by Kenyon Williams on 16 May 2007. The e-mail was entitled Pictures of Milan AAP ECM Accident-16 May 2007 and had 8 jpg photographs as enclosures.

Joint Munitions & Lethality Life Cycle Management Command, Department of the Army Bulletin, Vol. 2, Issue 6, June 2007, page 8.

NARENDRA AND COMPANY, DEHRA DUN, INDIA, 17 MAY 2007

Five laborers at a private ammunition factory were killed and five were seriously injured when an ammunition store caught fire, triggering a series of explosions that destroyed the entire factory. The explosions began at 7:35 a.m. on 17 May 2007 while workers were sieving fine particles of gunpowder at an open platform near two storage units. There was about 150 kilograms of explosives in the area at the time of the explosion.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2007,* page 7.

NOVOBOGDANOVKA, UKRAINE, 18 MAY 2007

The third explosion in as many years, and the fourth since May 2004, at Novobogdanovka resulted in two fatalities on 18 May 2007. One person died on site and a second died while on the way to the hospital. The accident occurred while the workers were trying to disarm a missile.

ISRAEL MILITARY INDUSTRIES, ISRAEL, 18 MAY 2007

A fire broke out in a warehouse at a munitions factory, causing a series of explosions on 18 May 2007. No one was hurt in the incident, largely because it was Friday (a non-work day), but the factory was completely destroyed along with tonnes (number of tonnes not given in report) of munitions. The ordnance was due to be destroyed.

MSIAC, MSIAC Newsletter, 2nd Quarter 2007, page 2.

CAMP NGASHI, MBANDAKA, DEMOCRATIC REPUBLIC OF CONGO, 17 JUNE 2007

A Congolese Armed Forces (Forces Armées de la République Démocratique du Congo [FARDC]) ammunition stockpile at Mbandaka exploded on 17 June 2007. The facility housed large- and small-scale weapons, small arms ammunition, and different caliber mortars and rockets, up to large aerial bombs. The initial explosion caused a huge fire that burned intensely for at least 6 hours, setting off numerous subsequent large explosions. The cause of the first explosion is unknown. Ammunition was ejected up to 3.5 kilometers outside of the camp. Three people were killed, around 100 injured, and over 200 families were displaced. The Mines Advisory Group (MAG) worked with the FARDC to destroy 3,500 weapons, 5,000 items of UXO, and 35 tons of munitions. Following the incident at Camp Ngashi, the remaining ammunition was regrouped in Bokala Camp, which had its own incident in August 2010.

Komorowski, Adam, *Testimony to the House Armed Services Committee on the work of the Mines Advisory Group in the Democratic Republic of the Congo,* 9 pp.
MSIAC, *MSIAC Newsletter 3rd Quarter 2007,* page 4.

MALHUXINE, MOZAMBIQUE, 23 JUNE 2007

During cleanup of unexploded ordnance from the 22 March 2007 disaster described above an additional 5 people were killed and 11 injured.

Parliamentary Forum on Small Arms and Light Weapons, *Conventional Ammunition Stockpiles Parliamentary Handbook 2008,* ISBN 978-91-633-3524-2, Annex A Ammunition Depot Explosions, pp. 6-10.
Berman, E.G., *The Threats of Excess Stockpiled Weapons and Unstable Munitions,* Southeast Europe Regional Approach to Stockpile Reduction of Conventional Weapons and Munitions, Zagreb, Croatia, 6 May 2009.
Tracey, L., *Ticking Time Bombs,* Institute for Security Studies, ISS Paper 223, April 2011, pp. 2-3.

BHADRAWATI ORDNANCE FACTORY,
INDIA, 29 JUNE 2007

A fire caused over 3,000 bombs stacked in two cellars to explode on 29 June 2007. There were no casualties. The cause of the fire was unknown. Preliminary estimates put the cost at nearly Rs 25 million (400,000 USD). The fire that broke out in the afternoon was brought under control after 2 hours. Solitary explosions continued until late evening.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2007,* page 5.

ALEPPO, SYRIA, 26 JULY 2007

High summer temperatures of 45°C caused fires that may have spread to the military complex that resulted in explosions at 9:00 a.m. on 26 July 2007. A total of 15 soldiers were killed and 50 wounded.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2007,* page 5.

KHANDROO, SOUTH KASHMIR, INDIA, 11 AUGUST 2007

At least 30 people were killed and 40 others wounded when a major fire broke out at the Army ammunition depot on 11 August 2007 resulting in explosions. White phosphorous reportedly caused the fire. About 35,000 villagers inhabiting 13 villages were evacuated. The fire continued to burn on 12 August.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2007,* page 6.

ROMARM SA MIJA PLANT, DAMBOVITZA, ROMANIA, 20 SEPTEMBER 2007

Four people were injured in an explosion at a munitions factory, Romarm SA, on 20 September 2007. The explosion occurred in the pyrotechnics section where the team was deactivating munitions. The munitions caught fire with the explosion following the fire. Three people suffered 30% burns and the fourth was slightly injured.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2007,* page 9.

MINH SON, VIETNAM, 20 SEPTEMBER 2007

Three soldiers were killed and four others wounded in an explosion at an Army powder magazine on 20 September 2007. The explosions damaged several tens of houses. People were evacuated while soldiers collected unexploded ordnance. The article linked the accident to other accidents where the cause was ammunition deterioration.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2007,* page 9.

FABRICA Y MAESTRANZA DEL EJERCITO DE CHILE, TALAGANTE, CHILE, 25 SEPTEMBER 2007

Four people were seriously injured in an explosion that occurred at 8:45 a.m. on 25 September 2007 during propellant deactivation operations. The incident occurred during the destruction of powder by burning. One of the injured had burns over 60% of his body and another had severe burns to the respiratory tract.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2007,* page 9.

BOMBONA BATTALION, MEDELLIN, COLOMBIA, 29 DECEMBER 2007

Six soldiers were missing and eight others injured after an ammunition depot blew up in Medellin, Colombia, on 29 December 2007. Later reports list six soldiers killed and six soldiers and four firefighters injured. The first of at least six blasts and fires was apparently triggered by a grenade that detonated inside the Bombona Battalion arsenal. Smaller explosions continued in the afternoon. It took firefighting crews over 8 hours to put out the blazes. Authorities said that hundreds of families from nearby houses were evacuated. More than 50% of the installation was destroyed and live grenades were found in a school and convent in the neighborhood. Windows, doors, and ceilings were destroyed in numerous buildings in the surrounding area. Figures 57 and 58 show the fires at the arsenal.

FIGURE 57. Fire at the Bombona Battalion Arsenal,
Medellin, Colombia, 29 December 2007.

FIGURE 58. Fire at the Bombona Battalion Arsenal,
Medellin Colombia, 29 December 2007.

http://covertress.blogspot.com/2008/08/dangerous-depots.html
http://www.abc.net.au/news/2007-12-30/colombia-ammunition-depot-explodes-six-missing/999012
http://www.democraticunderground.com/discussduboard.php?az=view_all&address=102x...[No longer available]
MSIAC, *MSIAC Newsletter, 4th Quarter 2007,* page 8.

GERDEC, ALBANIA, 15 MARCH 2008

A fire that started at approximately noon on 15 March 2008 caused a series of explosions that continued until 2:00 a.m. the next morning. The main explosion, involving more than 400 tons of propellant in containers, destroyed hundreds of houses, broke windows in cars on the Tirana-Durres highway, and shattered all of the windows at the terminal building at the country's only international airport. Unexploded ammunition and shell casings were dispersed through-out a radius of 2.7 kilometers. About 4,000 people were evacuated. There were 26 fatalities and one unaccounted for and approximately 300 injured. A total of 4,143 houses and business were reported damaged, with 308 destroyed and 3,835 heavily or partially damaged. The detonations carved out three large craters, the deepest over 100 feet.

There was an eyewitness to the start of the fire. Hekuran and Zelie Kaca, parents of a 4-year-old son and a 2-year-old daughter, worked at the depot. Hekuran and his wife worked in a four person crew. Around midday on 15 March, the factory director told Mr. Kaca that he could not take his lunch break until he had moved bags of reclaimed gunpowder to nearby storage containers. As Hekuran was taking the first load, a fire started in excess gunpowder on the ground, cutting him off from his wife. "Zelie, it's a fire, get out quickly," he recalled yelling to her, before running from the explosion he knew was coming. Mr. Kaca hoped that his wife had made it out the main entrance. The fire caused a column of smoke to raise high into the sky, sending villagers scrambling for the woods or underground bunkers. Without that warning, several said, the death toll would have been much higher.

With no news about his wife's fate, after searching morgues and hospitals, he finally returned to the site. Two days after the explosion, he sneaked back into the closed-off site. He found four bodies at the spot where he used to work, all burned beyond recognition. DNA (deoxyribonucleic acid) evidence confirmed a week later that his wife had been killed at the site.

The above details were from the *New York Times* article cited below:

http://www.nytimes.com/2008/04/19/world/europe/19albania.html?pagewanted=print
http://en.wikipedia.org/wiki/2008_G%C3%ABrdec_explosions
http://www.cbsnews.com/stories/2008/03/15/world/main3941268.shtml
http://articles.nydailynews.com/2008-03-15/news/17893334_1_prime-minister-Sali-berisha-tirana-explosion
United Nations Disaster Assessment & Coordination (UNDAC), *Assessments and recommendations following the Gerdec Explosions Albania 20 March-3 April 2008,* 8 April 2008.
MSIAC, *MSIAC Newsletter, 1st Quarter 2008,* page 8.

LODEINOPOLSKY, NEAR LENINGRAD, RUSSIA, 23 MARCH 2008

A fire at the aviation munitions depot of the 6th Army Strategic Air Command and Defense began at around 3:00 p.m. on 23 March 2008. In 1 hour, the fire destroyed 430 air-to-air missiles at a cost of 766.34 million rubles. There were no fatalities or injuries. The fire was blamed on smoking by personnel, but one version said the fire could have been caused by burning grass.

http://en.novayagazeta.ru/society/46877.html
http://novayagazeta.ru/society/46877.html?print=1
MSIAC, *MSIAC Newsletter, 2nd Quarter 2008,* page 6.

Another source listed a very similar accident at this same location but occurring on 23 May 2008. The article states that the fire began and within 1 hour destroyed the air-to-air missiles of unit 10232 of the Sixth Air Force and Air Defense Forces army. It stated that 450 missiles for the Su-27 interceptor fighters were stored at Lodeinoe Pole. These were mostly R-27 missiles of various modifications. The warheads for the missiles were stored in a separate area. Since the warheads were not involved, the estimated loss of the missiles was approximately $30 to 40 million.

http://dlib.eastview.com/browse/doc/15655030
http://news.bbc.co.uk/2/hi/europe/7418860.stm
Since the two sets of articles are so similar it is only listed as one entry.

AMMUNITION DEPOT ON THE ISLAND OF KINMEN, TAIWAN, 7 JUNE 2008

An underground ammunition depot on the island of Kinmen was on fire on 7 June 2008. The fire erupted in a tunnel at about 10:00 p.m. There were more than 27,000 munitions stored at the depot. All of the materials were obsolete and were scheduled to be disposed of in July. It was suggested that the fire might have been caused by self-ignition of the chemicals in the smoke canisters and flare bombs.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2008,* page 8.

CHELOPECHENE, NEAR SOFIA, BULGARIA, 3 JULY 2008

A fire that started at 6:00 a.m. preceded a series of powerful explosions that occurred about 6:30 a.m. and rocked an arms disposal depot storing 1,500 tonnes of obsolete munitions and 15 to 20 tonnes of TNT, injuring three people, damaging apartments, and resulting in evacuations of about 2,000 residents. The explosions continued for about

8 hours. NATO member Albania is due to destroy up to 100,000 tonnes of Soviet-era munitions.

http://uk.reuters.com/assets/print?aid=UKL0310406520080703
http://archive.ekathimerini.com/4dcgi/_w_articles_world_1_04/07/2008_98261
www.dailymail.co.uk/news/article-1031575/Arms-dump-explosions-rock-Bulgarian-capital---city-struck-earthquake.html
MSIAC, *MSIAC Newsletter, 3rd Quarter 2008,* pp. 6-7.

KAGAN, UZBEKISTAN, 9 JULY 2008

A fire broke out late on 9 July 2008 at a military base located near Kagan, Uzbekistan. The fire is thought to have started at the Soviet-era helicopter base and, despite efforts by soldiers to put it out, spread to an adjacent ammunition depot containing rockets and other explosive devices. The flames caused the munitions to explode. The first explosion occurred at 1:48 a.m. on 10 July. Three people died and there were 21 injured. (Although the Russia-based Ferghana news service said that casualties were much higher.) Kagan was evacuated. Witnesses said that a five-story building and a hospital close to the base were completely destroyed and that houses near the depot were razed to the ground. The explosions shattered windows in the city of Bukhara nearly 10 kilometers away.

http://www.reuters.com/assets/print?aid=USL1072672720080710
http://www.eurasianet.org/departments/insight/articles/eav071008a.shtml
http://en.wikinews.org/wiki/Comments:Uzbekistan_arms_depot_explosions_leave_three_dead
MSIAC, *MSIAC Newsletter, 3rd Quarter 2008,* page 7.

61ST ARSENAL NEAR LOZOVAYA, UKRAINE, 27 AUGUST 2008

A fire started in the forest near Lozovaya, Ukraine, a city of about 64,000 residents, on 27 August 2008. Due to high winds the firefighters could not contain the fire and it spread to the 500-hectare (1,235-acre) site 0829 that contained 94,300 tonnes of ammunition. About one half of the ammunition was slated for disposal. The fire caused explosions at two sites at about 4:00 p.m. where 120-mm mortar shells were stored. Because of the danger due to fire spreading to anti-tank rockets that had a range of several kilometers, Kiev declared a state of emergency and evacuated residents of the surrounding communities out to a radius of 5 kilometers. The explosions continued for several days. It was reported that 247 hectares of the arsenal territory were destroyed by the fires and only 15 of the 134 storage units remained untouched by the fires and blast. The blasts scattered much of the munitions. It was reported that about 4,500 pieces of unexploded munitions were recovered. There were no fatalities and only two injured. This installation was due to be closed in 2010.

http://www.eer.ru/en/news/2994.html
http://engforum.pravda.ru/index.php?topic/149234-kiev-declares-state-of-emergency-as-arsenal-fire-spreads/
http://for-ua.org/ukraine/2008/09/04/102916.html
http://verdimozart.wordpress.com/2008/08/27/blaze-sweeps-through-military-depot-in-east-ukraine/
http://rt.com/news/more-blasts-hit-ukrainian-arms-depot/
http://rt.com/news/ukrainians-rush-from-arms-depot-explosion/
http://dlib.eastview.com/browse/doc/18829038
MSIAC, *MSIAC Newsletter, 3rd Quarter 2008,* page 11.

AEROJET HIGHLAND INDUSTRIAL PARK, EAST CAMDEN, ARKANSAS, U.S., 17 SEPTEMBER 2008

One worker was killed when a rocket motor inadvertently ignited and exploded at the Aerojet plant on 17 September 2008. A spokesperson said that when the motor ignited a wall of the bay blew out as it was designed to do in case of emergencies. She also said that a part of the concrete bunker was damaged.

MSIAC, *MSIAC Newsletter, 4th Quarter 2004.*

PACIFIC OCEAN FLEET MUNITIONS DEPOT, FOKINO, RUSSIA, 30 SEPTEMBER 2008

A direct lightning strike on a depot building caused fires and explosions at around 3:30 p.m. at the Pacific Ocean Fleet munitions depot near Fokino, Russia, on 30 September 2008. There were no casualties.

http://rusnavy.com/news/column/prisoners.htm
http://en.novayagazeta.ru/society/46877.html
http://dlib.eastview.com/browse/doc/21941822

KAZAN, TATARSTAN, RUSSIA, 25 OCTOBER 2008

Four people were killed and five injured by an explosion in Kazan's gunpowder factory on 25 October 2008. The explosion occurred in a one story building on the factory grounds at 1:20 p.m. Moscow time. As a result, one third of the building partly collapsed in an area of 200 square meters. Nine workers were trapped under the debris. Four bodies and five survivors were recovered during the rescue operation. All of the injured were taken to the local burns treatment center.

MSIAC, *MSIAC Newsletter, 4th Quarter 2008,* pp. 11-12.

GANDHIDHAM, INDIA, 4 DECEMBER 2008

A fire in the Army ammunition depot near Galpadar village resulted in a blast that occurred on 4 December 2008 at around 5:00 p.m. The blast killed two soldiers and injured six others. The explosion that occurred at around 5:00 p.m. was caused by the fire in the depot.

MSIAC, *MSIAC Newsletter, 4th Quarter 2008,* page 13.

ORDNANCE FACTORY, JAWAHAR NAGAR, INDIA, 5 DECEMBER 2008

An explosion of propellant for artillery shells being made at the ordnance factory killed two workers and injured four others. Two of the injured sustained burns covering approximately 100% of their bodies and were stated to be very critical (and probably perished). The victims were handling nitroglycerine/nitrocellulose paste. The unit in which the accident took place dries the chemical that is processed at 80°C, and after a day of cooling it is unloaded. The chemical is so sensitive that even a small spark can trigger an explosion.

MSIAC, *MSIAC Newsletter, 4th Quarter 2008,* page 13.

AMMUNITION DISPOSAL PLANT, POLICAN, ALBANIA, 6 JANUARY 2009

One worker, a member of a six person team, was killed on 6 January 2009 while dismantling the fuzes of 57-mm shells. The woman dismantling Soviet-era munitions died when a shell fuze exploded after she and coworkers lit a fire nearby to warm themselves. The Defense Ministry said in a statement "To build the fire, they used the remains of the packaging of the fuzes…" According to the Ministry, work at the site had been suspended months ago, but workers were clearing the area of artillery fuzes.

MSIAC, *MSIAC Newsletter, 1st Quarter 2009,* page 5.

MUNITION DEPOT, ARYS, KAZAKSTAN, 20 MARCH 2009

Two people were killed, two were listed as missing and presumed dead, and sixteen were injured in a fire and subsequent explosions at a munitions depot near Arys, Kazakstan, at 9:30 p.m. on 20 March 2009. The munitions were stored for recycling. The fires were extinguished by 195 firefighters and 34 fire engines 7 hours after the fires started.

http://centralasiaonline.com/en_GB/articles/caii/features/2009/06/12/feature-09
MSIAC, *MSIAC Newsletter, 1st Quarter 2009,* page 10.

MBAGALA ARMY BASE, DAR ES SALAAM, TANZANIA, 29 APRIL 2009

A series of explosions occurred beginning at about 11:00 a.m. on 29 April 2009 at the Mbagala military base 15 kilometers from Dar Es Salaam. There were at least three major explosions over 2 hours with shockwaves causing the evacuation of people from high-rise buildings. The explosions caused 26 deaths (other reports listed 40 civilian deaths), over 1,000 injuries (other reports listed over 500 injuries), and with almost 400 families displaced from their homes. There were 396 homes destroyed (another report listed 400 homes as leveled while yet another report listed as many as 7,000 homes destroyed) and 1,945 homes damaged. The International Federation of Red Cross and Red Crescent Societies estimated some 18,866 persons (3,775 households) were affected. On 26 May 2009, the International Red Cross launched an appeal to care for more than 20,000 Tanzanians made homeless by the explosions. The cause of the explosion remains unknown.

ReliefWeb Briefing Kit for Tanzania: Explosion-May 2009, compiled on 3 August 2011.
http://news.bbc.co.uk/2/hi/africa/8026929.stm
http://www.usaid.gov/our_work/humanitarian_assistance/disaster_assistance/countries/tanza
U.S. Department of State's Bureau of Political-Military Affairs, *Dangerous Depots: The Growing Humanitarian Problem Posed by Aging and Poorly Maintained Munitions Storage Sites,* Summer 2010.
International Federation of Disaster Relief Emergency Fund (DREF), DREF operation no. MDRTZ009, dtd 11 May 2009, 21 May 2009, and 2 February 2010.
MSIAC, *MSIAC Newsletter, 2nd Quarter 2009,* page 5.

OWENSVILLE, OHIO, U.S., 24 MAY 2009

A fire broke out in gunpowder and 0.50-caliber ammunition stored in two semitrailers in Owensville on 24 May 2009. A series of explosions followed. It took county agencies and firefighters from five surrounding fire companies more than 2 hours to put out the fires. The fire chief said that the fires and resulting explosions were dangerous because the crews did not know what was on fire.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2009,* page 7.

JAFFNA, SRI LANKA, 6 JUNE 2009

Fire broke out at the ammunition dump in Jaffna, Sri Lanka on 6 June 2009. Debris was scattered about but there were no fatalities, nor injuries.

Sri Lanka Vanni Emergency Situation Report #21, 11 June 2009.

VAVUNIYA, SRI LANKA, 9 JUNE 2009

On 9 June 2009, a fire broke out at an ammunition dump at the Security Forces Headquarters in Vavuniya, Sri Lanka. The fires caused numerous explosions over a 4-hour period. Debris was widely scattered but there were no fatalities, nor injuries.

Sri Lanka Vanni Emergency situation report #21, 11 June 2009.

ALMATY, KAZAKSTAN, 9 JUNE 2009

At least one person was killed and dozens evacuated after fire caused a chain reaction of explosions that in turn led to ignition of large stores of heavy machine gun ammunition as well as artillery shells resulting in a huge fireball at a Soviet-era ammunition dump outside of Almaty on 9 June 2009. More than 157 emergency and military personnel and 40 pieces of equipment from across the country were sent to contain the fire and search for survivors. One serviceman died in the fire. Approximately 46 families and 120 servicemen were evacuated from the area.

http://centralasiaonline.com/en_GB/articles/caii/features/2009/06/12/feature-09
MSIAC, *MSIAC Newsletter, 2nd Quarter 2009,* page 8.

**TUOL KRAISAING MILITARY CAMP,
CAMBODIA, 28 JUNE 2009**

A truck loaded with rockets and other explosives caught fire and exploded injuring two people at about 7:30 p.m. on 28 June 2009. The fire occurred when a soldier lit a cigarette near a fuel leak in a truck laden with the munitions. One rocket flew over the Cambodian Prime Minister's house that is located at the military camp. About 30 rockets were destroyed in the blast, but there were no detonations.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2009,* page 8.

KARABASH, RUSSIA, 14 SEPTEMBER 2009

A fire broke out in an open area where artillery rounds were kept for demilitarization at approximately noon on 14 September 2009. The fire included roughly two carloads of rounds for 152-mm howitzers at the 96493 army base near Karabash. The fire caused some artillery rounds to detonate. Approximately 3,000 people were evacuated. The explosion caused fragments to be launched in surrounding areas, igniting brush in those areas. Three persons were injured with one of them being the deputy commander of the military unit. He later died in the intensive care unit. The cause of the fire, the discarding of a lit cigarette butt that ignited gunpowder, along with the guilty party, was identified.

http://www.accessmylibrary.com/article-1G1-207826396/deadly-fire-ammunition-depot.html
http://dlib.eastview.com/browse/doc/20620830
http://www.accessmylibrary.com/article-1G1-207925818/russia-conscript-blamed-fire.html
http://dlib.eastview.com/browse/doc/20636411
http://en.novayagazeta.ru/data/2011/060/01.html
MSIAC, *MSIAC Newsletter, 2nd Quarter 2009,* page 10.

HIGH ENERGY MATERIAL RESEARCH LABORATORY, SUTARWADI, PUNE, INDIA, 30 SEPTEMBER 2009

An explosion occurred around 3:45 p.m. during a remotely-controlled propellant mixing operation on 30 September 2009. The frangible roof was blown off the building. There were no casualties or injuries reported. The batch of propellant was 300 to 350 kilograms and was the next to last one of that size before scaling up the mixing to 1 tonne of propellant. This accident is an example of where several safety considerations "went right." The hardened cell with frangible roof obviously worked as planned, and the propellant that reacted was part of a program where the batch sizes were systematically scaled up in size.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2009,* page 11.

NAVY ARSENAL 31 DEPOT, ULYANOVSK, RUSSIA, 13 NOVEMBER 2009

Fire broke out in the military depot in Ulyanovsk, Russia at about 4:00 p.m. local time while ammunition was being disposed of at the depot. The resulting explosion set off additional explosions and fires. One report said that explosions went off about every 30 seconds. A local resident described it as follows: "There was a loud bang, then there was silence, and then there were explosions, explosions, explosions, like fireworks on New Year." The fires raged for several hours. At least 400 firefighters battled the blazes. It was estimated that around 120 tonnes of shells blew up. The resulting losses totaled more than 60 million rubles (1,989,000 USD). The fires and explosions resulted in two fatalities and 60 injuries. About 3,000 residents were evacuated from the surrounding area. Windows were shattered in houses several kilometers away. The fires and explosions destroyed about 200 structures—nearly half of the city. The governor of Ulyanovsk said that "a violation of procedures in technology of cutting ammunition" caused the fire. Figures 59 and 60 show some of the reactions.

FIGURE 59. Reaction Scene, Ulyanovsk, Russia, 13 November 2009.

FIGURE 60. Reaction Scene, Ulyanovsk, Russia, 13 November 2009.

http://www.reuters.com/assets/print?aid=USTRE5AC2ZU20091113
http://news.bbc.co.uk/2/hi/8359359.stm
http://www.unvamagazine.com/news-around-the-world/explosion-at-ulyanovsk-rus sian-military-depot-kills-several-and-devastates-town-2
http://www.msnbc.msn.com/id/33911663/ns/world-news-europe/t/blasts-russian-ammo-depot
http://en.novayagazeta.ru/data/2011/060/01.html
MSIAC, *MSIAC Newsletter, 4th Quarter 2009*, page 10.

NAVY ARSENAL 31, ULYANOVSK, RUSSIA, 23 NOVEMBER 2009

Ten days after the fires and explosions at the Navy Arsenal 31, eight Russian bomb disposal experts were killed while cleaning up after the previous fires and explosions. Two others were injured. The accident occurred at 2:30 p.m. when the team was loading ammunition into a truck. One report said that a shell "self-detonated," setting off ammunition already on the truck.

http://edition.cnn.com/2009/WORLD/europe/11/23/russia.explosion/
http://www.unvamagazine.com/news-around-the-world/another-deadly-explosion-at-ulyan...
http://www.broowaha.com/article/printArticle/5489
http://en.novayagazeta.ru/data/2011/060/01.html
MSIAC, *MSIAC Newsletter, 4th Quarter 2009,* page 11.

MIDZHUR EXPLOSIVES PLANT, GORNI LOM, BULGARIA, 3 FEBRUARY 2010

Four people were injured in an explosion that occurred at 6:12 p.m. at the Midzhur explosives plant on 3 February 2010. A fire broke out in a warehouse of a private firm and then spread to a building where 10 tonnes of ammonite were stored, resulting in an explosion. Firefighters arrived at the scene but withdrew after the first explosion. Explosions were reported throughout the night.

MSIAC, *MSIAC Newsletter, 1st Quarter 2010,* pp. 7-8.

UKROBORONSERVIS ENTERPRISE, HRUZEVYTSYA, UKRAINE, 13 MARCH 2010

A fire caused detonation of ammunition at the state-run Ukroboronservis enterprise on 13 March 2010. The fire started around 1:00 p.m. Greenwich Mean Time (GMT). Small caliber 23-mm explosive ammunition for aircraft detonated in the fire. The fire was put out at 2:10 p.m. One person was slightly injured.

MSIAC, *MSIAC Newsletter, 1st Quarter 2010,* page 9.

AMMUNITION DEPOT, PANAGARH, WEST BENGAL, INDIA, 26 MARCH 2010

An ammunition depot caught fire around 1:15 a.m. at the army base in Panagarh on 26 March 2010. The fire broke out at the 16th shed of the depot that contained small arms, ammunition, and explosives. The fire was brought under control in about 2 hours and completely doused by 4:30 a.m. There were no fatalities, nor injuries. Nearly 200 tonnes of small arms, explosives, and shells were destroyed.

MSIAC, *MSIAC Newsletter, 1st Quarter 2010,* page 10.

MILAN AAP, MILAN, TENNESSEE, U.S., 4 MAY 2010

An explosion at the Milan AAP sent two people to the hospital of 4 May 2010. The incident occurred at about 5:10 p.m. Unfortunately, MSIAC Newsletter information is extremely sketchy and an internet search did not turn up information.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2010,* page 8.

ABL, ROCKET CENTER, WEST VIRGINIA, U.S., 24 MAY 2010

Two Alliant Technical Systems (ATK) workers received minor injuries in an explosion around 4:40 p.m. and were treated at a local hospital on 24 May 2010. Other employees were treated on-site by the facility's medical staff. The explosion occurred at a remotely operated production mix facility. No one was in the building at the time of the explosion. The two employees treated for minor injuries were working in a nearby building.

http://times-news.com/local/x1414113334/ATK-blast-rocks-area
http://www.wvmetronews.com/index.cfm?storyid+37212&func+display full story
http://wowktv.com/story.cfm?func=viewstory&storyid=80360
MSIAC, *MSIAC Newsletter, 2nd Quarter 2010,* pp. 10-11.

ARMOURY 31, ULYANOVSK, RUSSIA, 1 JULY 2010

During handling of ammunition, an explosion took place in Armory 31. Two servicemen were injured.

http://en.novayagazeta.ru/data/2011/060/01.html

BIYSK MILITARY UNIT 30654, VERKHKATUNSKOYE, ALTAI TERRITORY, RUSSIA, 3 JULY 2010

An explosion occurred when a truck was taking explosive waste to a disposal site in the Altai region on 3 July 2010. Six people died, four of them civilians. A subsequent report on 6 July reported that workers dismantling defective ammunition with a chain saw caused the explosion.

http://rt.com/news/prime-time/training-grenades-deactivation-victims/
http://en.novayagazeta.ru/data/2011/060/01.html
MSIAC, *MSIAC Newsletter, 3rd Quarter 2010,* page 9.

SARATOV MILITARY BASE, RUSSIA, 5 JULY 2010

A senior officer and a serviceman were severely burned while attempting to deactivate gunpowder used for training, causing a fire and subsequent explosion on 5 July 2010. The officer died shortly thereafter and the other victim was still in critical condition. The victims were found guilty of safety violations.

http://rt.com/news/prime-time/training-grenades-deactivation-victims/
http://en.novayagazeta.ru/data/2011/060/01.html

REDSTONE ARSENAL, HUNTSVILLE, ALABAMA, U.S., 13 JULY 2010

A fire broke out in Building 7298 in the Redstone Arsenal Test Center at 11:55 a.m. on 13 July 2010. No one was hurt and everyone was accounted for. Flames caused partial damage to the building but firefighters worked quickly to keep the damage from spreading. While the fire was contained, it was allowed to smolder until the next day. There were no explosions. The cause of the fire was unknown. On 15 July, it was reported that Redstone Test Center personnel were conducting a Hellfire missile test at the time the fire was reported. Figure 61 shows the damage from the fire to Building 7298.

FIGURE 61. Damage to Building 7298, Redstone Arsenal,
Due to Fire on 13 July 2010.

http://www.whnt.com/news/whnt-redstone-arsenal-fire-071310,0,7910568,print.story
http://www.huntsvillenewswire.com/2010/07/13/injuries-reported-fire-redstone-arsenal-tuesday/
http://www.army-technology.com/projects/redstonearsenalalaba/redstonearsenalalaba4.html
MSIAC, *MSIAC Newsletter, 3rd Quarter 2010,* page 9.

CAMP BOKALA, DEMOCRATIC REPUBLIC OF CONGO, 23 AUGUST 2010

On 23 August 2010, a 107-mm rocket inadvertently launched from the FARDC stockpile at Camp Bokala, pierced two walls of the ammunition depot and landed in a tree in the center of the town. Fortunately, there were no fatalities or injuries but had the rocket been fully functional, its explosion could have maimed or killed high numbers of people. Following this incident the Mines Advisory Group destroyed over 23 tons of unstable ammunition in the stockpile at Camp Bokala.

Komorowski, Adam, *Testimony to the House Armed Services Committee on the work of the Mines Advisory Group in the Democratic Republic of the Congo*, page 9.

AVANGARD MILITARY FACTORY, STERLITAMAK, BASHKORTOSTAN, RUSSIA, 24 AUGUST 2010

At around 6:00 p.m., an explosion occurred at the Avangard Military Factory firing range during disposal of military equipment and ammunition. A 122-mm shell detonated, killing one serviceman.

http://en.novayagazeta.ru/data/2011/060/01.html

MECAR SPRL, SENEFFE, BELGIUM, 7 SEPTEMBER 2010

A fire broke out around 8:10 a.m. in the large caliber ammunition assembly building causing explosions for about 2 hours on 7 September 2010. The fire started on a wooden pallet containing 54 finished grenades. It was decided not to try to extinguish the blaze but wait until the explosions stopped. The factory was quickly evacuated. The area was viewed by helicopter, and traffic was kept at a distance of 4 kilometers. The article cites safety precautions having worked. The factory is built in an uninhabited area and consists of separate buildings with safe-separation distances between buildings. When one of the buildings explodes, other buildings are safe.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2010,* page 11.

KILGORE FLARES COMPANY, TOONE, TENNESSEE, U.S., 14 SEPTEMBER 2010

A flash fire injured six people, three of them critically, at the Kilgore Flares Company in Building No. 35 on 14 September 2010. The three victims were treated in Memphis for severe burns. One of the women assemblers had burns on 20% of her body. A male material handler had burns on 60% of his body and lost a leg due to amputation because of the severity of burns. The third victim, a female assembler, had burns on 80% of her body. She was in critical condition at Jackson General Hospital ICU on a feeding tube and respirator as of 13 September 2011. The tragic stories of the three victims are presented in the following two internet articles:

http://www.knoxnews.com/news/2011/feb/20/kilgore-flares-flash-fire-survivor-catrina-jones-c/?partner=RSS
http://tennesseenewspress.com/2011/09/15/kilgore-victims-struggle-one-year-after-explosion-burn-victims-face/

The third victim, Erika Jarrett, passed away Thursday, 29 September 2011 at Jackson-Madison County Hospital more than a year after the accident.
http://www.jacksonsun.com/article/20110930/NEWS01/109399313?Kilgore-employee-burned-2010-dies

Building 35 is an 800-square-foot building that is divided into two portions by a concrete wall and two 1-inch-thick reinforced steel doors. One side is the final assembly area where workers insert their hands through slits into a protective box similar to a laboratory glove-box. Workers take a "grain" that is a mixture of magnesium, Teflon, other chemicals and a binder and wrap them in a foil-like material. The material is then inserted into the flare's outer casing and cap the flare. The other half of the building is the slurry room. This is where the inner core of the flare is hand-dipped using plastic tongs by the assembly workers into liquid magnesium, Teflon and other ingredients known as slurry. The slurry is mixed in a separate building and manually transported to the slurry room on carts. The slurry mixture is highly flammable and can be ignited by static electric charge a company representative said. The flash fire occurred in the slurry room portion of the building. Some of the articles, and one of the victims, mention an explosion and fire, however a Kilgore representative told reporters that there was not an explosion. Instead he described what happened as a flash fire. The fire department decided to let the materials burn themselves out.

The company said that it had amassed over 4.5 million production-related hours without a work-related injury before the fire. Figure 62 shows a photograph of the fire in Building 35.

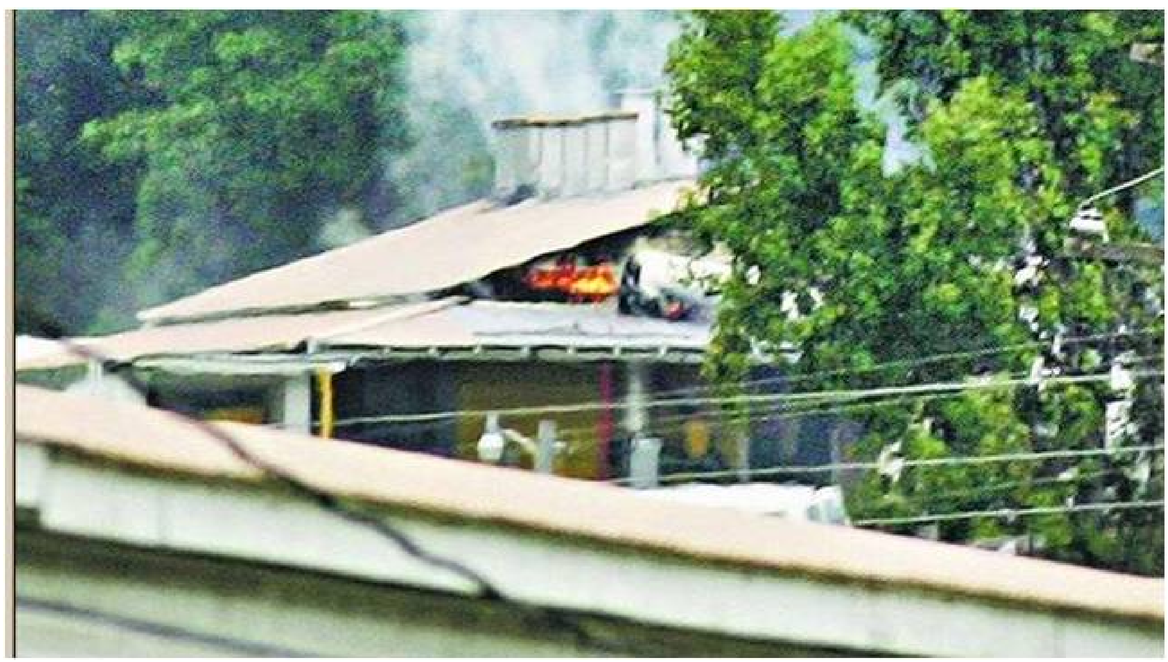


FIGURE 62. Fire in Building 35, Kilgore Flares Company, 14 September 2010.

In addition to the links presented above, see the following:
http://www.newschannel5.com/story/13152178/fire-at-tennessee-flare-plant-still-burning-s
http://www.wmctv.com/story/13151786/6-hurt-in-explosion-at-toone-pant-making-flares

http://www.abc24.com/news/local/story/Flare-Plant-Fire-Report-Released-Victim-Speaks/nykphAOs20eVIx3MbasKNA.cspx
http://www.bbc.co.uk/news/world-us-canada-11307807
www.kilgoreflares.com/Download.aspx?ResourceId=31702
MSIAC, *MSIAC Newsletter, 3rd Quarter 2010,* pp. 11-12.

ARMY AMMUNITION DEPOT, BINNAGURI, WEST BENGAL, INDIA, 20 NOVEMBER 2010

A major fire broke out in an Army ammunition depot in Binnaguri, India at about 5:00 p.m. on 20 November 2010. The fire evidently started with reaction of stored chemicals in a warehouse, and led to two blasts. The fire was put out at approximately 9:00 p.m. There was no loss of life or damage to serviceable ammunition.

MSIAC, *MSIAC Newsletter, 4th Quarter 2010,* page 9.

CORDITE FACTORY, INDIAN DEFENCE MINISTRY, TAMIL NADU, INDIA, 25 NOVEMBER 2010

A total of five workers at the Cordite Factory, Tamil Nadu, India were killed, two were seriously injured, and there were 10 minor injuries in an explosion at 3:15 p.m. on 25 November 2010. The accident occurred during a mixing operation for the manufacture of gun propellant used in firearms and artillery. It occurred in the dough making unit of Building 2 and resulted in the collapse of the entire building structure.

MSIAC, *MSIAC Newsletter, 4th Quarter 2010,* page 9.

SLOBODA MILITARY FACTORY, CACAK, SERBIA, 27 DECEMBER 2010

Fire and black smoke led to evacuation of the Sloboda military factory in Cacak, Serbia, on 27 December 2010. At 4:30 p.m. an explosion occurred, probably in the storage room of an ammunition warehouse covering 2,000 square meters in which 20-, 30-, and 40-mm ammunition was stored. There were no injuries. An official said detonations were still being heard 45 minutes after the first explosions. The damage was estimated to be approximately 10 million euros (12.9 million USD).

MSIAC, *MSIAC Newsletter, 1st Quarter 2011,* page 7.

KINEMATICS RESEARCH, OAKLAND, TENNESSEE, U.S., 5 JANUARY 2011

One person was killed and another injured in an explosion in the packing area of the Kinematics Research plant that occurred around 1:45 p.m. on 5 January 2011. It is believed that fire that led to the large explosion was caused by an explosion in the powder feeding mechanism that in turn ignited nearby combustibles and ammunition manufacturing components, that in turn led to other larger explosions.

MSIAC, *MSIAC Newsletter, 1st Quarter 2011*, pp. 7-8.

VENEZOLANA DE INDUSTRIAS MILITARES CORPORATION (CAVIM), NEAR MARACAY, VENEZUELA, 30 JANUARY 2011

A fire and series of explosions at the Cavim military arms depot at about 4:30 a.m. on 30 January 2011 resulted in one fatality and forced about 10,000 residents to flee their homes as the burning ammunition produced powerful blasts. The explosions started at 4:45 a.m. The fire burned four artillery-munitions storage sites (out of 20) that Cavim, Venezuela's military arms manufacturer has at its facility near Maracay. The cause of the early morning blaze was undetermined.

http://www.heraldonline.com/2011/01/30/2793444/blasts-fire-at-venezuela-arms.html [No longer available]
http://www.mysanantonio.com/business/article/Fire-explosions-at-Venezuela-arms-depot [No longer available]
http://www.boston.com/news/world/latinamerica/articles/2011/1/31/fire_sets_off_venzuela [No longer available]

Video at
http://www.youtube.com/watch?v=smEDeb11A1E&feature=player_embedded [No longer available]

GONGOLA MBOTO MILITARY BASE, DAR ES SALAAM, TUNISIA, 16 FEBRUARY 2011

A series of explosions started about 8:00 p.m. on 16 February 2011 at the Gongola Mboto military facility. The fire and ensuing explosions started at one storage facility and spread to adjacent facilities. The fires and explosions continued for approximately 3 hours. The explosions caused debris "to rain down" as far as 15 kilometers from the base. The explosions and fires resulted in 27 deaths and approximately 500 persons were injured. A 10-kilometer radius from the base was evacuated and about 4,000 people were evacuated to the national stadium in Dar Es Salaam. On the base, 23 weapons storage facilities, five vehicles, two soldier dormitories, and the general store were destroyed. In the surrounding community, an estimated 200 homes were either destroyed or severely damaged. The blasts closed the local international airport until the next day. The cause of the fires and explosions is unknown, although authorities said that the facilities had been inspected three days earlier and all had been well.

http://news.bbc.co.uk/2/hi/africa/8024656.stm
http://reliefweb.int/node/438677
http://www.the-african-org/blog/?p=450 [No longer available]
International Federation of Red Cross and Red Crescent Socities, DREF operation no. MDRTZ011 GLIDE no. OT-2011-000026-TZA dtd 7 March 2011 and 31 July 2011
http://www.huffingtonpost.com/2011/02/17/Tanzania-explosion-kills-n 824394.html
http://www.reuters.com/assets/print?aid+USTRE71G18E20110217
MSIAC, *MSIAC Newsletter, 1st Quarter 2011,* pp. 9-10.

WALLOP DEFENCE SYSTEMS, OVER WALLOP, HAMPSHIRE, UK, 20 FEBRUARY 2011

One of the flares on a production line at Wallop Defence Systems caught fire on 20 February 2011. The incident lasted just 3 seconds because the fire suppression system immediately activated dousing the flares with carbon dioxide. A spokesperson for the company said that there was little or no risk because the incident was not near a storage area, and the operation itself was made remotely with personnel behind secure barriers.

MSIAC, *MSIAC Newsletter, 1st Quarter 2011,* page 11.

LAKE CITY AAP, MISSOURI, U.S., 8 MARCH 2011

Six people were injured, one seriously enough to be air-lifted to a hospital, in an accident that occurred about 1:30 p.m. on 8 March 2011. The accident occurred in a construction area, although one worker said the area was where gunpowder is loaded into the small-caliber cartridges. The plant produces the majority of small-caliber ammunition used by U.S. and allied forces, and has the capacity to produce 1.4 billion rounds of small-caliber ammunition annually. Details of the accident in all reports were not thoroughly discussed.

http://www.nbcactionnews.com/dpp/news/region_missouri/Several-hurt-in-reported-explosion-at-Lake-City-Ammunition-Plant
http://www.patriotfiles.com/forum/archive/index.php/t-568549.html
http://www.nbcactionnews.com/dpp/news/region_missouri/One-person-remains-in-the-hos [No longer available]
http://www.kmzu.com/2011/03/six-injured-in-explosion-at-lake-city-army-ammunition-pla {No longer available]
http://www.justicenewsflash.com/2011/03/03/6-injured-in-blast-at-atk-lake-city-army-am

260TH CENTRAL MISSILE ARTILLERY BASE, AMMUNITION STORAGE AND DISPOSAL DEPOT, LIPETSK, RUSSIA, 6 APRIL 2011

An explosion occurred at the military base at Lipetsk at 10:30 a.m. on 6 April 2011, following "spontaneous ignition" of a box containing 40-kilograms of gunpowder. The gunpowder was to be disposed of by incineration. Three were killed and two were hospitalized, with one of the two succumbing in the hospital.

http://mysouth.su/2011/04/the-explosion-of-ammunition-under-thelipetsk-technical failure
http://mysouth.su/2011/04/three-people-died-in-the-explosion-at-the-artillery-base-at-lipetsk/ [No longer available]
http://english.ruvr.ru/_print/48541347.html
http://en.rian.ru/russia/20110406/163401515-print.html
http://www.upi.com/Top_News/World-News/2011/04/06/Three-killed-in-blast-at-military- [No longer available]
http://www.thainewsagency.com/english/world/04/07/2011/9566/ [No longer available]
http://en.novayagazeta.ru/data/2011/060/01.html
MSIAC, *MSIAC Newsletter, 2nd Quarter 2011,* page 15.

KILGORE FLARES, TOONE, TENNESSEE, U.S., 13 APRIL 2011

Three workers were hospitalized after an accident at Kilgore Flares on 13 April 2011. Two workers were burned and another was knocked unconscious. According to family members the men were mixing chemicals when the accident happened.

http://www.wreg.com/news/wreg-kilgore-accident-april,0,7762377,print.story [No longer available]
MSIAC, *MSIAC Newsletter, 2nd Quarter 2011,* page 15.

EXPLOSIA FACTORY, SEMTIN, CZECH REPUBLIC, 20 APRIL 2011

An explosion occurred at the Explosia factory at 6:45 a.m. on 20 April 2011. The blast occurred in part of Explosia's production plant and was thought to be caused by reaction of nitroglycerin. Four people were missing and presumed to be in the rubble pile and seven people were injured, mostly from flying glass. The blast was felt up to 10 kilometers away.

http://www.ceskapozice.cz/en/business/companies/semtex-plant-explosion-4-missing-7-injured/
http://www.firedirect.net/index.php/2011/04/plant-explosion-4-missing-7-injured/
MSIAC, *MSIAC Newsletter, 2nd Quarter 2011,* page 16.

99TH ARSENAL AMMUNITION DEPOT, URMAN, BASHKORTOSTAN, RUSSIA, 26 MAY 2011

Fire broke out at 11:30 a.m. Moscow time on Thursday, 26 May 2011 at the 99th artillery ammunition depot located about 500 meters from the village of Urman in the Bashkortostan Republic in Russia during demilitarization of 120-mm shells. The fires then caused explosions of adjacent stores with fragments flying 3 to 4 kilometers in all directions. The fragments resulted in additional fires. The massive explosions that began around 1:40 p.m. occurred at 2- to 3-minute intervals and necessitated evacuation of approximately 7,000 residents. Officials thought the fire was extinguished Friday because the number of explosions had diminished. On Saturday, the Illyushin II-76 and Be-200 firefighting planes of the Russian Emergency Situations Ministry (EMERCOM) left Bashkortostan. Unfortunately, evacuations were again necessary on Monday, 30 May 2011, when additional explosions occurred. It was reported that there had been approximately 100,000 tons of explosives stored in the depot. One report indicated that there were mostly projectiles of calibers between 120- and 152-mm stored in the arsenal. There were no casualties (although one report mentioned a death occurring during the evacuation), and 12 people injured. Over 90 buildings burned including 50 houses. More than 116 people were left homeless, and some 500 left unemployed after their businesses were destroyed by fire and explosions. Damage was estimated at 100 million rubles. Sappers from EMERCOM found 204 shells at depths of 20 centimeters to 50 meters spread over an area of 70 hectares and rendered them harmless.

http://dlib.eastview.com/browse/doc/24857933
http://dlib.eastview.com/browse/doc/24866212
http://www.speroforum.com/a/54444/site/privacy.asp
http://www.rferl.org/content/russian_arms_depot_blasts_force_evacuation/24214066.html
http://www.rferl.org/content/explosions_at_russian_military_base_finally_cease/24212549.html
https://russiandefpolicy.wordpress.com/tag/bashkortostan/
http://gamutnews.com/20110530/11914/russian-arms-depot-blasts-force-evacuation.html
http://www.euronews.net/2011/05/27/unknown-cause-for-russian-arms-depot-fire/
http://www.dawn.com/2011/05/27/arms-depot-blasts-force-evacuation-in-russia.html
http;//www.mchs.gov.ru/eng/news/detail.php?ID=344801
http://www.channelnewsasia.com/stories/afp_world/print/1131447/1/.html
http://news.windowstorussia.com/2011/06/01/
http://news.windowstorussia.com/how-one-conscript-cost-russia-3.5-million.html
http://www.itar-tass.com/en/c32/180058.html
MSIAC, *MSIAC Newsletter, 2nd Quarter 2011*, pp. 18-19.

102ND ARMY AMMUNITION DEPOT, PUGACHYOVO, UDMURTIA, RUSSIA, 2 JUNE 2011

Fire broke out at an arms depot storing around 10,000 tons of shells (although one report listed 10,000 to 150,000 tons) in about 10,000 train cars at the military base near the village of Pugachyovo in the Udmurtia Republic of Russia on Thursday, 2 June 2011, at about 11:10 p.m. (One report stated that there were 170,000 ordnance items stored at the depot.) The fires that are said to have been caused by a carelessly discarded cigarette butt caused explosions (occurring at a rate of about 40 explosions per minute) that resulted in debris over a 2-kilometer radius. Windows were shattered at distances of up to 10 kilometers. On Friday, approximately 28,000 people were evacuated from Pugachyovo and nearby villages. By Friday, some 150 buildings, including 18 ammunition storage facilities, were on fire. The fires and explosions continued on Saturday, 4 June, but the intensity of explosions had decreased to about 4 to 5 per minute. The Interfax news agency said that 106 of the arsenal's 152 buildings were destroyed by fire and explosions. One report listed 3,000 houses and social facilities were destroyed. The accident caused two fatalities (elderly suffering heart attacks), one military officer missing, and 100 injured. More than 500 people were involved in battling the blaze (one report said more than 1,100 people were involved) along with four planes, three helicopters, and robotic equipment. Officials estimated more than 40 tons of water had been dumped over the blaze by early 3 June. By Saturday afternoon, some of the evacuated were allowed to return to their homes.

http://www.itar-tass.com/en/c32/180058.html
http://www.itar-tass.com/en/c154/157237_print.html
http://www.defensenews.com/story.php?i=6711275&c=LAN&s=EUR
http://www.bt.com.bn/news-world/2011/06/05/shells-still-exploding-russian-arms-depot-th
http://www.itar-tass.com/en/c32/180058.html
http://www.speroforum.com/a/54912/Fire-Explosions-At-Russian-Military-Base-Force-Ev
http://www.euronews.net/2011/06/03/fire-at-russian-military-depot-affects-thousands/
http://www.seattlepi.com/news/article/Arsenal-fire-blasts-shake-Russian-region-1407870.p
[No longer available]
http://itar-tass.com/en/c170/157967.htmlhttp://www.rferl.org/articleprintview/24214066.html
http://www.euronews.net/2011/06/03/thousands-evacuated-after-russian-military-base-blast/
http://news.windowstorussia.com/criminal-case-opened-against-udmurtia-ammo-depot-co
http://news.windowstorussia.com/medvedev-says-heads-may-roll-over-arms-depot-blasts.html
http://www.cbsnews.com/stories/2011/06/03/501364/main20068639.shtml
http://themoscownews.com/russis/20110606/188726906-print.html
http://www.ocnus.net/artman2/publish/Defence_Arms_13/Scattered-Powder-Kegs_printed...
MSIAC, *MSIAC Newsletter, 2nd Quarter 2011*, pp. 19-20.

CAMP MINDEN, LOUISIANA, U.S., 7 JUNE 2011

An explosion occurred at the Goex plant at Camp Minden, Louisiana, at 6:20 a.m. on 7 June 2011. The Goex plant produces black powder. Approximately 1,000 pounds of black powder exploded. All of the work is done by remote control so no one was inside the building. Five employees were in the corning mill part of the plant. All together 10 people were evacuated. Because the operation was remote, there was no witness to what caused the explosion.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2011,* page 20.

PUGACHYOVO, UDMIRTIA, RUSSIA, 2 JULY 2011

The hot and dry weather triggered a series of explosions at the munitions depot in Pugachyovo, Russia, on 2 July 2011. Heated cartridge cases began to explode. Fortunately, the blasts did not pose a threat to adjacent buildings, and there was no need to evacuate the 450 families residing in Pugachyovo.

http://www.itar-tass.com/en/c154/178615.html

ABADAN (ALSO KNOWN AS BEZMEIN), TURKMENISTAN, 7 JULY 2011

At about 4:40 p.m. on 7 July 2011, a massive explosion occurred in the Turkmenistan town of Abadan. The town was reportedly evacuated. At 10:00 p.m., fires continued to burn out of control in the town and surrounding hills with occasional explosions.

There are widely conflicting reports of this accident. The official government reports, first denied that there were any casualties or major damage caused by the fires and blasts. Three days later the government admitted that 13 civilians and two military personnel were killed. The government listed the cause of the accident as ignition of pyrotechnic matter, intended for fireworks, stored in special warehouses in Abadan that then spread to military storage areas, where an estimated 5,000 to 50,000 tons of ammunition was stored. The munitions were reported to include ammunition, hand grenades, rocket-propelled grenades, and Grad and Smerch rockets. It was reported that shrapnel was found as far as 10 kilometers away. The authorities blamed the accident on extreme hot weather. It should be mentioned that Turkmenistan is considered one of the most closed societies in the world with very little dissemination of adverse information.

In contrast, eyewitnesses, and an opposition website based in Austria, Khronika Turkmenistan, reported many more deaths. Initial reports indicated 200 civilian fatalities, while later reports stated that the fatalities could be as high as 1,382. Estimates of fatalities were based in part on the number of buildings destroyed and the number of missing people.

For example, 127 homes and dozens of public buildings were reported destroyed. Part of the increased estimates was due to missing soldiers. At the time of the accident, 270 soldiers were stationed near the accident site; but, after the explosions, only 150 could be accounted for. While several more soldiers appeared in the days following the accident, reports of many servicemen being unaccounted for continued. In a news account dated 18 July 2011, it was reported that mothers of soldiers missing after the blast descended on the ruined town of Abadan. The mothers demanded to know whether their children were dead or alive but were rebuffed by authorities. Authorities refused to give out information on the status of several hundred soldiers believed to be in the immediate vicinity of the blast.

More soldiers continued to be killed in the cleanup of unexploded ordnance. At least five soldiers were reported killed on 19 July.

Not only was the extent of casualties a major difference but the energetic materials involved in the fires and explosions was another major difference between government reports and other evidence such as video, taken by Russian news media, Radio Free Europe/Radio Liberty, and private individuals who spread the word via e-mails and video. As can be seen in the photographs in Figures 63 through 65, the reactions appear to be those associated with fire and exploding munitions.

ScanEx, a Russian satellite company, published the before and after images of the military depot where fires and explosions occurred shown in Figure 63. The photograph on the right clearly shows the buildings within the depot before the accident, while the photograph on the left shows the craters and charred areas after the fires and explosions. Figure 64 shows a still photograph of the fire. Figure 65 show a series of still frames taken from a video of the fire and explosions.

FIGURE 63. Photographs Taken from Scanex Satellite Showing After and Before Views of the Military Depot.

FIGURE 64. Fire at Abadan, Turkmenistan, 7 July 2011.

FIGURE 65. A Series of Still Frames Taken From a Video of the Accident in Abadan, Turkmenistan, on 7 July 2011.

FIGURE 65. (Contd.)

FIGURE 65. (Contd.)

http://news.ca.msn.com/world/turkmen-police-guard-blast-site-deny-any-deaths
http://www.eurasianet.org/sites/eurasianet.org/files/imagecache/galleria_fullscreen/Abadan.j [No longer availalbe]
http://www.eurasia.org/print/63823 [No longer available]
http://www.eurasia.org/print/63829 [No longer available]
http://www.eurasia.org/node/63853 [No longer available]
http://www.eurasia.org/print/63870 [No longer available]
http://www.eurasia.org/node/63939 [No longer available]
http://www.eurasia.org/print/63942 [No longer available]
http://www.rferl.org/articleprintview/24263654.html
http://www.telegraph.co.uk/news/worldnews/asia/turkmenistan/8624430/Explosion-rocks-Turkmen-armoury.html
http://www.seattlepi.com/news/article/Turkmenistan-says-15-people-dead-after-explosion- [No longer available]
http://www.google.com/hostednews/afp/article/ALeqM5hh9DPXGS1iA8ZdtwquotsOt8_1 [No longer available]
http://www.defensenews.com/story.php?i+7043266&c+ASI&s+LAN
http://www.scanex.ru/en/news/News_Preview.asp?id=n838439
http://www.turkishweekly.net/print.asp?type+1&id=118621
http://www.cnbc.com/id/43703197 [No longer available]
MSIAC, *MSIAC Newsletter, 2nd Quarter 2011*, page 22.

EVANGELOS FLORAKIS NAVY BASE, MARI/ZYGI, CYPRUS, 11 JULY 2011

Much of the source information for this section was obtained from:

Sharp, Michael, *Accident in Zygi, Cyprus, 11 July 2011,* NATO Munitions Safety Information Analysis Center (MSIAC) presentation.
[Used with permission from MSIAC. MSIAC asked that the following disclaimer be presented.

- Much of the information presented here is taken from a Greek report produced by the research committee put together to investigate the sequence of events and responsibilities, which can be found at
  - http://media.cna.org.cy/pdfpPORISMA.pdf
- Other information has been taken from internet reports
- Some of the information presented here is based on unverified accounts that have been analyzed, and hence should not be taken as a definitive report.]

Polyviou, Polys, *Monomelous Research Commission for Conducting Research on Explosion that Occurred 11 IOULIOU [July] 2011, "Evangelos Florakis" in Mari* http://media.cna.org.cy/pdfpPORISMA.pdf [A machine translation was created from the original Greek Cyprus report provided by MSIAC.]

http://en.wikipedia.org/wiki/Evangelos_Florakis_Naval_Base_explosion
http://www.reuters.com/assets/print?aid+USTRE76A0EP20110711
http://www.bbc.co.uk/news/world-europe-14102253?print=true
http://www.bbc.co.uk/news/world-europe-14186169?print=true
http://famagusta-gazette.com/two-men-remain-in-critical-condition-p12435-69.htm
http://www.greeknewsonline.com/?p=17030
Hajjar, Roula, *Massive blast at Cyprus munitions depot kills 12,* Los Angeles Times, 12 July 2011, pg A3.

At approximately 3:40 a.m., 11 July 2011, a fire broke out in 98 stacked International Standards Organization (ISO) containers, many that contained gunpowder and were stored on a concrete slab in the open at Evangelos Florakis Navy Base, Cyprus. Figure 66 shows where the ISO containers were stacked at the Navy base.

FIGURE 66. The Location on the Evangelos Florakis Navy Base, Cyprus Where the 98 ISO Containers were Stacked [MSIAC presentation referenced above].

Figure 67 shows the stacked ISO containers before the fire and detonation. To provide security, the containers were closely stacked so that the doors of the individual ISO containers could not be opened.

FIGURE 67. Stacked ISO Containers Before Fire and Detonation.

Fire-fighting efforts continued until 5:55 a.m. when mass detonations occurred. In the time-line presented in the Polyviou report, mention is made of several “explosions” before the “big bang.” Specifically mentioned are the following explosions:

- 0345 Two employees at the power station heard an explosion (page 229)
- 0345 A soldier approaching saw the fire but “could not approach because they [sic] were occasionally bursts” (page 229)
- 0350 One of the power plant employees that heard the explosion at 0345 heard a second explosion (page 229)
- 0405 The warrant officer that was the Sergeant in the Central gate at the Navy base “… finding the existence of fire and small explosions...” (page 231)
- 0535 “…while the explosions continued until that time” (page 239)
- 0535 “…while I was behind the fire, I heard a terrible explosion and saw the direction of the containers coming toward me a ‘ball’ of about 2 floors, orange with black and I felt a terrible pressure on pushing…” (page 240)
- 0555 Big Bang (page 240)

[Note: These are taken from the machine translation and are subject to errors typical in a word for word mechanical translation.]

Thirteen people were killed including the Commander of the Navy, Base Commander, Navy personnel, and firefighters. There were 62 injured including one that succumbed in the hospital.

All 98 ISO containers and their contents were destroyed. Figure 68 presents an aerial view of the Navy base on the left and the Vassilikou power plant in the middle of the figure before the accident. Figure 69 shows a close-up high resolution view of the area of the Navy Base where the containers were stored and part of the power plant.

FIGURE 68. Aerial View of the Evangelos Florakis Navy Base on Left and the Vassilikou Power Plant in the Center, Before the Accident.

FIGURE 69. High Resolution Aerial View of the Naval Base, and a Portion of the Power Plant Before the Detonation. The stack of ISO containers is shown to right of information box.

Figure 70 shows the same view as Figure 68 but after the detonations.

FIGURE 70. Aerial View of the Evangelos Florakis Navy Base and the Vassilikou Power Plant After the Detonations.

Figure 71 presents a higher resolution view of the crater and damage to power plant.

FIGURE 71. High Resolution Aerial View of the Crater Left after the Detonation, and the Resultant Damage to the Adjacent Power Plant.

The crater was formed when the gunpowder in 80 of the 98 ISO containers depicted in Figure 67 detonated after the fire had burned more than 2 hours. [Note: In the following discussion, both 80 and 81 are used as the number of ISO containers containing gunpowder. This is because there were 81 containers containing gunpowder when the ISO containers were placed at the Navy base. The contents of one of the containers reacted on 4 July 2011, and the other 80 reacted on 11 July 2011.]

Figure 72 presents an aerial view of the crater and the associated dimensions, and compares to the dimensions of the stack of ISO containers.

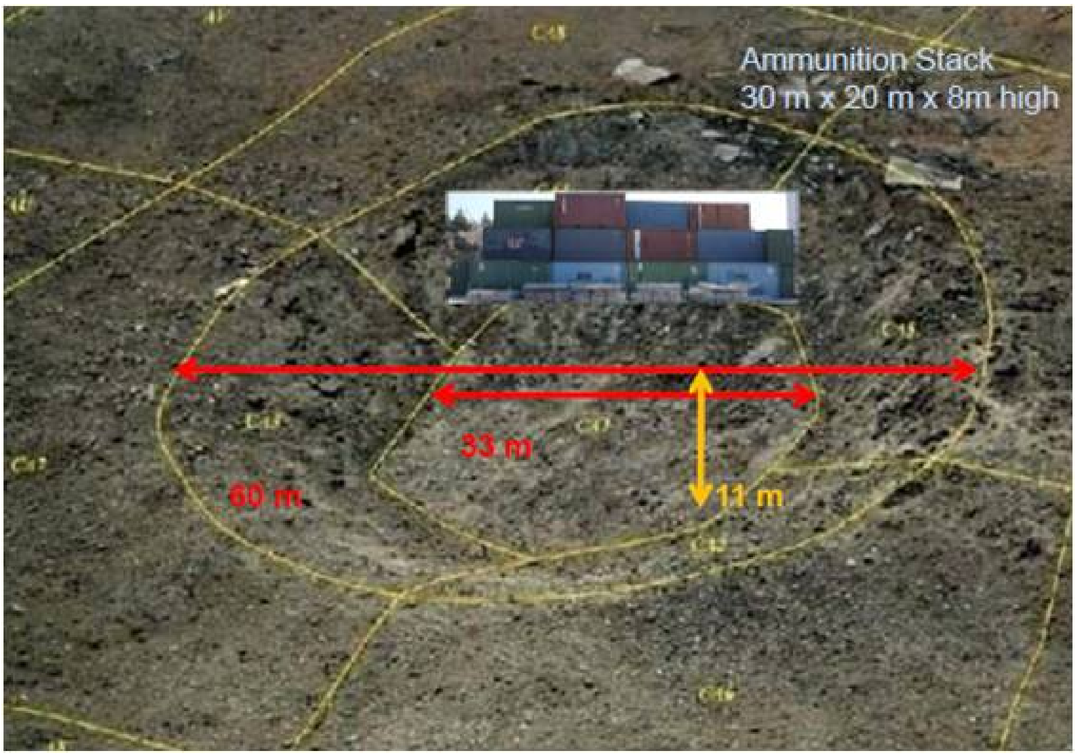


FIGURE 72. Dimensions of the Crater, and Comparison
to the Original Stack of ISO Containers.

What caused the fire that burned for about 2 hours before the mass detonations? Part of the answer to that question is the answer to the question “What was in the ISO containers?” The material involved in the fire and detonations was primarily gun propellant that had been cargo on the Cypriot flagged *MV Monchegorsk.* The ship carried 481,000 kg of gunpowder plus other cargo from the Iranian port Bandar Abbas and destined for Latakia or Tartous, Syria. The manifest listed the materials as being mostly HD 1.3 and HD 1.3C1 gun propellants. [Page 156 of the Polyviou report lists the materials and some of the hazards classifications, but it does not give the quantities of each. It also presents “Of the 98 containers, 81 contained various types of gunpowder…”. Then on page 629 and 630, it lists 208,320 kg of Class 1.3 propellants, 122,440 kg of Class 1.3C1 propellants, and 150,637 kg Class 1 propellant, for a total of 481,397 kg of propellant.

Page 630 also lists 30,000 Class 1.3C1 missile fuses.] Figure 73 shows photographs of some of the containers of gunpowder stored within an ISO container.

FIGURE 73. Containers of Gun Propellant Contained in ISO Containers.

The 98 ISO containers, 81 of which contained gun propellant, were confiscated in January 2009; and on 14 February 2009, the ISO containers were stored on a concrete slab in the open at the naval base. During the day, especially during the summer, the gun propellant in the ISO containers stored in the open got hot. Temperatures in Mari in July typically reach 32 to 33°C. On 11 July 2011, the temperature between 1:00 and 6:00 a.m. in Zygi, adjacent to the Evangelos Florakis Navy Base, was 21.5 to 23.2°C, and the humidity was between 91 and 97%. As discussed earlier in this report in the section on stabilizer depletion and auto-ignition, gun propellants, especially single- or double-based gun propellants, start to decompose when they get hot. As they decompose, the stabilizer gets depleted. Eventually enough stabilizer is depleted so that the decomposition reactions accelerate and ignition of the gun propellant can occur. Once gunpowder starts to burn, the pressure within a closed container rapidly rises and the container may come apart violently, and form and accelerate debris from the container. [The section on tests presents ECMs rupturing producing large pieces of debris <u>one second</u> after ignition of gun propellant.] Could that have happened at Evangelos Florakis Navy Base, Cyprus? Yes. As mentioned above, one week before the 11 July 2011 detonations, on 4 July 2011, one ISO container was discovered with evidence of reaction and fire. Figure 74 shows the ISO container with bulged walls and roof, and the doors blown partially open. The force of the reaction was sufficient to move the 10.5-ton ISO container approximately 30 cm in two directions as shown in Figure 74.

FIGURE 74. ISO Container in the Stack Showing Evidence of Reaction and Fire by the Bulging Walls and Roof and the Door That Has Been Blown Partially Open. The force of reaction moved the ISO container approximately 30 cm in two directions.

When propellant decomposes porosity is produced in the propellant. Propellant with porosity or voids is usually significantly more sensitive to mechanical shock to detonation transition than undamaged material. That is, it does not take as much input shock level to initiate detonation in the damaged material as it does in undamaged material. While the undamaged gun propellant originally may have truly been HD 1.3 as per UN tests, the damaged material that had been in ISO containers sitting in the hot sun for 2+ years may not have been HD 1.3 any longer. The storage of gun propellant in a stack of ISO containers in the hot sun may have been a recipe for disaster.

The disaster was not limited to the Navy base. As shown in the aerial view of Figures 68 and 69, the Vassilikou Power Plant was immediately adjacent to the Navy base. Figures 75 through 79 show the considerable damage to the power plant.

FIGURE 75. Damage to Vassilikou Power Plant.

FIGURE 76. Damage to Vassilikou Power Plant.

FIGURE 77. Damage to Vassilikou Power Plant.

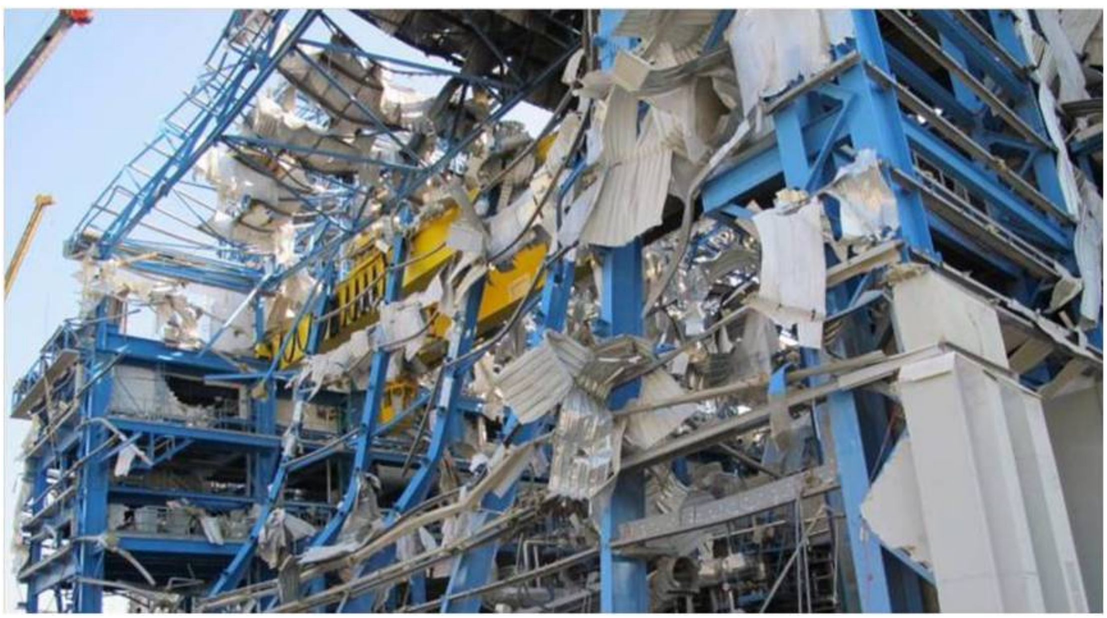


FIGURE 78. Damage to Vassilikou Power Plant.

FIGURE 79. Damage to Vassilikou Power Plant.

The estimated cost of the damage to the power plant was approximately 2 billion Euros. MSIAC personnel performed an analysis in which the NEQ was estimated based on the crater dimensions. The crater was predicted to have been formed by the detonation of 200,000 to 850,000 kg of explosive. This amount was narrowed down based on crater diameter (crater depth was under-represented due to the concrete slab) to an NEQ in excess of 400,000 kg of TNT equivalence. Using a 0.8 TNT equivalence for gun propellant, MSIAC estimated that approximately 500,000 kg of gun propellant detonated. This compares to the 481,000 kg, minus the amount burned in the 4 July reaction, of gun propellant in 80 ISO containers. The MSIAC personnel also estimated the amount of gun propellant detonated based on the AASTP1 damage descriptors applied to the Vassilikou power plant (approximately 300 to 600 m from the ISO container site) and damage to structures in Mari and Zygi (4.5 km from the ISO container site), Psematismenos and Maroni (both approximately 7 km away), and Parekklisia (11 km away). Based on the damage, an estimated 400,000 kg TNT or 500,000 kg of gun propellant detonated.

One of the lessons learned is that supposedly HD 1.3 material exposed to the hot conditions in ISO containers in the open subject to the hot sun, and in the confinement of the ISO containers, may decompose and auto-ignite due to stabilizer depletion. (As evidenced by the pre-4 July reactions, and the initial 11 July fires that burned for 2 hours) The confinement of the ISO containers allows rapid pressurization within the containers once ignition occurs and can result in a pressure burst or explosion. The stacked configuration increased the confinement, especially since the door opening was restricted by adjacent container. The damaged propellant having some porosity is more shock sensitive than undamaged propellant facility detonation. Thus, material that may have started out as HD 1.3 as determined using UN Series 6 tests may over time and exposure behave as HD 1.1. This has been true of some of the other accidents. [Note: In the test section, tests performed by Tozer are discussed where gun propellant was placed in ISO containers subject to fire. In Tozer's tests the ISO container doors were not restricted like the doors in the stacks at Evangelos Florikas. In Tozer's tests the over-pressure in the ISO container due to propellant combustion blew open the doors and allowed venting of combustion with association of plume outside the container.]

ASHUUK TRAINING RANGE, ASTRAKHAN REGION, RUSSIA, 23 AUGUST 2011

Six soldiers died almost instantly, another soldier died later, and 11 were injured (several very serious injuries) by an explosion that occurred at 6:20 a.m. Moscow time on 23 August 2011. The explosion occurred when soldiers were laying down 122-mm multiple-launch rocket system Grad missiles in a disposal operation. The cause of the explosion according to a source from the Russian Ministry of Defense was given as: "When laying down ammunition at a disposal site, the propulsion engine [rocket motor] of one of the shells for the Grad installation got spontaneously self-triggered [ignited]. The reactive spray [exhaust plume] from the engine caused detonation of three more rounds. Fortunately, the main stock of ammunition did not detonate."

http://southdistr.eng.kavkaz-uzel.ru/articles/18125/
http://www.itar-tass.com/en/c154/210184_print.html
http://www.itar-tass.com/en/c154/212634_print.html
http://en.rian.ru/russia/20110823/166087741-print.html
http://www.itar-tass.com/en/c32/210060_print.html
http://www.eutimes.net/2011/08/blast-kills-6-injures-12-in-russia/
http://www.firedirect.net/index.php/2011/08/soldiers-killed-injured-after-explosion-at-a-fir...

BRAZZAVILLE, REPUBLIC OF CONGO, 4 MARCH 2012

On 4 March 2012, explosions and detonations at the arms depot at the Regiment Blinde located near the center of Brazzaville leveled the surrounding community. The first blast occurred about 8:00 a.m., and several smaller blasts followed. Another major explosion went off around 1:00 p.m. The Defense Minister stated "It [was] an incident caused by fire at the munitions depot." Other officials said that the fire was caused by faulty electrical wiring. As of 6 March reports, there were 246 fatalities at the main morgue and 70 at the morgue of the military hospital, with many more expected as rubble was cleared. The injured numbered over 1,500 (with one report listing 1,500 to 2,000), many of them critically. That number was also expected to increase, in part as rubble was being cleared and in part because shells, rockets, and other munitions were widely scattered miles from the site by the explosions. This scattered ordnance was continuing to explode during the rescue operations. The possibility of further explosions from the unexploded ordnance hampered rescue efforts. All buildings within a 2 kilometer (1.25 mile) radius were completely flattened. Two nearby churches packed with worshippers collapsed. The shockwaves shattered glass in downtown Kinshasa, capital of the neighboring Central African nation of Democratic Republic of Congo, 10 kilometers (6 miles) away. Firefighters had brought the fires under control by the morning of Tuesday, 6 March, and prevented them from spreading to a second munitions depot just about 100 meters away. Had the flames spread to the second depot that contained even larger caliber weapons, the tragedy would have greatly increased.

Dixon, R., *In Republic of Congo, risk of new blasts seen,* Los Angeles Times, 6 March 2012, p A3.
http://www.seattlepi.com/news/article/Rep-of-Congo-236-dead-after-arms-depot-blasts-338
http://www.washingtonpost.com/world/africa/official-witnesses-strong-explosions-heard-in-...
http://in.reuters.com/article/2012/03/04/congo-explosion-idINDEE82306020120304
http://en.wikipedia.org/wiki/2012_Brazzaville_arms_dump_blasts
http://www.time.com/time/world/article/0,8599,2108265,00.html
http://www.guardian.co.uk/world/2012/mar/05/congo-arms-depot-rescue-efforts-hampered/...
http://www.bbc.co.uk/news/world-africa-17249480

ACCIDENTS INVOLVING TRANSPORTATION

The previously mentioned accidents were associated with storage operations. Accidents have also been associated with transportation and some are presented in References 7 and 24. Table 5 is a summary of the accidents involving transportation of munitions.

TABLE 5. Accidents Involving Transportation of Munitions and Explosives.

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
6-Dec-17	Canada	Halifax,	2,000	9,000	Fire	Explosions, Detonations	
4-Jun-71	USA	Waco, GA	5	33	Fire	Explosions,	
28-Apr-73	USA	Roseville, CA	0	300	Fire	Explosions, Detonations	$23,000,000
24-May-73	USA	Benson, AZ	0	2	Fire	Explosions, Detonations	$884,600
10-May-85	USA	Bonneville, KY	0	0	Fire		
4-Aug-85	USA	Checotah, OK	0	49	Fire	Explosions, Detonations	$5,000,000
5-Aug-85	Canada	Walden, Ontario	0	2	Fire	Explosions,	
18-Feb-04	Iran	Neyshabur	300	450	Fire	Explosions, Detonations	
9-Aug-05	USA	Spanish Fork Canyon, UT	0	11	Fire	Detonations	
13-Jun-09	USA	Interstate 80, UT	1	1	Fire	Explosions	
23-Jun-10	Russia	Seltsy	1	40	Fire	Explosion	
			2,307	9,888			

Other accidents involving transportation of AN are presented in the section on Accidents Involving the Ingredients Ammonium Nitrate and Ammonium Perchlorate.

Lessons learned from transportation accidents include

- While many of the accidents involved explosions and detonation that resulted in fatalities and widespread damage, all of them were preceded by fire. In many of the accidents, the fire burned for a significant period of time—time for people to be evacuated, time for rescue efforts to be started, time for film crews to arrive on the scene.
- The fires can cause explosions that quickly transition to detonations.

HALIFAX, NOVA SCOTIA, CANADA, DECEMBER 1917

On 6 December 1917, the *SS Mont-Blanc*, a French cargo ship fully loaded with wartime explosives, collided with the empty Norwegian *SS Imo* in “the narrows” section of Halifax Harbor. The *Mont-Blanc* caught fire 10 minutes after the collision and exploded 25 minutes later. All buildings and structures covering nearly 2 square kilometers (500 acres) along the adjacent shore were destroyed. The explosion caused a tsunami that rose as high as 60 feet (18 meters) in the harbor and a pressure wave snapped trees, bent iron rails, demolished buildings, grounded vessels, and carried fragments of the *Mont-Blanc* for kilometers. About 2,000 people were killed by debris, fires, and collapsed buildings and over 9,000 people were injured. The explosion was the largest man-made explosion up to that time. It was roughly equivalent to 3 kilotons of TNT. The fireball from the explosion rose over 1.2 miles (1.9 kilometers) in the air forming a large mushroom cloud.

WACO, GEORGIA, U.S., 4 JUNE 1971

On 4 June 1971, an automobile collided with a tractor-semitrailer transporting non-military explosives near Waco, Georgia. Gasoline and diesel fuel leaked from the vehicles and a fire quickly engulfed both vehicles, and the cargo exploded. A total of 5 people were killed and 33 people were injured (Reference 25).

TWO RAILROAD ACCIDENTS IN 1973

In 1973, two separate railroad accidents occurred in the western U.S. involving military shipments of bombs destined for Vietnam: one at the Antelope Railyards in Roseville, California, and the second near Benson, Arizona. Neither of the accidents resulted in fatalities. Both resulted in extensive damage to railroad equipment, and the Roseville fire, explosions, and detonations essentially destroyed the town of Antelope, California.

ROSEVILLE, CALIFORNIA, U.S., 28 APRIL 1973 (ALSO REFERRED TO AS THE ANTELOPE ACCIDENT)

The following is a summary of several documents, including the Railroad Accident Investigation Report No. 4187 published by the Federal Railroad Administration Office of Safety, Department of Transportation.

http://ntl1.specialcollection.net/scripts/ws.d11?browse&rn=3966 [No longer available]

At 6:05 a.m. 28 April 1973, a train, Southern Pacific Extra 9117 West, from Sparks, Nevada, stopped at the entrance to the Roseville railyard. The train contained 21 Department of Defense-owned railcars (DODX boxcars) carrying 7,056 250-pound general purpose Mk 81 bombs. Each car carried 336 unfuzed bombs loaded on 28 metal pallets, with each pallet containing 12 bombs. The bombs had been produced at the Hawthorne Naval Ammunition Depot, Nevada, and were headed to the Naval Weapons Station, Concord, to be shipped to Vietnam. The 21 DODX boxcars were cars 17 through 37 in the train.

Each Mk 81 bomb contained approximately 125 pounds of tritonal explosive with 80w% TNT and 20w% flaked aluminum composition. [This was the value given in the official accident report. Other documents list the weight of the explosive at 96 to

99 pounds.]. Over seven million tritonal-loaded Mk 80 series bombs had been produced and shipped over land without incident prior to the Roseville accident.

Figure 80 presents a schematic of the Roseville railyard.

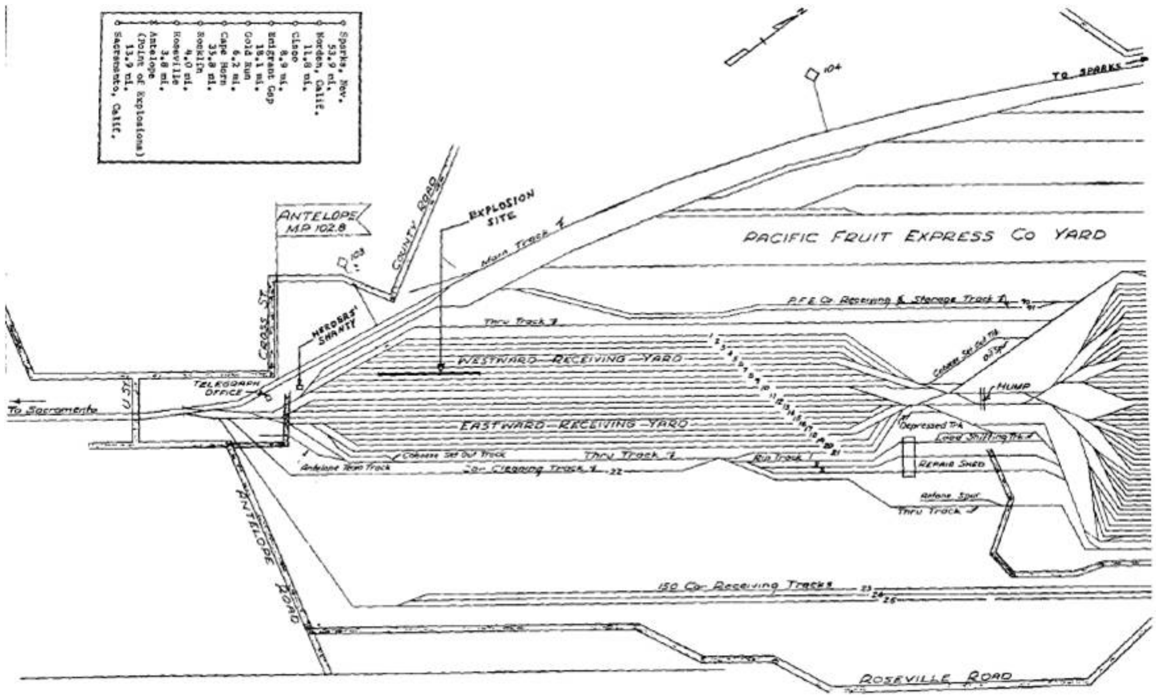


FIGURE 80. Schematic of Roseville Railyard.

At approximately 6:30 a.m., the train began to enter the Roseville yard system. It proceeded through the departure and classification yards and entered the east end of track 7 of the receiving yard. At approximately 7:00 a.m., the train stopped on track 7. The front end extended several car lengths beyond the west switch to track 7 because track 7 was not of sufficient length to accommodate the entire train. As a result of a double-over movement, three of the DODX boxcars were located on track 3, while 18 of the DODX boxcars were located on track 7. At about 7:40 or 7:45 a.m., a resident of Antelope and a switchman noticed smoke rising in the vicinity of the west end of track 7. The Antelope resident said that the smoke was black when he first observed it. It then turned white and diminished. The resident then saw flames rising from the end of a boxcar. Immediately after observing the flames, he heard a “poof” of an explosion. At about 7:59 a.m. an inspector heard the same explosion. He then ran some distance to get a better vantage point. He saw a thick column of black smoke mixed with orange-red flames rising from the roof of one of the DODX boxcars. Soon after climbing down from his vantage point, reporting what he had seen, and beginning to flee, the blast from a detonation knocked him to the ground.

The other 17 cars at the west end of track 7 exploded at various intervals until approximately 10:30 a.m. Bombs strewn in burning debris exploded intermittently until 4:05 p.m. the following day. Figures 81 through 85 present photographs taken of the events and the aftermath of the accident.

FIGURE 81. Accident at Roseville Railyards, 28 April 1973.

FIGURE 82. Accident at Roseville Railyards, 28 April 1973.

FIGURE 83. Aerial View of Accident at Roseville Railyards, 28 April 1973.

FIGURE 84. Aerial View Showing Damage at Roseville Railyards, 28 April 1973.

FIGURE 85. Aerial View Showing Damage at Roseville Railyards, 28 April 1973.

Post accident examinations showed the 18 DODX cars that had been on the west end of track 7 were completely destroyed by the explosions. A total of eight craters were in the area where the cars had been. The craters were 12 to18 feet in depth. Five were roughly circular in shape with 20- to 60-foot diameters at the top of the crater, while three were oval shaped 40 to 65 feet wide and 80 to 100 feet long at the top of the crater.

Fortunately, there were no fatalities, but 15 Southern Pacific employees and approximately 335 residents were injured. Approximately 5,500, mostly residential, buildings were damaged by the explosions. There were 169 freight cars destroyed and 98 freight cars and one locomotive damaged. The cost of damages and casualty claims were estimated to be $23 million.

The Railroad Accident Investigation Report 4187 presented two possible likely causes of the accident: (1) possibility of fire as the causal factor, and (2) possibility of unstable bomb as the causal factor. While the report states, "We are unable to make a positive determination as to the cause of the initial explosion," the following text clearly stated the following:

- "Smoke and fire were observed 15 to 20 minutes before the first explosion." It is believed that what the report really meant to say was that the actual cause of the fire in the DODX car(s) was not conclusively identified, but that fire was clearly observed before the explosions and detonations.
- "The evidence available is not sufficient to support a conclusion that an unstable bomb or bombs was the causal factor of the accident." The report, in fact, presents much evidence that argues against this possibility.

BENSON, ARIZONA, U.S., 24 MAY 1973 (SOMETIMES REFERRED TO AS OCCURRING NEAR TULLY, ARIZONA)

The major source of the following was the Railroad Accident Report NTSB-RAR-75-2 (http:/ntl1.specialcollection.net/scripts/ws.dll?browse&rn=3965).

While the Roseville accident was being investigated, another accident involving boxcars carrying bombs bound for Concord Naval Station and ultimately to be used in Vietnam occurred. The accident occurred at 6:43 p.m., on 23 May 1973, as the Southern Pacific freight train second Blue Streak Merchandise (BSM) was approaching Benson, Arizona. The train consisted of five locomotives, 106 cars, and a caboose. Cars 35 through 46 contained 2,600 500-pound Mk 82 bombs. These bombs were filled with tritonal (80w% TNT and 20w% flake aluminum). An explosion occurred in boxcar 38—car Missouri-Kansas-Texas Railroad Company (M-K-T) 6259, owned by the M-K-T. Part of the car flooring and lining, parts of bomb pallets and strapping, pieces of tritonal were blown out and the right-of-way was littered with car and lading fragments. The explosion was unknown to the train crew and the explosion did not interfere with the progress of the train. About 5 miles further, another explosion occurred in car 38, scattering six bombs and a portion of a seventh bomb, fragments from a pallet, and car fragments in the right-of-way. When the rear end crew saw the black smoke, a flash, and a huge fireball, they set the emergency brakes and detrained. About a mile further on, a large explosion occurred as the train stopped. A series of explosions between 6:50 p.m. and 1:15 a.m. destroyed the 12 munition cars. Based on seismograph recordings and the crater patterns, there were at least three massive explosions at the main (final) reaction site, each involving several cars.

Figure 86 shows a railcar very similar to boxcar 38. Note that the car has truck assemblies (a swiveling frame with two or more axles with pairs of wheels) at front and rear of the boxcar. Later discussions will focus on sparks from the brakeshoes acting on the wheels causing the fire.

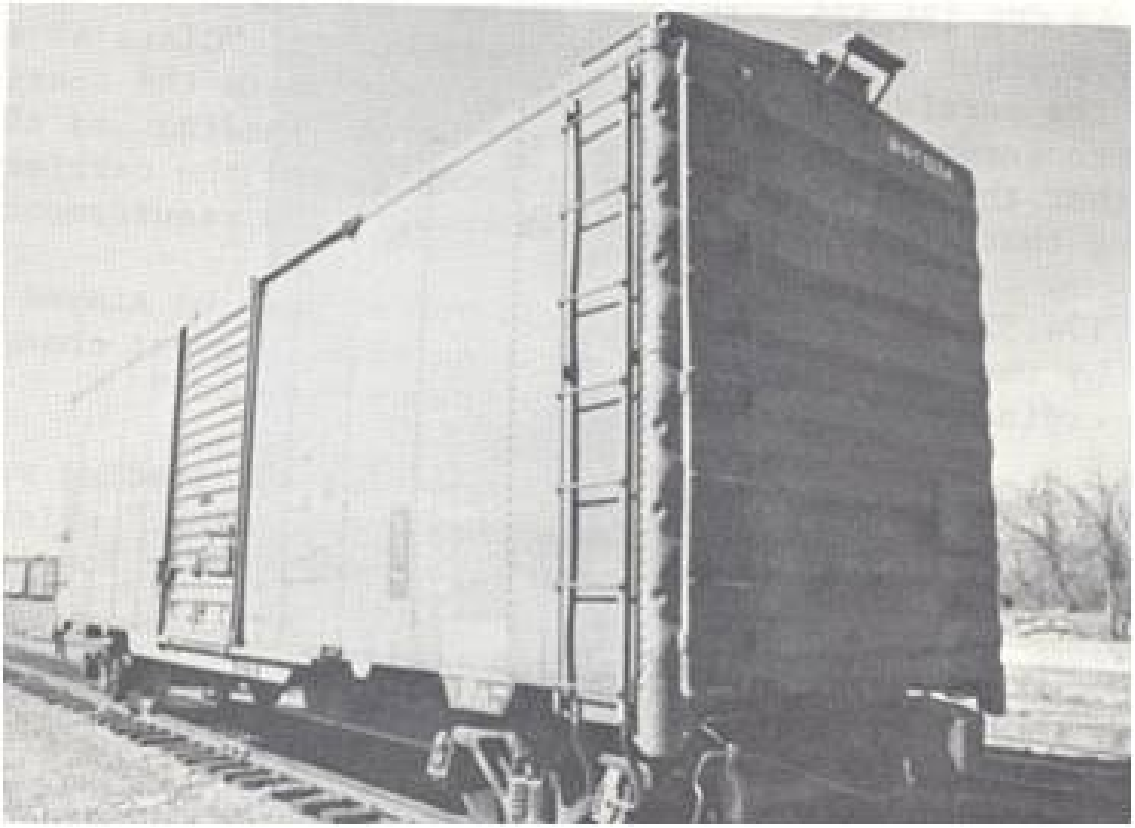


FIGURE 86. Railcar Very Similar to Boxcar 38 Involved in Accident Near Benson, Arizona, 24 May 1973.

The damage from the third explosion is shown in Figure 87. Fortunately, the accident occurred in a sparsely populated area of Arizona.

The major explosions produced a 115- by 93-foot crater, 25 feet deep, and scorched the desert for a quarter mile in all directions. A total of 460 feet of track and roadbed were destroyed. Cars 35 through 46 were totally destroyed. Total damage was estimated at $884,600.

About 500 of the 2,600 bombs were recovered unexploded. Bombs were blown as far as 1 mile from the main crater area. Windows were shattered in a home 5 miles away.

Fortunately, there were no fatalities and only two injuries that occurred when crewmembers jumped from the moving caboose.

FIGURE 87. Aerial View Showing the Damage From the Accident Near Benson, Arizona, 24 May 1973.

The cause of the accident was attributed to fire in car 38. It was estimated that part of the flooring below a pallet that contained bombs was exposed to fire of 1,500°F for 25 minutes. The fire was located almost directly above an area where sparks from the brake shoes could impinge on the floorboards. There were no spark shields on this car. The location of bombs and the location of the front wheel on the front truck are shown in Figure 88.

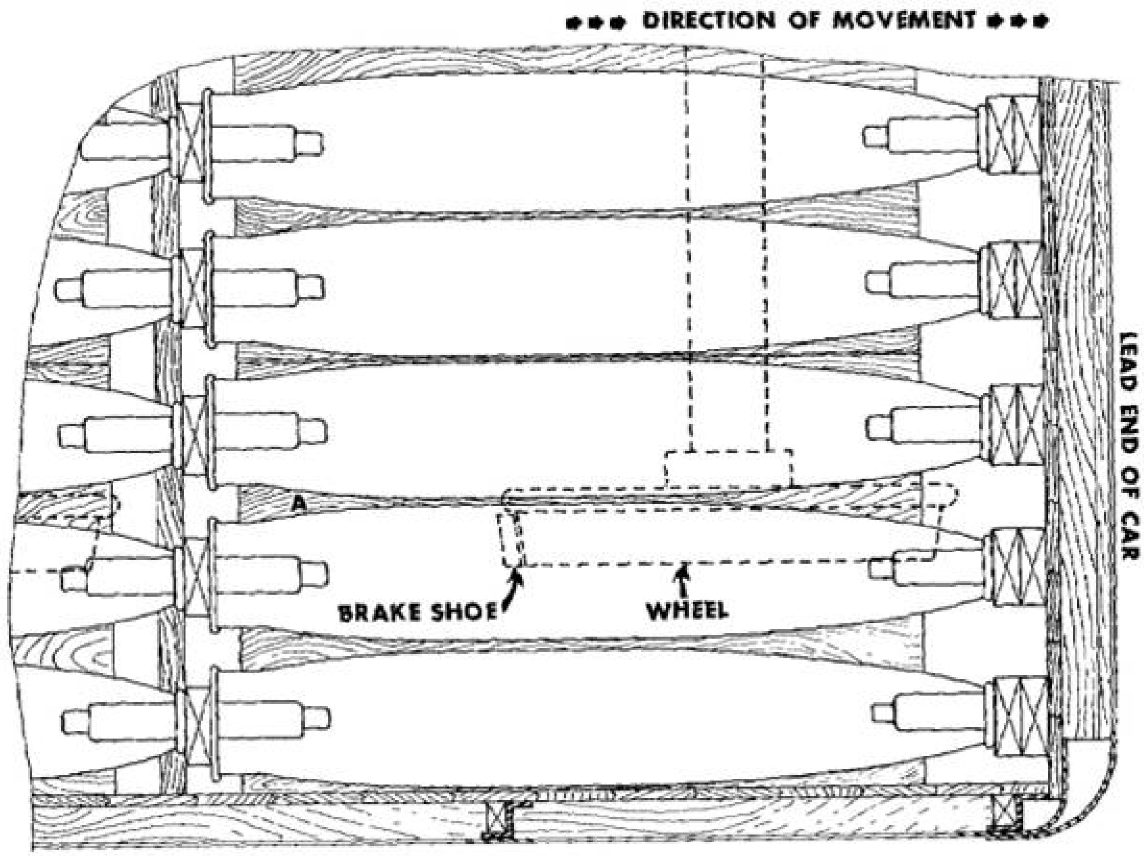


FIGURE 88. Schematic Showing Location of Bombs Over the Brake Shoe/Wheel of the Railcar for Railcar 38.

The ignition of the floorboards was facilitated by the presence of sodium nitrate. Records show that car 38 had carried 400 100-pound bags of sodium nitrate on 28 April 1972. During transit, 21 bags had broken open. On 12 June 1972, an inspection of this car at Ray, Texas, revealed that it had been damaged by fire. It was not repaired until April 1973. The interior of the car had been washed with water before it left M-K-T shops on 5 May 1973. Analysis of some of the burned boards from boxcar 38 showed sodium nitrate levels from 3% at the surface to 0.10% a half inch into the board. The floorboards also were impregnated with oil. Once the floorboards were ignited, the sodium nitrate and oil sustained the burning of the floorboards.

After the accident, debris from the first explosion (that occurred at milepost 1052.6), debris from the second explosion (that occurred at milepost 1048), and a piece of board found at milepost 1051 were reconstructed into a partial mock-up. This mock-up indicated that all of the debris came from boxcar 38.

Additional support for fire caused by brake shoe sparks impinging on the wooden floor of the railcar enabled by the absence of spark shield, and abetted by contamination of the wooden floor boards by sodium nitrate and oil, was provided by a review of the history of car fires experienced by Southern Pacific in this district. Of the 237 car fires reported in the previous five years, 77% resulted from brake shoe sparks. The reports included a 16 December 1972 accident where a car transporting Mk 82, 500-pound bombs caught fire at Hughson, California, as a result of "dragging brakes."

Lessons learned include:

- Because of the possibility of wooden floors igniting and burning, later cars were constructed with steel flooring.
- Instead of all of the cars carrying munitions being consecutive, "spacer" cars not carrying munitions, should be inserted between cars carrying munitions.
- As mentioned in other transportation accidents, the first reaction in the Roseville and Benson accidents was fire that was followed by explosions that in turn caused detonations. In the Benson accident, it was estimated that a fire of 1,500°F burned for at least 25 minutes before the explosions in car 38. These fires went undetected by the train crew. So just because the smoke and fire may not be visible, it does not necessarily mean that the burning is not taking place. Put another way, by the time anyone see flames outside the car or storage, it may be almost too late. Fires that have been burning for some time can result in the following:
    - Have damaged the energetic material making it more vulnerable and more sensitive. For example, a small amount of damage induced porosity dramatically decreases the critical diameter and initiation pressure required for a detonation.
    - May set up the possibility of explosions that can, in turn, lead to detonations.

BONNEVILLE, KENTUCKY, U.S., 10 MAY 1985

On 10 May 1985, a truck-trailer transporting munitions struck a parked vehicle on Interstate 65 near Bonneville, Kentucky, resulting in fire. An estimated 30 gallons of gasoline poured on the ground and ignited. C-4 plastic explosive, transported in the dromedary on the truck, ignited and burned intensely. The Class A (now HD 1.1 or 1.2) and Class B (now HD 1.3) explosive munitions on the trailer did not ignite or explode (Reference 25).

CHECOTAH, OKLAHOMA, U.S., 4 AUGUST 1985

On 4 August 1985, a tractor-semitrailer loaded with 10 Mk 84 2,000-pound general purpose bombs, collided with an automobile of Interstate 40 near Checotah, Oklahoma. The automobile fuel tank ruptured and spilled gasoline that quickly ignited. Both vehicles were engulfed in flames. The bombs exploded destroying the vehicles and produced a crater 27 feet deep and 35 feet wide. A total of 371 residences were damaged. Total damages were estimated at $5 million. A total of 49 people reported to the hospital emergency room for treatment of injuries, most from breathing smoke and gases from burning tritonal. There were no fatalities. The National Transportation Safety Board investigation stated "…the principal threats to the safe transportation of general purpose bombs and other Class A (now HD 1.1 or 1.2) and Class B (now HD 1.3) explosive munitions are fire and heat" (Reference 25).

WALDEN, ONTARIO, CANADA, 5 AUGUST 1998

On 5 August 1998, a tractor and trailer carrying 18,000 kilograms (40,000 pounds) of blasting explosives went off the road near Walden, Ontario, Canada. Fire immediately broke out. The contents exploded about 35 minutes after the fire throwing fragments of the truck up to 2,740 meters (5,800 feet). There were no fatalities and two minor injuries.

NEYSHABUR, IRAN, 18 FEBRUARY 2004

On 18 February 2004, a 51-car-long runaway train that contained 17 cars of sulfur, six cars of petrol, seven cars of fertilizer, and 10 cars of cotton wool derailed and caught fire and then after several hours of fire exploded near Neyshabur in northeastern Iran. There were more than 300 fatalities and more than 450 injured. It was reported that 182 of the fatalities were emergency workers. The loss of so many firefighters and rescuers suggests that they were trying to fight the fire. In the village of Dehnow, which was about 550 yards from the blast, nearly all of the 150 inhabitants were killed. The village was flattened as if hit by an earthquake. Iranian seismologists recorded a 3.6-magnitude tremor at the exact time of the blast.

http://www.news.bbc.co.uk/2/hi/middle_east/3498851.stm
http://www.cbsnews.com/stories/2004/02/18/world/main600853.shtml
http://www.firstcoastnews.com/cleanprint/?1292530958922 [No longer available]

> [Note: This accident is reported in this section because while seven of the cars contained fertilizer the reports did not specify what type of fertilizer (AN?), and because the train also contained petrol and sulfur, as well as the cotton.]

SPANISH FORK CANYON, UTAH, U.S., 9 AUGUST 2005

An accident occurred on Route 6 in Spanish Fork Canyon near Thistle, Utah, on 9 August 2005. A tractor-trailer carrying 35,500 pounds of HD 1.1 commercial booster explosives went off the road, overturned, and caught fire. Rescuers were able to free the driver and his passenger. The dazed driver told rescuers that the trailer was carrying explosives. People were in the process of evacuating when the boosters exploded/detonated. Figure 89 shows an aerial view of the accident site. The crater that was produced (Figure 90) was 21 meters (70 feet) wide and 9 meters (30 feet) deep. There were no fatalities and 11 were injured.

MSIAC, *MSIAC Newsletter, 3rd Quarter 2005,* page 10.

FIGURE 89. Aerial View of Accident Site in
Spanish Fork Canyon, Utah.

FIGURE 90. Accident Involving 35,500 Pounds of HD 1.1 Commercial Booster Explosives That Occurred in Spanish Fork Canyon Near Thistle, Utah, on 9 August 2005.

INTERSTATE 80, UTAH, U.S., 13 JUNE 2009

A fiery crash on Interstate 80 near the Tooele County-Salt Lake County line, Utah, killed one person, injured one, and closed the highway for several hours. The crash occurred at about 11:00 a.m. when an eastbound Dodge Dakota crossed the median and hit a westbound FedEx triple semitrailer head on. Part of the truck was loaded with ammunition. The collision started a fire that engulfed the truck and part of the semi. Some of the ammunition exploded as emergency crews worked to clean up the crash scene depicted in Figures 91 and 92.

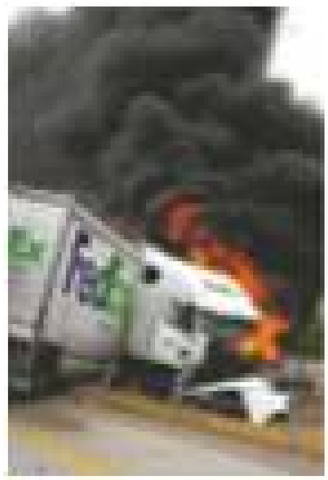


FIGURE 91. Crash Scene on Interstate 80,
13 June 2009.

FIGURE 92. Crash Scene on Interstate 80, 13 June 2009.

MSIAC, *MSIAC Newsletter, 2nd Quarter 2009,* page 8.

SELTSY, RUSSIA, 23 JUNE 2010

Two trucks carrying gunpowder for the disposal of obsolete ammunition caught fire and then exploded on 23 June 2010 at the Artillery Command Academy at Seltsy, Russia. One serviceman was killed and up to 40 injured with 30 reportedly received burns. An official said that the fire could have been caused by spontaneous combustion of gunpowder. A criminal case was opened.

http://zeenews.india.com/news/world/army-personnel-killed-40injured-in-explosion-in-ru
[No longer available]
http://en.novayagazeta.ru/data/2011/060/01.html
MSIAC, *MSIAC Newsletter, 2nd Quarter 2010,* page 13.

ACCIDENTS INVOLVING FIREWORKS

There have been several very serious accidents involving commercial fireworks in Europe and elsewhere. These accidents are discussed here because, while the materials were not military explosives or ordnance:

- Some of the lessons learned are applicable to a discussion of determination of safe-separation distances for HD 1.3 and HD 1.4 materials.
- This relevance has been recognized in Europe. Recent work by the Netherlands and Germany in determining safe-separation distances for military materials is based in part on discussions and work performed in the Control of the Hazards Associated with the Transport and Bulk Storage of Fireworks (CHAF) program. The CHAF program, discussed in a later section, was a European Union funded project to provide a better understanding of critical conditions that give rise to explosions in packaged fireworks, and improved methods of predicting hazards in large scale storage.

The European accidents that are discussed include the following:

- The 1991 accident at the MS Vuurwerk in Culemborg, the Netherlands.
- The 2000 accident at the SE Fireworks factory in Enschede, the Netherlands.
- The 2004 accident at Villeneuve sur Lot (lot et Garonne) France.
- The 2004 accident in Kolding, Denmark.

References and links to other accidents associated with fireworks were found, but unfortunately there was not enough detail in the articles to assess what caused the accidents and discern lessons learned. These accidents and links are presented in Appendix B.

The following sections discuss four of the major accidents. These were chosen because there was detailed reporting and discussion, so that lessons learned could be extracted. Table 6 is a summary of the major accidents involving fireworks.

TABLE 6. Major Accidents Involving Fireworks.

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reactions	Cost
14 Feb 91	Netherlands	Culemborg	2	6 serious	?	Mass explosion	$30,000,000
13 May 00	Netherlands	Enschede	22	1,000	Fire	Explosions	€ 500,000,000
1 Jun 04	France	Villeneuve sur Lot	2		Explosion	Detonation	
3 Nov 04	Denmark	Kolding	1	76	Fire	Explosions, detonations	
		Totals	27	1,082			

Note: This table only includes the results from four major accidents with fireworks. Appendix B of the report contains several hundred reports of additional accidents dealing with fireworks. These accidents were not described in the main text because often the reports of these accidents did have enough detail and lessons learned were hard to discern.

CULEMBORG, THE NETHERLANDS, 14 FEBRUARY 1991

On 14 February 1991, a heavy explosion completely destroyed the assembly plant for display fireworks "MS Vuurwerk" in Culemborg. An investigation was performed by the Netherlands Organisation for Applied Scientific Research (TNO) Prins Maurits Laboratory (PML). A summary of their report is presented in Reference 26.

The assembly plant was located 5 kilometers southwest-west from the town of Culemborg, which in turn is located 15 kilometers south of Utrecht in the center of the Netherlands. The heart of the plant was a bunker from World War II. The bunker was situated at the foot of a dike that was part of the eighteenth-century water defense system of Holland. The plant was situated 50 meters from the dike. Houses and farms were situated against the other side of the dike. The dike has a height of 5.8 meters. On the plant side of the dike only a few farms were present with the nearest about 200 meters away. Two areas of buildings were present on the premises: (1) the old bunker, an administration office, an assembly hall of 25 by 16 meters and five small storage rooms, and (2) a new building consisting of an assembly hall of 20 by 12 meters, four storage rooms, and two work rooms, as shown in the Figure 93.

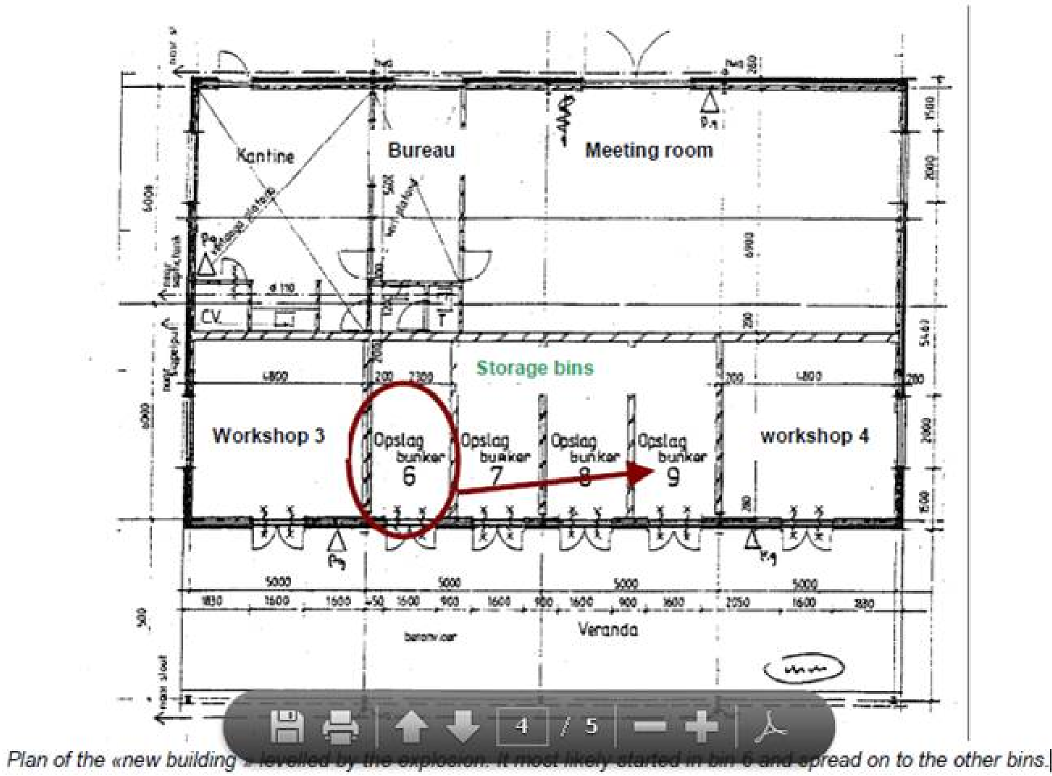


FIGURE 93. Schematic of the New Building, Culemborg, the Netherlands as it Existed Before Accident.

At about 11:50 a.m. on the morning of 14 February 1991, a big bang was heard by farmers and inhabitants of Culemborg. About 20 seconds later a much stronger explosion occurred. The second explosion caused concrete and wood debris to “fall from the sky.” The new building was completely gone and a large crater of 10 by 5 meters with a depth of more than 2 meters was left. The old bunker was set on fire, and fire and minor explosions occurred during the rest of the day.

Extensive damage occurred to buildings in and around the plant. There was considerable damage caused by flying debris in addition to the damage caused by the blast. Most of the debris was the size of bricks or parts of brick and was thrown 300 to 550 meters. However, large pieces of steel girders were thrown beyond 400-meter radius.

There was also considerable damage in Culemborg. The estimated cost of the damage was about $30 million USD.

It was estimated that the explosions had the equivalent of about 2,000 kilograms of TNT. Based on the quantities present at the moment of the explosion and the estimated strength of the explosion it was concluded that a mass explosion of all the fireworks in the new building occurred. As only HD 1.3 articles were allowed to be stored this explosion was not expected at all. The Q-Ds based on HD 1.3 were not sufficiently large to protect against a mass explosion.

During the investigation it was confirmed that 200 kilograms of black powder had been on the premises but it was not found in the old bunker where it should have been. Tests performed at TNO-PML on display fireworks with similar pyrotechnic substances as were recovered indicate a HD 1.1 rather than a HD 1.3 hazard, indicating that some of the fireworks may have been improperly classified.

In the investigation, definitive indications for the direct cause of the explosion were not found. However, a reasonable explanation was that the explosion probably started in storage room 6, immediately followed by explosions in storage rooms 7, 8, and 9.

ENSCHEDE, THE NETHERLANDS, 13 MAY 2000

The accident occurred on Saturday, 13 May 2000 around 3:00 p.m. at the SE fireworks facility. The facility consisted of:

- 17 bunkers used in operations with fireworks, primarily repackaging
- 16 20-foot ISO-type metal shipping containers
- 7 light concrete prefabricate garage type structures (MAVO box).

The facility (Figure 94) was located in a residential district in the city of Enschede. The company stored and repackaged fireworks imported from China.

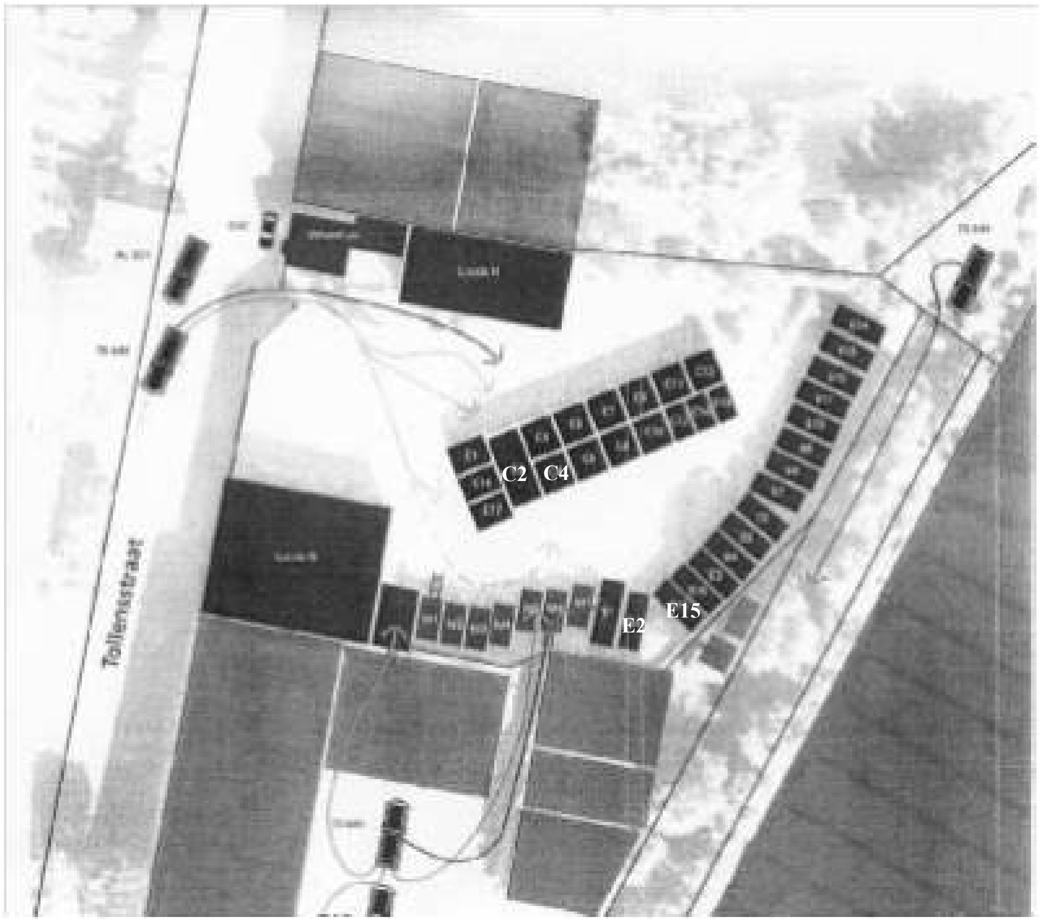


FIGURE 94. Location of the Various Structures at Prior to Accident. M = MAVO box, C = central zone cells, E = ISO containers. The diagram indicates the position of firefighting vehicles prior to the explosions.

http://ec.euroopa.eu/environment/impel/pdf/lessons_learnt_accidents_en.pdf [No longer available]

At about 3:00 p.m., a fire broke out in one of the workshops used for working on the fireworks. The doors were blown outwards due to the pressure associated with the fire. The fire spread via ignited firework rockets to containers located opposite the original fire. The fire, and ensuing projections of rockets, caused many people who were in the town center to approach the site. At about 3:30 p.m., the heat produced by the fire caused a container of fireworks having a large explosive charge to explode. The fireworks stored in the MAVO boxes then exploded. Other explosions then occurred and the resulting shock waves destroyed doors in the various storage facilities. The central bunker caught fire and then exploded violently, generating an enormous plume of smoke and devastating damage to the surrounding areas (Figures 95 through 99).

FIGURE 95. Fireworks Explode at Enschede and
Flames Extend 40 Meters Into the Air.

http://news.bbc.co.uk/2/hi/europe/747674.stm

FIGURE 96. Fire Crews Battle to Bring the
SE Firework Blaze Under Control.

http://news.bbc.co.uk/2/hi/europe/747674.stm

FIGURE 97. Plumes of Smoke Cover Enschede.

http://news.bbc.co.uk/2/hi/europe/747566.stm

At the time of the accident the following materials were on site:

- 16 tonnes of class 1.4 fireworks of the type for private citizens.
- 154 tonnes of class 1.3 professional fireworks.
- 5 tonnes of class 1.2 professional fireworks that typically involved projections.
- 1.5 tonnes of class 1.1 professional fireworks.

The damage caused by the accident included:

- 22 deaths (including four firefighters) with three people missing. [Subsequent reports did not indicate if the missing were ever found or simply assumed to have perished.]
- 1,000 injuries with 50 being seriously injured (hospitalized at least 5 days).
- Total destruction of homes and other structures within a radius of 250 meters.
- Extensive damage to buildings within a 750-meter radius. The city of Enschede decided to demolish everything in this zone. In all, about 500 homes or businesses were destroyed or severely damaged.
- Property damage was estimated at 500 million euros.

FIGURE 98. Aftermath of the Blaze Looked Like a Bomb Site.

http://news.bbc.co.uk/2/hi/europe/747674.stm

FIGURE 99. Cars and Homes Destroyed in the Explosion at Enschede.

http://news.bbc.co.uk/2/hi/europe/747674.stm

An extensive investigation ensued, especially given the previous disaster at Culemborg.

The final report published by the Ministerie van Binnenlandse Zaken en Koninkryjksrelaties can be found at the following web addresses:

http://www.minbzk.nl/actueel/publicatics
htttp://www.emergency-management.net/enschede1.pdf

Lessons learned included:

- The initial cause of the accident was fires that burned approximately 30 minutes before the explosions occurred. The final report addressed the causes of the fire and spread.
- There was mixed storage in the facility:
    - 16 tonnes of class 1.4 fireworks of the type for private citizens.
    - 154 tonnes of class 1.3 professional fireworks.
    - 5 tons of class 1.2 professional fireworks that typically involved projections of burning materials.
    - 1.5 tonnes of class 1.1 professional fireworks.
- There was more fireworks stored at the site than allowed by permit, and the majority of the fireworks were of “a heavier class than was permitted by the two environmental permits in force” according to the final report. The final report also identified four items that were crucial in the origin and development of the fire and explosions.
    - Fireworks were present in the repackaging area C2 where the first fire started. Fireworks were not permitted in this area when no work was being performed, as was the case on Saturday, 13 May 2000.
    - An opening for a water pipe existed between C2 and C4 that allowed the fire to jump across.
    - Two ISO containers with no permits had been added in 1999. One of the containers (E15) was positioned in such as manner as to form one side of a triangle into which fireworks ejected and also closed off access.
    - The area within the triangle was not kept clean, allowing fire to develop against the wall of container E2 and spread to fireworks within that container.

The final report concluded that, “If the permit had been observed in these four items, fire could not have occurred, or at least not an escalation of it. The weight of the fireworks in storage would presumably not have mattered in that case.”

VILLENEUVE SUR LOT (LOT ET GARONNE), FRANCE, 1 JUNE 2004

On 1 June 2004 at 11:40 a.m., a series of explosions destroyed building 9 at Villeneuve sur Lot (Lot et Garonne), France. Figure 100 shows the facility before the explosions.

The workshop (building 9) involved in the accident was dedicated to the manufacture of candle fireworks. It contained two workshops and a storage area, as shown in Figure 101.

FIGURE 100. Site Before the Explosions. The building where the explosions occurred is building 9, in the foreground.

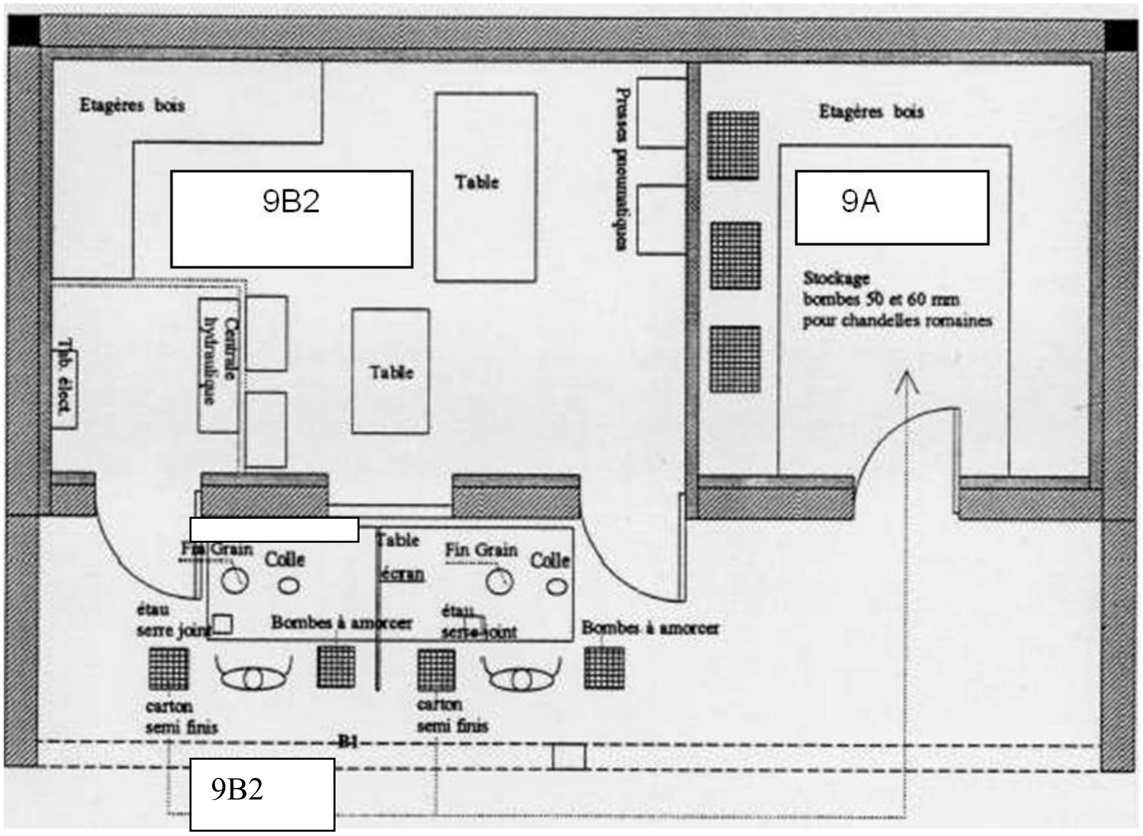


FIGURE 101. Floor Plan of Building 9.

The areas and sequential activities performed in this building included:

- The shell assembly area, under the building's awning (9B1 in Figure 101). The operation consists of manually filling the lower part of the plastic shell with a bursting and star charge, and then bonding it to the upper part and arm the shell.
- Intermediate storage of these shells in storeroom 9A. The shells were stored in plastic boxes stacked on five levels on the wall separating 9A from 9B2.
- The shells were loaded into the candles in 9B2. This operation consisted of using a low-power hydraulic press to insert a series of armed shells and cups filled with powder into a cardboard tube having a closed base. The composition of the powders ensures the ejection of the shell from the tube.

Figure 102 shows the plastic shell with a bursting charge and stars (the main component of fireworks that are designed to produce light effects) and a cutaway of a candle containing shells and lifting charges.

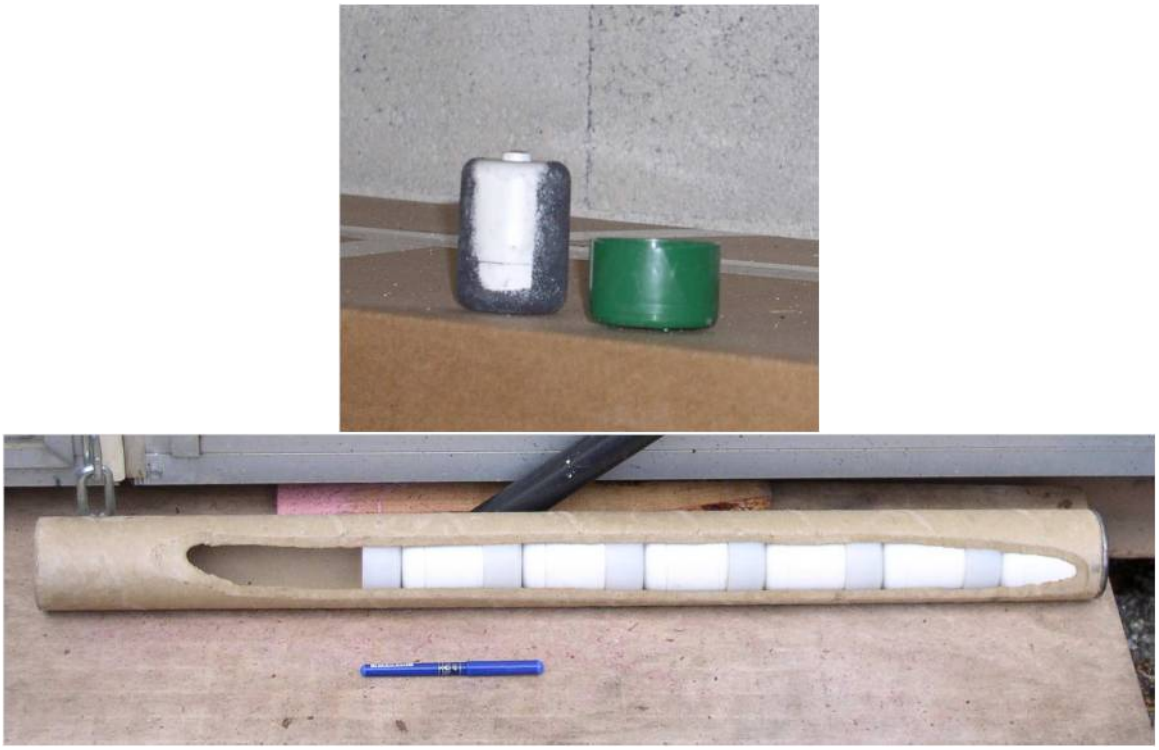


FIGURE 102. Light Effect Shell Containing Stars and Bursting Charge and Cutaway of a Candle Showing Shells and Lifting Charges.

Authorization to use this building prohibited simultaneous shell assembly and candle loading operations. The shell storage area had a maximum limit of 300 kilograms of active ingredients, characterized as non-detonating materials. The maximum limit of the two assembly areas and loading workshops was 5 and 2 kilograms of detonable material because operators were handling powders in these areas.

At the time of the accident two people were working in the building loading 60-mm diameter shells under the awning in area 9B1 to make a few candles. The accident took place in two reactions. An initial explosion occurred, followed immediately by a second, more violent explosion that generated thick white smoke. The two employees were killed. Their extensively mutilated bodies were found 20 and 25 meters from the epicenter of the explosion. Two employees working in the area were injured.

As shown in Figures 103 and 104, building 9 was completely destroyed. The walls were completely blown out and there was a 3- by 1.5-meter by more than 50-centimeter deep crater near the outside wall in the shell store room (9A).

FIGURE 103. Remains of Building 9 After the Accident.

FIGURE 104. Aerial View Showing Where Building 9 Had Been Located Before the Accident.

Figure 104 also shows that the explosion caused damage to the neighboring buildings due to overpressure and fragments. Wall and roof debris from Building 9 was found up to 160 meters away.

The effect of the explosion on building 9 was surprising because of the classification of the shells as HD 1.3 as defined by the regulations governing pyrotechnic materials at that time. The investigating team estimated that the detonation was equivalent to 15 to 30 kilograms of TNT. The shock wave recalculated on the basis of the TNT equivalency would give a radius of 40 and 70 meters for the lethal effect and irreversible effects, respectively.

The origin of the original ignition as well as its location could not be determined. The first explosion at one of the workstations had left a mark on the concrete.

Lessons learned included:

- Even though the candles were classified as HD 1.3, a detonation occurred, as evidenced by the crater and shock wave.
- The first event was not a detonation as the only evidence was a mark on the concrete. But the first explosion caused the detonation that produced the crater and shock wave, and scattered debris.

KOLDING, DENMARK, 3 NOVEMBER 2004

On 3 November 2004, a series of fires and explosions at a fireworks depot in Kolding, Denmark, killed one firefighter, seriously injured three firefighters, with minor injuries to 13 firefighters. Around 60 people were treated for hearing problems or irritation due to inhalation of smoke. The firefighting operations that lasted until the morning of 7 November involved 332 people and 55 vehicles. Approximately 1,500 tonnes of fireworks (about 282 tonnes in NEW) were destroyed. Debris of buildings was found over 1,000 meters from the disaster.

The fireworks depot was located in a sparsely populated small industrial zone about 2 to 3 kilometers from the center of Kolding. The company does not manufacture fireworks; it imports them. It accounts for about 25% of the total Danish imports of fireworks for private use. The site was classified as a top risk level Seveso site with a sited capacity of 300 tonnes NEW. On the day of the accident the depot was practically full with 282 tonnes NEW. [Note: Two days before the accident there was 292.26 tonnes on site as described in Table 7.]

Figure 105 shows an aerial view of the site before the accident. Fireworks were stored in seven single-story buildings having over 9,000 square meters of space and in outside containers (Figure 106). Two buildings were subdivided into two warehouses by an internal firewall (buildings 1/2 and 6/7). The distribution of fireworks 2 days before the accident is given in the Table 7.

FIGURE 105. Aerial View of the Fireworks Depot Before the Accident.

http://barpipdf.geniecube.info/28480_kolding_dk_ih_gb.pdf

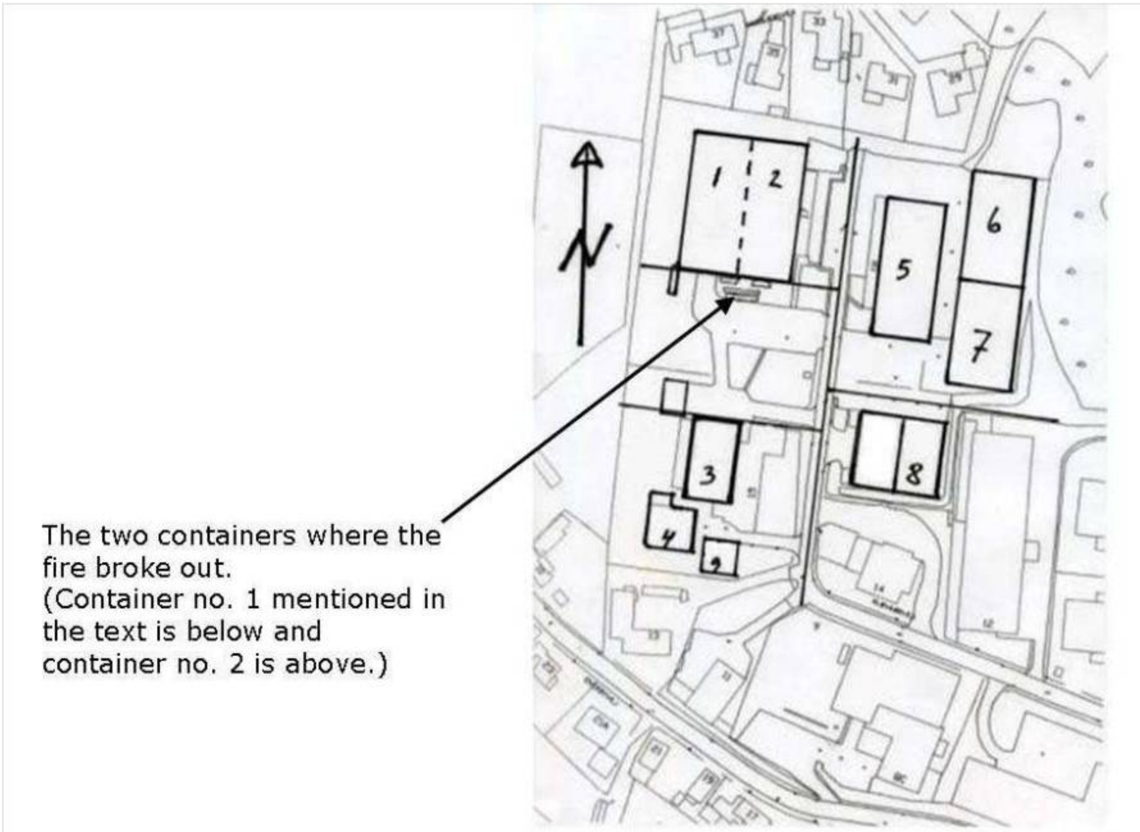


FIGURE 106. Schematic Showing Warehouses and Numbers.

TABLE 7. Distribution of Fireworks Two Days Before the Accident.

Warehouse No.	Surface, m^2	Quantity NEW, tonnes
1+2	2,250	38
3	940	8.7
4	280	7.1
5	1,200	31
6	1,550	85
7	1,550	62
8	970	50
9	140	0.46
	Total	292.26

The accident started on 3 November 2004 just before 2:00 p.m. when three employees were unloading ISO containers 1 and 2 that are shown in Figure 107. The containers were being manually unloaded. An employee took a stacked box in the container and handed it down to another employee who placed the box on a palette. The third employee operated a forklift and took the filled palettes away. An employee accidently dropped a carton of rockets that ignited in container 1, and quickly spread to the other fireworks in the container. The fire quickly spread to the fireworks on the pallets outside the container and into container 2. The company triggered its internal plan and evacuated the staff. The fire alarm was sounded at 2:02 p.m., and the first unit of eight firefighters soon arrived. Efforts were focused on cooling the two containers and protecting the nearest buildings to keep the fire from spreading. Additional aid was requested. Police evacuated residents within a 500-meter radius.

FIGURE 107. Attempts to Put Out the Fire in the Containers.

http://barpipdf.geniecube.info/28480_kolding_dk_ih_gb.pdf [No longer available]

At 3:25 p.m. a major explosion occurred in the area of the burning containers with results shown in Figure 108. The explosion occurred much to the surprise of the rescue workers because there were no signs of an increase in the intensity of the fire immediately preceding the explosion. There were contradicting versions of what happened at 3:25 p.m. Some reports said that container 2 exploded. However, that was also questioned because container 2 was two-thirds empty at the start of the accident (2:00 p.m.) and was on fire for about 90 minutes by 3:25 p.m. It is hard to imagine that any material still on fire in container 2 at 3:25 p.m. could have reacted so violently and caused so much damage. It is more likely that during the 90 minutes between the initial fire and the explosion, one of the 20-foot ISO containers between containers 1 and 2 and buildings 1 and 2 were heated and then exploded at 3:25 p.m. Post accident analysis showed no crater at the location of the containers.

FIGURE 108. Explosion Occurred at 3:25 p.m.; Approximately
1 Hour 25 Minutes After the Initial Fires Broke Out.

http://barpipdf.geniecube.info/28480_kolding_dk_ih_gb.pdf [No longer available]

The explosion destroyed the doors and windows of warehouses 1, 2, and 4. Ignited fireworks (or firebrands) were projected into these buildings. At 3:33 p.m., the fireworks in buildings 1 and 2 exploded.

Three major explosions that resulted in a spectacular fireball (Figure 109) of several meters in diameter occurred at 5:45 p.m. These explosions were presumed to have occurred in buildings 6 and 7. These buildings contained 150 tonnes of fireworks.

FIGURE 109. Explosions That Occurred at 5:45 p.m.

The firefighting operations continued until the morning of 7 November.

Figure 110 shows an aerial view of the site after the accident, and can be compared to Figure 105 that showed the site before the accident.

FIGURE 110. Aerial View of the Site at Fireworks
Site Near Kolding After the Accident.

http://barpipdf.geniecube.info/28480_kolding_dk_ih_gb.pdf [No longer available]

The accident resulted in one death, three serious injuries, and 13 minor injuries to the firefighters. Around 60 people were treated for hearing problems and smoke inhalation. The firefighting operations required 332 personnel and 55 vehicles. Approximately 1,500 tons of fireworks with 282 tons NEW were destroyed in the fires and explosions.

A 2 meters squared by 15 centimeters thick fragment of a concrete wall, weighing approximately 1 tonne, was found 150 meters from building 6. Debris of the buildings was found over 1,000 meters from the disaster. The damage to buildings was approximately 100 million euros.

The post accident investigation found 10 craters where buildings 1, 4, 6, 7, and 8 had been located. These are described in Table 8.

TABLE 8. Craters Found in Post Accident Investigation.

Crater Number	Building	Surface, m^2	Depth, m	Location in Building
1	1	8	0.2	East/center
2	4	3	0.08	West
3	4	5	0.26	East
4	6	35	0.22	Northwest
5	6	29	0.5	Northeast
6	6	75	0.59	Center/east
7	6	110	0.49	Northeast
8	7	25	0.25	Southwest
9	8	24	0.48	Center
10	8	70	0.52	South

http://barpipdf.geniecube.info/28480_kolding_dk_ih_gb.pdf [No longer available]

Several of the containers between the buildings burned for several hours without exploding. Some of them were deformed by heat and possible rise in internal pressure. The door and fragments from the lateral walls of the container that exploded at 3:25 p.m. on 3 November were found at 50, 120, 80, and 96 meters from the container. However, no crater was found indicating a violent pressure rupture of the container.

Lessons Learned

The cause of the accident was inadvertent fire of fireworks in ISO containers during unloading operation.

The fires burned for approximately 90 minutes before there was an explosion. From lack of crater, the explosion may have been a pressure burst rather than a detonation. This is like so many other accidents where fire is the first reaction and burns for some time before other more severe reactions, such as an explosion, occurs.

However, the explosion caused doors and windows in adjacent storage buildings to fail, and dispersed burning materials into these adjacent storage buildings. While the explosion was not a detonation, it quickly spread the reactions, and resulted in later detonations.

Within about 6 minutes (3:33 p.m.) there were explosions in two of the adjacent storage buildings. A crater (8 square meters x 0.2 meter deep) was found where one of the two buildings had been located. While a detonation occurred at one of the sites, the fires preceded it by more than 90 minutes and continued after the detonation.

The containers between the buildings burned for several hours without exploding. Just because energetic materials are subjected to fire for long periods of time does not mean that they will explode or detonate.

At 5:45 p.m. there were at least three additional explosions/detonations in buildings 6 and 7 producing three craters in building 6 and two craters in building 7. While there were many explosions, the fire continued to burn until the morning of 7 November after starting a little before 2:00 p.m. on 3 November.

THE CHAF PROGRAM

The following section summarizes the work reported in Reference 27.

Because of the number of serious accidents in European Union (EU) countries involving fires and explosions in large scale fireworks storage facilities (see the preceding section on Firework Accidents and Appendix B) the EU funded a project called Quantification and Control of Hazards Associated with the Transport and Storage of Fireworks (CHAF). The program ran from 1 January 2003 through 30 June 2006. The prevention of accidents such as those that occurred at Enschede, the Netherlands, that involved 23 deaths, numerous injuries, and major damage to a large area of the town, and Kolding, Denmark, that also involved major damage but with only one fatality, was the rationale for the CHAF project.

One of the contributing factors in these accidents was that the fireworks did not react as expected given their transport classification as determined using the UN Series 6 tests. In particular, certain fireworks were classified as HD 1.3 by the UN tests, yet can have a mass explosion hazard when stored in large quantities. Often accidents with these materials started with inadvertent burning that resulted in explosions that in turn led to detonations. Some of the fires burned for days and had multiple explosions and detonations during that time.

The CHAF program defined several work packages (WPs) defined below:

- WP 1 Management and coordination
- WP 2 Critical review panel
- WP 3 Transfer of information
- WP 4 Literature review
- WP 5 Instrumentation development
- WP 6 Instrumented benchmarking
- WP 7 Small-scale characterization
- WP 8 Medium-scale characterization of packaged fireworks

- WP 9 Instrumented full-scale testing
- WP 10 Development of testing methodology

The program was undertaken by three groups: the Health and Safety Laboratory (HSL), United Kingdom; the TNO-PML, the Netherlands; and Bundesanstalt fur Materialforschung und-prufung (BAM), Germany.

Work packages 6 through 9 are of interest to the DDESB program and are more fully defined below:

WP 6—Characterize selected packaged fireworks in standardized UN tests with additional information recorded, employing additional instrumentation.

WP 7—Quantify the reaction mechanisms taking place within single firework articles, and then expand this to the propagation of reaction between fireworks articles.

WP 8—Develop and utilize a medium-scale apparatus to quantify the increase of pressure with time when stocks of fireworks are ignited when stored in a fashion that is relevant to the situations encountered in bulk storage and transport.

WP 9—Obtain data for validation and verification of small-scale article characterization test and medium-scale package test by performing fire trials using full scale transport and storage containers.

The results from the various WPs are summarized in the following sections.

WP 6. The fireworks selected for testing in this work package are given in Table 9.

TABLE 9. Summary of Fireworks Selected for Testing in WP 6.

Code	Fireworks Type/Description	Expected UN Transport Classification
R1	Large fountains with silver effect, NEC 443 g	1.4
R2	Waterfall gerbs in a dense package (thermal effects)	1.3
R3	Roman candles 2 inches (for projection effects)	1.3
R4	Report shells, caliber 60-mm	1.1
S1	Roman candles with report units, caliber 26-mm	1.3/1.1
S2	Star shells with flash burst charge, caliber 150-mm	1.3/1.1
S3	Rockets with report charge (with sticks)	1.3/1.1
S4	Stickless star-burst rockets, densely packed	1.3/1.1
H1	Mines in mortar, caliber 75-mm	1.4/1.3
H2	Bag mines, caliber 75-mm	1.4/1.3
H3	Connected waterfalls	1.4/1.3

Note: Definitions of terms used to describe fireworks and their operation can be found in the following links:

- http://www.pyrouniverse.com/glossary.htm
- http://science.howstuffworks.com/fireworks1.htm
- http://www.pbs.org/wgbh/nova/fireworks/anat_nf.html
- http://en.wikipedia.org/wiki/Fireworks
- http://www.pyrouniverse.com/consumer/howtheywork.htm

The letters in the code section of Table 9 were used for reference in later tests with R indicating a reference sample, S a sample intended for study of shock effects, and H for study of thermal initiation.

Testing was performed at BAM and HSL using the UN series 6(b) and 6(c) tests. Three tests or more were performed on each article, and were distributed between laboratories as 2+1 or 1+2. This section does not discuss the 6(c) results in any detail. The 6(c) results were not presented until WP 10.

The results demonstrated that those fireworks selected for reference had been well chosen. The expected classifications were confirmed and reference data were collected. For the articles chosen to study shock effects, the results gave some indication that reaction propagation via shock wave may perhaps be less prevailing than initially assumed. From the selected articles, only the rockets with reports were able to show clear mass explosive behavior.

Overall, the provision of additional instrumentation to the existing UN series 6 test proved to give much valuable data. The results are combined with the results from WP 7 and presented later in Table 10.

WP 7. The purpose of WP 7 was to quantify the reaction mechanisms taking place within a single fireworks article and then expand this understanding to the propagation of reaction between firework articles. The reaction mechanisms considered include:

- Mechanical deformation leading to friction, shear stress, adiabatic compression followed by initiation.
- Impact (not blast) from debris.
- Pure thermal initiation (conductive, convection from flames and pressure, and radiation from flames and hot parts).
- Pressure leading to increased burning rates.
- Shock initiation.
- Pressure causing the crushing of shells and pyrotechnics.

The articles used in testing in WP 7 are given in Table 10.

TABLE 10. Articles Used for WP 7 Studies (as Ordered From WP 6).

Reference Articles	Shock Initiation Study Articles	Heat Initiation Study Articles
Fountain (R1)	Roman candle with report charges (S1)	Ground mine (H1)
Waterfall (R2)	150-mm star shells (S2)	Bag mine (H2)
Roman candle (R3)	Report rocket (S3)	Waterfall (H3)
Report shell (R4)	Unsticked starburst rockets (S4)	

In addition, tests were performed on 75-mm peony shells. The results from WP 6 and 7 are shown in Table 11.

TABLE 11. Summary Results From WP 6 and WP 7.

Article	Code WP 6/7	WP 6 Results	WP 7 Results
Fountain, 500 grams	R1	1.4	Sequential ignition; regular burning
Waterfall gerb, 24-mm cal	R2	1.4	Sequential ignition; heat radiation function of number of articles simultaneously reacting, total burning time approximately the same; no violence expected
Roman candle, 30-mm, 8 shots	R3	1.2	Sequential ignition; ejections, no irregular behavior in bulk
Report shells	R4	1.1	Mass explosion, hardly influenced by current mitigation and packaging; probably flash powder shock propagation
Roman candles with report	S1	1.3	Quasi-simultaneous reaction of reports, but under high confinement possibly mass explosion
150-mm shells	S2	1.3	Under conditions (packaging, mitigation, initiation, confinement) possibly mass explosion (or simultaneous reaction); lift charges play a role in fast (flame) propagation; stronger stimulus may lead to shock propagation
Report rocket	S3	1.1	Mass explosion, independent of confinement, orientation and mitigation; very sensitive flash powder shock propagation
Rocket without stick	S4	1.3	Unconfined no propagation; under conditions (packaging, mitigation, initiation, confinement) mass explosion
Mine	H1	1.4	Sequential ignition; regular flame spread, when contained faster burning; no severe reaction

TABLE 11. (Contd.)

Article	Code WP 6/7	WP 6 Results	WP 7 Results
Bag mine	H2	1.3	Sequential ignition; flame spread, violence depends on confinement. Possible explosion (by pressure) in container
Waterfall connected	H3	1.3	Heat radiation non-linear function of no. of articles simultaneously reacting.
Silver Peony, 75-mm shell	TNO	1.3	Mixed reactions. Depending on confinement, scaling effects? Crushing: initiation above certain (high) velocity (>70 m/s), reason uncertain

WP 8. The purpose of this WP was to develop and utilize a medium-scale apparatus to quantify the increase of pressure with time when stocks of fireworks are ignited while stored in a fashion that is relevant to the situations encountered in bulk storage and transport.

The test vessel chosen is shown in Figure 111. The vessel is a horizontal steel cylinder of 914-mm nominal outside diameter with 12.5-mm wall thickness by 14.39-mm long flange face to flange face.

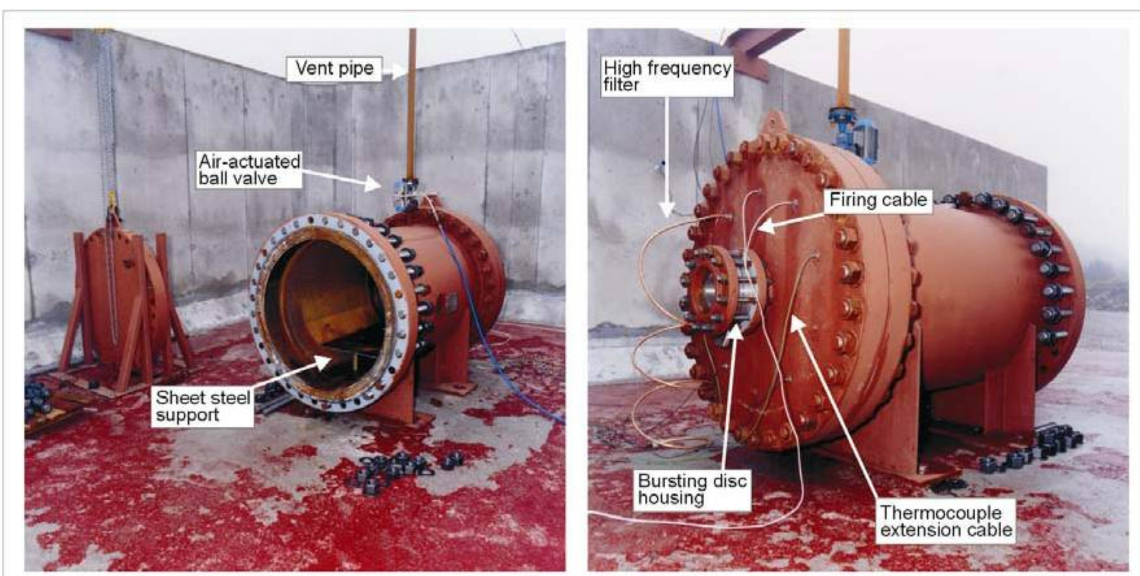


FIGURE 111. Pressure Vessel Used in WP8.

The fireworks tested in WP 8 are given in Table 12.

TABLE 12. Fireworks Tested in WP 8.

Firework	Article Type	Description
WP6 Roman candles	R3	30-mm inside diameter (I.D.) fiberboard tube 900-mm long. Ejects eight 14 g stars.
WP6 Roman candles with report	S1	Seven 13 g report effects ejected sequentially from a 26-mm I.D. fiberboard tube.
WP6 150-mm shells	S2	137-mm outside diameter (O.D.) plastic cased spherical shell containing gold effect stars and flash burst charge. Comet attached to outside of shell.
WP9 150-mm shells	S2	Card cased spherical shells containing peony, chrysanthemum, or palm tree effects in various colors. No comet.
WP6 Unsticked rockets	S4	36-mm O.D. rocket head containing 6-mm dia. stars. No stabilizing sticks.
WP9 Unsticked rockets	S4	Rocket head contains burst charge and effects. No stabilizing stick.
WP9 75-mm shells	S5	Card cased spherical shells containing peony, chrysanthemum, or palm tree effects in various colors. No comet.
WP6 Mines in mortar	H1	Approx. 65-mm mine in 80-mm O.D. fiberboard tube 350-mm long.
WP6 Bag mines	H2	65-mm-dia. fiberboard tube containing pyrotechnic effects.
WP9 Bag mines	H2	Fiberboard tubes containing lift and effects.
WP9 Connected waterfalls	H3	20 waterfall gerbs linked by quickmatch.

These fireworks were tested in the vessel shown in Figure 111. The pressure–time (p-t) data were used to determine the maximum rate of pressure rise and specific impulse (area under the p-t curve between 10% and 90% of the maximum pressure. The specific impulse used is shown in Figure 112.

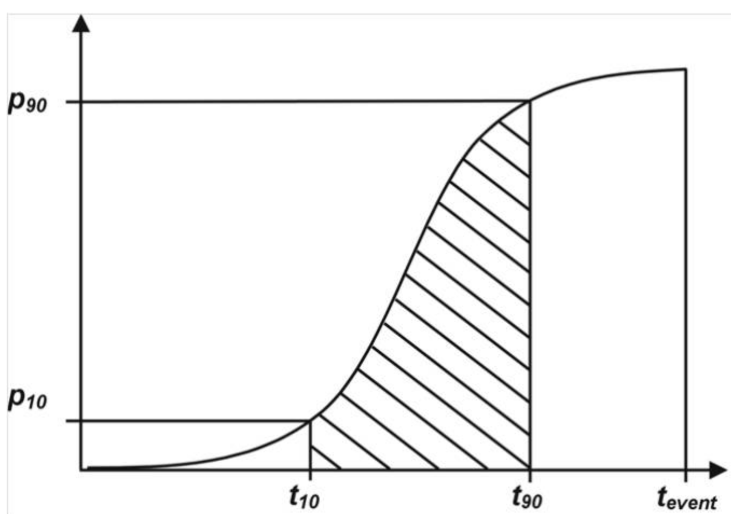


FIGURE 112. Portion of the p-t Curve Used to Calculate the Specific Impulse.

The specific impulse, I_s, used is the shaded area divided by the NEW and is given by Equation 1. The portion from 10% to 90% was chosen to eliminate beginning effects such as heat loss and end effects such as tail-off near burn-out, thus giving more reproducibility.

$$I_s^{10-90} = \frac{1}{NEW} \int_{t10}^{t90} p\,dt \qquad (1)$$

The data obtained from the closed vessel tests with single transport packages of various fireworks are presented in Table 13.

TABLE 13. Data From Closed Vessel Tests of Single Transport Packages of Various Fireworks.

Test Description	NEW, kg	pmax, kPa	dp/dtmax, kPa/s	Is^{10-90}, kPa.s/kg
WP9 Connected waterfalls	19.6	10500	1.4E+08	0.2
WP9 Unsticked rockets	7.0	5523	2.8E+04	0.5
WP9 150-mm shells	9.6	4742	4.0E+05	47.1
WP6 150-mm shells	13.5	4359	2.9E+05	66.3
WP6 Roman candles with report	6.9	7567	2.0E+05	93.4
WP7 75-mm shells	9.5	5626	6.6E+04	110.5
WP6 Bag mines	15.1	7067	4.7E+04	127.5
WP6 Mines in mortar	3.3	2783	7.2E+03	150.0
WP6 Unsticked rockets	2.5	443	2.8E+03	201.4

Table 13 presents data for two different configurations of stickless rockets, WP 6, and WP 9. The difference between the two types of samples was how the stickless rockets were configured in the packaging. The WP 6 stickless rockets were packaged with a layer of cardboard between layers of stickless rockets. The packing arrangement for each layer of WP 6 is shown in Figure 113.

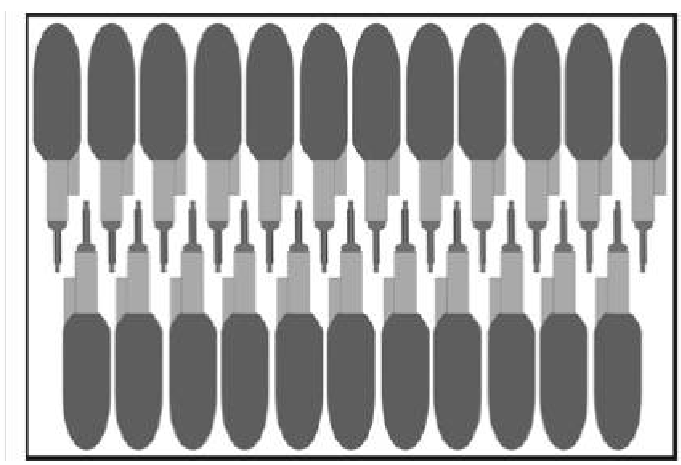


FIGURE 113. Packing Arrangement for Each Layer of WP6 Stickless Rockets. Each layer of stickless rockets separated with a layer of cardboard.

In contrast, the packing arrangement for the WP 9 stickless rockets did not have a layer of cardboard and the two layers had the center two rows of rockets with the energetic heads closely together, as shown in Figure 114.

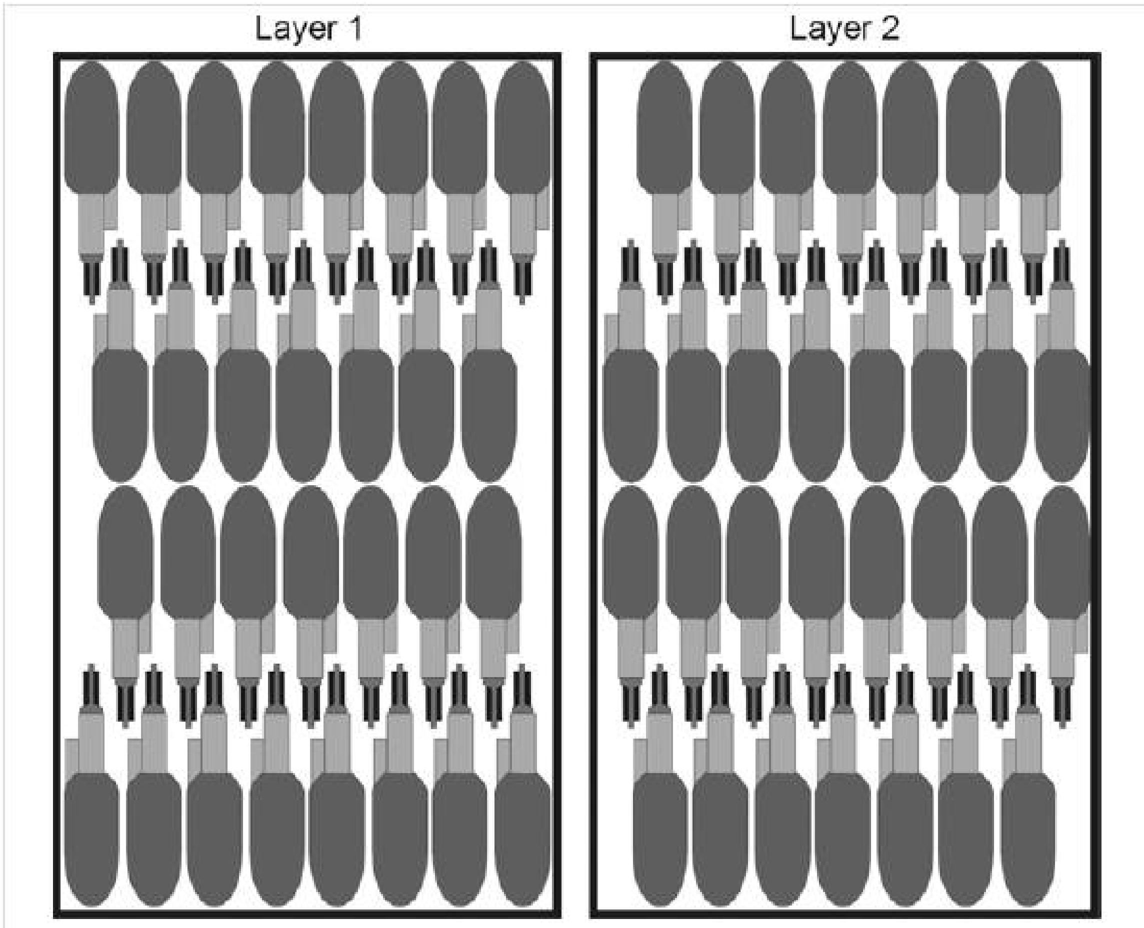


FIGURE 114. Packing Arrangement for Two Layers of WP 9 Stickless Rockets, With No Cardboard Separating Layers.

When the maximum dp/dt (rate of reaction) and the specific impulse obtained for the various firework samples were plotted against each other, the result was a plot that discriminated between packaged materials that mass exploded and those that did not. This is shown in Figure 115.

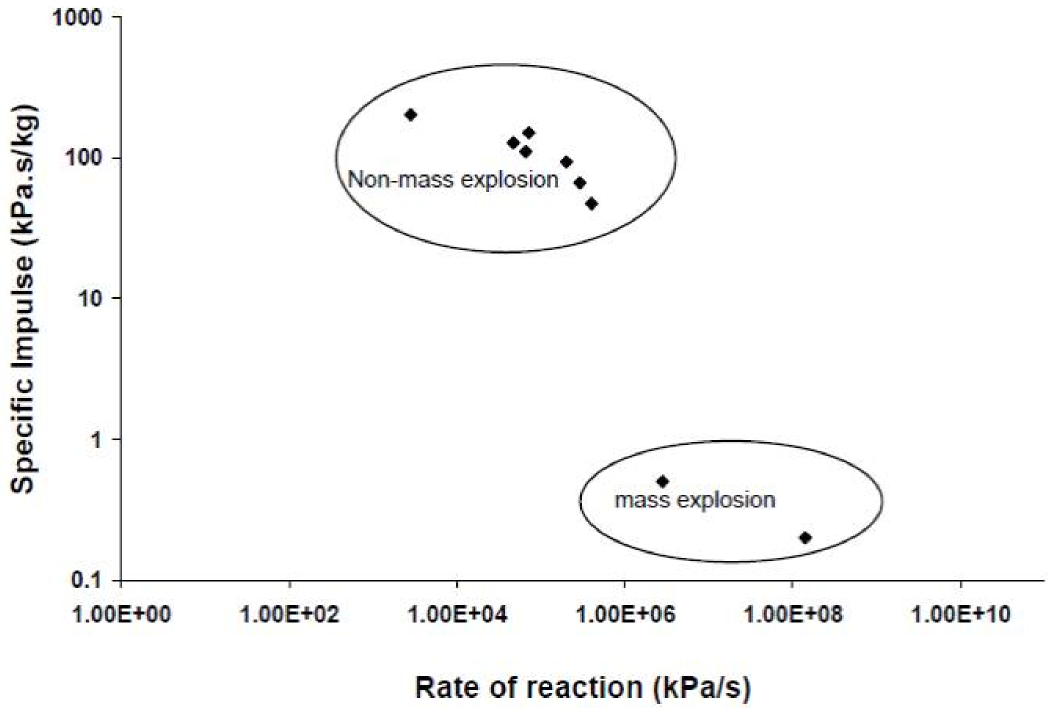


FIGURE 115. Relationship Between Maximum Rate of Reaction (Maximum Dp/Dt) and Specific Impulse (I_s^{10-90}) for a Range of Packaged Fireworks.

WP 9. The full-scale tests involved various fireworks load-outs in modified 20-foot-long ISO containers. The instrumentation for the tests included in the following:

- Temperature and pressure sensors inside the containers.
- Internal video camera.
- Blast and heat sensors outside the containers.
- External video cameras.

In total eight large-scale tests and three reduced-scale tests were performed with five different firework types. The test series is shown in Table 14.

TABLE 14. WP 9 Test Series.

Test	Firework Items	Test Situations
A1	150-mm color shells	Full container
A2	75-mm color shells	Full container
A3	150-mm color shells	Partially filled (aisle) container
A4	75-mm color shells	Partially filled container; covered by sand
A5	Bag mines	Partially filled container
A6	Waterfall	Full container
A6-2	Waterfall	Low loading container
A6-6(b)	Waterfall	Std UN 6(b)
A6-6(b)mod	Waterfall	Scaled up UN 6(b)
B7	Rockets without stick	Full container
B7-2	Rockets without stick	Full container, duplicate

Figure 116 shows the typical sequence of events as the fireworks were ignited, followed by pressure causing the doors to open and generation of a large fireball.

FIGURE 116. Sequence of Events as the Fireworks Were Ignited.

The damage to the containers varied from simple bulging of container walls to destruction of the container to fragmentation of the container and projection of fragments, as shown in Figures 117 through 119.

FIGURE 117. Damage to ISO Container From the 75-mm Shell Test.

FIGURE 118. Damage to ISO Container From the 150-mm Shell Test.

FIGURE 119. Fragments From the ISO Container From the Waterfalls Test.

Videos of the large-scale tests are presented at the link: http://www.chaf.info/videos.htm

Table 15 summarizes the behavior from the WP 9 tests.

TABLE 15. Summary of the WP 9 Results.

Fireworks Type	Storage/Transport Conditions	UN HD	Full-Scale Behavior
Color shells (150-mm)	Storage and transport	1.1G[a]	Thermal effects, no mass explosion
Color shells (150-mm)	Extra confinement by earth covering; worst case transport and storage	1.1G[a]	Mass explosion
Color shells (75-mm)	Transport	1.3G	Thermal effects, no mass explosion
Bag mines	Storage	1.3G	Thermal effects, no mass explosion
Waterfalls	Transport[b]	1.3G	Mass explosion[b]
Rockets without sticks	Transport	1.1G[a]	Mass explosion

[a] In WP 6, this article was classified as 1.3G. UN classification tests with the articles used in the full-scale tests proved differently.

[b] Reduced scale additional tests were carried out (including a container test with 1,768-kg net explosive mass) that were not related exclusively to transport or storage.

The column Storage/Transport conditions refers to configuration: transport was essentially a full container, while storage configuration was a partially filled container with an aisle.

> [Note: Up to this point in this report on the CHAF program, the author has been summarizing the work presented in the final report. In these next three paragraphs, the author had added thoughts and analyses of his own. Any errors or misinterpretation is the author's fault not the fault of the final report or the investigators who contributed to that final report.]

The results of the tests with the waterfall fireworks are very interesting. The small-scale UN series 6 results would classify these materials as HD 1.3, yet the full-scale tests resulted in mass explosion. The obvious question is what did the WP 8 tests show? The WP 8 tests showed that the connected waterfalls had a maximum dp/dt of 1.4E+08 kPa/s and a specific impulse of 0.2 kPa.s/kg. These values are in the mass explosion area of Figure 115, so the large-scale test results should not be surprising. Similarly the 150-mm color shells using the UN series 6 tests would classify these materials as HD 1.1, yet there was no explosion until extra confinement was provided to the ISO container by earth covering. The extra confinement by earth covering produced a mass explosion. So once again, what were the results from the WP 8 tests? The WP 8 results were 4.0E+05 kPa/s and 47.1 kPa.s/kg for the WP 9 150-mm shells, and 2.9E+05 kPa/s and 66.3 kPa.s/kg for the WP 6 150-mm shells. Both of these sets of values place the 150-mm shells in the non-mass explosion area of Figure 115.

The test with rockets without sticks is another very interesting result. In the WP 8 tests, there were two configurations of rockets without sticks: the WP 6 configuration that had cardboard between layers and the energetic material facing out and the WP 9 configuration with no cardboard between layers and the center rows having energetic heads close together (see Figures 113 and 114). Going back to the WP 8 tests, the WP 9 unsticked rockets configuration had 2.8E+4 kPa/s and 0.5 kPa.s/kg placing it in the mass explosion area in Figure 115, while the WP 6 unsticked rockets configuration had 2.8E+3 kPa/s and 201.4kPa.s/kg placing it in the non-mass explosion area in Figure 115. The WP 6 single article UN series 6 test gave a 1.3 classification. Given all of the results with the rockets without sticks samples, the middle-scale WP 8 tests did a good job in predicting the results of the large scale tests.

The test sequence described in this report, especially the medium-scale tests using the closed vessel and the validation provided by the large-scale tests is an outstanding contribution in improving the safety during transportation and storage of fireworks. We recommend that the DDESB consider a research effort applying a similar effort to munitions to see if a predictive small- to moderate-scale method could be used to predict large scale behavior to improve safety in transporting and storing munitions.

WP 10. The purpose of WP 10 was to summarize and make conclusions from the work of the preceding work packages.

In the report, WP 10 presented a summary of the data from the various tests. This is presented in Table 16.

Table 16 presents data that were not previously presented in their report in WP 6. That is the heat flux data presented in the column UN 6(c). The distinction is made as to whether the heat flux (labeled as thermal output in the table) was greater than, or less than, 4 kW/m^2. The 4 kW/m^2 at 15 meters is the value that distinguishes between HD 1.3 and HD 1.4. As discussed in a later section and presented in Figure 200, 4 kW/m^2 would correspond to an exposure time of approximately 26 seconds before a person would receive second-degree burns, using the methods and data from Reference 28.

The final report also recommended using the closed vessel and the resulting pressure time data, when reduced to maximum dp/dt and specific impulse to predict the large-scale ISO container tests instead of just relying on the UN series 6 tests. The data in the report made a good case for the following: While the UN series 6 data often successfully classified the materials and predicted the large-scale event, there were times when there was a mass explosion event when the materials were stored in ISO containers, even though the materials were classified as HD 1.3 based on the UN tests. The medium-sized test presented in the CHAF final report was able to correctly predict the large-scale ISO container test results.

RECOMMENDATION

The test sequence described in this report, especially:

- The medium-scale tests using the closed vessel,
- The prediction of large-scale test results based on maximum dp/dt and specific impulse data derived from the p-t history from the closed vessel tests, and
- The validation provided by the large-scale tests is an outstanding contribution in improving the safety during transportation and storage of fireworks. The question is does it also apply to munitions.

We recommend that the DDESB consider a program applying a similar effort to determine if the method can also improve safety in transporting and storing munitions.

TABLE 16. Summary of Data Presented in WP 10 Used in Identifying a Test Methodology.

Firework	WP 6		UN Classification	WP 7	WP 8	WP 9
	UN 6(b)	UN 6(c)				
Fountain	Sequential ignition	Thermal output < 4 kW/m^2	1.4	Sequential ignition	-	-
Waterfall gerb	-	Thermal output < 4 kW/m^2	1.4	Sequential ignition	-	-
Roman candle	-	Sequential ignition, penetration of witness screen	1.2	Sequential ignition	Incomplete reaction	-
Report shell	Mass explosion	Mass explosion	1.1	Mass explosion	-	-
Roman candle with report	Sequential ignition	-	1.3	*1*	Ramping to violent explosion	-
150-mm shell (WP6)	Usually no mass explosion *2*	Sequential explosion of transport packs	1.3	Different results	Ramping to violent explosion	-
150-mm shell (WP9)	Mass explosion	-	1.1	-	Ramping to violent explosion	Usually no mass explosion *3*
Report rockets	Mass explosion	Orientation dependent behavior	1.1	Mass explosion	-	-
Stickless rockets (WP6)	Sequential ignition	Projection of burning matter	1.3	Mass explosion *4*	Incomplete reaction	-
Stickless rockets (WP9)	Mass explosion	-	1.1	-	Violent mass explosion	Violent mass explosion
75-mm shell (WP7)	-	-	1.3	Different results	-	-
75-mm shell (WP9)	No mass explosion	-	1.3	-	Sequential ignition	Sequential ignition
Mines in mortar	Slow sequential ignition	Thermal output < 4 kW/m^2	1.4	Sequential ignition	Sequential ignition	-
Bag mines (WP6)	-	Thermal output > 4 kW/m^2	1.3	Sequential ignition	Sequential ignition	-
Bag mines (WP9)	-	Thermal output close to 4 kW/m^2	1.3	-	Sequential ignition	Sequential ignition
Connected .waterfalls (WP6)	-	Thermal output close to 4 kW/m^2	1.3	*5*	-	-
Connected waterfalls (WP9)	No mass explosion	Thermal output > 4 kW/m^2	1.3	-	Violent mass explosion	Violent mass explosion

1 a mass explosion was observed only under higher confinement
2 mass explosion seems possible under slightly higher confinement than in an UN 6(b) test
3 only additional confinement by sand mounding lead to a mass explosion
4 mass explosion under medium confinement
5 thermal output, respectively violence of reaction, depends non-linearly on amount of fireworks

ACCIDENTS INVOLVING THE INGREDIENTS AMMONIUM NITRATE (AN) AND AMMONIUM PERCHLORATE (AP)

BACKGROUND

AN and AP are ingredients that have been used, and continue to be used, in propellants and explosive, because they are excellent oxidizers. Both have a history of being involved with accidents, even though both are hard to ignite and initiate to a detonation.

This section of the report discusses some of the major accidents that have occurred with either AN or AP.

AMMONIUM NITRATE (AN)

AN has been used in both military and commercial explosives such as ammonium nitrate and fuel oil (ANFO). ANFO type explosives have been used in commercial mining and also as an explosive used by terrorists. An ANFO-type explosive was the explosive used in the infamous Oklahoma City Alfred P. Murrah Federal Building bombing. It has recently been used by insurgents in Afghanistan in improvised explosive devices (IEDs).

AN has also been used as a fertilizer for many years. In fact, many of the accidents with AN were with AN intended for fertilizer use rather than as an ingredient for propellants or explosives.

AN (NH_4NO_3) is a white crystalline solid at room temperature and standard pressure. It is valued for its nitrogen for fertilizer application, and for its oxidizing potential (and hydrogen) for explosive and propellant applications.

The melting point of AN is 169°C. The sensitivity of the molten material is higher than that of the solid. At 245°C and higher, shock sensitivity is quite high, and at 260°C molten AN can be initiated by 6 to 7 kilobars (kbars) input shock (Reference 29).

AN reacts with heat: reversible endothermic dissociation occurs at 80 to 93°C

$$NH_4NO_3\ (s) \rightleftharpoons NH_3\ (g) + HNO_3\ (g) \qquad -\Delta H = 186\ \text{kJ/mole AN}$$

Followed by a number of irreversible exothermic reactions at higher temperatures, e.g.,

$$NH_4NO_3\ (s) \rightleftharpoons N_2O\ (g) + 2\ H_2O\ (g) \qquad -\Delta H = -37\ \text{kJ/mole AN}$$
$$2\ NH_4NO_3\ (s) \rightleftharpoons 2N_2\ (g) + 4\ H_2O\ (g) + O_2\ (g) \qquad -\Delta H = -118\text{kJ/mole AN}$$

(Reference 30).

If AN is subject to heat but in a vented compartment, or in the open, the endothermic dissociation offsets the exothermic reactions, so that if the heat is removed, the temperature of the decomposing material drops rapidly (Reference 29). However if there is a significant increase in pressure associated with tight confinement, the pressure can reach a critical level and the exothermic reactions over-power the endothermic vaporization reactions and the temperatures and reaction rates can accelerate to explosion/detonation. If pure AN is involved in the fire, the pressures would have to reach kilobar levels for an explosion or detonation to occur. These levels are unlikely in most storage or transportation situations. As will be shown in the section on tests, most structures rapidly start coming apart when internal pressures reach about 10 bars. However, if the AN is in contact with fuel or contaminants it becomes more sensitive and less pressure would be required for a deflagration or detonation to occur.

Grenier (Reference 29) also lists accidents with AN where there were fires but no explosions, as shown below:

- **Independence, Kansas, 1949**. This fire involved nearly 1,400 tons of wax-coated, bagged AN fertilizer, the same type of AN that was in the hold of the ship that blew up at Texas City in 1947. The limited water supplies made firefighting difficult. The fire went out-of-control; and, after several hours of burning, the building was completely destroyed and all but 100 to 150 tons of the nearly 1.400 tons of fertilizer-grade AN had been consumed. The building was well vented during the fire allowing for the release of the products of combustion. No explosion took place in spite of the fact that the AN was coated with wax and that a number of other contaminants had come in contact with the molten nitrate including aluminum, copper, iron, zinc, and carbonaceous materials such as wood and asphalt. Quantities of aluminum and copper had melted during the fire. Since the melting point of copper is approximately 1901°C, it would appear that flame temperatures were at least at or above this temperature. The temperature of the AN was self-limiting, even in a runaway fire, because of the powerful endothermic action of the volatizing material.
- **Barksdale, Wisconsin, 1920.** A total of 30,000 pounds of AN were destroyed in a well-vented storage building fire. No explosion.
- **Brooklyn, New York, 1920.** A total of 1,944,500 pounds of AN were consumed in a fire in the holds of the Norwegian freighter, the *S.S. Hallfried*. No explosion.

- **Muscle Shoals, Alabama, 1925.** Two boxcars filled with AN were destroyed by fire. No explosion.
- **Gibbstown, New Jersey, 1940.** 147,000 pounds of uncoated AN in paper sacks were consumed in a warehouse fire. No explosion.
- **Presque Isle, Maine, 1947.** 80,000 pounds of mixed fertilizer containing AN and superphosphate and potassium salts were involved in a plant fire. No explosion.
- **St. Stephen, Canada, 1947.** 400 tons of AN fertilizer were consumed in a fire. No explosion.
- **Railroad Boxcars, 1946 to 1949.** From 1946 to 1949, there were 13 separate railroad cars involved in fire, each containing 80,000 to 100,000 pounds of AN fertilizer. There were no explosions during any of these fires.
- **Independence, Kansas, 1949.** This fire involved nearly 1,400 tons of wax-coated, bagged AN fertilizer, the same type of AN that was in the hold of the ship that blew up in Texas City in 1947. The limited water supplies made firefighting difficult. The fire went out of control and after several hours of burning, the building was completely destroyed and all but 100 to 150 tons of the nearly 1,400 tons of fertilizer-grade AN had been consumed. The building was well-vented during the fire allowing for the release of the products of combustion. No explosion took place in spite of the fact that the AN was coated with wax and that a number of other contaminants had come in contact with the molten nitrate including aluminum, copper, iron, zinc, and carbonaceous materials such as wood and asphalt. Quantities of aluminum and copper had melted during the fire and since the melting point of copper is approximately 1,901°C. It would appear that flame temperatures were at least at or above this temperature. The temperature of the AN was self-limiting, even in a runaway fire, because of the powerful endothermic action of the volatizing material.
- **Boron, California, 1960.** 20 tons of prilled AN were destroyed in a burning warehouse. At the peak of the fire the heat was so intense the steel roof glowed red and collapsed on the burning and molten AN. No explosion.
- **Potosi, Wisconsin, 1967.** A boxcar loaded with 50 tons of AN caught fire. The boxcar was steel with a wooden interior. All of the wood burned, melting the nitrate and leaving a large crusted mass. No explosion.
- **Rocky Mountain, North Carolina, 1978.** A storage facility containing 500 tons of AN fertilizer was destroyed by fire. No explosion.
- **Moreland, Idaho, 1979.** Fire involved the wood framework and belting of the overhead conveyor system in a fertilizer distribution plant while it was being used to unload a railroad car of AN fertilizer. The fire spread from the conveyor system to the roof. About 200 tons of AN were involved. There was no explosion.

- **Cartagena, Murcia, Spain, January 2003.** The fertilizer storage facility of Fertiberia held a self-sustained decomposition (SSD) fire in January 2003. The fire was controlled after most of the material was removed by mechanical means.
- **Mesa, Arizona, 2006.** On 15 June 2006, a truck carrying dynamite, blasting caps, and 11 tons of AN (four times the amount of AN involved in the Oklahoma City bombing) caught fire on Loop 202 in Mesa, Arizona. Fortunately, the trucking company had another employee following the truck who noticed the fire and alerted the driver and emergency crews. The fire was quickly extinguished before it could spread to the cargo.

  http://www.620ktar.com/index.php?sid=189194&nid=6
- **Estaca de Bares, Spain, 17 February 2007.** The ship, *Ostedijk,* was transporting 6,012 tons of 15-15-15 nitrogen, phosphorus, potassium (NPK) fertilizer from Porsgrun, Norway to Valencia, Spain. On 17 February, the ship's captain radioed that there was "a chemical reaction" in the ship's cargo. The ship was near A Coruna, Spain. The Spanish authorities sent a team to examine the situation, but the team found nothing wrong, and the ship was allowed to continue to Valencia. On 18 February, the captain radioed that the chemical reaction continued and white smoke was coming out of the hold. Spanish authorities towed the ship away from the coast and started consultation with technical experts. Specialists were sent to the ship. The temperature at the top of the fertilizer was estimated to be about 200^{o}C, but no action was taken and the plume continued to grow. Personnel were sent to the ship on 21 February to open the cargo holds. As the holds aired the smoke plume grew in a matter of minutes to about 10 meters in diameter and several hundred meters in length. On 22 February, three special water pipe/spears were inserted inside the cargo and delivered water. The fire decayed and was pronounced extinguished by 1 March. The *Ostedijk* was sent to the nearby port of Bilbao to unload the cargo. The cargo had sustained an SSD fire for 11 days.
- **Bryan, Texas, U.S., 30 July 2009.** The El Dorado Chemical Company that processes AN into fertilizer caught fire at approximately 11:40 a.m. Over 80,000 residents in the Bryan/College Station area were asked to evacuate due to the toxic fumes generated by the fire. Only minor injuries were reported.

In contrast, if there is insufficient venting and pressure is allowed to build, or if there are contaminants that catalyze the decomposition or lead to combustion, the exothermic reactions become dominant and not only combustion may occur, but also explosion or detonation might occur. Table 17 is a summary of 23 accidents involving AN where the reactions resulted in explosions and detonation that resulted in 1,718 fatalities and between 13,431 to 20,931 injured.

TABLE 17. Accidents Involving AN.

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reaction	Cost
4 Oct 18	USA	Morgan, NJ	0		Explosion	Detonation	
26 Jul 21	Germany	Kriewald	19		Mining explosive	Detonation	$1.7 million (1921 $)
21 Sep 21	Germany	Oppau	561	1,952	Mining explosive	Detonation	
21 Mar 24	USA	Nixon, NJ	40		Explosion, fires	Fire spread leading to explosions	
5 Aug 40	France	Miramas			Hit by shell	Explosion	
29 Apr 42	Belgium	Tessenderlo	189	600	Mining explosive	Detonation	
16 Apr 47	USA	Texas City, TX	581	5,000	Fire	Explosions	$100,000,000 (1947 $)
23 Jul 47	France	Brest, *Ocean Liberty*	29		Fire	Explosion 5 hours later	
23 Jan 54	Red Sea	*Terrenia*	0	0	Fire	Explosion several hours later	
7 Aug 59	USA	Roseburg, OR	14	125	Fire	Explosion	
17 Dec 60	USA	Traskwood, AR	0	0	Fire	Explosion	
30 Aug 72	Australia		3		Fire	Detonation	
17 Jan 73	USA	Pryor Creek, OK	0		Fire	Explosions	
29 Nov 88	USA	Kansas City, MO	6		Fire	Detonation	
2 Aug 94	New Guinea	Papua	11		Explosion, fires		
2 Aug 94	New Guinea	Papua	0		Fire	Larger explosion	
13 Dec 94	USA	Port Neal, IA	4	18	Runaway chem react	Detonations	
21 Sep 01	France	Toulouse	30	10,000	?	Explosion	€1.5 billion
9 Mar 04	Spain	Barracas	2	3	Traffic accident	Detonation of AN + diesel	
24 May 04	Romania	Mihailesti Buzau	18		Fire	Detonation	
22 Apr 04	North Korea	Ryongchon	162	3000	Live electric wire	Detonation	€300 million
12 Sep 05	China	Shenganzhai	12	43	?	Detonation	
10 Sep 07	Mexico	Monclova, Coahuila	37	190	Fire	Detonation	

These accidents that resulted in explosion or detonation are described in more detail below.

- **Morgan (now Sayreville), New Jersey, U.S., 4 October 1918, no fatalities.** An explosion occurred at the Morgan Depot and many artillery shells were launched into the air. Some of them landed on a neighboring warehouse where over 4,000 tons of AN were stored in barrels. One of the shells caused a large explosion resulting in craters of approximately 150 feet x 140 feet x 20 feet, but the majority of the AN did not detonate although exposed to fire and shock.
- **Kriewald, Germany (now Poland), 26 July 1921, 19 fatalities.** In this railway town, workers tried to dislodge 30 tonnes of AN that had aggregated (solidified into one mass) in railroad cars. Mining explosives were used on this solid mass to disaggregate the material (a relatively common practice at that time as will be discussed in the Oppau incident). Unfortunately, the contents of the railcars exploded and killed 19 people.
- **Oppau, Germany, 21 September 1921, 450 fatalities.** Another attempt to disaggregate a fertilizer mix using industrial explosives. This will be discussed more fully in a subsequent section.
- **Nixon, New Jersey, U.S., 1 March 1924, 40 fatalities**. The Nixon Nitration Works covered about 12 square miles near New Brunswick. Nixon leased a building to the Ammonite Company. The Ammonite Company was using the facility to salvage the amatol (an explosive containing 80% AN and 20% TNT) from artillery shells to recover the AN to be used as agricultural fertilizer. The building reportedly contained one million gallons of AN in storage and 15 tank cars, each holding 90,000 gallons of AN in process of crystallization. The 11:15 a.m. explosion started fires in surrounding buildings in the Nixon Nitration Works. The flaming debris set sheets of cellulose nitrate on fire, feeding an even greater conflagration. Six hours after the explosion, flames were still burning over an area of one square mile.

  http://en.wikipedia.org/wiki/1924_Nixon_Nitration_Works_disaster
- **Miramas, France, 5 August 1940.** After being hit by a shell from a fire in a nearby munitions train, 240 tonnes of AN in sacks exploded.
- **Tessenderlo, Belgium, 29 April 1942, 189 fatalities and 600 injured.** Another attempt to disaggregate a pile of 150 tonnes of AN using industrial explosives killed 189 people and injured about.
- **Texas City, Texas, U.S., April 1947, several hundred fatalities.** This incident will be described more fully in a later section.
- **Brest, France, July 1947, 29 fatalities.** The cargo ship *Ocean Liberty* was loaded with 3,300 tonnes of AN and various flammable products when it caught fire at 12:30 p.m. The captain secured the hold and tried to fight the fire with pressurized steam. The situation worsened. The vessel was towed out of the

harbor at 2:00 p.m. Black smoke and red flames ensued and worsened at 5:00 p.m. Other ships moved away and the freighter exploded at 5:25 p.m., causing 29 deaths and extensive damage to the city of Brest.

- **Red Sea, 23 January 1954, no injuries**. The freighter *Tirrenia* carrying 4,000 tons of AN caught fire in the morning. The captain used steam to try to stop the fire to no avail. Crew abandoned ship, and it exploded that night.
- **Roseburg, Oregon, U.S., 7 August 1959, 14 fatalities.** A truck carrying dynamite and AN caught fire early in the morning. When it exploded it killed 14 people and injured 125. Several blocks of downtown Roseburg were destroyed.
- **Traskwood, Arkansas, U.S., 17 December 1960**, **no injuries.** Train cars carrying AN, nitric acid, and petroleum products were derailed resulting in fire and explosion.
- **Australia, 30 August 1972, 3 fatalities.** A train containing 20 tons of AN caught fire in an uninhabited area. The nitrate melted and ran on the road. A fuel tank exploded and fuel mixed with the molten AN. A massive detonation ensued that caused three deaths, created a huge crater, and threw debris some distance from the train.
- **Pryor Creek, Oklahoma, U.S., 17 January 1973, no fatalities.** A fire broke out in a work area where AN was being bagged and spread to a warehouse where a piece of equipment had a propane-powered engine. After a few minutes the propane tank exploded and spread propane and lubricating oil. The resulting explosion caused several injuries and extensive damage but no fatalities. A large pile of AN was located about 3 meters away and did not explode but rather melted.
- **Kansas City, Missouri, U.S., 29 November 1988, 6 fatalities.** At 4:07 a.m., two trailers containing approximately 50,000 pounds (23,000 kilograms) of AN exploded at a construction site located near the 87th street exit of Highway 71 in Kansas City, Missouri. The explosives were to be used in the blasting of rock while constructing Highway 71. The explosions resulted in the deaths of six firemen from the Kansas City Fire Department's Pumper Companies 30 and 41. Both companies were dispatched after 911 calls indicated that fire had been set to a pickup truck located near the trailers. The responding companies were warned that there were explosives on-site; however, firefighters were unaware that the trailers were essentially magazines filled with explosives. At 4:07 a.m., one of the "magazines" caught fire and a catastrophic explosion occurred, killing all six firemen instantly. A second blast occurred 40 minutes later, although all fire crews had been pulled back at this time. The blasts created two craters, each approximately 100 feet (30 meters) wide and 8 feet (2.4 meters) deep. The explosions also shattered windows within a 10-mile (16-kilometer) area and could be heard 40 miles (64 kilometers) away. It was later determined that the

explosions were acts of arson, set by individuals embroiled in a labor dispute with the construction company contracted to build the highway.

http://www.kansascity.com/mld/kansascity/news/special_packages/star_history/calamities_crime/12508853.htm

- **Papua, New Guinea, 2 August 1994, 11 fatalities.** At 9:45 a.m., eleven fatalities occurred when the sensitized AN emulsion plant exploded at the Porgera gold mine. The fatal explosion involved a few tons of explosive at the most. At 11:02 a.m., a larger explosion of about 80 tons of AN was caused by fires under storage facilities. There were no fatalities due to the second explosion because the site had been evacuated. A mushroom cloud was seen to rise.

- **Port Neal, Iowa, U.S., 13 December 1994, 4 fatalities and 18 injured.** At about 6:00 a.m., two explosions occurred at the Terra Industries AN plant. Approximately 5,700 tons of anhydrous ammonia were released for approximately 6 days after the explosion. Ground water under the facility was contaminated due to chemicals released as a result of the blast. The Port Neal plant produced 83% AN by reacting ammonia and nitric acid in a vessel called a neutralizer. In the two days prior to the explosion, the nitric acid plant was shut down for maintenance. With the nitric acid plant not in operation, the AN facility was also shut down. During this shutdown, the pH of the neutralizer vessel contents dropped to an unusually low level and leaks in other equipment led to the introduction of chloride ions that catalyzed the final reaction. Unaware that the 18,000-gallon capacity neutralizer was in a highly acidic and contaminated condition, Terra employees injected superheated steam to try to keep the vessel contents from freezing due to the cold winter weather. The energy from the injected steam led to the runaway chemical reaction of the sensitized AN solution and resulted in the subsequent detonations.

  http://www.exponent.com/process_plant_explosion/

- **Toulouse, France, 21 September 2001, 30 fatalities and an estimated 10,000 injuries.** This accident will be discussed in more detail in a subsequent section.

- **Neyshabur, Iran, 18 February 2004, 300 fatalities and 450 injured.** A previous section of this report dealing with transportation accidents with munitions and explosives reported the accident near Neyshabur, Iran, where a 51-car long runaway train that had 17 cars of sulfur, six cars of petrol, seven cars of unidentified fertilizer (AN?), and 10 cars of "cotton wool" derailed and burned several hours before exploding. There were more than 300 fatalities and more than 450 injured.

- **Barracas, Spain, 9 March 2004, 2 fatalities.** A truck carrying 25 tonnes of AN fertilizer collided with a car and rolled into a ditch. Diesel fuel mixed with the AN, which then exploded half an hour after the traffic accident on 9 March 2004. Two people were killed and three others injured. The explosion, which could be heard at a distance of 10 kilometers (6 miles), caused a crater 5 meters (16 feet) deep.

NIMIC, *NIMIC Newsletter 1st Quarter 2004,* page 5.

- **Ryongchon, North, Korea, 22 April 2004, 162 fatalities.** On 22 April 2004, there was a large explosion at the train station in the town of Ryongchon, North Korea. A freight train carrying AN exploded in this important railway town near the Chinese border. The explosion occurred during shunting operations at the railyard. Two cars each containing 40 tonnes (44 tons) of AN came into contact with a car containing fuel oil. The massive explosion created a large crater 15 meters (49 feet) deep and leveled everything in a 500-meter (1,640-foot) radius. The cause of the accident was unclear but may have been initiated when the railcars came in contact with a live electrical wire. There were 162 fatalities, including 76 school children and 3,000 others were injured. The station was destroyed, as were most buildings within 500 meters (1,625 feet), and nearly 8,000 homes were destroyed or damaged. Damages have been estimated at 300 million euros. Another report said that there were two craters of about 10 meters (33 feet) in depth were seen at the site of the explosion. Figure 120 shows the crater, while Figure 121 shows the damage to the primary school.

  http://en.wikipedia.org/wiki/Ryongchon_disaster
  http://news.bbc.co.uk/2/hi/in_pictures/3655751.stm
  http://www.globalsecurity.org/military/world/dprk/ryongchon-pics.htm
  http://www.unep.fr/scp/sp/disaster/casestudies/northkorea/
  NIMIC, *NIMIC Newsletter 2nd Quarter 2004,* page 5.

FIGURE 120. Crater at the Ryongchon, North Korea
Railyard Following Explosion.
http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/arorai.pdf

FIGURE 121. Damage to the Ryongchon Primary School.
http://www.cdc.gov/niosh/mining/pubs/pdfs/arorai.pdf

- **Mihăileşti, Buzău, Romania, 24 May 2004, 20 fatalities.** A truck carrying more than 20 tonnes (22 tons) of AN tipped over and caught fire on the European road E85 near Mihăileşti (50 kilometers (31 miles) northeast of Bucharest, Romania) at 4:57 a.m. on 24 May 2004. The driver tried to fight the fire. A few cars stopped and watched the fire. Two reporters got to the site of the accident and started filming the fire. Firefighters arrived and started to fight the fire. The last mistake of untrained Romanian firemen occurred when water was used in an attempt to extinguish burning chemicals (all firefighting instructions indicate not to use water but carbon dioxide (CO_2) in case of burning chemicals and/or fuel). Around 5:50 a.m., the truck blew up, killing 20 and wounding 13 people. A crater 6.5 meters (21 feet) deep and 42 meters (137 feet) in diameter was formed by the explosion. Once again, the fire burned a significant time (enough time to get television film crews to the site) before the explosion took place. Figure 122 presents the scene after the accident.

  http://en.wikipedia.org/wiki/Mih%C4%83ile%C5%9Fti-explosion

FIGURE 122. Accident in Romania in Which 20 Tonnes (22 Tons) of "Nitrous Fertilizer" Caught Fire and Later Exploded, Killing 20 People.
http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/arorai.pdf

- **Shengangzhai, China, 12 September 2005, 12 fatalities and 43 injured.** On 12 September 2005, a truck carrying 18 tonnes (19.5 tons) of AN exploded in the village of Shengangzhai, China, producing a crater 18.5 meters (60 feet) in diameter and 5.6 meters (18 feet) deep, killing 12 people and injuring 43.

- **Monclova, Coahuila, Mexico, 10 September 2007, 37 fatalities and 150 injured.** A truck with 25 tons of AN—picked up from an Orica, Ltd. Explosives plant in Monclova, Coahuila, México—was heading to a mine in the southwestern state of Colima and crashed into a truck, leaving three dead at the crash. A fire started on the trailer, and approximately 40 minutes after that, a very huge explosion occurred, resulting in around 150 people injured and 37 more fatalities. A crater 30 feet (9.1 meters) deep and 6 feet (1.8 meters) wide was created due to the explosion.

  MSIAC, *The MSIAC Newsletter 3rd Quarter 2007,* page 8;
  The Economist, 15 September 2007, p. 47 but in less detail than above,
  See also
  http://www.trekearth.com/gallery/North_America/Mexico/Northeast/Coahuila/San_Juan_de_Sabinas/photo731167.htm...] [No longer available]

In addition to accidents, there have been terrorist activities that have used AN-based explosives. Some of the terrorist use of AN-based explosives are listed below but are not fully discussed.

- **University of Wisconsin, Madison, 24 August 1970, 1 fatality and 3 injuries.** Four men stole a Ford Econoline van, filled it with six 55-gallon drums of ANFO (approximately 2,000 pounds), parked it next to Sterling Hall at the University campus, and detonated it in the pre-dawn hours. Unfortunately, there were five people in the building—one died and three were injured. Pieces of the van were found on top of an eight-story building three blocks away. A total of 26 nearby buildings were damaged.

- **Baltic Exchange Building, London, England, 10 April 1992, 3 fatalities.** A bomb consisting of a fertilizer device with a Semtex detonation cord was placed in a truck and detonated at the Baltic Exchange. The detonation caused £800 million worth of damages. The bomb attack was attributed to the Provisional Irish Republican Army.

- **World Trade Center, New York City, New York, U.S., 23 February 1993, 6 fatalities and 1,042 injuries.** A truck bomb containing a complex bomb weighing 1,310 pounds was detonated below the North Tower of the World Trade Center in New York City. While this bomb is often listed with other ANFO devices it was made of an urea nitrate main charge with aluminum, magnesium, and iron oxide particles surrounding the explosive. Nitroglycerine, AN, and smokeless powder served as the booster explosive. In addition, three tanks of bottled hydrogen were placed in a circular configuration around the main charge to enhance the fireball and after burning of metal particles. A detailed account of the bombing and the aftermath can be found at the following web address:

http://en.wikipedia.org/wiki/1993_World_Trade_Center_bombing

- **Bishopsgate, London, England, 24 April 1993, 1 fatality and 44 injured.** A dump truck carrying a 1-tonne AN fertilizer bomb was placed by the Provisional Irish Republican Army in the Bishopsgate financial district of London at the Hong Kong and Shanghai Bank. A series of telephone warnings were received and the area evacuated. The bomb exploded at 10:25 a.m., causing an estimated £1 billion in damages. Fortunately, it was a Saturday morning so casualties were low.
- **Oklahoma City, Oklahoma, U.S., 19 April 1995, 168 fatalities and more than 680 injured.** Timothy McVeigh detonated an explosive-filled truck parked in front of the Alfred P. Murrah Federal Building in downtown Oklahoma City. The blast destroyed or damaged 324 buildings within a 16-block radius. The bomb was estimated to have caused $652 million in damages. The explosives consisted of 108 50-pound bags of high-grade AN fertilizer, three 55-gallon drums of liquid nitromethane, several crates of Tovex explosive, and 17 bags of ANFO. These materials were loaded into 13 barrels. Each filled barrel weighed nearly 500 pounds (230 kilograms). Of the 13 barrels, nine contained AN and nitromethane, and four contained ANFO. The 350 pounds of Tovex Blastrite Gel served as the booster materials. These materials were placed in a rented Ryder truck. At 9:02 a.m. central standard time (CST), an excess of 4,800 pounds (2,200 kilograms) of the material described above and contained in the Ryder truck detonated in front of the north side of the building. Approximately one third of the building was destroyed and a 30-foot (9.1-meter) wide and 8-foot (2.4-meter) deep crater was created. The blast was heard and felt 55 miles (89 kilometers) away and registered approximately 3.0 on the Richter scale at the Science Museum seismometers 4.3 miles (6.9 kilometers) away. A detailed discussion of the bombing can be found at the following web address:

  http://en.wikipedia.org/wiki/Oklahoma_City_bombing
- **Karachi, Pakistan, 14 June 2002, 12 fatalities and 51 injured.** A truck carrying a fertilizer bomb driven by a suicide bomber was detonated outside the U.S. Consulate in Karachi, Pakistan.
- The wars in Iraq and Afghanistan have seen much use of devices called Improvised Explosive Devices (IEDs). The IEDs used in Iraq were often based on explosives such as 155-mm shells with various triggering devices, while the IEDs used in Afghanistan often were often based on ammonium nitrate.

The previous sections on accidents with AN and terrorist use of AN were brief descriptions. The next sections describe in much greater detail three AN accidents that started by fire (Texas City), by contamination (Toulouse), and by shock-to detonation (Oppau).

Texas City, Texas, U.S., 16 April 1947

Much of the description below is based on the following sources of information:

The Texas City Disaster of 16 April 1947 reported by the Fire Prevention and Engineering Bureaus of Texas, Dallas, Texas, (http://www.local1259iaff.org/disaster.html).

The National Board of Fire Underwriters, (http://www.local1259iaff.org/report.htm).

Texas City Disaster, (http://en.wikipedia.org/wiki/Texas_City_Disaster).

The Texas City explosion of 1947 (http://www.essortment.com/all/texascityexplo_rkvi.htm).

Texas City Disaster: a Painful Way to Learn (http://nobombs.net/brucel/explosiveincidents.html).

Many other documents were also reviewed.

The French cargo ship *S.S. Grandcamp* (the former Liberty ship *S.S. Benjamin R. Curtis*) arrived at Texas City on 11 April 1947. Figure 123 shows the Texas City port before the accident.

FIGURE 123. Port Area of Texas City Before the Accident.

Already on board the *Grandcamp* were 16 cases of small arms ammunition; 59,000 bales of sisal twine; 380 bales of cotton; 9,334 bags of shelled peanuts; and oil-filled refrigeration and farm equipment. Over the next few days, 100-pound bags of AN fertilizer (32.5% N) were loaded onto the ship. By the morning of 16 April 1947, the number 2 hold contained 1,420 tons of AN while the number 4 hold had 880 tons. Longshoremen entered the number 4 hold to continue loading the fertilizer. At about 8:10 a.m., smoke was detected in the hold. Preliminary efforts to put out the fire were futile and the crew was ordered out of the hold. About 8:30 a.m., the captain ordered the hatches battened and covered with tarps, the ventilators closed, and the steam system turned on in an effort to suppress the fire. As a precautionary move, the ammunition was removed from hold 5. The compressed steam fed into hold 4 blew off the hatch covers and a thick column of orange smoke billowed into the sky. Several hundred onlookers, attracted by the unusual colored smoke and the fire sirens, gathered a few hundred feet from the ship. Fire crews sprayed water on the deck of the ship, which apparently was hot enough to vaporize the water. Around 9:00 a.m., flames erupted from the open hatch. Figure 124 shows the *Grandcamp* minutes before the explosion.

FIGURE 124. *Grandcamp* Minutes Before Explosion.

Twelve minutes later slightly more than an hour after the smoke was detected, a massive explosion (actually two—one from the AN in hold 4 followed very quickly—

some said 5 seconds—by the AN in hold 2) disintegrated the *Grandcamp* sending lethal fragments and blast waves into workers, firemen, and the crowd of onlookers. The explosion blew almost 6,350 tons of the ship's steel into the air. Fragments from the *Grandcamp*, some weighing several tons, showered down throughout the port and town extending the range of casualties and damage well into the business district a mile away. For example, the *Grandcamp*'s 2-ton anchor was hurled 1.62 miles (2.61 kilometers) while the 5-ton anchor was hurled ½ mile (800 meters). At the Monsanto plant, located across the slip, 145 of 450 shift workers perished. The tremendous blast sent a 15-foot high wave that carried a 150-foot long x 28-foot wide x 11-foot deep barge, the *Longhorn II*, about 200 feet inland as shown in Figure 125.

FIGURE 125. Barge *Longhorn II* was Picked up and Carried About 200 Feet Inland by the Tidal Wave Caused by the Blast Caused by the Explosion of the *Grandcamp*.

Flames quickly spread, helped by the burning bales of sisal and cotton, to the Monsanto plant and the nearby refineries (Figure 126).

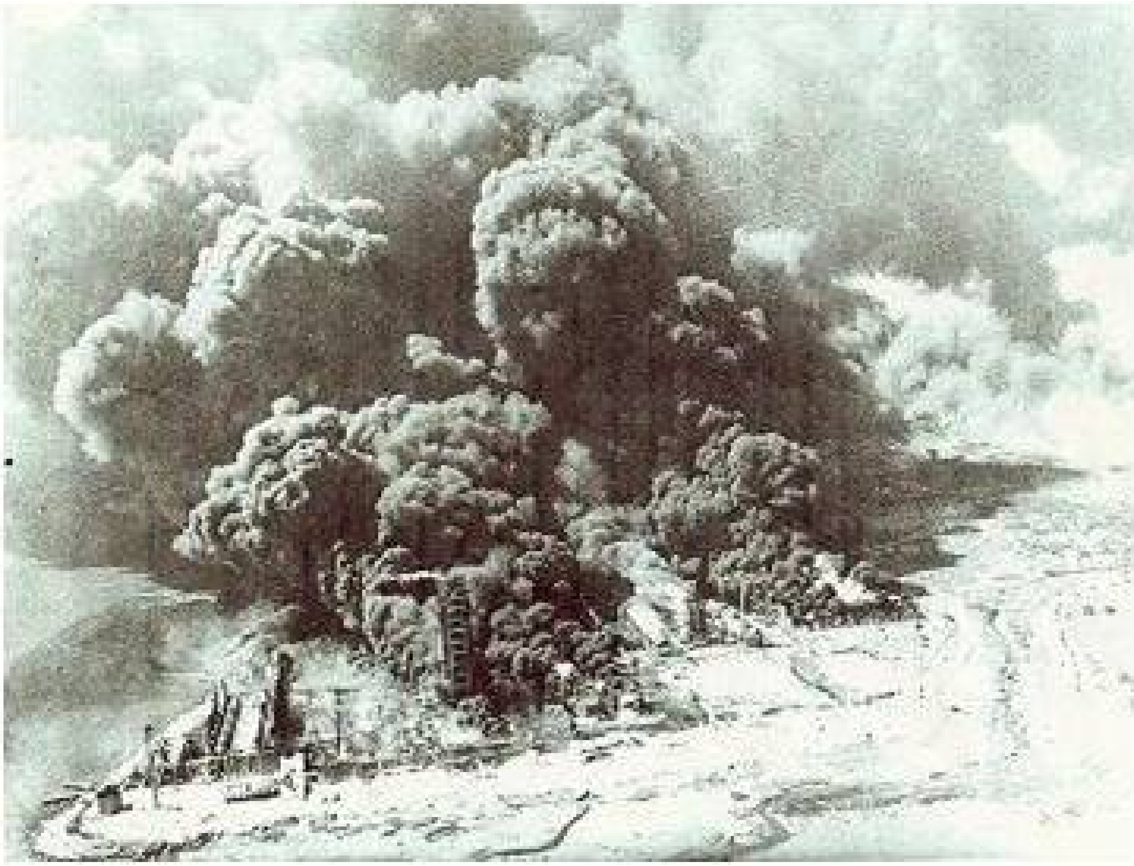


FIGURE 126. Burning Following the Detonation
on the *Grandcamp* at Texas City.

But the disaster was not over yet. There was another Liberty ship, the *High Flyer*, moored at the adjoining slip, about 600 feet (200 meters) from where the *Grandcamp* had been berthed. The *High Flyer* was loaded with 1,800 tons of sulfur [one account said 2,000 tons of sulfur] and 961 tons of AN. The force of the *Grandcamp* explosions had torn the *High Flyer* from its moorings and caused it to drift across the slip where it lodged against another ship, the *Wilson B. Keene*. Later in the afternoon, flames were noticed coming from one of the holds of the *High Flyer*. Unfortunately, nothing was done until about 11:00 p.m., when tugs tried to pull the burning ship from the docks. The efforts to pull the *High Flyer* out of the harbor failed. By 1:00 a.m. on 17 April, flames were shooting out of the hold. Ten minutes later the cargo of the *High Flyer* exploded in a blast that witnesses thought even more powerful than that of the *Grandcamp*. Casualties were light because by now the area had been evacuated. However, the blast resulted in further fires and property damage. The fires burned for days. Figure 127 shows the port area after the disaster. The 1 indicates where the *Grandcamp* had been berthed while the 2 was the location of the *High Flyer*.

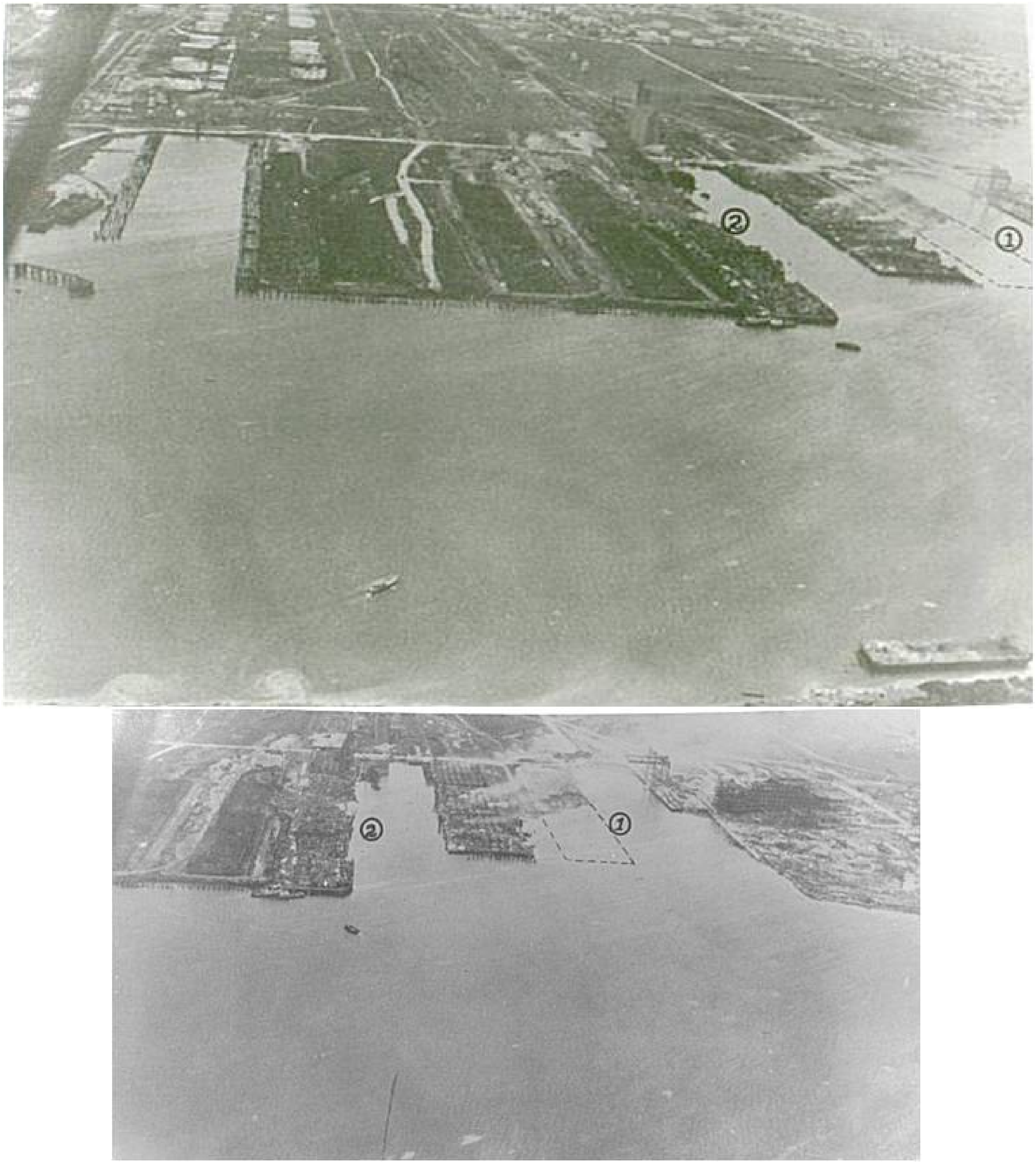
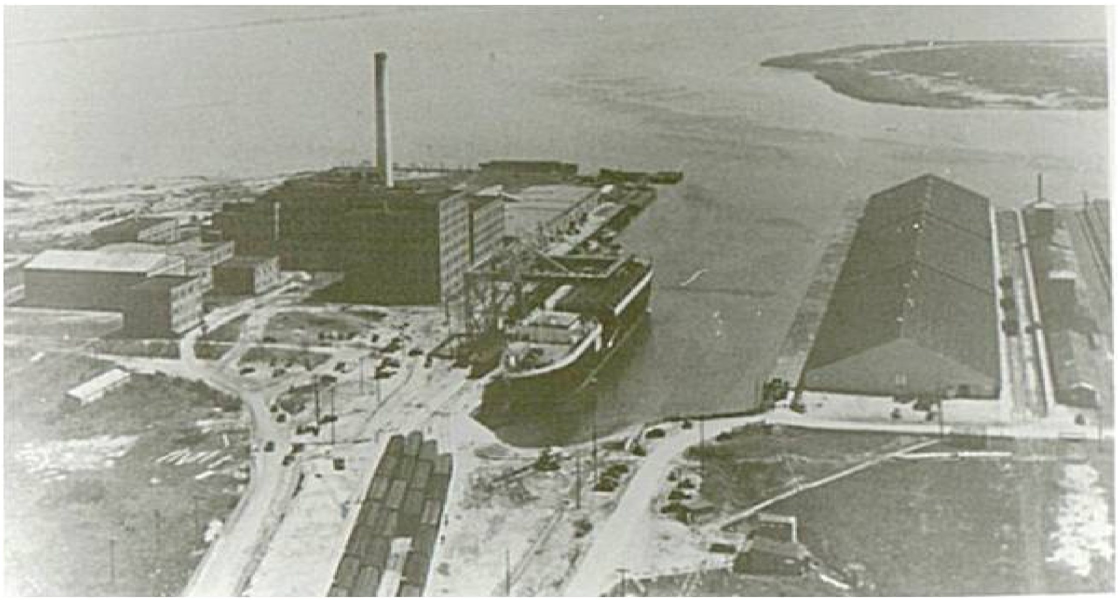


FIGURE 127. Texas City Port Area After the Disaster.

Another indication of the damage caused by this disaster is shown in Figure 128, which shows the adjacent Monsanto plant before and after the disaster.



(a) Before disaster.

(b) After disaster.

FIGURE 128. Monsanto Plant.

No one was able to accurately determine the number of fatalities and injuries. The official death toll was placed at 581. The Red Cross and the Texas Department of Public Safety counted 405 identified and 63 unidentified dead. Another 100 persons were classified as "believed missing" because no trace of their remains was ever found. Estimates of the injured were 3,500 persons in one report and over 5,000 in another. Property damage was estimated to be at least $100 million (1947 dollars) but that may have been low. The report by the Fire Prevention and Engineering Bureaus of Texas, Dallas, Texas, and the National Board of Fire Underwriters has a listing of the damage by sites.

http://www.local1259iaff.org/report.htm

Lessons learned included:

- While AN was believed to be a rather benign fertilizer having low hazards, the accident proved what powerful and tragic effects can occur.
- Once again, the devastation resulted from fire that burned for quite a long time (over an hour for *S.S. Grandcamp* and several hours for the *S.S. High Flyer*) before explosions and detonations occurred. If the fires had been prevented, or controlled, the devastation might not have occurred, or perhaps to a lesser extent.
- The relatively long times of burning allowed crowds to gather in the vicinity, which in turn resulted in many fatalities. The morbid attraction of crowds to accidents must be considered, as well as the lack of traffic egress routes. This was also a lesson learned in the Enschede, Netherlands, fireworks accident (13 May 2000); the Pacific Engineering Production Company of Nevada (PEPCON) accident in Henderson, Nevada (4 May 1988); the 24 May 2004 accident at Mihăileşti, Buzău, Romania; and several other accidents.

Toulouse, France, 21 September 2001

Much of the description below is based on information contained in the following documents:

De la Iglesia, L. B. *Conclusions drawn from the Toulouse accident: application to loss estimation for explosions.*

Salvi, O. and N. Dechy. *Toulouse disaster prompts changes in French risk management,* The Environmental Times.
http://www.grida.no/publications/et/ep3/page/2607.aspx

Dechy, N., S. Descourriere, and O. Salvi. *The 21st September 2001 disaster in Toulouse: an historical overview of the Land Use Planning.* Proceedings of the ESReDA 28th Seminar—June 14th-15th 2005, Karlstad University, Sweden.

Washington State Department of Labor & Industries, *Process Safety management (PSM) Module 1-A review of Industrial Catastrophes Related to PSM*, July 2010
Grande Paroisse. *The AZF Trial.*

Grande Paroisse, *September 21, 2001*
http://en.azf.fr/the-disaster/september-21-2001-800283.html

Grande Paroisse, *The Investigation*
http://en.azf.fr/the-azf-trial/the -investigation-800294.html

Grande Paroisse, *The Different Theories*
http://en.azf.fr/the -azf-trial/the-different-theories-800295.html

Grande Paroisse, *Questions & Answers*
http://en.azf.fr/press/questions--answers-800303.html

Many other documents were also reviewed.

At 10:17 a.m., on 21 September 2001, an explosion occurred in Shed (warehouse) 221 at the AZote Fertilisant (AZF) plant in Toulouse, France.

> "A number of witnesses maintain that they heard two distinct noises that sounded like explosions. The accident investigation located seven sound recordings made on 21 September, in seven different locations. On these tapes, two noises can clearly be heard, corresponding to the two different explosions reported by witnesses. The report submitted by the legal expert Hodin in early March 2005 states that some of the occurrences of smoke seen just before the disaster could correspond to the first explosion occurring in a confined space and generating a rapid release of gasses." Grande Paroisse, *The AZF Trial*

Shed 221 contained about 300 tonnes of AN that did not meet commercial specifications. It was being stored while awaiting shipment to other plants to be used in making compound fertilizers. The explosion left a crater several tens of meters across and was heard more than 40 kilometers from Toulouse. The estimated TNT equivalence was between 20 and 40 tonnes. The explosion registered the equivalent of an earthquake measuring 3.5 on the Richter scale. The explosion caused 30 deaths, including 21 people working in the AZF plant. More than 4,500 people were injured. [Some reports estimated 2,500 seriously injured and the total injured to be as high as 9,000 to 10,000.] Buildings destroyed in the surrounding area totaled approximately 27,000. The cost of damages has been estimated to be 1.5 billion euros. Figure 129 shows the plant before and after the explosions.

(a) Before explosion.

(b) After explosion.

FIGURE 129. AZF Plant, Toulouse, France.

An aerial view of the northern area of the plant, Figure 130, shows the wide spread destruction. Figure 131 shows the destruction at ground level.

FIGURE 130. Aerial View of the Northern Portion of the AZF, Toulouse, France After the Explosion.

FIGURE 131. Ground Level View Showing the Extent of Destruction Due to the Explosion at the AZF Plant, Toulouse.

The cause of the accident is subject to debate. There are several different theories. According to the judicial investigation, a warehouse worker in Shed 335 mistakenly tipped 500 kilograms of a chlorine derivative (NaDDC—sodium dichloro-isocyanurate), which he assumed was AN, into a tipper containing AN. Two days later, the contents of the bin were apparently transferred to a pile of nitrate awaiting disposal that was inside Shed 221. Some 15 minutes later, this mixture exploded and the blast spread to the AN stockpile in the main part of Shed 221, which then exploded. After four more years of investigation, the experts concluded that only a few kilograms of the chlorine compound were involved.

The basis for this theory is that 11 days after the accident, an empty and turned inside out bag that had contained NaDCC had been found in Shed 335. Shed 335 was the main storage site for empty bags that had contained AN and industrial nitrate. In theory, no bags that had contained chlorine containing compounds should have been stored in that shed.

This theory was rejected by the Grande Paroisse (the parent company of AZF) based on tests conducted on 9 and 11 October (no year given). In these tests, NaDDC was added to AN shovel-full by shovel-full. After four shovels-full, the odor of chlorine was so unbearable that no-one could remain nearby. One of the experts even tried to shovel some while holding his breath but dropped the shovel and withdrew after five small shovels full. Grande Paroisse also stated the following:

> "In 2005, the experts proposed another hypothesis: a few kilos of NaDDC had been 'dumped between some wet ammonium nitrate and some industrial nitrate'. This remains the official version today. However, the theory has yet to be demonstrated scientifically, as the laboratory conditions under which one of the experts managed, after 5 years, to bring about an explosion during his experiments with various chemicals were far removed from the conditions (mechanical, physical and chemical) existing at the AZF site on 21 September 2001."

While a terrorist attack (this accident occurred only a few days after the infamous 9/11 terrorist attacks in the U.S.) had been ruled out in the early stages of the investigation, a malicious act was deemed technically possible.

The bottom line is that while there is an "official" theory as to the cause of the accident, there is reasonable doubt concerning this theory. In fact, several of the reports reviewed said that the cause of the accident remains unknown.

Lessons learned included:

The controversy over the cause of the disaster serves to underscore points that we made at the 2010 DDESB Safety Seminar and presented in Reference 31 (as well as other sections of this report). The following is reproduced from the paper:

> "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 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 ECMs. 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, 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.

Oppau, Germany, 21 September 1921

Much of the discussion below is based on information from documents listed below:

French Ministry of Environment, *Explosion in a Nitrogenous Fertiliser Plant, 21 September 1921* (Reference 32)

Timelines, 21 September 1921.
http://timelines.com/1921/9/21/oppau-explosion

Oppau explosion.
http://en.wikipdeia.org/wiki/Oppau_explosion

Oppau blast (Timothy Melton).
http://yarchive.net/explosives/oppau_blast.html

At approximately 7:30 a.m., on 21 September 1921, two explosions occurred at the Baden Aniline and Soda-Fabrik (BASF) plant in Oppau, Germany—the first being weak and the second was disastrous. Seismic readings at Stuttgart, 150 kilometers from Oppau, showed two distinct explosions spaced one half-second apart. The explosions were heard in Munich, 275 kilometers from the plant. Soon after, there were multiple fires and less intense explosions at the plant. The explosion created a crater 90 meters x 125 meters and a depth of 20 meters. According to experts, only about 450 tonnes (about one-tenth) of the mixture was involved in the explosion. The explosion was estimated to be equivalent to about 500 tonnes of TNT while another report listed an equivalent of 1 to 2 kilotonnes of TNT.

Figure 132 shows the crater and extent of damages to the BASF plant, while Figure 133 documents the depth of the crater and extent of damage at ground level.

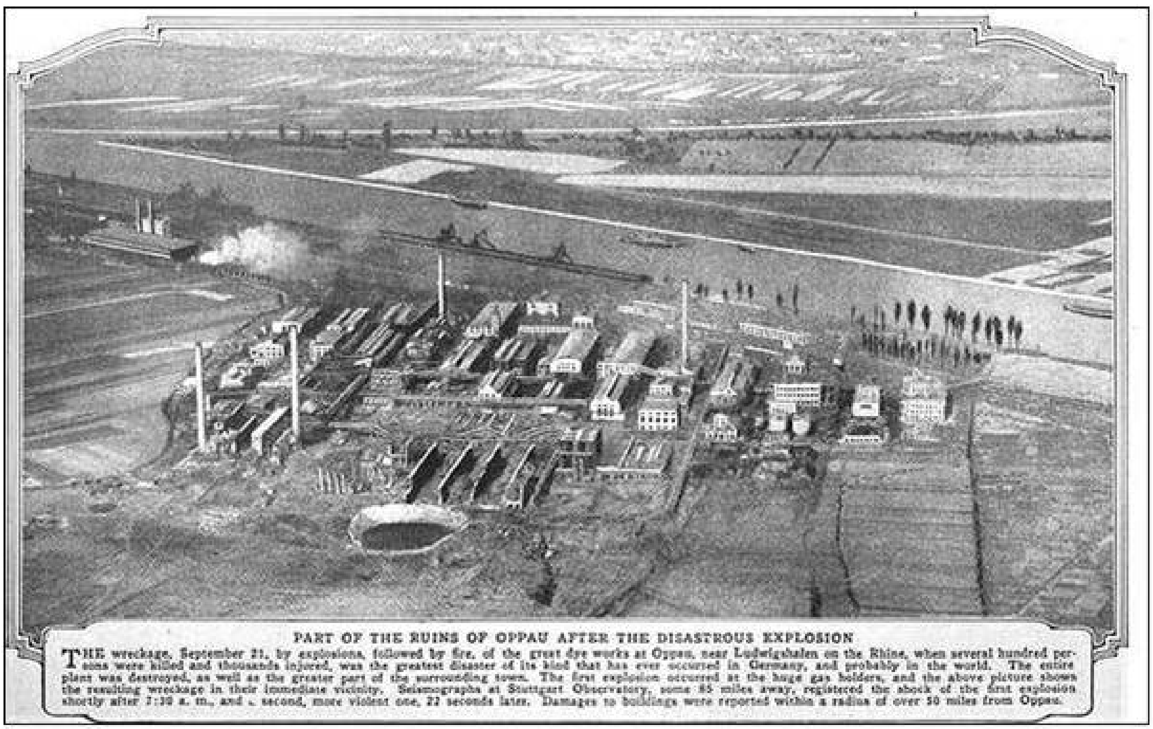


FIGURE 132. BASF Plant After the Explosion. The crater and extent of damage are apparent. This was from *Popular Mechanics Magazine* 1921.

FIGURE 133. Crater and Extent of Damage at Ground Level.

The number of fatalities and injuries reported varied from 430 fatalities in one report to 500 to 600 fatalities and 2,000 injuries in another report to 561 fatalities and 1,952 injuries in two other reports. About 80% of the buildings in Oppau were destroyed. The estimated damage was 321,000,000 marks, or $1.7 million, at that time. Figure 134 shows some of the damage in the town of Oppau.

FIGURE 134. Damage to Houses in Oppau Caused by the Explosion at the BASF Plant, Oppau.

The accident occurred in silo 110, a half-buried building that was 60 meters x 30 meters x 20 meters. It contained 4,500 tonnes of a mixture of AN and ammonium sulfate in roughly a 50/50 mixture. AN is very hygroscopic so the mixture clumped together under the pressure of its own weight, forming a plaster-like substance in the 20-meter high silo. To break up the mass, the standard practice was to use small charges of dynamite placed in the mass and then initiated. The reports say that this procedure had been used over 16,000 times (one report) to 20,000 times (three other reports) to 30,000 times (one report) without any mishap until the explosions on 21 September. Unfortunately, communication must have been slow, because two months before the Oppau accident, an accident at Kriewald, Germany occurred due to charges set off to deconsolidate the AN that had set up in train cars. Unfortunately, the material in the tank cars detonated. A total of 19 people were killed in that accident.

The following was excerpted from Reference 32:

> "The investigation subsequent to the accident, led by an expert panel headed by a parliamentary commission, was difficult to carry out due to the extent of damage and absence of direct witnesses, all victims of the disaster. The investigation lasted 2 years and the report was finally published in 1925.
>
> It was established that one of the firings carried out in silo 111 to loosen the fertilizer mass was the cause of the accident; some holes were drilled in an area of the mixture softened by the firings of the previous day.
>
> The study of the explosive properties of the 50/50 ammonium sulphonitrate (AN and ammonium sulfate combination) and mixtures of similar composition show the following:
>
> - The explosibility of the 50/50 mixture in highly confined conditions and a relatively low density, the explosion is limited to the region around where the explosives are placed.
> - The significant influence of some physical properties of the fertilizer (density, humidity, etc.) on its capacity to explode.
> - An increase in the concentration of AN in a 50 to 55% mixture and especially in a 55 to 60%, contributed to significantly increasing the explosive power of the mixture.
>
> The investigation shows that a few months before the accident, the manufacturing process was modified: the humidity level (2% instead of 3 to 4%) as well as the apparent density of the mixture produced was lower than before. The experts concluded that these modifications made it easier for the mixture to explode.

> Moreover, several testimonies which tally lead us to believe that the composition of the 4,500 tonne pile of mixture in the silo that was built up in the month before the explosion was not uniform. There may have been several dozen tonnes of zones richer in AN even if the post-accident samples and analysis have shown that AN levels in the mixture were between 47 and 49%.
>
> Consequently, the accident scenario can be explained as follows:
>
> - Holes were drilled in a zone containing a 55 to 60% mixture of AN.
> - During firing, this mixture enriched in AN could explode causing the adjoining 50/50 mixture to detonate.
> - Only 10% of the stock was involved in the explosion; the entire content of the silo 110 did not detonate, especially in zones of 50/50 composition where the density of the aggregated product is relatively high."

Lessons learned (or reinforced) included the following:

- Accidents are problematic and may only occur a few times in many instances of performing the operation. Often people say that an operation is safe because the operation has been performed many times without incident. Deconsolidating caked AN (or mixtures of AN and ammonium sulfate) using dynamite charges was thought to be safe. After all, the operation had been performed 16,000 times (or 20,000 or 30,000 times depending on the report) without incident. But the tragic accident at Oppau (and at Kriewald) indicated that the deconsolidation by blasting operation was not as safe as believed. (The authors of this report are concerned that there are many new or recently hired employees performing operations with energetic materials. It is hoped that many of the lessons learned in the past by the "old-timers," because of injuries and fatalities, are not relearned by the current generation in that same fashion.)
- AN (and AN mixtures), while normally thought of as benign oxidizers and fertilizers, can detonate via a mechanical shock-to detonation transition.
- The lessons learned from the Toulouse accident are applicable here as well.

AMMONIUM PERCHLORATE (AP)

AP is also an oxidizer. It is also a mono-propellant in that it will burn on its own in inert atmospheres. However, at room temperature it takes a significant pressure, on the order of 300 psi, for pure AP to burn. Commercial AP, especially granular AP that incorporates the anti-caking agent tri-calcium phosphate, will not burn at pressures below about 1,200 psi (Reference 33).

AP is classified as an oxidizer unless its particle size is less than 15 microns in diameter. Then it is classified as an explosive and usually with HD 1.1. Following the fire and detonations at the PEPCON plant in Henderson, Nevada on 4 May 1988 (accident summarized below) there was question as to whether AP should be classified as a HD 1.1 material. A large-scale government, academia, and industry technical study was established. One part of that effort was a research program that focused on the response of AP to thermal and mechanical shock stimuli. The results of that multi-laboratory study are presented in Reference 34.

While AP is classified as an oxidizer and is very hard to ignite or initiate a detonation, inclusion of a fuel component (even just a small amount) makes the mixture subject to inadvertent ignition and detonation.

Eugene Elzufon performed a study for the DDESB on AP accident scenarios in which he analyzed 34 accidents (References 35 and 36). Of the 34 accidents, two involved loaded rocket motors, 12 occurred sometime during the mixing cycle for solid propellants containing AP, 10 involved oxidizers in bulk (eight AP, one AN, and one potassium perchlorate), and there were 10 unusual events involving AP to some degree.

The two rocket motor incidents were unrelated to AP in the formulations. The first was a case failure caused by a propellant to inhibitor bond failure giving increased burn area leading to a severe overpressure. The second accident occurred when propellant was being drilled from a motor in a reclamation incident. The propellant ignited and an explosion ensued.

Of the 12 incidents that occurred during mixing, 10 were typical mixer hazard related. Typical was solid debris in the mixing bowl, excess friction during dry mixing, scraping of bowls by mixer blades, and in one case hand scraping of a just emptied mixer bowl. Two incidents involved spontaneous exothermic reaction between AP and methylaziridinly phosphine oxide (MAPO).

The 10 incidents involving bulk oxidizer included six during grinding, two caused by fire of other origins, one occurred with manhandling a 500-pound drum of AP, and one was caused by poor housekeeping and/or maintenance in a grinding facility. In three of these accidents, it appears that the AP detonated. The likelihood of detonation increased as the particle size is reduced, the confinement is increased, and the total bulk amount is increased.

The 10 unusual events involving AP were almost all either research and development or involved unusual ordnance design or practice. All of these events were due to the highly reactive nature of AP in the presence of any kind of fuel.

Elzufon recommended that a serious long term test program be established. Reference 34 was a step in that direction.

Table 18 is a summary of serious accidents involving AP. The table lists only five accidents involving ammonium perchlorate (AP), and all of those started with fire. The most serious was the accident at PEPCON, Henderson, Nevada, on 4 May 1988. That accident resulted in 2 fatalities, 372 injured and approximately $100M in damages. The detonations came somewhat as a surprise because AP was classified as an oxidizer and HD 1.3 unless the particle size was smaller than 15 microns. The smaller size AP was classified as HD 1.1. AP by itself, while a monopropellant, has a low pressure deflagration limit of approximately 300 psi for pure AP and higher for commercial grade AP and is very hard to ignite unless a fuel is present.

The tragedy of the PEPCON accident did result in lessons learned that were applied as evidenced by the accident that occurred at Kerr-McGee in Henderson a little over 2 years later.

TABLE 18. Accidents With AP.

Date	Country	Location	Fatalities	Injured	First Reaction	Subsequent Reactions	Cost
4 May 88	USA	PEPCON, Henderson , NV	2	372	Fire	Detonations	$100 million
12 Jul 90	USA	Kerr-McGee, Henderson, NV	0	0	Fire	None	$135,000-235,000
30 Jul 97	USA	WECCO, Cedar City, UT	1	4	Fire	Explosion	$200,000
16 Oct 01	USA	AeroTech Las Vegas, NV	0	6	Fire	3 explosions	$12-15 million
5 May 10	USA	Redstone Arsenal, AL	2		Fire	Explosion	
		Totals	5	382			

The following are descriptions of these five accidents.

PEPCON Disaster, Henderson, Nevada, U.S., 4 May 1988

Much of the information presented in the following discussion was obtained from the following:

Mniszewski, K. R. *The PEPCON Plant Fire/Explosion: A Rare Opportunity in Fire/Explosion Investigation* (Reference 37)

Routley, J. G. Fire and Explosions at Rocket Fuel Plant Henderson, Nevada (4 May 1988)" (Reference 38)

PEPCON Disaster/A History of Mayhem http://ahistoryofmayhem.com/?p=42

PEPCON Disaster

http://en.wikipedia.org/wiki/PEPCON_disaster

AP Explosion
www.freepyroinfo.com/Pyrotechnic/Historical.../Explosion_Long_File.rtf

Videos of the accident at PEPCON can be viewed on the following web addresses:
http://www.youtube.com/watch?v=HJOUgCm5JK&feature=mfu_order&list1watch?=UL
http://www.youtube.com/watch?v=HJOUgCm5JK&nofeather=True
http://www.youtube.com/watch?v=y8RY_1bNq3c

On 4 May 1988, a major accident occurred at the PEPCON plant in Henderson, Nevada. The fire and subsequent detonations resulted in two fatalities, 372 injuries, and an estimated $100 million of damages, as well as the potential to seriously impact the National Aeronautics and Space Administration (NASA) and DOD.

The plant produced AP (NH_4ClO_4), a very strong oxidizer that is the principal ingredient (approximately 70+% by weight) in the Space Shuttle booster motors and in DOD missile motors. PEPCON was one of two manufacturers of AP in the U.S. The other manufacturer, Kerr-McGee, was also located in Henderson about 1.5 miles (2.4 kilometers) from the PEPCON facility.

Following the Challenger accident in 1986, Space Shuttle operations were suspended. Both of the two Shuttle boosters have four segments of about 300,000 pounds of propellant, for a total of 2.4 million pounds of solid AP-based propellant for each Shuttle. Since the propellant has approximately 70% AP by weight, each Shuttle launch used more that 1.68 million pounds of AP, when scrap and mixing wastes are considered. With the grounding of the Shuttle, and the continued manufacture of AP, the oxidizer kept accumulating. PEPCON stored all of the material on-site, originally in the aluminum tote-bins that held about 5,000 pounds of AP, and then in 55-gallon high density polyethylene (HDPE) plastic drums holding about 550 pounds of AP. Unfortunately, the HDPE can act as a fuel with the AP as a strong oxidizer. At the time of the accident, approximately 4,000 tons of AP was at the PEPCON site.

On the day of the accident, a welding crew was repairing the drying process structure that had been damaged by a previous windstorm. The structure was a steel frame with fiberglass panels forming the walls and roof. Sparks/slag from the welding/cutting operation caused a fire to start in the fiberglass that probably had some AP residue. Stiff winds (approximately 17 miles per hour (mph) from the southwest at about 210 to 240 degrees) quickly spread the fire into the area where AP in the 55-gallon HDPE drums was stored.

Figure 135 shows the fire.

FIGURE 135. Fire at PEPCON.

Fires due to welding operations had occurred in the past. About one fire incident per year was attributed to welding operations at the plant (Reference 37).

Reference 37 also presents an excellent mapping of the fire spread and subsequent events. The fire/explosion analyses utilized photographs, videotapes, statements, and depositions. For example, videotapes were superimposed over computer-aided design (CAD) images of the plant layout. Figures 136 through 141 show the maps of buildings and AP storage areas, areas where smoke was observed, areas where flames were observed, and the two major explosion sites as a function of several times.

The batch house dryer building is shown west of most of the AP storage areas. Unfortunately, there was a brisk wind (approximately 17 mph) blowing from the southwest to the northeast that spread the fires as shown in Figures 136 through 141.

At 11:45 a.m., flames were observed in the AP storage located between the batch house dryer building and the dryer building as shown in Figure 137. As cited in Reference 37, several witnesses observed a burning poly drum in the southwest corner of the batch dryer building. One noted the drum burning looked “like a rocket engine, with flames at least 15 feet high. Other observations indicate fire along the floor from north to south of the batch dryer building, possibly due to a burning drum toppling causing jetting across the floor.

Reference 37 also presents a timeline flow chart of the fire spread and occurrence of minor and major explosions. This timeline lists a minor explosion occurring in a poly drum or batch dryer just prior to 11:50 a.m.

Figure 138 shows the snapshot at 11:50 a.m. By this time most of the poly barrels near the batch house dryer building and dryer are on fire and the drums to the east are starting to show signs of smoke.

By 11:51 a.m., the flames and areas of smoke have spread as shown in Figure 139. Obviously the brisk wind is driving the reaction towards the northeast.

By 11:52 a.m., the poly drums containing AP are vigorously burning in the areas shown in Figure 140. Between 11:52 a.m. and 11:53 a.m., the fireballs in Lot A and the poly drum rows coalesce into a single fireball approximately 270 feet high. The map does not show flames to the drums just south of batch house dryer building, east of the blender building, and north of the rail-line. This is probably due to the AP/drums having been consumed.

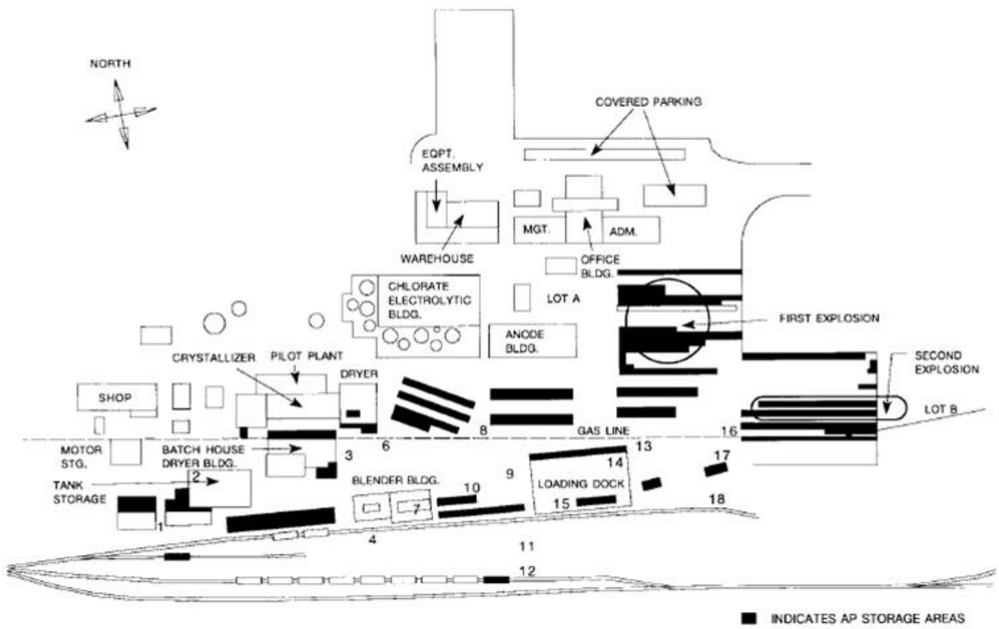


FIGURE 136. Mapping of the PEPCON Facility Showing the Buildings and AP Storage Areas (Reference 37).

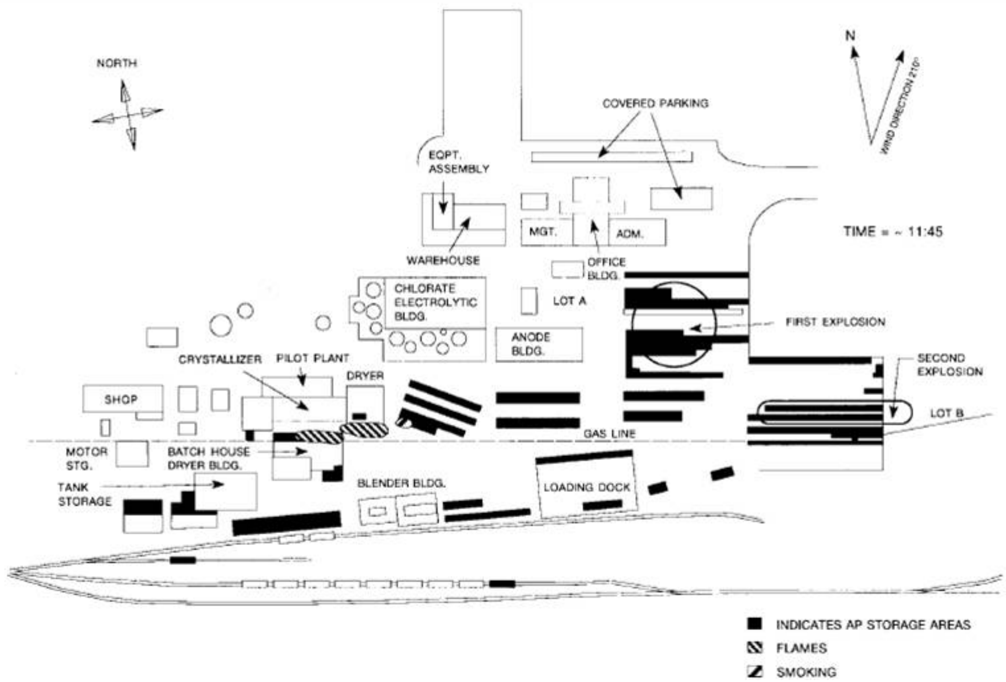


FIGURE 137. Mapping at Time 11:45 a.m. Showing the Buildings, AP Storage Areas, and the Fire Adjacent to the Crystallizer and Dryer Buildings (Reference 37).

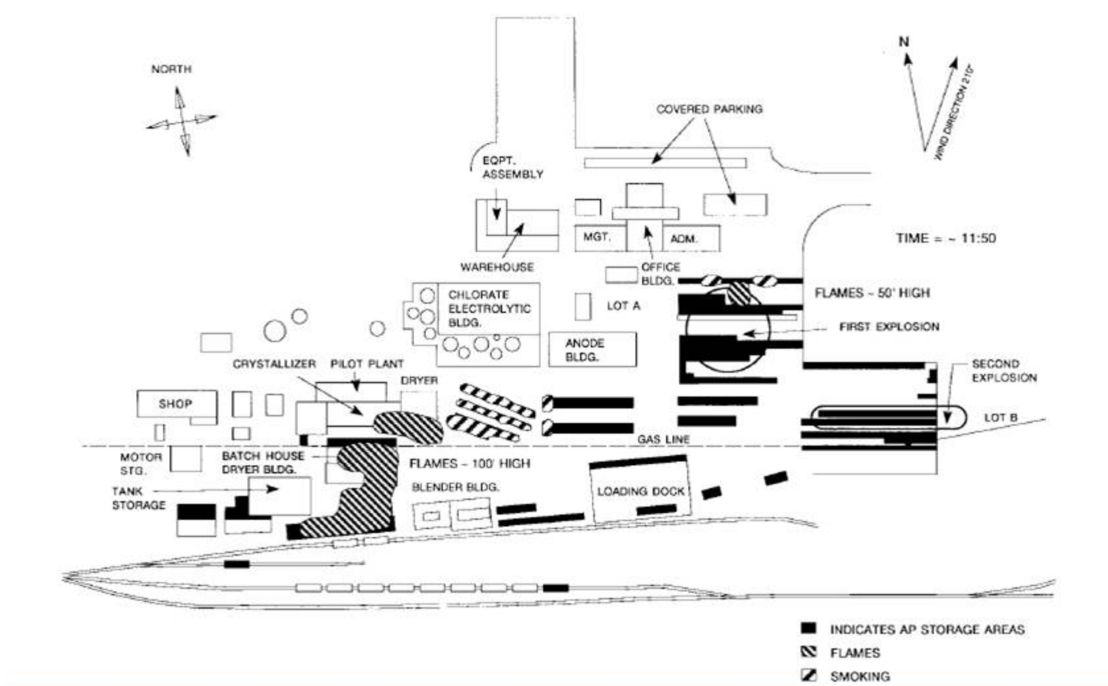


FIGURE 138. Mapping at 11:50 a.m. Showing Buildings, AP Storage Areas, Flames, and Smoke Locations (Reference 37).

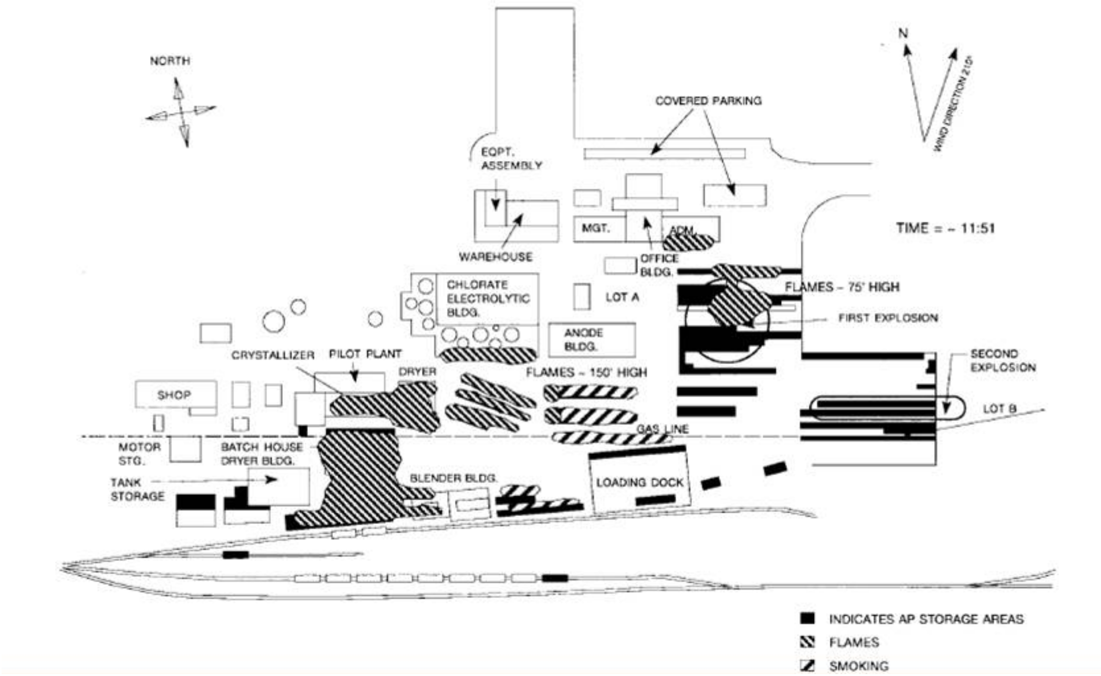


FIGURE 139. Mapping at 11:51 a.m. Showing Buildings, AP Storage Areas, Flames, and Smoke Locations (Reference 37).

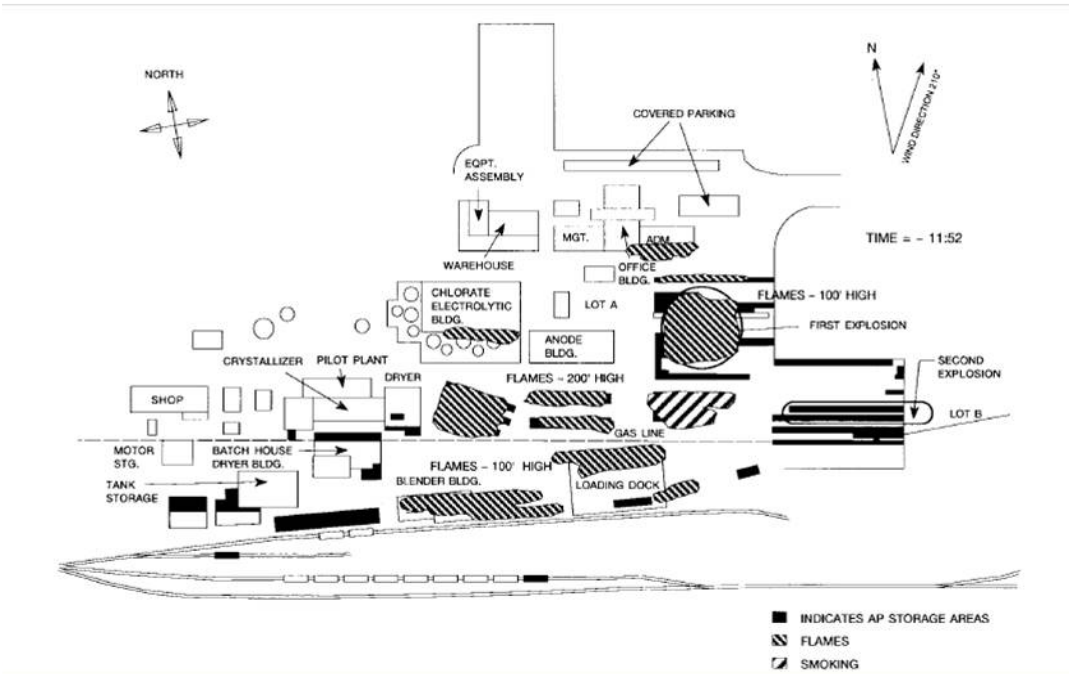


FIGURE 140. Mapping at 11:52 a.m. Showing Buildings, AP Storage Areas, Flames, and Smoke Locations (Reference 37).

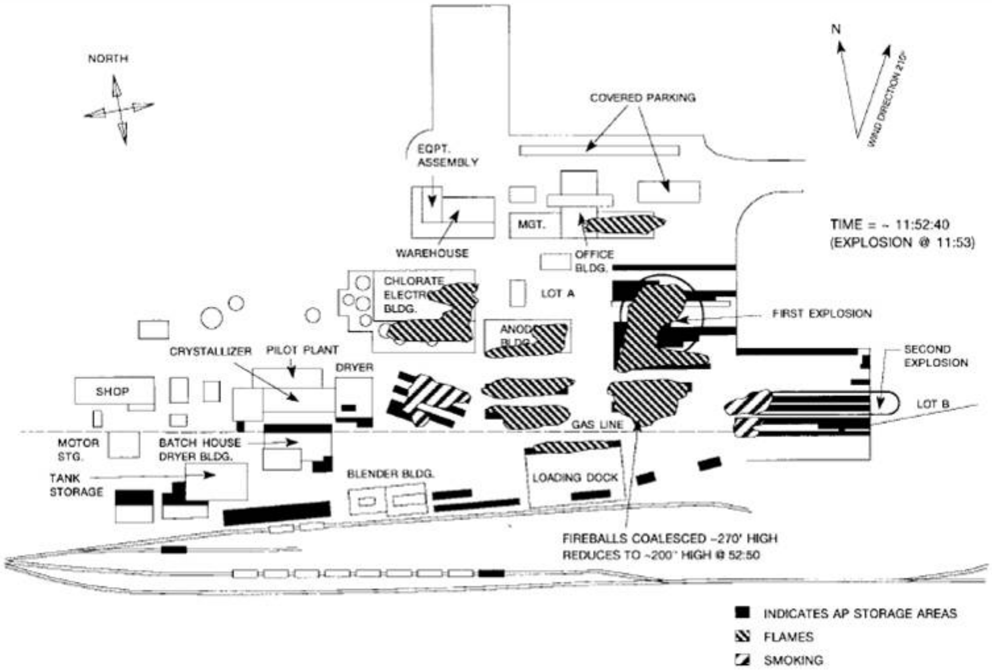


FIGURE 141. Mapping at 11:52:40 a.m. Showing Buildings, AP Storage Areas, Flames, and Smoke Locations. Explosion occurred at 11:53 a.m. (Reference 37).

Figure 141 shows the snapshot at 11:52:40 a.m., just prior to that first major explosion that occurred at 11:53 a.m. Obviously, much of the AP/poly drums in Site A are burning, producing the single fireball with flames 270 feet high, leading to the major explosion that occurred shortly. This first major explosion was equivalent to a few hundred tons of TNT. The first explosion registered 3.0 on the Richter scale at an observatory in California. Immediately after that explosion (about 1.1 seconds later), another smaller explosion occurred in the crystallizer/dryer building. A third explosion occurred about 1.14 seconds later in the chlorate building. Several small explosions followed in various areas. At 11:57 a.m., a second major explosion occurred, this one in Lot B at the southeastern portion of the plant. Lot B was where several hundred of the large aluminum tote-bins of AP were stored. Witnesses reported that this second explosion was larger than the first and produced a visible shock wave coming toward them across the ground. This second explosion registered 3.5 on the Richter scale at that same observatory in California. It produced a crater estimated at 15 feet deep and over 200 feet long. The TNT equivalence of the second blast was estimated to have been between 250 and 1,000 tons of TNT. Figure 142 shows the largest explosion.

FIGURE 142. Largest Explosion at PEPCON.

This second explosion ruptured a 16-inch, high pressure (300 psi) natural gas line that ran under the PEPCON plant. A flame plume resulted and burned until the Southwest Gas line was shut down at 12:59 p.m.

Damage assessment included the following:

- Two fatalities
- 372 injuries
- Approximately $100 million in damages
- The PEPCON plant and the Kidd & Co. marshmallow plant located 500 feet from PEPCON were both destroyed.
- Heavy damage within a 1.5-mile radius with destroyed cars, structural damage to buildings, and downed power-lines.
- Extensive window breakage and moderate structural damage within a 3-mile radius.
- Damage extended out to a 10-mile radius.

- Windows were cracked and doors pushed open at McCarran International Airport in Las Vegas, 7 miles away. A Boeing 737 on final approach was buffeted by the shock wave.

Lessons learned included:

- As with many other accidents, this accident started with a fire that eventually led to detonations.
- While pure and commercial grade AP is hard to ignite and does not burn below a pressure of approximately 300 psi for pure AP and about 1,200 psi for commercial AP with tri-calcium phosphate anti-caking additive, a small amount of fuel contaminant can cause the mixture to easily ignite and burn at one atmosphere. In the PEPCON accident, AP was stored in 55-gallon HDPE drums. The HDPE served as a fuel.
- While AP is somewhat difficult to initiate to detonation, it can detonate if it has been heated (Reference 34 and references cited in Reference 34.)
- This was not the first fire at PEPCON associated with welding operations. Approximately one welding accident per year occurred but without the serious consequences of this accident. Perhaps the frequency of accidents without serious consequence led to an unfounded complacency, especially given the tremendous amount of AP at the plant, AP stored in polyethylene containers, and the brisk wind.
- Reference 38 also presents lessons learned from agency planning perspectives.

Kerr-McGee, Henderson, Nevada, U.S., 12 July 1990

The information presented below was based on the following sources:

- Henderson Home News, Vol. 41, 57th Edition, July 17, 1990, "Ammonium Perchlorate Burns in Storage at Kerr-McGee."
- "Fires, Blasts, Chemical Releases Noted at Henderson Plants," Las Vegas Review-Journal, August 5, 1998.
  http://www.reviewjournal/lvrj_home/1998/Aug-05-wed-1998/News/7974260.html
- Personal recollection. Thomas L. Boggs was a member of the accident investigation team assembled by Clark County, Nevada.

A fire broke out in the storage area of the Kerr-McGee plant in Henderson, Nevada, at approximately 11:30 p.m. on 12 July 1990. Barrels each holding 500 pounds of out-spec or contaminated AP were stored on a pad. The storage of barrels was modified based on lessons learned from the PEPCON accident of 1988. The various pads were separated by walls almost 5 feet tall. The pads were also separated 100 feet apart. Each pad could contain as much as 125 tons of AP. The fire occurred on one of the pads containing about 106 tons of AP, out of a total of about 4,000 tons stored at Kerr-McGee. In the fire, a line of barrels would burn; and just about the time a line was about burned out, the next line would ignite. The burn propagated line by line. The fire department stood off at a safe distance and allowed the fire to burn line by line until it burned itself out on that pad early the next morning. It did not spread to other pads. The loss was estimated to be between $135,000 and $235,000.

The subsequent investigation spanned several meetings where many scenarios were proposed and investigated. The effort was concluded when Mr. Boggs presented the simple sample + stimuli + environment → reaction diagram, and stated that it is obvious that “we are trying to swim upstream” with no one scenario more probable than others. We all agreed that lessons had been learned from the PEPCON accident. Mitigation efforts were put in place, and the mitigation efforts were successful. After all, the fire department was content to stand-off at a safe distance and watch the fire, making sure that it did not get out of control. There were no fatalities or injuries.

Accident at Western Electrochemical Company (WECCO), Cedar City, Utah, U.S., 30 July 1997

Much of the information reported below was from the following sources:

Las Vegas Review-Journal, “Explosion kills one at chemical factory” 31 July 1997.

http://www.reviewjournal.com/lvrj_home/1997/Jul-31-Thu-1997/news/5810376.html

Exponent, “AP Dust Explosion.”

http://www.exponent.com/Ammonium-Perchlorate-Dust-Explosion/

ICIS News, “U.S. starts probe of Utah explosion.”

http://www.icis.com/Articles/1997/07/31/34206/us-starts-probe-of-utah-explosion.html

ICIS News, “Utah presses probe of deadly blast”
http://www.icis.com/Articles/1997/1997/08/07/34361/utah-presses-probe-of-deadly-blast.html

A flash fire and single explosion at the WECCO AP plant at Cedar City, Utah, occurred at 9:00 a.m. and resulted in one fatality, one serious injury due to burns, and three minor injuries. Damage to the plant was estimated to be less than $200,000. Cause of the fire was attributed to cleaning out a clogged dust collector located outside of the batch dryer building. Approximately 1,500 tons of AP were at the plant at the time of the accident.

Failure Analysis Associates (FaAA) (in March 1998, FaAA became Exponent) an engineering and scientific consulting firm, conducted an engineering investigation of the July 1997 explosion. The facility was inspected, and the results were documented. Representative samples of AP were obtained from similar dust collector systems at the product blenders at the plant. Based on observations by FaAA personnel, eyewitness accounts of the accident, chemical analysis, and explosion tests of the AP collected at the site, the following conclusions were made:

> "The incident was triggered by a fire which initiated in or on the Nomex fiber tube sock type filters inside the bag house. These filters were mounted over a steel wire structure and were completely saturated with AP. The initial ignition of the tube socks likely occurred due to metal-to-metal friction after an employee used a non-authorized, steel-tipped shovel to clear out AP-clogged areas immediately around the Nomex filters. The burning Nomex filters provided a continuous ignition source for the dust cloud and may also have contributed to additional dispersion of the AP fines. Experimental testing commissioned by FaAA established that dispersed AP fines, less than 50 microns in diameter and otherwise comparable to product present inside the subject dust collector, will cause a dust explosion if a sufficiently large ignition source is available.
>
> The dust explosion propagated back towards the batch dryer via the vacuum lines. The event terminated at locations where the dust concentration dropped below a level that could sustain propagation of the deflagration. The AP fines, which were largely consumed in the incident, appeared free of fuel contamination. Based on chemical analysis of the samples collected at the scene, FaAA ruled out rust or hydrocarbon contamination as causes of the explosion (Reference 39)."

Accident at AeroTech Inc. Plant, Las Vegas, Nevada, U.S., 16 October 2001

The information below is based on the following:

Las Vegas Sun, "Fire raises safety question"
http://www.lasvegassun.com/2001/oct/16/fire-raises-safety-question/

A fire followed by three explosions occurred at a plant that manufactured model rockets in eastern Las Vegas, resulted in two critical injuries and another injury to employees, and three firefighters were treated for smoke inhalation. The fire started shortly after noon when a spark from a manufacturing machine contacted raw materials used to manufacture the model rocket motors. The raw materials included 2,500 pounds of AP and 800 pounds of magnesium. There were two initial explosions at 12:15 p.m., and that fire was put out within an hour. A third explosion occurred at about 4:20 p.m.

The fires continued to burn into the next day. The fire and explosions gutted the AeroTech building and caused an estimated $12 million to $15 million in damages.

The accident caused quite an uproar, because it forced evacuation within a half-mile radius of the plant. In that area were residents and a mobile home park that was home to many senior citizens, many of whom were bedridden or immobile, and whose caregivers were not allowed past police blockades.

Accident at Redstone Arsenal, Huntsville, Alabama, U.S., 5 May 2010

The information below is based on the following:

K. Henry, Redstone Announces Investigation Results, Redstone Arsenal Press Release, 25 February 2010. https://ams8.redstone.army.mmil/portal/page?_pageid=735,2902915&dad=portal&_schema=PORTAL[3/4/2011 2:43:35 p.m.]

MSIAC, *MSIAC Newsletter 2nd Quarter 2010,* page 8.

The accident occurred at about 8:45 a.m. at Building 7352 in the Aviation Missile Research and Development Center test area 10 at Redstone Arsenal. The fire and explosion resulted in two fatalities and damage to facilities shown in Figure 143. According to the 25 February 2011 news release from the Redstone Arsenal Public Affairs Office, the accident occurred during an attended (as opposed to remote) operation involving a decanter centrifuge in a demilitarization process involving AP. The operation was intended to develop an optimal process for reclaiming pure, dry AP at maximum volume. The operation used n-butanol to dissolve away impurities from the AP. The AP and the n-butanol were mixed together to form a slurry. The decanter centrifuge was then used to remove the n-butanol and impurities from the AP and dry the AP. The investigation concluded that on 5 May friction from the rotating parts inside the decanter centrifuge generated enough heat to cause the AP/n-butanol slurry to ignite. The resultant flame led to an explosion within the decanter centrifuge, causing fragmentation and producing an intense fireball that engulfed personnel present in the building resulting in fatalities.

FIGURE 143. Damage to Building 7352, Redstone Arsenal From Explosion That Occurred 5 May 2010.

Lessons learned include the combination of the AP (a powerful oxidizer) and n-butanol (a fuel) provided a flammable mixture. The ignition and subsequent combustion of the mixture within the centrifuge caused the centrifuge to fragment and led to the fireball. The fireball and explosion resulted in the fatalities and damage to the building.

LESSONS LEARNED FROM ACCIDENTS

In the previous sections, after each description of the accidents there often is a lessons learned discussion. Among the incidents, there were many common lessons, regardless of whether the accident involved storage of ingredients (such as AP and AN), gun propellants, rocket propellants, explosives, fireworks, or all-up munitions, or transportation of munitions, nitrate fertilizer, or commercial boosters.

The lessons learned from analysis of the accident reports 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-based gun propellant were 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 or instantaneously.
  - Heated, and sensitized, adjacent energetic material.
  - In a heavily confined environment such as an ECM, fires may have caused significant overpressure resulting in rupture of the structure that produced large pieces of debris and may have caused these pieces to be thrown significant distances. The section on Testing in this report will provide additional information on this phenomenon.
- Fires do not have to burn for long periods of time when there is significant confinement before overpressure causes rupture and debris to be thrown from the structure. This also will be addressed in the Testing section. High pressures and rapid pressurization leading to failure of structures and debris projection can occur within seconds of ignition if the energetic material has a high surface area as is the case with gun propellants.
- In several of the accidents, overpressure blew open the double doors or even the entire head wall, releasing the overpressure 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 Testing section.
- 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 HD 1.1 and 1.3. The HD 1.3 material, especially AP-based propellants in rocket/missile motors, is generally easier to ignite than HD 1.1 and burns well even at atmospheric pressure, while many HD 1.1 materials do not burn well at atmospheric pressure. The burning HD 1.3 materials can serve as the stimulus for the explosion of HD 1.3 materials in confinement and/or explosion or detonation of HD 1.1 materials.
- Several of the reviewed accident reports contained the following two common misrepresentations:
  - The assumption was made that HD 1.3 materials can be considered as “wooden round,” and that HD 1.3 reactions are rather benign.
  - The assumption was made that HD 1.1 items are the most sensitive (easiest to initiate reaction) materials.

As previously mentioned, HD 1.3 energetic materials, such as AP-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 HD 1.1 military munitions, a mechanical shock on the order of tens of kbars is required. Such a mechanical shock level is almost never found in storage or transportation conditions.

- Even after the detonation of HD 1.1 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 ECMs if there is ample venting).
- 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.

TESTING THAT STARTS WITH FIRE

As mentioned earlier in the Accidents portion of this report, one of the problems associated with reviewing accidents to try to understand the initial reactions and spread of reaction is, as noted by Wilkinson (Reference 40):

> “Regrettably, the dramatic consequences of an ammunition explosion normally make the key witnesses to the event among its first victims. Therefore, any subsequent investigation tends to concentrate on the

practices and regulations in force at the time, as key witnesses are not available."

This is certainly true with the accidents cited in this report. One of the key lessons learned in many of the storage or transportation accidents is that one of the initial reactions was fire. That is a rather global finding, but it lacks technical detail as just mentioned in the preceding section.

The next parts of this survey address testing and trials. But before that the following section will address some of the fundamental differences between controlled testing and the largely uncontrolled accidents.

SIGNIFICANT DIFFERENCES BETWEEN ACCIDENTS AND TESTING/TRIALS

Much of the information in the following paragraphs has already been presented. At the risk of being overly redundant, it is presented again because the authors are now changing from descriptions of accidents to descriptions of testing and test results. Keep in mind the fundamental differences between controlled tests and uncontrolled accidents.

A significant part of the literature search focuses on accidents and on test and trials. Indeed, more pages of this report describe accidents than the number of pages that describe tests and the results of these tests. While both of these areas are important and yield valuable lessons learned, there are some fundamental differences that need to be recognized upfront.

As mentioned before, both areas use a simple relationship given below:

$$\text{Sample} + \text{Stimulus} + \text{Environment} \rightarrow \text{Reaction}$$

In tests/trials the three areas to the left of the yields sign are systematically varied. For example, in the Sample area, different materials, different geometries, and different amounts may be used in the testing. In the Stimulus area, different levels of energy inputs, such as heat flux, may be applied to the sample. The Environment may be changed by changing the confinement/venting and thus the pressure and pressurization rate. In performing the tests/trials, as systematic changes in Sample, Stimulus, and Environment are made we look at changes in reaction mechanism and response level. If enough tests are performed, mechanistic understanding of the phenomena can occur, and can lead to analytical models that can be used to predict the behavior in other situations.

In accidents, an undesired, inadvertent reaction such as fire or explosion is produced. During the accident investigation the investigators try to determine what aspects of sample, stimulus, or environment, and the combination of these factors produced the unwanted, inadvertent reaction. For example, the sample may have changed with time. An example might be depletion of stabilizers in nitrocellulose gun propellants. When the stabilizer was depleted to a low enough level, the gun propellant could “spontaneously” ignite. Lightning strike might be an example of a stimulus that could cause the unwanted reaction. Burning of energetic materials in heavy confinement, such as would be the case for samples stored in ECMs with small vent areas is an example of how the environment could produce deflagration/explosion and significant throw of debris as the unwanted reaction.

A major difference between tests/trials and accidents, is that in the tests/trials you move from left to right in the above equation and you control the variables. In an accident, you are essentially trying to swim upstream, going from right to left. You know what the undesired reaction was but you must try to explain how the sample, stimulus, and environment combined to produce that result. This is made even more difficult, because many of the clues or much of the evidence, as well as the witnesses who had firsthand knowledge, were destroyed/perished during the undesired reaction.

Another consideration is the level of documentation available from test/trials versus accidents. Reports from test programs, even when written many years ago, tend to be more detailed and comprehensive than accident reports. Part of this is a reflection of the discussion above. The investigators in a test program had control of the variables and were able to report the reactions that occurred as the variables were systematically varied.

Accident reports reflect that the investigation had to swim upstream with many of the clues destroyed by the accident; was often surrounded by emotion, especially if fatalities occurred; and often are produced within a very short time line with an eye toward possible litigation. In reviewing accident reports, much of the detail and recollection are lost with time.

[Note: This is not a criticism. Performing an accident investigation and writing the report is a very demanding task, with many of the clues destroyed during the reactions and many of the witnesses died.]

TESTS AND TRIALS

Unfortunately, a large data base of tests concerned with mass fires of energetic materials does not exist. Most of the tests have been either fast cookoff tests of munitions engulfed in fuel fires or slow cookoff tests with relatively slow heating rates. The majority of the tests have been pass/fail tests for insensitive munitions “scoring,” instead of being heavily instrumented to obtain mechanistic understanding of the chemistry and physical behavior. And because the tests are relatively expensive, especially if the ordnance item is large, not very many tests have been performed where the variables are systematically varied. The fast cookoff fuel fire tests are simply the ordnance item subjected to a pool fire; there is no confining structure.

In the past, consideration of fire involving energetic materials in buildings was often trials using various amounts and configurations of specific propellants burning in a building being proposed for construction. Based on the results, recommendations were made on how much of what kinds of propellants in what configuration could be stored in the proposed building. Reference 41 from the 1970s is a good example of this approach. The building that was proposed and tested had a rectangular cross-section with the two side walls and the rear wall being of stout construction, the front wall having a large vent area with iron grid, and a frangible roof of large concrete tiles. The plan view and section view are shown in Figures 144 and 145.

This type of building was thought to allow venting of product gases and associated pressure if the stored propellant inadvertently ignited—first through the iron grid and if pressure still increased venting through the roof by blowing off the concrete roof tiles. Conversely if a fire were on the outside of the magazine, the concrete roof tiles would protect the propellant from fragments and firebrands coming from outside. It was intended that this design could be used singularly or in a row of several cells. The propellant to be stored in this type of magazine was both artillery gun propellant in bulk (bags) and small arms ammunition in plywood drums and/or in bulk (bags). Tests were conducted with combustion of various quantities of propellant ranging from six to up to 60 tons.

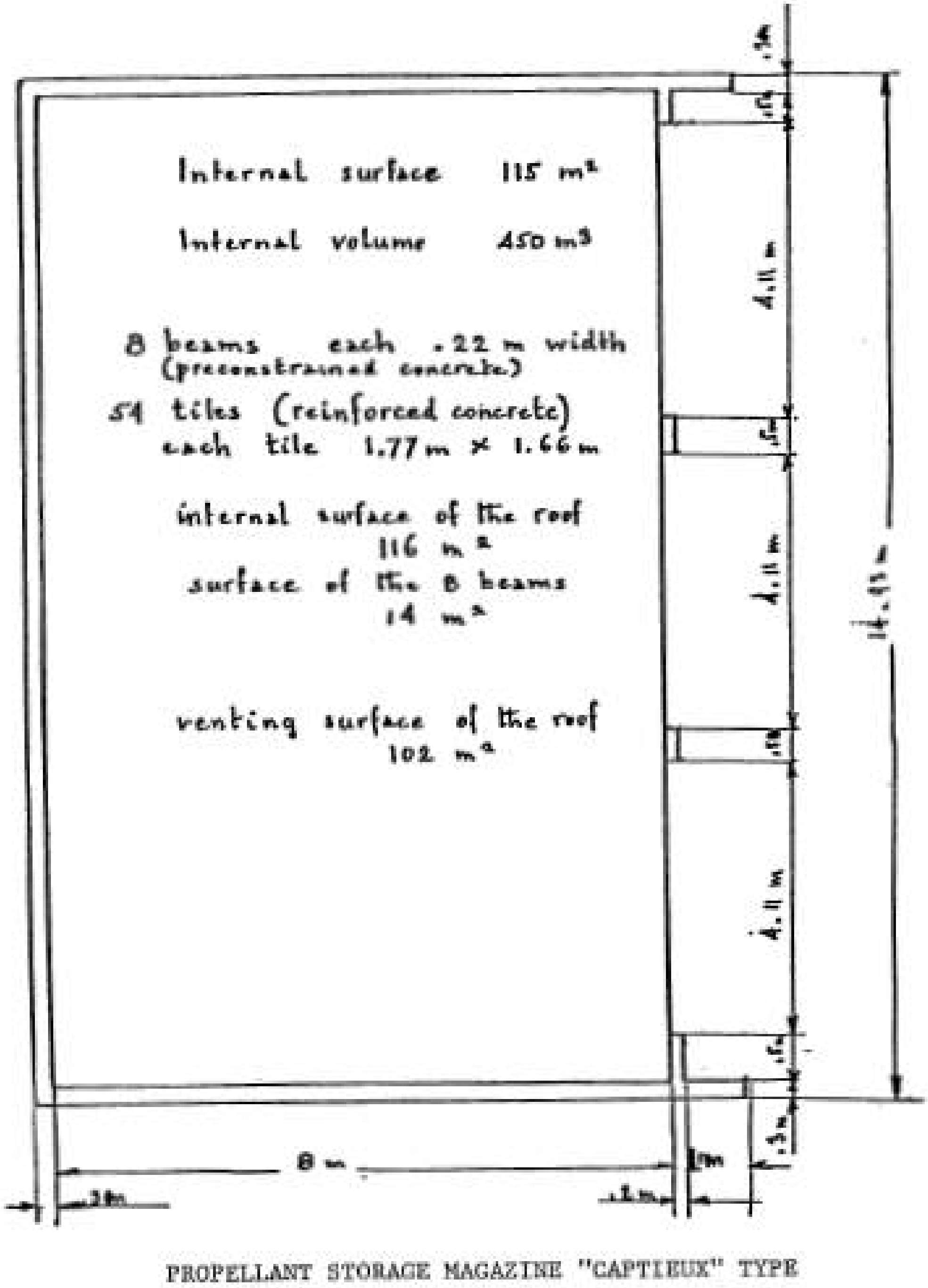
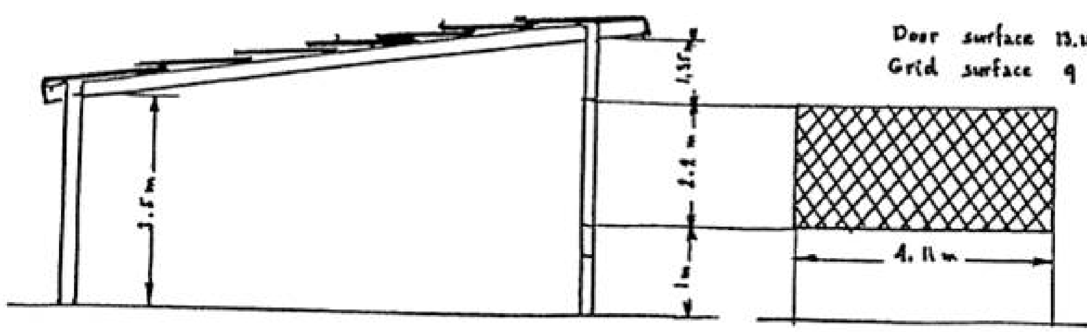


FIGURE 144. Plan View of Proposed Building
for Storing Propellants.



PROPELLANT STORAGE MAGAZINE "CAPTIEUX" TYPE

Elevation

FIGURE 145. Elevation of Proposed Building for Storing Propellants, With Detail of the Proposed Grid.

Sensors and results for the various tests (individual test results were presented in Annex II) included:

- Temperatures measured by thermocouples near to the side or rear walls never exceeded 100°C.
- Temperatures measured by thermocouples at 60 meters in front of building never exceeded 160°C (at 40 meters mean temperature was about 250°C).
- At 40 meters in front of building, the maximum velocity of combustion gases never exceeded 10 m/s.
- Regardless of the quantity and the web of the propellant, combustion of propellant in bulk (bags) lasted for about 30 seconds and about 3 to 4 minutes for propellant in drums.
- Damage to concrete was more severe from tests with bags than test with drums.
- Tests with 40 tons of bulk gun propellant blew out all concrete roof tiles, while tests with 20 tons of small arms ammunition in bulk did not blow out all of the concrete roof tiles.

Based on the test results, the following recommendations were made:

- Storage of propellant in bulk (bags)
  - Internal volume of building — 10 m^3/ton of propellant
  - Front wall aperture (vent) — 1 m^2/ton of propellant
  - Pressure discharge surface from roof — 3 m^2/ton of propellant

- Storage of propellant in plywood drums
  - Internal volume of building — 6.5 m^3/ton of propellant
  - Front wall aperture — 0.65 m^2/ton of propellant
  - Pressure discharge surface, roof — 2 m^2/ton of propellant

- Proposed building "adequate" for 50 tons of gun propellant in plywood drums and 33 tons of gun propellant in bulk (bags).

- Safe-separation Distances
  - From front
    - Inhabited buildings, highway — 100 meters
    - Workshop — 80 meters
  - From side or rear walls
    - Inhabited building or highway — 60 meters
    - Workshop — 40 meters

In the late 1970s and 1980s, DDESB had a program entitled Fire Hazards From Combustible Ammunition. This work, other work presented at DDESB Safety Seminars, and other studies are presented in this section. This section concludes with lessons learned from these efforts.

The Statement of Work for the DDESB program from the 1970s and 1980s included:

> "A program of research and testing has been undertaken to correct the deficiencies in the safety standards for articles and substances of Class 1, Divisions 3 and 4 (Reference 42)."

Some of the deficiencies listed in Reference 42 included the following:

> "*It has been observed that, while cube-root scaling [of the weight of explosive material] applies to the blast overpressures from explosions, thermal radiation incident on a surface exposed to a burning source does not scale in this manner. Furthermore, source parameters other than the total weight of combustible material present, such as geometry, affect the irradiance from the source*. [Italics added in this paper for emphasis.]
>
> The complexity of packaging and storage arrangements necessitates experimental evaluation of relevant source parameters and effects of various types of bulk material and finished ammunition which may be assigned to Class 1, Division 3 or 4. It is expected that a rational system of safety distances will follow from adequate characterization of the actual thermal output of combustible ammunition. It will also be necessary to develop standard tests for characterizing the outputs and effects of new formulations and devices as they are added to the inventory."

The Statement of Work listed four successive phases of effort:

- Phase I was to address Methodology Development. This was addressed and a final report was published in 1989 (Reference 43). The results will be discussed in the following paragraphs.
- Phase II addressed the Effects of Scale and Confinement and a final report was published in 1984 (Reference 44). The results will be discussed in the following paragraphs.
- Phase III proposed revision to United States Hazard Classification, Hazard Class/Division 1.3 and 1.4 Quantity-Distance Tables. The tables were to reflect the following:
  - Quantification tests-thermal flux data
    - "Information which indicates the quantity-distance relationships which approximates 0.3 calories per square centimeter per second [12.56 kW/m^2].

    [Note: The Statement of Work only gave this heat flux with no exposure time. As stated elsewhere in this report heat flux is only one part of the consideration. The other part, the exposure time, must also be considered. For example, at 12.56 kW/m^2, the time to blistering is on the order of 5 to 7.5 seconds. This short time may be insufficient to recognize the threat and to take evasive action, and fatalities could result.]

    - Information that indicates burning rate as related to the material quantity.
    - Information that indicates the size of the combustion zone as related to the material quantity and energy needed for thermal initiation of storage structure materials.

  - Quantification tests—firebrands data
    - Spatial distribution, thermal capacity, and size of firebrands ejected from the source material.
    - Maximum distance the firebrands are ejected.

  - Hazard classification test-direct radiation measurement
    - Information that relates the thermal energy released relative to that of a reference material.
    - Information that relates the distance required to obtain a thermal energy value of 0.3 calories per square centimeter per second from the source material.

    [Note: See the note above.]

    - The burning rate of the material.

> "Based on identified gaps in the data compiled and the types of storage facilities (materials) in use, a test program is to be developed/conducted to provide a definitive data base for determining revised Q-D for HD 1.3/1.4 materials. A test plan is to be developed for a full-scale series of tests to verify the proposed revised Q-D tables."

- Phase IV, Full-Scale Validation Tests, will be formulated and conducted to verify the revised Q-D tables recommended in Phase III.

While the first two Phases had final reports associated with them, no final reports were found for Phases III and IV.

The last two pages of the Statement of Work list six tasks. These tasks included the following:

Task 1. Review Phases I and II and identify any gaps in the data and models.

Task 2. Determine typical construction of storage facilities and what stimuli would breach these facilities. Conduct limited number of surveys of facilities (did not mention what was to be surveyed. Storage methods might be one consideration.).

Task 3. Review technical literature to determine HD 1.3/1.4 initiation thresholds, minimum thermal initiation thresholds for building materials, and thermal flux versus distance relationships. Determine what gaps exist.

Task 4. Based on data gaps identified earlier and the storage facilities in use, conduct a preliminary test program utilizing open air arena tests and confinement tests.

a. Open air arena tests—various quantities and types of propellants/pyrotechnics against candidate construction materials of appropriate materials and thicknesses.

b. Confinement tests—igniting various materials and amounts inside of substantial structure and determining temperatures, pressures, mass burning rates as well as plume locations and firebrand dispersal.

Scaling should also be considered in Task 4.

Task 5. Based on the data and conclusions of Task 4, revised Q-D tables for HD 1.3 and 1.4 should be developed/proposed. Comparisons should be made to existing Q-D called out in DOD 6055.9-STD, and associated effects suggested changes might make.

Task 6. Develop a test plan for full-scale validation tests.

It is interesting to note that the program described in the Statement of Work is similar to the effort being proposed, with some differences such as the current emphasis on having ranges of heat fluxes and associated exposure times that would result in second-degree burns and possible fatalities. This is in contrast to the 0.3 cal/cm^2-sec [12.56 kW/m^2] called out in the Statement of Work (Reference 42). Other differences primarily reflect improvements in experimental and analytical modeling capabilities between this earlier program and what was used in the NASA project (Reference 45) that is described later and is being proposed today.

As previously mentioned, Phase I was completed and a final report was published in June 1980 (Reference 43). This program had two major objectives:

- "To develop quantity-distance standards and criteria for combustible compositions assigned to classes 1.3 and 1.4."
- "To develop standard test procedures to classify the materials with respect to hazards they present to exposed materials, structures, and persons during storage and transport."

In addressing the first objective, the following was stated:

> "By the basic nature of these materials, the hazards are all fire related, but the fires can be sustained burns or quick bursts (fireballs). Potential for harm from these materials is due to radiant heat and firebrands."

This is very similar to the approach recently taken in the NASA effort (discussed in a later section in this report and in Reference 45) that considered both the reaction plume from the burning energetic materials as well as the heat flux radiated to distance.

The test methodology development effort, Phase I, was divided into three parts:

- "To identify (from the literature) or develop scaling models for evaluating experimental results for freestanding flames and fireballs, enclosure fires (i.e., storage facilities), and firebrand lofting. Flame characteristics of interest included the heat flux emitted from the flame and the flame geometry."
- "Second, the pertinent instrumentation techniques were surveyed and summarized. Instrumentation of interest included devices for measuring radiated heat flux, flame temperature, gas velocity, firebrand trajectories, and firebrand ignition potential."
- "The third segment of work involved seven series of experiments. For these experiments, four sample materials were selected. These were M1 propellant, Western Cartridge 844 (a ball powder), 2.75-inch rocket motors, and ALA17 candles (an incendiary). These materials were tested in their shipping containers and removed from the containers."

Seven series of tests were performed to determine the following:

- To screen the different instrumentation to select the most promising to be used in the following tests.
- To determine how to test the 2.75-inch rocket motors. The concern was that these motors would go propulsive and create a safety hazard. Fortunately, the 2.75-inch motors did not self-propel themselves very far.

  [Note: This result was obtained for very small motors should not be generalized to the behavior of other rocket motors. The 2.75-inch rocket had an eight-point star center perforation of the propellant grain and a separable head closure, so that the burning motors had exhaust products coming out the head end of the motor as well as out through the nozzle.]
- The third test series involved single packages (boxes) of each of the munition items. The shipping container for rocket motors has four tubes with each tube normally containing a rocket motor. In the single shipping container tests, only one of the tubes actually had a rocket motor, the others were empty.
- The fourth series involved stacks of boxes to simulate storage or transport configurations. For example, 12 boxes of ALA17 candles, or eight boxes of M1 or WC844 propellant, or six shipping containers containing 24 rocket motors.
- The fifth series was burning piles of bare propellant in the open.
- Series 6 burned these materials inside of a small enclosure that simulated a storage structure.
- Series 7 burned propellant inside of its storage container with the top removed.

A summary of results was presented in bar chart format and is shown in Figures 146 and 147.

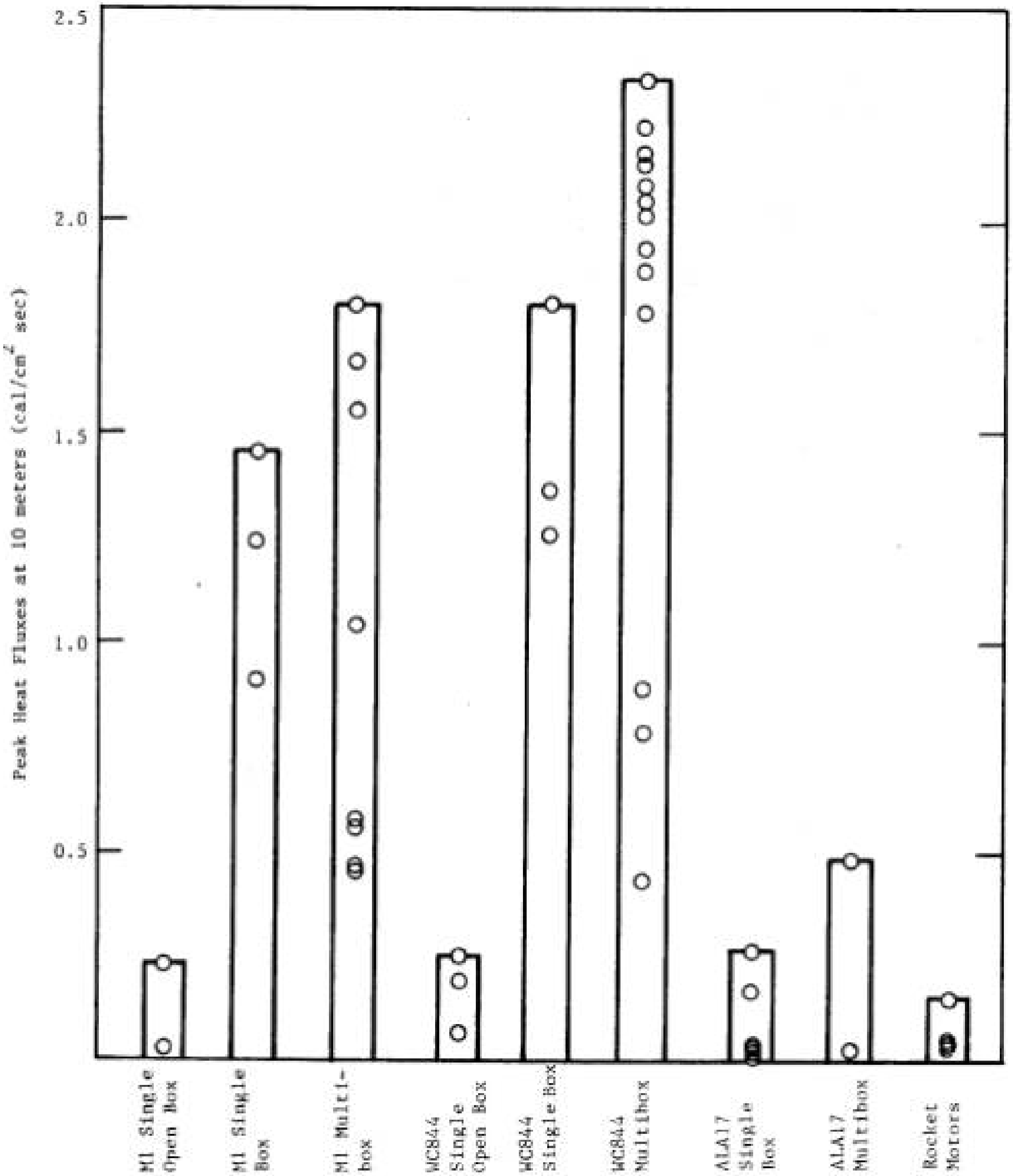


FIGURE 146. Comparison of Heat Fluxes (Figure 34 From Reference 43) [1 cal/cm^{2}sec = 41.868 kW/m^2].

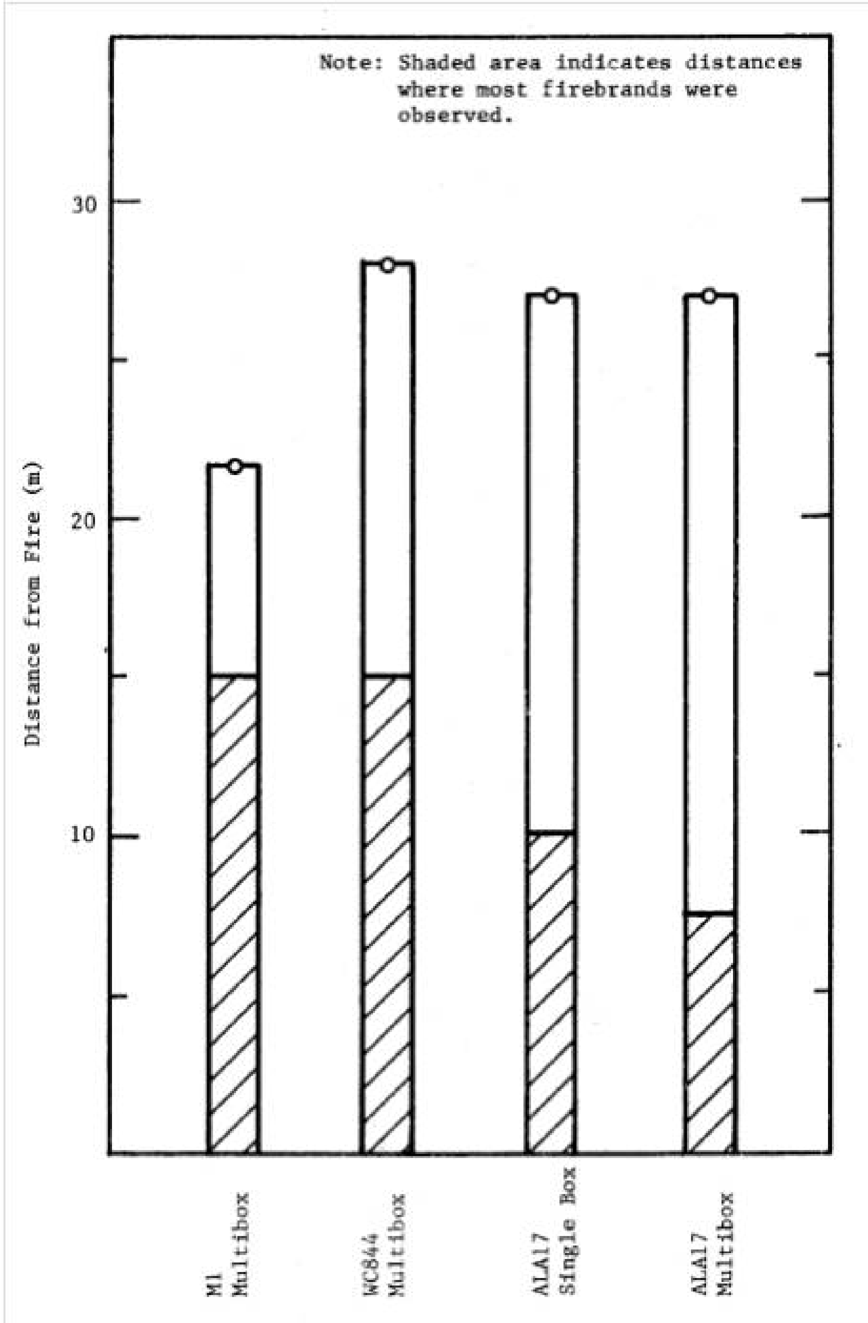


FIGURE 147. Comparison of Firebrand Distances
(Figure 35 From Reference 43).

As evidenced in Figure 146, there is a wide range of fluxes (from about 0.1 cal/cm^{2}sec (4.17 kW/m^2) to approximately 2.3 cal/cm^{2}sec (95.8 kW/m^2)) at a distance of 10 meters. The numbers vary with the material and the configuration (open box, single box, or multiple boxes). It should be noted that while the 2.75-inch rocket motors produced some of the lowest fluxes regardless of configuration, this may be somewhat misleading, because the rocket motors are relatively small. The burning times were long (17 minutes, 23 seconds to 35 minutes, 35 seconds), exhaust was out the front of the motor as well as through the nozzle limiting the pressure in the motor, and the propellant was a non-metalized double-based propellant. Fluxes from the burning of aluminized AP-based composite propellants determined in the NASA program (Reference 45) described later in this report were in the hundreds of kW/m^2. Nevertheless, the data indicate that the material and configuration is important in determining the heat fluxes produced, and the reaction duration.

In the second figure from the summary (Figure 146), firebrands were expelled up to almost 30 meters from the fire, and can cause additional fires to start.

As mentioned earlier, a Phase II was completed and the final report was published in December 1984 (Reference 44). Phase II studied the effects of scale and confinement on hazards from smoke grenades, bulk gun propellants, and flares. Tests were performed in two vented, intermediate scale enclosures. One enclosure was cubical 8 feet on a side made from fire-resistant material (Marinite). The other enclosure was a tenth-scale model of a standard storage igloo.

The smoke grenades, bulk propellant, and flares were tested in the cubical configuration. The smoke grenade tests were quite benign. In the propellant tests, two types of single-based nitrocellulose gun propellants (IMR-5010 and IMR 8208) were burned. These tests showed that beyond 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 higher in the exhaust plume than in the cubicle. The tests with the flares had poor reproducibility, but simultaneous ignition of the flares produced large fireballs. The last series of flare tests produced high enough pressures within the cubicle to cause the refractory walls to fail.

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. The thermal flux from this external fireball can be the major hazard from accidental fires within igloos or other heavily confined magazines. The authors also noted:

> "The cardboard model canisters usually served as good protection for the acceptor propellants within the igloo structure, and did not ignite, thus strongly reducing thermal effects compared to tests with bulk propellant."

The report also contains analyses that may be used to scale effects, and should be considered in any future efforts.

Reference 46 discussed the continuation of the work described above. Confinement tests were performed in the instrumented 1/10th scale model igloo shown in Figure 148.

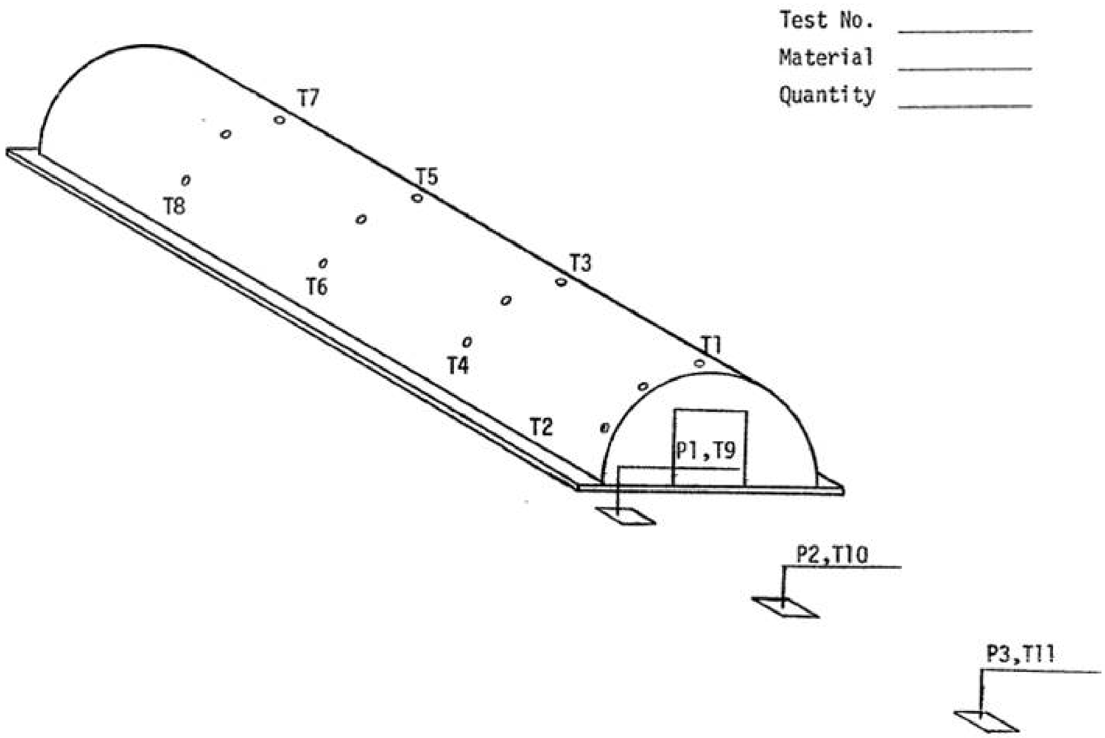


FIGURE 148. Schematic of 1/10th Scale Igloo With Sensors/Location.

The test matrix is shown in Table 19.

[Note: The vents were square, so a 12-inch vent was 12 inches x 12 inches). The term "vent area ratio: is often used. This term is defined as follows:

$$\text{Vent area ratio} = \text{Area of vent(s)}/(\text{volume of structure})^{2/3}$$

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 a magazine with double doors (vent area ratio of 0.07) and a 6-inch vent would correspond to an igloo with single door (vent area ratio of 0.03)].

TABLE 19. Matrix of Test Conditions for 1/10th Scale Igloo (Table 4 From Reference 46).

Test	Material	Quantity, lb	Vent Size, in.
8	IMR 8208	2	12
9	IMR 8208	4	12
10	IMR 8208	6	12
11	M1	1	12
12	M1	5	12
13	IMR 8208	1	12
14	IMR 8208	5	12
15	IMR 8208	10	12
16	M1	10	12
17 (Repeat 12)	M1	5	12
24 (Repeat 16)	M1	10	12
18	IMR 8208	5	9
19	M1	5	9
20 (Repeat 18)	IMR 8208	5	9
21	IMR 8208	1	9
22	M1	1	9
23	M1	10	9
31	IMR 8208	10	9
25	M1	1	6
26	IMR 8208	1	6
27	M1	5	6
28	IMR 8208	5	6
32	M1	10	6
33	IMR 8208	10	6
39	M1	10	6
29	ALA 17	0.5	12
30	ALA 17	1	12
34	ALA 17	1	9
35	ALA 17	1	6
36	ALA 17	2	12
37	ALA 17	2	9
38	ALA 17	2	6

Notes

Test 12. This test was performed using black powder boosters to initiate the propellant in the canisters.

Test 16. This test had instrumentation problems on Channels 1, 3, 5, and 7.

Test 17. Channel 6 was lost during this test.

Test 27. This test was conducted during gusty wind conditions.

The propellant tests were conducted using scaled model cardboard canisters to simulate storage drums. In all of the propellants tests, the canisters were ignited by an electric match placed just below the surface of the propellant. Multiple canisters were simultaneously ignited. The canisters were centered inside the igloo under thermocouple location 3.

The results of the tests are presented in Table 20. Two plume lengths are shown. “Max” refers to the maximum extent of the plume, while “Hot” refers to the dimension of the hot interior core.

The report showed plots of combustion product gas 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 igloo and was pulsating back and forth outside the igloo indicative of choked or near-choked flow.

> [Note: While some of the tests in this program had choked or near-choked flow, the degree was nominal compared with the choked flow in some other tests reported below where the choked flow was more severe and resulted in overpressure that destroyed the confining structure.]

Temperature data from the many tests also showed interesting behavior. A typical plot is shown in Figure 149.

The distance (7.8 feet) corresponds to the thermocouple just inside the igloo and the distance 8.2 feet corresponds to the first thermocouple outside the igloo door.

As clearly seen in the temperature data, the maximum temperature shows the hottest temperatures outside of the igloo as compared to the temperatures inside of the igloo. This strongly indicates that unburned propellant is carried outside of the igloo and burns out in the plume.

In comparison, Figure 150 shows the effect of the choked flow for the 6-inch vent, and 10 pounds of IMR 8208 propellant. The 12- and 9-inch vents show higher temperatures outside the igloo than inside (un-choked flow results in some of the combustible material expelled from the structure and burning outside), but the temperatures for the 6-inch vent show that the temperatures are higher inside of the igloo than outside (choked flow). This indicates that the majority of burning is occurring inside of the igloo. With the choked flow and more of the burning occurring inside of the igloo, the pressures would rise and increase the burning rate, causing further pressurization. [But again, in these tests, not to the degree seen in some of the other tests performed in other programs such as those reported by Joachim (Reference 47) and Allain (Reference 48).]

TABLE 20. Igloo Confinement Test Matrix (Table 5 From Reference 46).

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	0.5	12	10	5
30	ALA 17	1	12	20	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

Notes

Test 12. This test was performed using black powder boosters to initiate the propellant in the canisters.

Test 16. This test had instrumentation problems on Channels 1, 3, 5, and 7.

Test 17. Channel 6 was lost during this test.

Test 27. This test was conducted during gusty wind conditions.

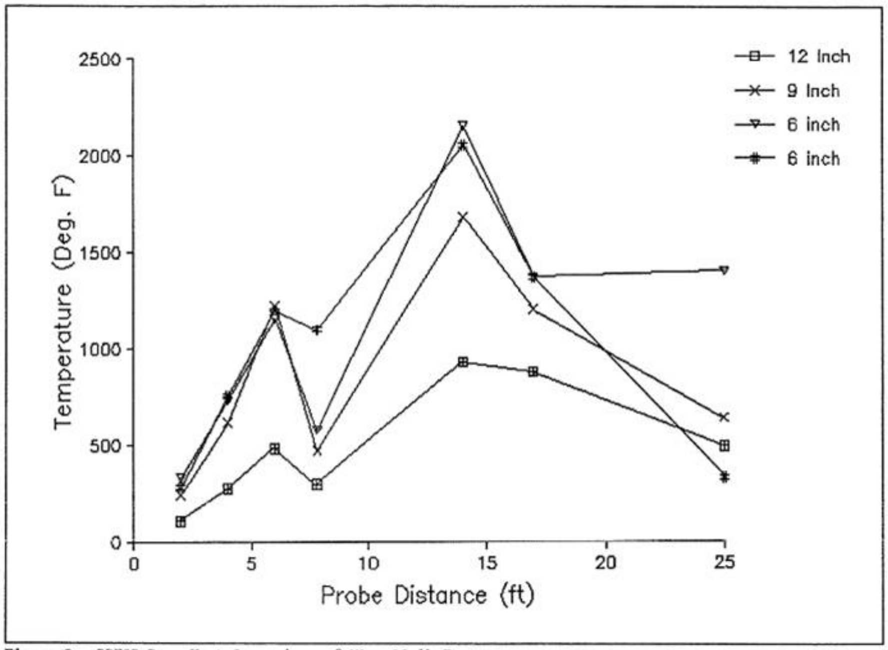


Figure 8. DDESB Door Vent Comparison of M1 - 10-lb Test

FIGURE 149. Temperature–Distance for 10-Pound M-1 Propellant Test.

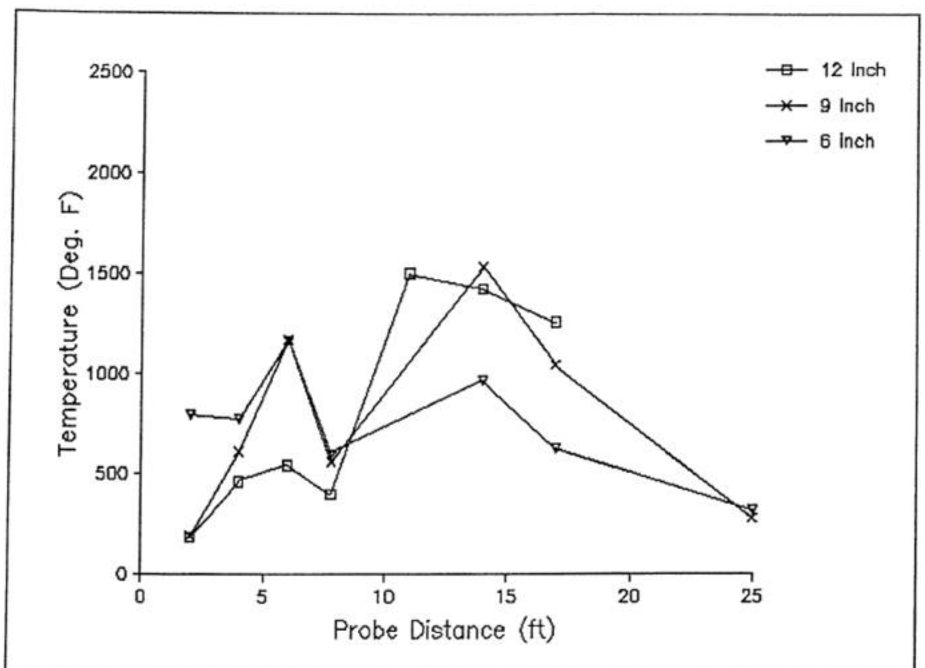


Figure 9. DDESB Door Vent Comparison of IMR 8208 - 10-lb Test

FIGURE 150. Temperature–Distance for 10 Pounds of
IMR 8208 Propellant at Various Vent Openings.

Once again, the distance 7.8 feet corresponds to the thermocouple just inside the igloo, and the distance 8.2 feet corresponds to the first thermocouple outside the igloo door.

The authors also implied what their 1/10th scale results might mean for full-scale condition of 10,000 pounds of propellant in a full-scale earth-covered igloo. A 250-foot plume with a velocity in excess of 1,500 feet per second was also implied. However, for the larger quantities, the flow out of the igloo would become choked and the plume would travel less distance outside the igloo. Choked flow would cause pressurization within the igloo and could subsequently result in pressure rupture of the igloo.

The results of the above study provide good rationale for wanting a rather large vent area for HD 1.3 materials, especially gun propellants with their large surface area available for burning. That vent area could either be large vents in heavily constructed enclosures or by having frangible walls and roofs that as pressure built inside the enclosure the wall or roof would fail thereby relieving the pressure. The resulting fireball and radiation from the fireball would still have to be considered.

In addition to these works directly funded by DDESB, papers addressing either the need for a heat flux-exposure time-based approach for determining safe-separation distances, or describing heat flux data, or pressure buildup within structure and venting were presented at various DDESB symposia. Some of these are reviewed below.

Tozer (Reference 49) presented data on fire tests with two single-based (one with 93% nitrocellulose and one with 95% nitrocellulose) perforated gun propellants in M2 containers in various configurations and loaded in an ISO shipping container placed over a fuel fire. Unfortunately, the copy of the document that the author of this report obtained had very poor quality graphics that could not be legibly copied.

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 was no explosion or detonation.

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

In test series 3, both propellants were subject to tests with a two tiered pallet load. The lower tier had 13 M2 cans of propellant (about 700 kilograms total) with the upper tier having 13 cans of sand/sawdust mixture. The pallet load was suspended over a liquid fuel fire. Similar cookoff 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 periodic burning, similar to a roman candle, was observed. The cans were ruptured, and some were thrown from the pallet. Again, there was no detonation.

Test series 4 was the major trial with pallets of M2 cans containing gunpowder were loaded into an ISO shipping container. A 20-tonne steel ISO container was packed with 12 pallets of cans with a total of 9 tonnes of gun propellant. The loaded ISO container 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 fuel ignition. Vigorous burning commenced about 3 minutes after fuel ignition, reaching a peak at 3 minutes 25 seconds when the ISO container doors burst open and the container was displaced longitudinally about 3 meters. The ensuing fireball extended to a radius of about 30 meters. Cans were propelled from the open end of the container for a distance of about 80 meters and the propellant was totally consumed within 4 minutes. Again there was no detonation. The flame temperature of at least 550°C was achieved over the entire fire within 40.5 seconds. The propellant in the cans reached a temperature of 175°C in 31 to 33 seconds. The pressure generated by the burning propellant was too small to be recorded by the pressure transducers. As will be discussed later, this is a good example of un-choked flow.

Joachim (Reference 47) describes research on combustion of M-1 gun propellant in partial confinement. Rationales for the study were that propellants burn and are usually considered as HD 1.3, but are often treated as HD 1.1 if stored in a chamber or other confined space. “The theory exists, however, if propellant is stored in a chamber or other confined area, an accidental fire could quickly ignite the propellant mass and rapidly produce a large volume of combustion gases. Because this rapid buildup of gases can only vent through the relatively small entrance into the chamber, the chamber becomes highly pressurized. The theory postulates that such high pressures can cause the deflagration of the propellant to transition to a detonation. Consequently, propellant stored under confined conditions must be classified as a mass-detonating explosive, or HD 1.1, instead of 1.3. This, in turn, requires much larger “buffer zones,” or Q-D separations between magazines, inhabited buildings, public traffic routes, etc.” The work described in Reference 47 had as its objective to determine the combination of confinement pressure and loading density required for M-1 propellant to transition from a combustion to a detonation in an accidental fire.

The program plan called for tests using a small concrete bunker with tests having increased loading densities of 2, 5, 20, 50, and 100 kg/m^3 until the concrete bunker either failed from the transition to detonation or structural failure due to buildup of internal pressure. The bunker and venting arrangement are shown in Figure 151.

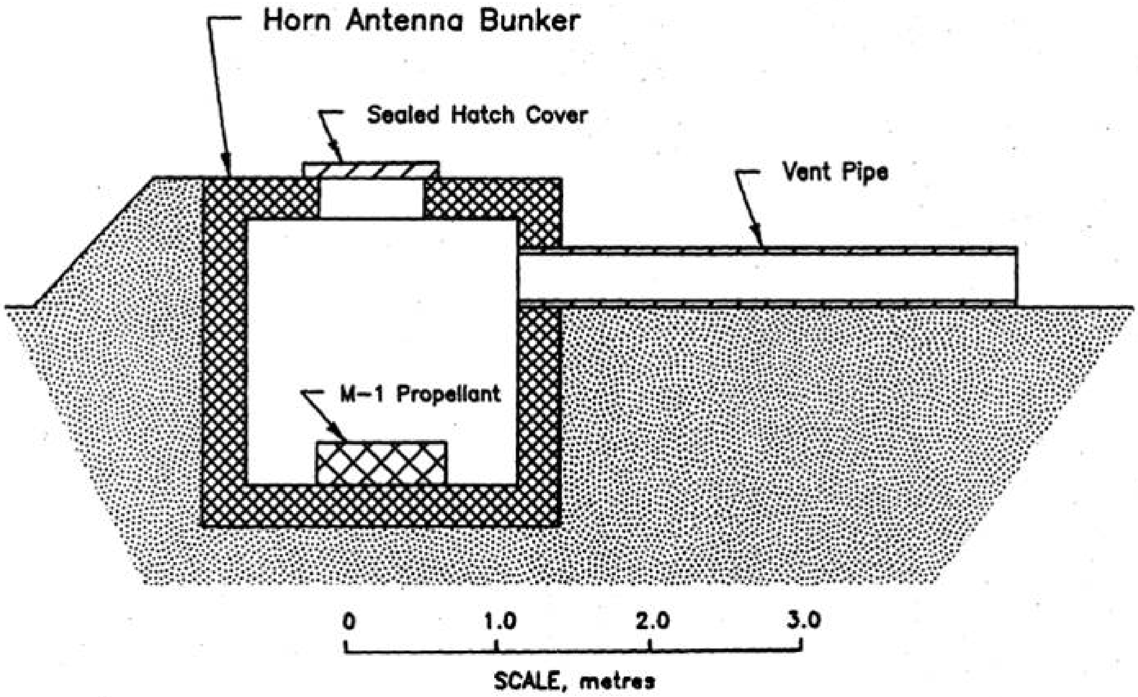


FIGURE 151. Schematic of Test Chamber and Vent Pipe (Reference 47).

The internal dimensions of the chamber were 1.4 meters side-to-side, 1.9 meters front-to-back, and 1.9 meters height. The internal volume was 5 m^3. The reinforced concrete walls, roof, and floor were 30 centimeters thick. The vent tube size is 35.6 centimeters (14 inches) in diameter, and the cross-sectional area was selected to simulate the chamber and access tunnel proportions of the Shallow Underground Tunnel/Chamber Explosion Tested conducted at China Lake, California, in 1988.

The M-1 propellant was a single perf grain with dimensions 5 mm long, 1.1 mm O.D., 0.5 mm I.D., and 0.36 mm web. For tests C-1 and C-2, the M-1 powder was placed in a cardboard box in the center of the floor. In test C-3, four boxes of the propellant were taped together. The individual boxes were 4.92 centimeters wide, 6.50 centimeters long, and 4.92 centimeters deep. For test C-4, the propellant was simply poured on the floor forming an approximate conical shape. The charge weights, volumes, and surface areas for each test are given in Table 21.

TABLE 21. Parameters for Tests (Table 1 of Reference 47).

Test	Charge Weight, kg	Charge Surface Area, m^2	Charge Volume, m^3	Surface Area to Volume Ratio, m^{-1}
C-1	10	0.1334	0.01771	7.796
C-2	25	0.1334	0.04277	3.118
C-3	100	0.5335	0.1771	3.118
C-4	250	1.95[a]	0.4277	4.547

[a] Estimated.

Test C-1 was 10 kilograms of M-1 propellant in the 5 m^3 chamber giving a 2 kg/m^3 loading density. The initial visual observation was black smoke 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. Total duration of the external flame was about 11 seconds. The initial gas flow out the end of the pipe was 3.47 m/s. 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 occurred in the vented gas plume. The video recorded a pulsating flame in the gas plume. Herrera, et al. (Reference 46), also reported unburned propellant propelled outside the structure with combustion occurring outside the structure with overpressures about 1.6 kPa. When the chamber was opened, the cardboard box was charred but not destroyed indicating lack of oxygen during deflagration.

> [Note: gun propellants are often fuel-rich in comparison to rocket propellants, which are more oxidizer to fuel balanced.]

The heat flux measured in the vent pipe is given in Figure 152.

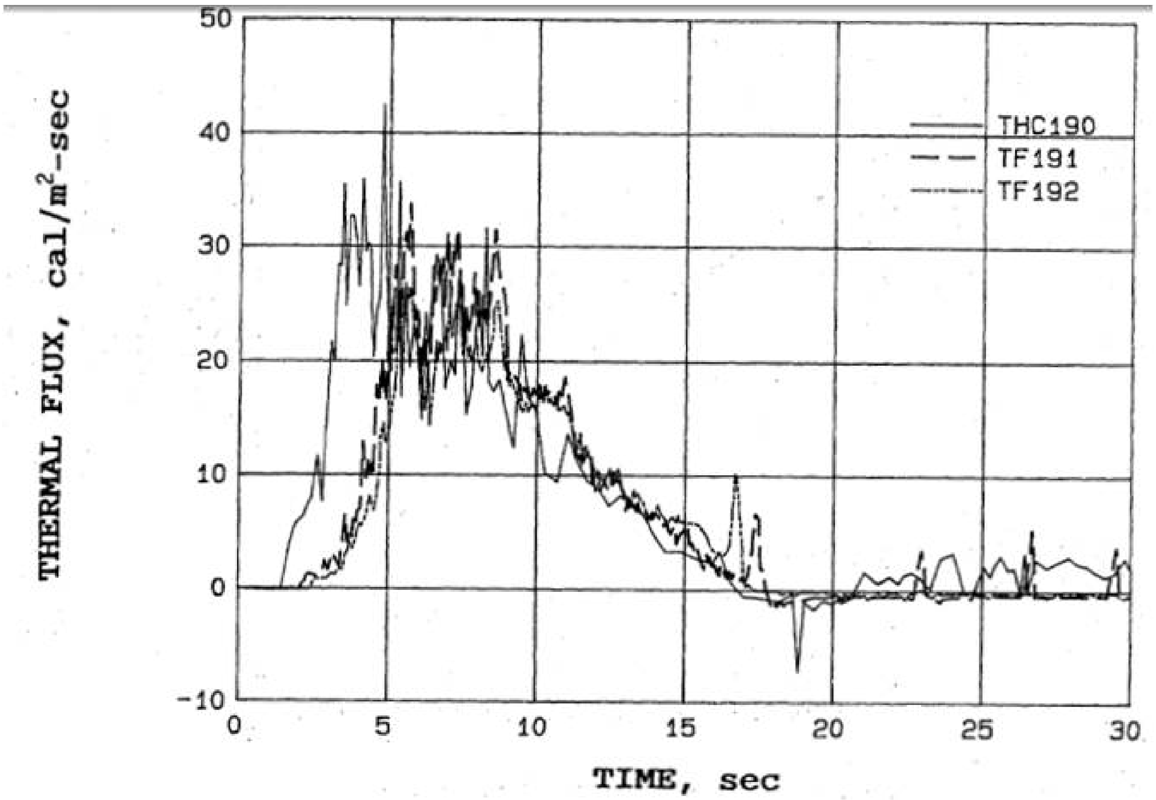


FIGURE 152. Calculated Pseudo-Thermal Flux (from Temperature Measurements of Gage (THC190) in the Bunker Chamber Compared to Measured Thermal Flux-Time Histories in the Vent Pipe (Gages TF191 and TF192) (Figure 14 of Reference 47).

Test C-2 had 25 kilograms of M-1 propellant (5 kg/m^3 loading density). The initial visual observation was a glowing plume projected 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 toward the exit of the pipe. Total duration of the external plume was about 18 seconds. Although the peak external overpressures were approximately 20% higher than in test C-1, the results still indicated that unburned gas and propellant were propelled outside and burned outside the chamber. Once again the plume appeared to be pulsing. Again, the cardboard box was charred but not destroyed. The heat flux values in the tube are presented in Figure 153.

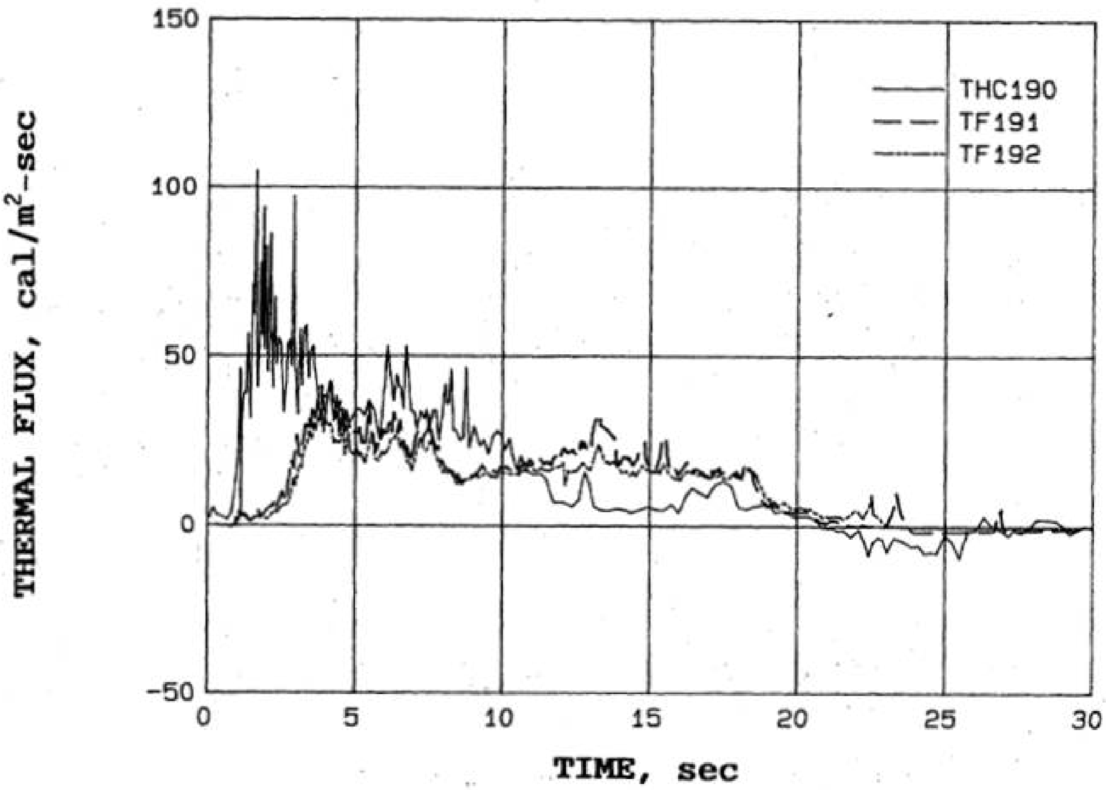


FIGURE 153. Calculated Pseudo-Thermal Flux (from Temperature Measurements of Gage (THC190) in the Bunker Chamber Compared to Measured Thermal Flux-Time Histories in the Vent Pipe (Gages TF191 and TF192) (Figure 18 From Reference 47).

Test C-3 had 100 kilograms of M-10 propellant in the chamber (20 kg/m^3). The first visual was a smoke plume 1.5 meters beyond the end of the pipe at approximately 0.2 second. The plume extended 16 meters in approximately 6 seconds. The initial plume velocity was 5.58 m/s. After about 6 seconds, the plume retreated toward the exit of the pipe. At approximately 11 seconds, a violent gas jet with a velocity of about 29.5 m/s 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 and burned outside of the chamber. Again, the plume had a pulsating flame. Once again the boxes were charred but not destroyed. The flux data are shown in Figure 154.

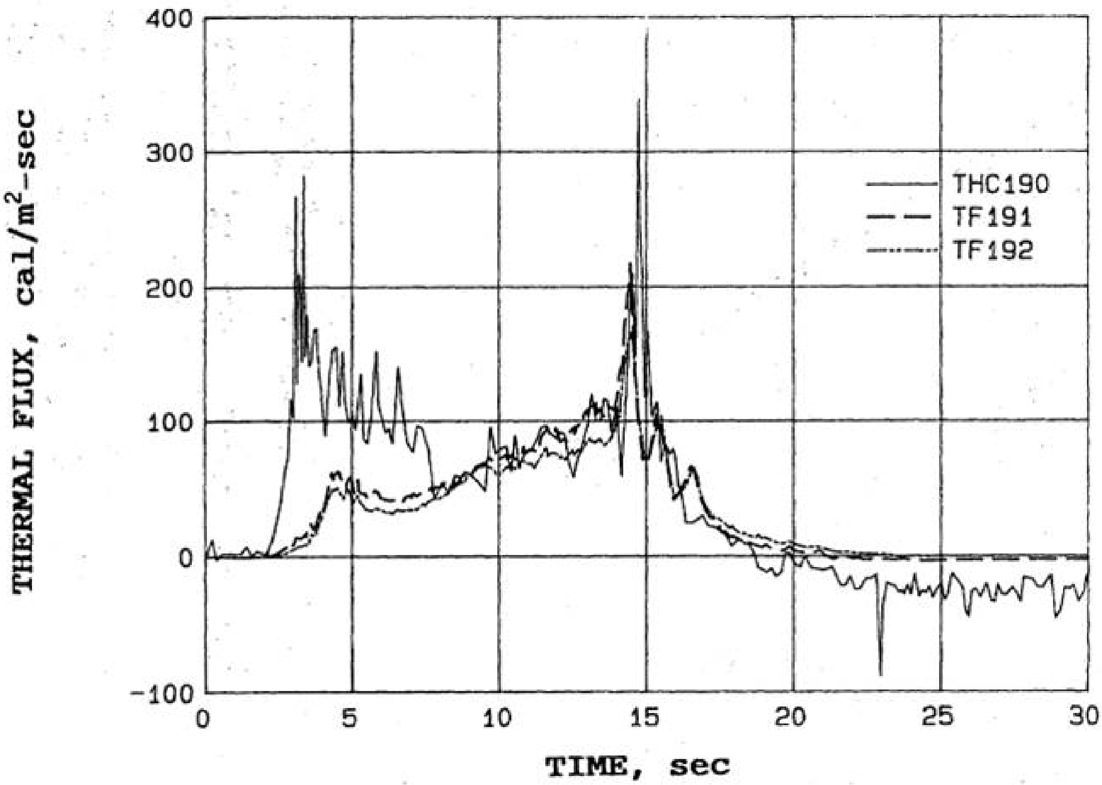


FIGURE 154. Calculated Pseudo-Thermal Flux (from Temperature Measurements of Gage (THC190) in the Bunker Chamber Compared to Measured Thermal Flux-Time Histories in the Vent Pipe (Gages TF191 and TF192) (Figure 22 From Reference 47).

Test C-4 had 250 kilograms of M-1 propellant (50 kg/m^3). The first visual was a smoke plume 1.3 meters past end of pipe within approximately 0.3 second. 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 excess 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/s (hatch) and 11 m/s (roof). The peak pressure on the side wall was about 10 bars (1 MPa). This test indicated that internal overpressure caused the failure not a transition to detonation (Reference 47).

Allain (Reference 48) presents the results of four 1/3 scale 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, similar to M-1, contains 83% nitrocellulose, 10% dinitrotoluene, 5% dibutylphtalate, 1% diphenylamine, and residual solvent <1.08%. The web thickness is 0.8 mm. Figure 155 gives the geometry of the three igloos and their dimensions.

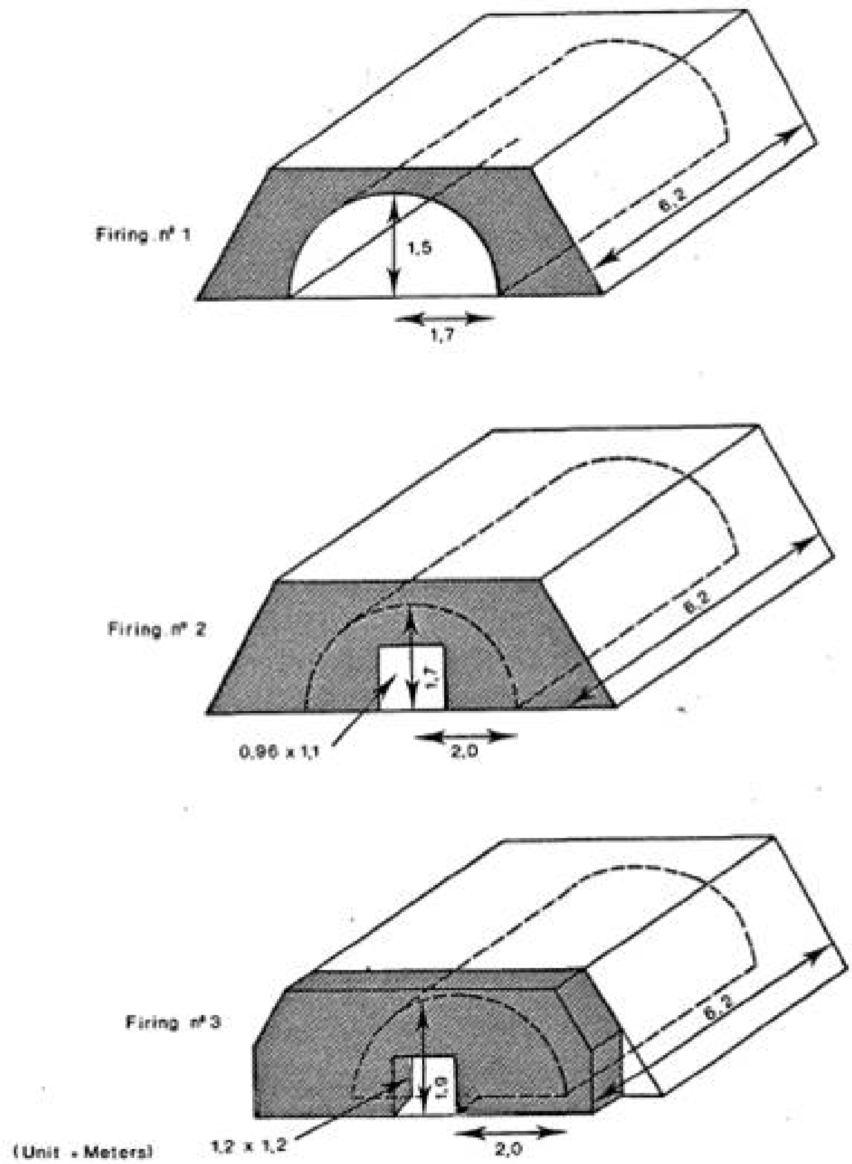


FIGURE 155. Igloo Shape and Dimensions (Reference 48).

Trial 1 was an earth-covered metal arch, placed on the ground, without front wall.

Trial 2 was an earth-covered metal arch, placed on ground with a 0.5-centimeter metal front wall.

Trial 3 was a reinforced earth-covered metal arch, fixed on ground with concrete front wall.

The earth thickness above each metal arch was about 30 centimeters.

The charge consisted of 364 cartridge bags stacked in a configuration of approximately 17.6 meters long x 7.36 meters tall and 8.88 meters wide at the base and 7.77 meters at the top. The charge volume was 3 m^3.

Ignition occurred via ignition of two of the cartridge bags at the back of the respective stack as indicated in Figure 156 for Tests 1 through 3.

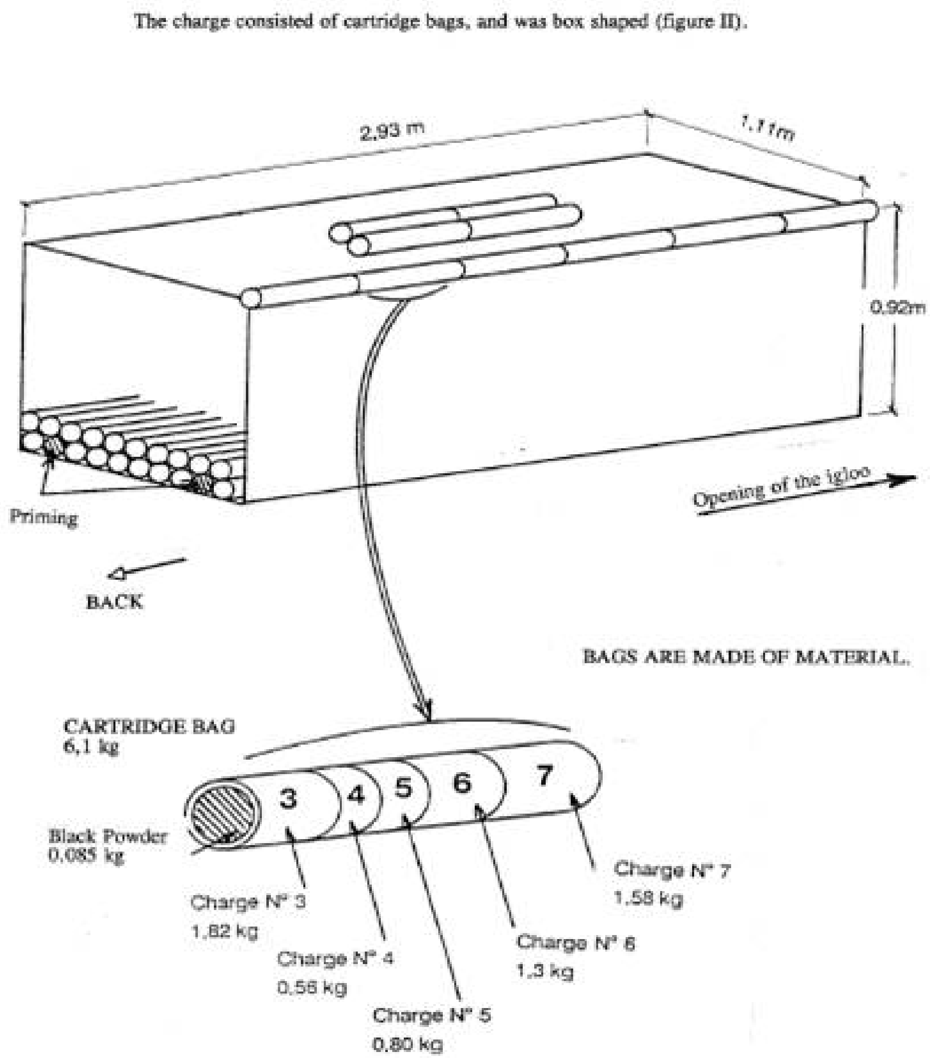


FIGURE 156. Charge Characteristics.

The loading and ventilation coefficients (vent area ratios) are given in Table 22. Flux and overpressure sensors were placed at various locations as shown in Figure 157.

TABLE 22. Loading and Ventilation Coefficients for Three Tests.

Firing n°	Arch Volume, m^3	Opening Area, m^2	Loading Coefficient	Ventilation Coefficient
1	24.8	4	0.12	0.47
2	33.4	1.04	0.09	0.1
3	37.3	1.44	0.08	0.13

Loading coefficient: $\frac{\text{charge volume}}{\text{arch volume}}$

Ventilation coefficient: $\frac{\text{open area}}{(\text{arch volume})^{2/3}}$

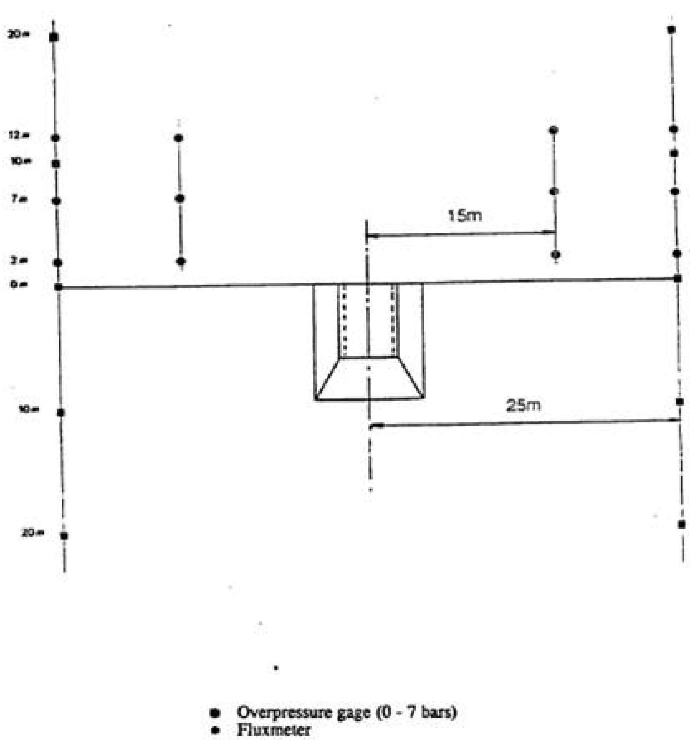


FIGURE 157. Location of Flux Sensors 2, 7, and 12 m x 15 and 25 m and Overpressure Gauges at 0, +20 m, and -20 m by 25 m (Reference 48).

The results of the firings were as follows:

Firing 1. Simultaneously with development of the plume (approximately 40 meters from igloo), the rear part of the igloo lifted from the ground and then ruptured, creating a second plume at a 45-degree angle. Burn duration was about 15 seconds. The average flux at the various points was

Firing 1, flux values in W/cm^2 (1 W/cm^2 = 10 kW/m^2)

Lateral distance	15 m	25 m
at 2 m	8.5	5
at 7 m	11	5.5
at 12 m	12.5	5.7

Unburned propellant was found 45 meters from igloo.

Firing 2. The entire igloo lifted approximately 1 meter off the ground but remained intact. Plume extent was 40 meters long and the burning duration was 15 seconds. The average flux at the various points was

Firing 2, flux values in W/cm^2

Lateral distance	15 m	25 m
at 2 m	5.2	3.6
at 7 m	10.3	4.3
at 12 m	12.8	5.8

Unburned gun propellant was found 45 meters from igloo.

Firing 3. 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. Unburned gun propellant was found 70 meters from igloo.

The author recognized that heat flux is only part of the thermal hazard. Exposure time must also be considered.

Test 4 considered a very different igloo shape as shown in Figure 158.

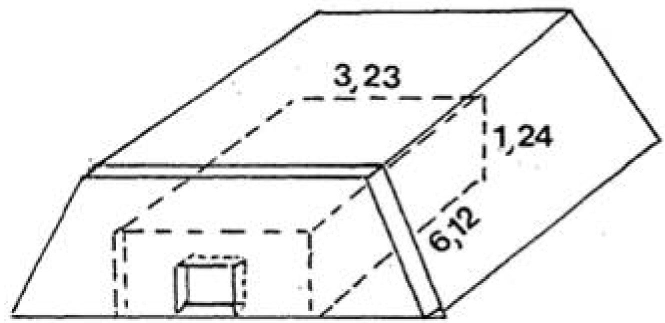


FIGURE 158. Igloo Shape for Test 4 (Reference 48).

To keep the same loading density as the previous test, the amount of gunpowder was modified to 2.037 metric tons and 334 cartridge bags. The cartridge bag configuration was also changed to that shown in Figure 159.

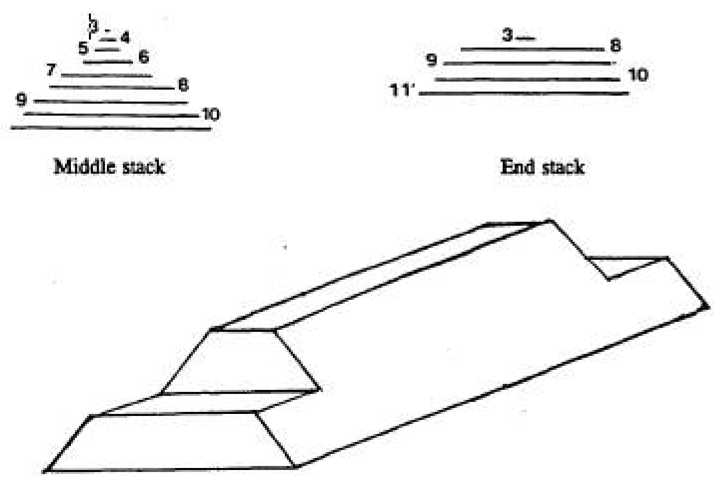


FIGURE 159. Charge Configuration for Test 4 (Reference 48).

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 = 0.11 and ventilation coefficient = 0.013.

> [Note: While the author gives 0.013 as the ventilation coefficient, calculation of $0.33m^2/(24.5\ m^3)^{2/3} = 0.039$.]

Test 4 used a similar ignition of two cartridge bags as the rear and bottom of the stack as used in Tests 1 through 3.

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

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 160.

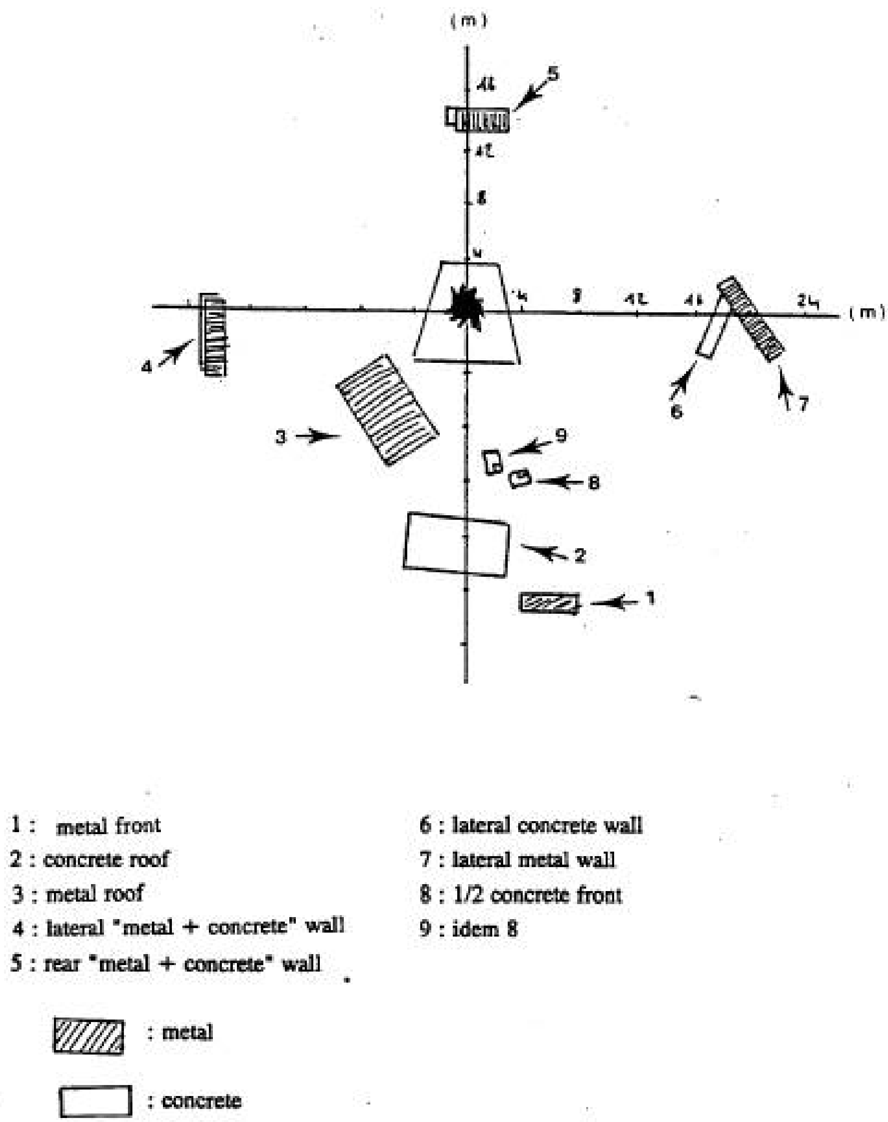


FIGURE 160. Location of Debris (Reference 48).

Figure 161 shows the igloo before the tests and the post event photograph.

(a) Before.

(b) After.

FIGURE 161. Captieux Trial Shot (Reference 48).

Interestingly, none of the overpressure gauges recorded any signal, nor did Figure 161b show a crater, indicating neither strong explosion nor detonation occurred. One of the internal overpressure gauges recorded an overpressure of 7 bars before saturating. The author estimated that the maximum overpressure before rupture at 10 to 12 bars.

The author also calculated the internal pressures reached within the structure for various combustion durations tc. The results of the calculations are shown below.

tc, s	10	15	30	60
P, bar	7.9	5.3	2.6	≤ 2

The author stated that although the values are approximate, they show combustion duration plays a prominent role in the igloo's internal pressure and that it determines when the rupture and formation of debris occurs.

Loading density (mass of explosive/volume of container) and Area Ratio (area of vent/ (volume of container)$^{2/3}$ are two important parameters. Figure 162 plots these two important parameters for the various tests presented above.

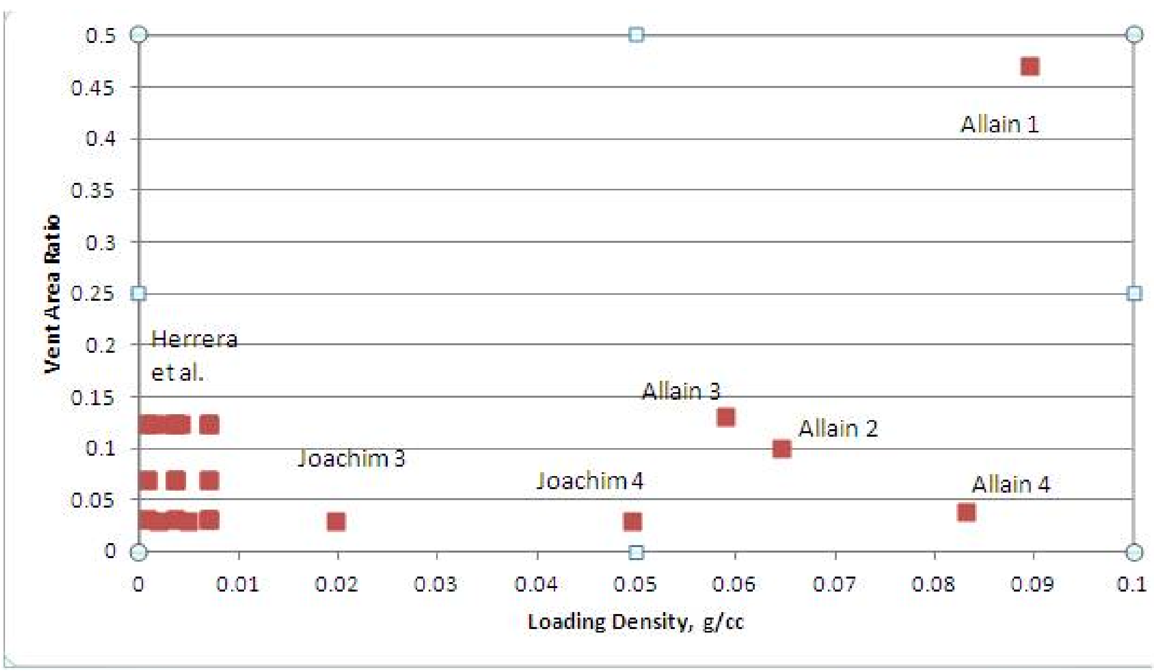


FIGURE 162. Plot of Loading Density vs. Area Ratio for Tests.

Henderson (Reference 50) presents the argument as follows: “There has been concern for some time within the UK military explosives community that the rules governing the storage of HD 1.3 explosives were too conservative.” The document presents two levels within HD 1.3:

- HD 1.3.3 contains the more hazardous items with mass fire hazard and considerable thermal radiation
- HD 1.3.4 contains the less hazardous items that burn sporadically

Reference 50 also describes tests with various materials to determine class designation. The materials tested are listed below:

- Charge propelling 155-mm Howitzer
- Charge propelling 120-mm TK, high explosive squash head (HESH)
- Cartridge propelling 105-mm
- 120-mm TK armor-piercing fin-stabilized discarding sabot (APFSDS) charge propelling
- Flare tripwire Mk 3/1
- Rocket pack seat ejection Mk 10A
- Cartridge impulse Mk 9
- Cartridge electric engine starter (EES) no. 10 Mk 3

The results of the UN Series 6 tests were summarized in the following excerpt:

> “In no instances in the testing did any of the ammunition exhibit any tendency to react as a mass fire risk. In all circumstances each round, cartridge or item functioned separately. In the external fire tests the items burnt sporadically. In some instances, e.g., the 120-mm or 155-mm propelling charges, the individual thermal events are not insignificant but there was no evidence of any propagation between the cartridges as packed in their normal transport containers. There is no doubt that if the cartridges were taken out of their container and piled up, then they would undoubtedly propagate and give rise to a mass fire event. Indeed from the same series of tests the 155-mm propelling cartridges were shown to react violently, with a full 100% TNT equivalence, when the HE projectiles in the same container were initiated.”

The results of the UN Series 6 tests showed that the following items should be in HD 1.3.4:

- Charge propelling 155-mm Howitzer
- Charge propelling 120-mm TK, HESH
- Cartridge propelling 105-mm
- 120-mm TK APFSDS charge propelling

- Flare tripwire Mk 3/1
- Rocket pack seat ejection Mk 10A

Based on the test results, it also determined that the following items were of such low hazard that they could be realistically reclassified as being in HD 1.4:

- Cartridge impulse Mk 9
- Cartridge EES no. 10 Mk 3

The materials were subjected to a liquid fuel fire in storehouses constructed of internal block-work with external brick-work and a reinforced concrete roof. A typical building is shown in Figure 163.

The result of the 55-mm MTV flares subjected to a standard liquid fuel fire in the storage building produced the result shown in Figure 164.

FIGURE 163. Typical Storage Building Before Test (Reference 50).

FIGURE 164. Storage Building After Test With 55-mm MTV Flares Subject to Standard Liquid Fuel Fire (Reference 50).

The building appears in remarkably good shape with minor structural damage most likely due to prolonged exposure to the heat from the fuel fire. Any projection of debris most likely occurred after the door was blown open.

The results of subjecting the 155-mm charges to the liquid fuel fire are shown in Figure 165.

FIGURE 165. Results of the Tests With 155-mm Propelling Charges Subjected to Standard Liquid Fuel Fire Within Building (Reference 50).

Again there is only minor damage probably due more to the long exposure to fire rather than reaction violence of the ordnance.

Figure 166 shows the results of tests with the 120-mm propelling charges subjected to the liquid fuel fire in the building.

(a) Front view.

(b) Rear view.

FIGURE 166. Result of 120-mm Propelling Charges Subjected to Standard Liquid Fuel Fire in Building (Reference 50).

As can be seen from the photographs, serious damage occurred to the building in which the internal fire test took place. The initial propellant event caused localized failure of the front wall and the continuing fuel fire caused significant structural damage and disruption to all four walls. The charges initiated by the fire lasted over a 3- to 4-minute period.

In comparison to the fire tests, Figure 167 shows the effect of five of the propelling 120-mm propelling charges being simultaneously initiated. As a result of the large-scale initiation, the front wall of the structure failed although it was not projected, effectively being pushed out and falling over. The remaining damage to the building was less than that observed in the liquid fuel fire, perhaps not surprising given that there was no long duration fire to stress the building further although the remaining charges initiated over a period of just over one minute.

FIGURE 167. Effects of Functioning 120-mm Propelling Charges
When Contained Within an Explosive Storehouse Structure,
View of Front of Magazine (Reference 50).

The following citations were given as a result of the tests:

> "…there is no need to specify a separation between structures intended to hold ammunition and explosives of HD 1.3.4 ..."
>
> "Further consideration of the trials results suggest that there is little need for significant separation of any type of building from storehouses containing these explosives. However, it seems sensible to ensure that occupied buildings should be separated by a nominal distance of, say 25 meters, provided that there is a traverse or other equivalent protection in terms of building structure between a potential explosive site (PES) and an exposed site (ES). Where no such additional protection exists, the separation should be increased to a nominal 50 meters to provide adequate protection. Put another way, it is expected that the effects from an accidental initiation of HD 1.3.4 will be contained by any reasonable structure, constructed with walls of a minimum of 215-mm brick (or equivalent) with a protective roof of 150-mm reinforced concrete (or equivalent) and that any residual hazard from such explosives would be defeated by a similar structure."

There were no recommendations to change HD 1.3.3 from a mass fire categorization. These results are important because they, coupled with other results, underscore that the current HD 1.3 contains many and varied materials that will react differently, and to have a simple classification, and two k factors (one for IBD and one for intraline) in a weight-based approach to safe-separation is a gross oversimplification that needs to be addressed.

More recent work described in References 51 and 52 also addressed the combustion of HD 1.3 materials (flares and gun propellant) in storage conditions. Experience with civil fireworks in the CHAF project caused concern as to whether military HD 1.3 articles might also be so sensitive to storage conditions that they would cause unexpected effects in the event of an inadvertent ignition. The work by the Netherlands and German MoD started with experimental work of increasing scale (starting with approximately 100 grams of energetic material and progressing up to 50 kilograms of energetic material) and complexity leading to the development and application of a model for vented burning of the HD 1.3 material. Of particular concern was heavy confinement of the energetic, as might occur with an ECM, coupled with insufficient venting, that might lead to significant overpressure in the magazine followed by magazine breakup and debris throw. The tests by Allain at Captieux on 1/3 scale magazines described by Swisdak and Montanaro (Reference 53) were cited, specifically Test 4 where 2,500 kilograms of gun propellant was stored (loading density of 100 kg/m^3). There was no crater to indicate a detonation, but there was significant debris throw.

The second portion of Reference 52 is titled "Safety of HD 1.3 Munition: The verification of the transport classification of flares and propelling charges—Meppen (D)

2003." This portion of the report describes the results of the standard UN-transport classification tests (with added instrumentation). The conclusions of these tests are that the selected items for the tests in the first portion of the document were correctly classified as HD 1.3 materials.

Some of the significant conclusions from the Dutch and German work include the following:

- Small-scale detonation tests on the M4C4 gun propellant showed that this material can sustain a detonation or detonation-like reaction if it is heavily confined. In medium-scale, unconfined detonation tests the bags of M4C4 propellant can be brought to a violent reaction by high explosive detonation and the reaction can propagate to bags in an adjacent box. However, the propagation seemed to be marginal and not all bags in adjacent boxes reacted violently. The authors make the point that mixed storage of HD 1.3 with 1.1 or 1.2 must be regarded as being capable of producing a mass explosion.
- Small- and medium-sized tests showed that the metal storage container could significantly delay ignition of propellant in the adjacent boxes. It was later concluded after some of the analytical modeling, that the packaging is a critical determinant of the violence of the magazine burst.
- An analytical model was developed. Results showed that when the packaging has a reasonable time delay for ignition of adjacent stores the deflagration is mild enough to limit burst of the magazine to a weak explosion. When the packaging allows low ignition delay of adjacent boxes, or if the magazine fails at elevated pressures, the burst can be violent. The vent pressure was very sensitive to the size of the vent.
- Practical measures can be taken to limit the effects of HD 1.3 accidents. These include:
    - Store HD 1.3 articles in a weak magazine, i.e., a non-ECM, preferably with a weak lightweight roof.
    - Package the articles in well-insulated boxes that are airtight up to approximately 100 kPa.
    - If stored in a strong magazine like an ECM.
        - Make sure that the door will fail at low internal pressure (less than 25 kPA).
        - Keep the NEQ limited to such amount that the vent pressure does not exceed the strength of the ammunition boxes.
        - Preferable keep the NEQ limited to such an amount that the vent pressure is lower than the strength of the magazine.

Although this study does not specifically address the heat flux, it does mention:

> "Because the break-up occurs at the low failure pressure of the magazine, blast and debris throw are very limited, and their hazards are significantly smaller than the hazard caused by the heat radiation."

Also, included in the report was a discussion of fireballs and it mentions that DOD 6055.9-STD provides an estimation of the size of a fireball to be given by

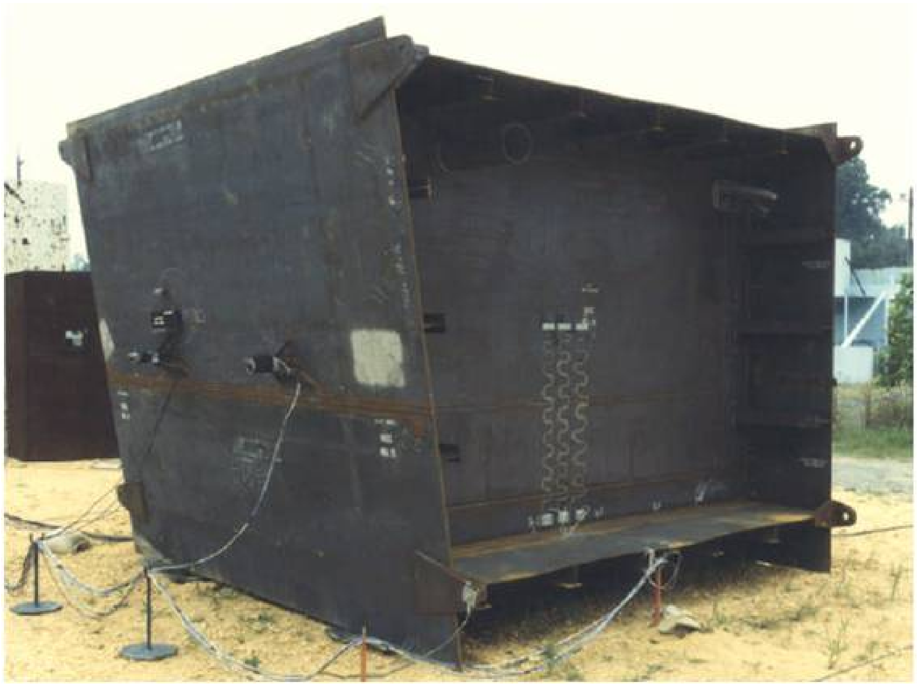
$$D_{fire} = 10\ W_{eff}^{1/3}$$

Where D_{fire} is the diameter of the fireball in feet, and W_{eff} is the quantity of 1.3 material involved multiplied by a 20% safety factor (i.e., 100 pounds of 1.3 energetic material = 120 pounds W_{eff}).

It then states that other references give different sizes due to variability in combustion rate and energy, but regardless of the size, it states, "<u>People caught in the fireball have practically zero chance of survival</u>" (emphasis added). It mentions the desirability of light building confinement.

Swisdak and Montanaro (Reference 53) presented what they called "Real World Events." The first of these were tests performed at the Naval Surface Warfare Center, Carderock, that used burning propellant to provide internal pressurization for testing ship structural components. Figure 168a shows one of these test fixtures having nominal dimensions of 9 feet x 8 feet x12.75 feet and a volume of 918 ft^3. When approximately 300 pounds of propellant were burned in this fixture (loading density of 0.33 $lb/ft^{3)}$, the catastrophic failure shown in Figure 168b occurred.

Swisdak and Montanaro also presented the results of Allain's French Captieux Trials discussed earlier in this document (Reference 48).



(a) Before.

(b) After.

FIGURE 168. Tests Burning 300 Pounds of Propellant in 918 ft^3 Chamber.

LESSONS LEARNED FROM TESTS AND TRIALS THAT STARTED WITH A BURNING REACTION OF HD 1.3 AND 1.4 MATERIALS

Most of the testing with fires have involved gun propellants with various loading densities (mass of gun propellant/chamber volume) and varying degrees of structural confinement and venting.

Two of the critical determinants of reaction violence are (1) the rate of pressurization in the chamber due to the combustion of the propellant, and (2) the venting of combustion product gases from the confining chamber.

- The pressure–time history in the chamber is largely determined by the mass burning rate of the propellant. The mass burning rate is determined by the propellant density, the surface regression rate, and the burn area. Because the gun propellant has a very high surface area burning, it quickly pressurizes a chamber, as was shown in some of the tests described in the previous sections.
- If there is no venting and the confinement is robust as in steel pressure vessels like the kind used to determine burning rates of gun propellants (often referred to as closed bombs), the internal pressures can be quite high (tens of thousands psi) for burning a modest loading density (14,000 psi for 0.1 g/cc).
- If venting is available, and the confinement is more like typical storage conditions rather than steel pressure vessels, then the reaction violence is determined by whether the flow from the confining structure is choked or un-choked. If the flow is choked, as in Joachim's Test 4 and Allain's Tests 3 and 4, pressure can build in the chamber and result in catastrophic rupture of the chamber, throwing large pieces of debris from the chamber. If the flow is un-choked, the hot combustion products flow out of the chamber, often times carrying unburned gun propellant that in turn burns outside. The hot combustion products and burning propellant form a plume or fireball outside the chamber. The temperatures in the plume are often higher than the temperatures in the chamber. The hazard for the un-choked situation is the hot plume itself—any person in the path of the hot plume will have serious burns and probably perish, and radiation from the hot plume. The heat fluxes measured were as high as 125 kW/m^2 at 12 meters from the centerline of the plume (Allain). The heat flux will decrease roughly with distance squared. Response to the plume radiation will be dependent on heat flux (distance dependent) and exposure time.

- It is best to avoid choked flow by providing sufficient venting, but there will still be plume and thermal radiation to worry about. As will be shown later in the section on analytical modeling describing the determination of safe-separation distance from the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC) with eight 5-segment boosters (approximately 11.6 million pounds of solid propellant), analytical modeling can be used to determine safe-separation distances due to fire and radiation from the fire. In that study, it was determined that using a heat flux based approach with prevention of second-degree burns as the risk/consequence criterion, significant amount more propellant could be stored in the VAB than would have been allowed using the $D = kW^{1/3}$ approach used to determine the hazard arcs for Space Shuttle in the VAB.

TESTS WITH HD 1.2 AMMUNITION SUBJECTED TO FIRE STIMULUS

The previous section on tests with fire hazards dealt with HD 1.3 (mass fire minor blast or fragment) and HD 1.4 (moderate fire no blast or fragment) materials. There is literature that describes a series of tests performed on HD 1.2 materials (non-mass explosion, fragment producing) subjected to fire. These tests are reviewed here with some comparisons made to HD 1.3 and 1.4 materials.

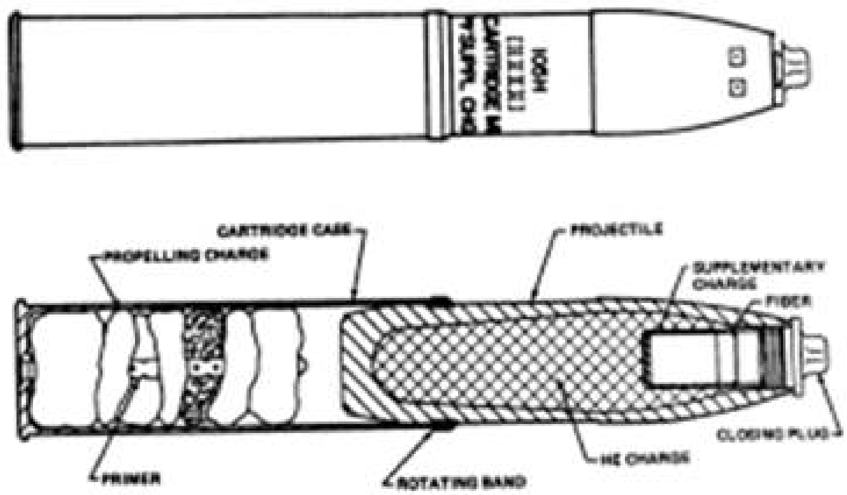
In 1989, NATO AC/258 agreed that a program of tests should be carried out to investigate the consequences of an HD 1.2 event. Tests beginning in 1991 were performed to investigate the behavior of 105-mm projectile ammunition and 81 mm mortar ammunition subjected to bonfire in the open. The results of the first five tests were reported at the 25th DDESB Explosive Safety Seminar (Reference 54). Tests 1 through 6 were also discussed in Reference 55. Tests 1 through 7 were discussed in 1994 in Reference 56. The results of the 12 open air tests were presented at the Twenty-seventh DDESB Explosives Safety Seminar (Reference 57). The 12 tests are shown in Table 23.

TABLE 23. HD 1.2 Bonfire Test Program.

Test	Date	Test Items	Warhead Fill	Packaging	No. of Pallets	No. of Rounds*	Note
1	5-7-91	M1 105-mm Artillery Cartridges	TNT	Standard wooden boxes	1	30	
2	6-24-91	M1 105-mm Artillery Cartridges	TNT	Standard wooden boxes	1	30	
3	7-29-91	M1 105-mm Artillery Cartridges	TNT	Standard wooden boxes	1	30	
4	10-29-91	M1 105-mm Artillery Cartridges	TNT	Standard wooden boxes	8	240	
5	4-29-91	M1 105-mm Artillery Cartridges	TNT	Standard wooden boxes	8	240	
6	10-28-92	M1 105-mm Artillery Cartridges	TNT	Standard wooden boxes	27	864	
7	5-3-94	M1 105-mm Artillery Cartridges	Comp B	Standard wooden boxes	3	96	Nose plugs omitted
8	5-3-94	M374A2 81-mm Mortar Cartridges	Comp B	Standard wooden boxes	2	180	
9	5-11-95	M374A2 81-mm Mortar Cartridges	Comp B	Metal boxes/plastic sleeves	2	180	
10	5-11-95	M1 105-mm Artillery Cartridges	Comp B	Standard wooden boxes	4	128	
11	5-11-95	M374A2 81-mm Mortar Cartridges	Comp B	Metal boxes/plastic sleeves	--	15	
12	5-11-95	M374A2 81-mm Mortar Cartridges	Comp B	Metal boxes/plastic sleeves	8	30	

* NOTE: Test nos. 1 through 5 were conducted using pallets that contained 30 rounds (15 boxes) each. Test nos. 6, 7, and 10 were conducted using pallets that contained 32 rounds (16 boxes) each.

The configuration of the M1 105-mm artillery cartridge is shown in Figure 169. The 105-mm cartridges are packed head to tail two-to-a-box.



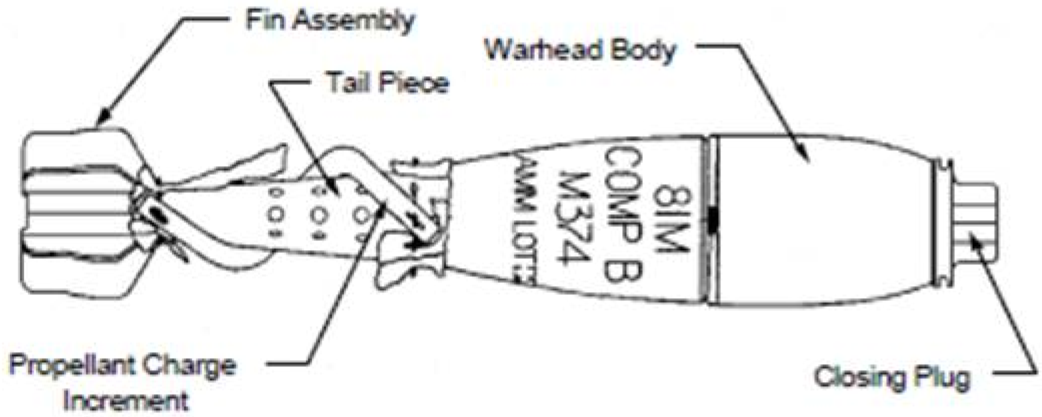
Nominal Characteristics

Projectile Body:	Forged Steel
Projectile Body Weight:	25.8 lb
Explosive Fill (HE charge):	TNT or Composition B
Explosive Weight (HE charge):	4.6 lb
Propelling Charge Case:	Spiral Wrap Steel
Propellant:	M1 Propellant
Propellant Weight:	2.8 lb
Net Explosive Weight (total)	7.4 lb

FIGURE 169. M1 105-mm Artillery Cartridge (Figure 1 from Reference 54).

[Note: This is the U.S. 105-mm cartridge. Later tests performed in Spantech magazines also used Australian 105-mm rounds that have a slightly different configuration, e.g., a brass propelling charge case instead of the spiral wrap steel casing.]

The configuration of the M374A2 mortar cartridge is illustrated in Figure 170.



<u>Nominal Characteristics</u>

Warhead Body:	Forged Steel
Warhead Body Weight:	5.05 lb
Explosive Fill (HE charge):	Composition B
Explosive Weight (HE charge):	2.1 lb
Tail Piece/Fin Assembly:	Aluminum Alloy
Propellant:	M1 Propellant
Propellant Weight:	0.3 lb

FIGURE 170. M374A2 81-mm Mortar Cartridge (Figure 3 from Reference 57).

The cartridges are packaged in wooden boxes three rounds per box. A complete pallet consists of 30 boxes. For tests 9, 11, and 12, the cartridges were repackaged in plastic tubes and metal boxes to simulate a packaging configuration used in the UK. Aluminum nose plugs were used in place of live fuzes for each of the 81-mm cartridges.

The following is taken from Reference 57 (Figures 171 through 173).

> "Test nos. 1 through 4 were conducted generally in accordance with the methodology prescribed in the UN Recommendations on the Transport of Dangerous Goods'. The test items were stacked on a steel test stand that provided approximately 30 inches clearance between the bottom of the stack and ground level. The top of the test stand was constructed as shown in Figure 4 to function as a grate. Dried lumber placed beneath the test stand and around the pallet(s) was used as kindling to provide fuel during the initial stages of the test. Four shallow steel troughs containing a small amount of gasoline (less than 5 gallons each) were placed around the base of the stack to provide an ignition source for the fire. The gasoline in the roughs was ignited using an electric squib. In order to eliminate ground cratering and burrowing of unexploded test items at the

stack site (ground zero), the stack was constructed over a concrete pad. The top of the concrete pad was protected by a steel plate. A typical completed test setup is shown in Figure 5."

FIGURE 171. Construction of Test Stands
(Figure 4 from Reference 57).

FIGURE 172. Completed Test Setup for Test Number 1
(Figure 5 from Reference 57).

"The remaining tests were conducted in the same manner except that kindling was only placed directly beneath the test stand is shown in Figure 6. This was done to more realistically simulate an accident scenario in which the test item packaging materials and the energetic components are the primary fuel source for a fire. The use of the steel plate to protect the concrete pad was discontinued after test no. 5."

FIGURE 173. Completed Setup for Test Number 4
(Figure 6 from Reference 57).

> "The tests were conducted on a flat, dried lake bed. The area surrounding ground zero was scraped clear of virtually all vegetation to a range of approximately 1300 ft. The vegetation beyond the 1300-ft range consisted of clusters of desert grasses and scrub brush. In order to facilitate recovery of the test item debris, the cleared region was marked with a 10° x 200 ft grid. Recovery of the test item debris was accomplished manually through systematic visual searches of the area by test personnel. The debris that were recovered inside the 200 ft range were not retained for analyses due to their large numbers. However, these debris were segregated according to type (i.e., warhead case piece, cartridge case piece, or miscellaneous) and the total weight of all warhead body pieces was determined. The posttest searches were limited to a range of 2000 ft or less. On-site observations and review of the video records indicated that few, if any, fragments impacted at ranges greater than 2000 ft. Thus recovery beyond this range was not considered cost effective. Additionally, the likelihood of finding any fragments that might lie in this region was considered low due to the presence of vegetation."

The general observations for each test are given in Table 24.

TABLE 24. General Observations for Each Test (Table 2 from Reference 57).

Test Observed No., ft	Stack Size, No. of Cartridges	Elapsed Time to Initial Reaction, min:sec	Elapsed Time to First/Last Explosion, min:sec	No. of Explosions	No. of Projectile Bodies Recovered Intact	Maximum Fragment Range
1	30	15:32	18:24 48:53	13	17	1600-1800
2	30	20:22	24:14 42:36	9	21	1600-1800
3	30	20:05	36:48 78:40	11	18*	1400-1600
4	240	18:13	20:48 61:08	66	174	1800-2000
5	240	14:15	18:37 41:13	65	174	3140**
6	864	21:11	25:54 73:39	324#	546	1800-2000
7	96	23:48	31:38 51:58	8	82	1200-1400
8	180	17:03	22:42 41:42	89#	93	1000-12
9	180	22:18	26:11	1	102	1400-1600
10	128	15:49	19:43 ~241##	39	88	1400-1600
11	15	10:46	16:27 18:43	4	8	800-1000
12	720	18:35	18:35 115:59	177	502	1200-1400

*A 19th projectile body was recovered with only minor damage in the nose region (e.g., small fracture)
**The remaining fragments that were recovered were found at a range less than 1,600 ft
#Based on pressure records. The frequency of explosions was so great at times that the number of explosions could not be determined from visual observations on video records. Some of these events may have been caused by propellant reactions.
##Observed by test personnel after all recording instrumentation was stopped.

The paper also gives several tables of fragment recovery data, fragment maps, photographs of fragment, and maps where explosions occurred. The reader is referred to the paper for these data. The authors, Reference 57, concluded with the following.

> "A fire in an open stack of 105-mm cartridges or 81-mm cartridges typically results in a series of explosions. The first reactions are relatively nonviolent deflagration reactions and are typically observed approximately 10 to 15 minutes after the stack is completely engulfed in flame. Considerably more violent reactions begin to occur a short time later. The overall duration of the event may range from less than one hour to several hours with the last few explosions occurring after the fire is effectively out.
>
> The most violent reactions are explosions or detonations involving one or more warheads. These reactions often produce relatively large, high velocity fragments that may have ranges approaching and possibly exceeding 2,000 feet. However, not all of the warheads react violently. Some of the warheads burn in a manner that does not fragment the case, while others are thrown clear of the fire and do not react. During this test series, the highest percentage of warheads that reacted in a manner that caused fragmentation of the case was approximately 48%.

> Fragments are dispersed randomly in azimuthal angle and the fragment density decreases rapidly with range from ground zero. Warhead body fragments are the primary contributor to far-field fragment hazards. Most of the fragments produced by the propellant charges and packaging are limited to a range of roughly 600 feet or less.
>
> Although intact (i.e., live) warheads have been recovered several hundred feet from the ground zero, there have been very few occasions in which a warhead was thrown more than 50 feet from the burning stack and then exploded. There have been no instances in which a warhead was thrown more than 150 feet from the fire and then exploded. Thus, it appears that the post-impact explosion of lobbed rounds does not contribute appreciably to overall fragment ranges."

In addition to the tests described above, the German Federal Armed Forces Material Office conducted tests on one pallet (240 rounds) with DM31 40 mm by 365 HE ammunition subjected to a UN Bonfire test. The UK Explosives Storage and Transport Committee analyzed the data and determined IBD, NEQ, and Fatality Probability/Range relationships. The data were compared to data on 40-mm HD 1.2 ammunition presented by the U.S. in Reference 58. http://www.dtic.mil/dtic/tr/fulltext/u2/a521197.pdf. The committee also presented data from Norway, Reference 59 in their comparison. The conclusion was that the data for the German and Norwegian tests with steel boxes were very similar. The Norwegian data for the ammunition in wooden boxes was a slightly worse case. But, a large discrepancy was found between the German and Norwegian data and data from the U.S., with the U.S. predicting a significantly larger IBD required. The committee mentioned that the U.S. was investigating the cause of the differences.

The tests described above were all done in the open. In November 1994, tests were performed with the 105-mm rounds contained in an earth covered igloo. The tests were performed at the range in Woomera, Australia, and used a Spantech igloo. The Spantech igloo is made with a steel arch constructed with specially designed interlocking steel sections which are then sprayed with a layer of 250-mm concrete. The 7 bar head wall and rear wall are reinforced concrete. The resulting arch is covered with a 600 mm minimum depth of earth. There is one ventilation shaft at the rear of the roof. The structure and tests are discussed in Reference 60. The paper calls out Figure 1 showing the Spantech igloo. Unfortunately, the figure was not in the paper. A drawing of a Spantech igloo was found in Reference 61. The drawing is reproduced in Figure 174. However, it must be noted that Figure 174 shows two sliding doors in the head wall; the Spantech igloo used in the tests described below only had a single door.

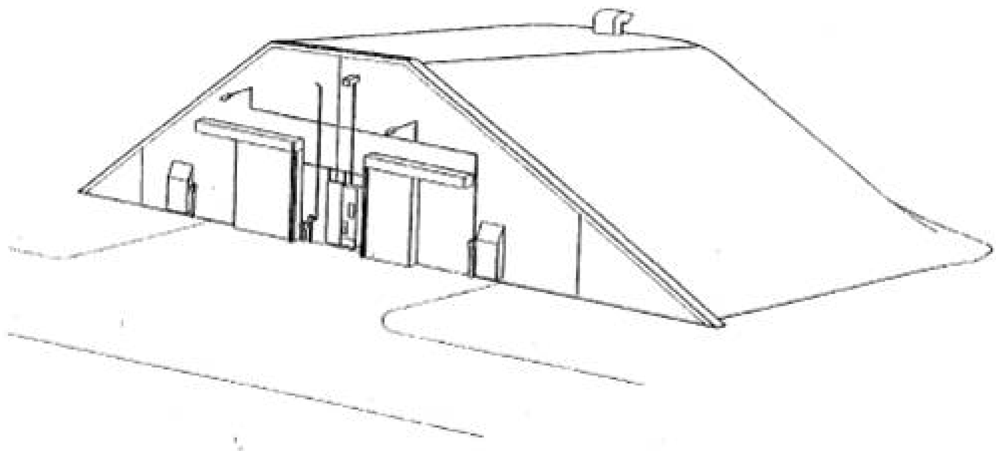


FIGURE 174. The Spantech Igloo (Figure 2 from Reference 61).

Figure 175 shows a photograph (with an overlay) of the Spantech igloo with single door.

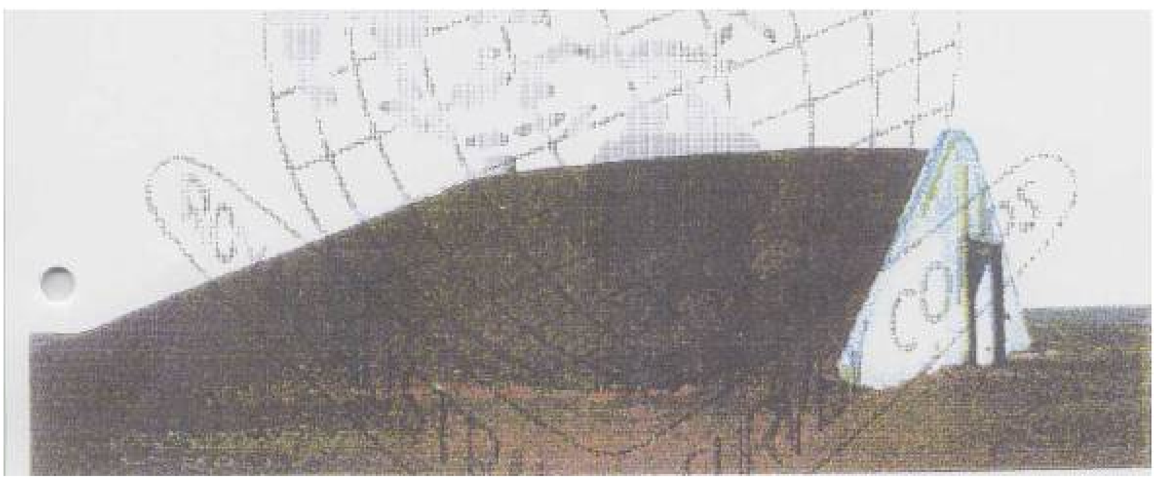


FIGURE 175. Spantech Igloo with Single Door (from Reference 62).

A still photograph from test footage shows the igloo during one of the trials (Figure 176).

FIGURE 176. Explosive Event as Viewed from Safety Area (from Reference 62).

Four tests were carried out with stacks of M1 105-mm artillery cartridges subjected to bonfires tests within the Spantech magazines in November 1994. The details of the number and types of rounds and their location in the Spantech igloo are given in Table 25.

TABLE 25. Details of Ammunition and Its Location for Tests (Table 1 from Reference 61).

Test Number	Number of Pallets	Number of Rounds	HE Filling	Position in Igloo
1	1	32	Comp B	Rear corner
2	1	32	TNT	Mid point on one side
3	1	32	Comp B	Mid point on opposite side to Test 2
4	8	256	Comp B	Rear corner opposite to Test 1

The locations for the four tests are shown schematically in Figure 177 (Reference 63).

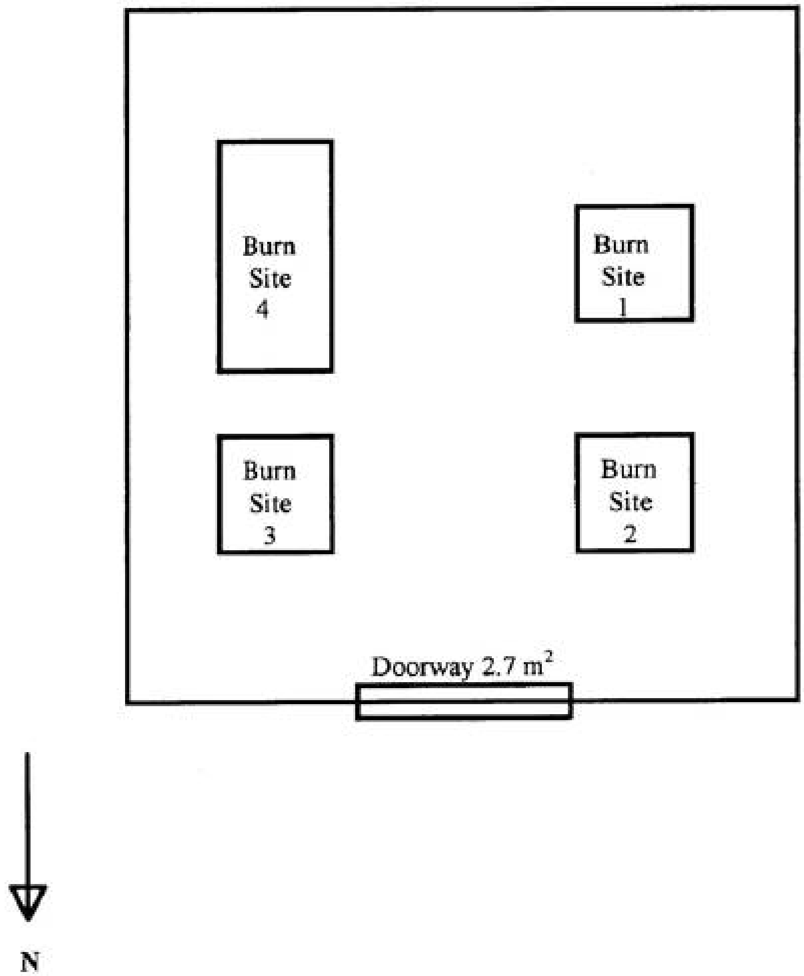


FIGURE 177. Location of Tests Within Spantech Igloo (From Reference 63). [Note: The figure shows "Doorway 2.7m^2." Believe that it was 2.7 x 2.7 m judging from some photographs that showed the door and personnel.]

Tests 1 through 3 were single pallet tests configured as shown below. The pallet was placed on a steel support 90 cm above the floor. Dried wood was placed beneath the steel support structure. Just before the test the wood was soaked with a five to one mixture of diesel and gasoline to ensure good ignition and an even fire.

Figure 178 is the configuration used for Spantech Tests 1 through 3.

FIGURE 178. Pre Burn Two (Figure 11 from Reference 63).

The configuration for the four pallets of Test 4 is shown below in Figure 179.

FIGURE 179. Pre Burn Four (Figure 27 from Reference 63).

The general observations for the four tests are given in Table 26.

TABLE 26. General Observation Data for the Tests (Table 2 from Reference 60).

Test No.	Time to First Event, m:s	Time to Last Event, m:s	Duration of Events, m:s	No. of Events	Fraction of Stack Reacted
1	21:23	36:44	15:21	17	0.53
2	26:00	50:48	24:48	9	0.28
3	23:01	44:12	21:11	19	0.59
4	32:52	85:55	53:03	141	0.55

The test with TNT fill was similar to the open tests. The rounds with Comp B were higher (53 and 59% reacted) for the contained test vs. the open tests. The individual rounds exploded either in a low-energy event or more rarely as a full round detonation. Most of the fragments were contained in the igloo with a relatively small number escaping via the door. Temperatures in the igloo rose to about 300^{o}C.

MINIATURE MAGAZINE TESTS

In 1996, tests were performed in the U.S. with a miniature magazine (Reference 64). The Miniature Magazine was designed in 1994 by the Huntsville Division of the U.S. Army Corps of Engineers. Plans for two magazines were developed—one for a capacity of 68 kg (150 lbs) and one with a capacity of 181 kg (400 lbs) of HD 1.1 material. In both designs the majority of material was stored in the center compartment with smaller amounts stored in two side compartments. Because of its design, the Miniature Magazine provides heavy confinement for the materials stored within it, and also provides for relatively large vent area facing a barricade.

The test described below used a configuration based on the smaller of the Miniature Magazines (Figure 180).

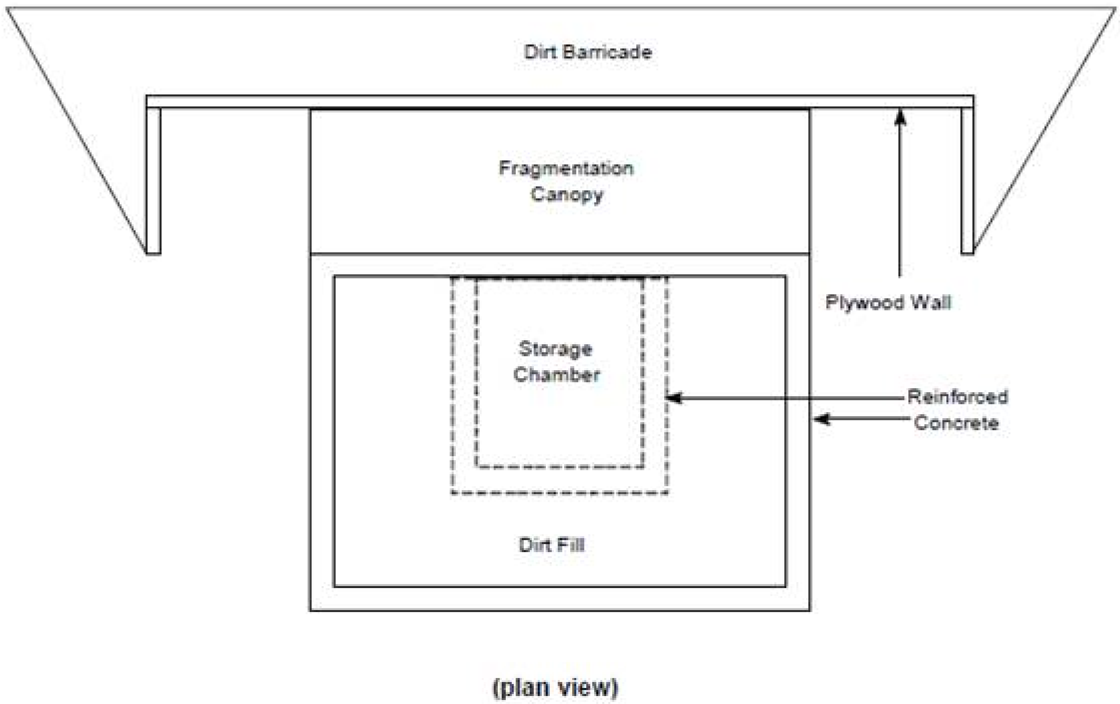


FIGURE 180. Miniature Magazine Test Configuration
(Figure 1 from Reference 64).

The dimensions of the storage chamber were 2.13 m (7 ft) long x 2.13 m (7 ft) wide x 2.44 m (8 ft) high giving 11.1 m^3 (392 ft^3) chamber volume. The walls were 0.30 m (1 ft) thick reinforced concrete while the floor and roof were 0.46 m (1.5 ft) reinforced concrete. The dirt fill was 0.61 m (2 ft) of sand on the sides, rear, and top. The fragmentation canopy extended from the front wall of the chamber and was 0.30 m (1 ft) thick x 6.4 m (21 ft) long x 1.83 m (6 ft) deep reinforced concrete. The canopy stopped just 12.7 mm (1/2 inch) away from the single-revetted barricade facing the magazine. The barricade was a plywood wall 2.74 m (9 ft) high with earth fill behind it.

There was a 1.3 m (51 inches) x 2.08 m (82 inches) door at the front of the storage chamber. There were three vents in the storage chamber: two vents of 15.2 cm (6 inches) x 61 cm (24 inches) were adjacent to the door—one on each side of the door. There was one circular vent [20.3 cm diameter (8 inches)] exiting the rear wall with a 90-degree turn and exiting the dirt sand fill. The door was open for the test.

Sixty boxes of M1 105 mm cartridges (120 rounds) with a NEQ of 433.3 kg (955.2 lbs) were placed in the test storage chamber. If the propellant weight is not counted the NEQ would be 276.5 kg (609.6 lbs). The explosive fill was Composition B. The rounds had aluminum nose plugs. The boxes were placed on a wooden frame. Pans with 38 liters (10 gallons) of gasoline were placed under the wooden frame.

The test was conducted on 24 June 1996 at the Naval Air Warfare Center Weapons Division, China Lake. The first event occurred 22 minutes after the start of the fire. There were 35 major reactions. The last event occurred about 2 hours and 33 minutes after start of the fire.

The debris recovery netted 30 rounds recovered unreacted. A total of 47 empty (burned out) projectile bodies were recovered. Approximately 327.5 kg (722 lbs) of projectile pieces (fragments) were recovered inside the magazine or just outside the door. Reference 64 concluded that the 105-mm cartridges subjected to fire in the magazine behaved very similarly as those tested in the open. The time to first reaction was similar. The "popcorn" nature of reactions was similar. As in the open tests about one-third of the rounds reacted. The temperatures within the magazine were determined to have been of 700^{o}C during the first 22 minutes, and 1,040^{o}C at the end of the fire.

1996 SPANTECH IGLOO TEST

The previous Spantech tests were at low loading densities. Tests 1 through 3 (32 rounds in the Spantech igloo) had loading density of 0.000128 g/cc if only the explosive weight is considered and 0.000206 g/cc if the total weight of explosive and propellant was considered. Test 4 (256 rounds) had loading density of 0.00103 g/cc if only the explosive is considered and 0.00165 g/cc if the weights of both explosive and propellant is considered. In the 1996 tests, the igloo was filled to capacity as specified in the ESTC standards: 160 pallets of M1 105 mm HE ammunition. The 160 pallets were stacked inside the Spantech igloo in a "U" shaped configuration. (Unfortunately a figure showing the configuration was not given.) One stack of pallets was omitted during the preparation of the right hand side of the stack. In this gap a timber platform was constructed 0.5 m above the floor level. A single pallet of ammunition was broken down and stacked on the platform. The volume beneath the platform was filled with wood and prior to positioning the electrical ignition set, diol fuel was mixed with gasoline and poured over the wood to insure ignition. The stack was ignited remotely. The arrangement was considered a good approximation of the standard UN bonfire test.

Instrumentation included

- Blast over-pressure at 3 locations outside the igloo
- Temperature at several locations
- Video cameras at several locations

Fragments were recovered in an area outside the open door out to 800 m. [Unfortunately, the document references a Figure 8 showing the fragment search area, but the figure was not included in the report.]

Twenty minutes after ignition of the stack, ignition of the propellant occurred. Explosive events continued for approximately 5½ hours, and propellant sporadically burned for an additional 2 hours. All activity ceased within the igloo approximately 8 hours after ignition of the wood stack. The bulk of the unconsumed explosive items were found in the zone 25 m from the doorway. This consisted of some 45 items, including projectiles with partially consumed HE filling, cartridge cases containing propellant, and/or primers, separate charge bags and supplementary charges. A total of 123 burnt out projectiles were recovered from this area. The list of debris recovered are given in Tables 27 and 28 (Reference 60).

TABLE 27. Debris Recovered Out to 150 m.

Range, m	Total Lethal Fragments	Total Non Lethal Fragments	Area of Search Zone, m^2	Lethal Fragment Density, per 56 m^2	Pseudo Trajectory Normal
0-25	182	Not assessed	1,250	8.154	26.387
25-50	136	21	1,875	4.062	12.156
50-75	145	10	2,812.5	2.887	5.396
75-100	30	4	3,437.5	0.489	2.053
100-125	11	8	4,062.5	0.152	1.323
125-150	8	1	4,688.5	0.0956	1.015

TABLE 28. Debris Recovered From 150 to 500 m.

Range, m	Total Lethal Fragments	Area of Search Zone, m^2	Lethal Fragment Density, per 56 m^2	Pseudo Trajectory Normal
150-175	14	2,836	0.276	1.520
175-200	6	3.272	0.103	1.078
200-225	10	3.708	0.151	0.861
225-250	9	4,145	0.122	0.635
250-275	6	4,581	0.073	0.465
275-300	5	5,017	0.056	0.357
300-325	7	5,454	0.072	0.277
325-350	7	5,890	0.067	0.190
350-375	4	6,326	0.035	0.115
375-400	1	6,673	0.008	0.075
400-425	2	7,199	0.016	0.062
425-450	2	7,635	0.015	0.044
450-475	1	8,072	0.007	0.028
475-500	1	8,508	0.007	0.019
500-525	1	8,944	0.006	0.013
525-550	1	9.381	0.006	0.006

The furthest fragment was found 549 m from the doorway.

Results from the pressure transducers indicated that there were many explosions (with a blast over-pressure of only approximately 1 kPa), although there were a few overpressures recorded that indicated some of the projectiles underwent a full detonation.

The tests with the HD 1.2 ammunition underscore some of the lessons learned from tests with HD 1.3 and 1.4 materials. Obviously the reactions were not rapid nor simultaneous explosions or detonations. The reactions were described as having a "popcorn" nature of reaction. The first reactions did not occur until approximately 15 minutes after the fires were ignited. The reactions were not simultaneous. The reactions spanned

- 15 minutes to almost 100 minutes for the twelve open bonfire tests.
- 15 to 54 minutes for the Spantech Tests 1 through 4.
- 2 hours and 33 minutes for the U.S. Miniature Magazine tests.
- 7½ to 8 hours for the 1996 Spantech tests with 160 pallets (5120 rounds). All of the ammunition did not react.
- Less than ½ of the ammunition reacted in the open bonfire tests
- 28 to 59% reacted in Spantech Tests 1 through 4. Few of the reactions were full detonations
- Approximately a third of the rounds reacted in the Miniature Magazine test.
- The percentage that reacted was unknown in the 1996 Spantech tests.

It was mentioned above that when the data of the tests with HD 1.2 was considered the proposed quantity-distance was decreased from previous U.S. and NATO regulations. However, the proposed changes did not consider the timeline of reactions and that all of material did not react as mentioned above. Since the first reactions did not occur until almost 15 minutes after the onset of the fire, and since the reactions occurred "popcorn" fashion over the next 15 minutes to hours after the first reactions, and since all of the material did not react, it would seem that there would be ample time for evacuation of personnel. It would seem that the actual safe separation distances could be reduced further than proposed if the time-line of reactions was considered. Reference 65 alludes to this on page 8: "*This hazard is generated over a longer time period, generally in excess of one hour (and possibly days) after the initial explosive event. It does not happen immediately as items continue to react/explode long after the initial event. Because of this long duration effect, individuals have the opportunity to escape or seek greater protection from the fragment threat.*"

Other considerations include that the tests with the HD 1.2 had loading densities and vent area ratios that precluded choked flow and pressure bursts of the structure (not explosions or detonations). This is in contrast to some of the tests performed with HD 1.3 ammunition, particularly Joachim's Test 4 and Allain's Tests 3 and 4, where the confining structures ruptured and threw large pieces of debris from the structures.

Some may question having so much wood in a magazine, although it was mentioned earlier in this report that in the Red River Army Depot accident 21 August 1996, there was significant wood dunnage (pallets and crates) in the magazine and its combustion behavior impacted events. One study, Reference 66, estimated that there was 84,052 kg of wood vs. 11,854 kg of Comp B HE, 7,215 kg M1 propellant, 2,597 kg M10 propellant, 17 kg M9 propellant and 29 kg black powder in the Red River magazine.

CONSIDERATION OF LOADING DENSITY AND VENT AREA RATIO ($A/V^{2/3}$)

Several of the reports mentioned that the behavior of the rounds in the Spantech igloo or the U.S. miniature magazine was not very much different than the behavior in the open tests, with the exception that the walls of the magazine contained “the throw” of many of the fragments. The fact that the behavior in the magazine was very similar to that in the open test is not overly surprising when the loading density and vent area ratios are considered.

As presented earlier in the discussion of tests with HD 1.3 materials, it is often useful to calculate the loading density of the energetic material in the confining structure (mass of energetic material/volume of the confining structure) and the vent area ratio ($A/V^{2/3}$) and then plot them one against the other for the various tests. The violent reactions for the HD 1.3 material occurs at the right side of the plot where the loading density is the highest. It is interesting to do the same for the Spantech and U.S. miniature magazine tests.

Spantech Tests 1 through 3 had 32 rounds in the igloo. At 2.87 kg/round, if only the explosive fill is considered, there was 66.78 kg of explosive for each test. The weight of propellant and explosive is 3.357 kg/round, or 107.4 kg of propellant and explosive in each test. The loading densities for Tests 1 through 3 were 0.0000387 if only the mass of explosive is considered, and 0.0000622 if propellant and explosive is considered. For Test 4 (256 rounds) the loading densities are 0.000309 g/cc for explosive only, and 0.000498 g/cc if propellant and explosive is considered. These are very low loading densities compared to those used by Joachim and Allain in their tests of gun propellant described earlier in the tests with HD 1.3 materials. (Loading densities were 0.049 g/cc for Joachim Test 4, 0.059 g/cc for Allain Test 3 and 0.083 g/cc for Allain Test 4.) The vent area ratio ($A/V^{2/3}$) for the Spantech magazine was approximately = 0.060. The extremely low loading density, and the fact that the door was open to allow air to burn the wood, guaranteed un-choked flow, and hence minimum internal pressure build-up in the igloo occurred during the tests. [Note: Joachim and Allain also used gun propellant samples. The gun propellant had high surface area resulting in high mass burning rate and thus high pressurization in the container.]

In the 1996 Spantech tests with the 160 pallets (5120 rounds), the loading density was 0.0062 g/cc if only the mass of explosive is considered, or 0.010 g/cc if the mass of explosive and propellants is considered. Again, these are relatively low loading densities when compared with the loading densities of Joachim Test 4 and Allain Tests 3 and 4 that produced violent reactions that destroyed the confining structures and occurred within seconds of the ignition of the gun propellant.

The U.S. miniature magazine test had 120 rounds of M1 105 mm artillery ammunition in the magazine. This was 276.5 kg of explosive and 433.3 kg of propellant and explosive, giving loading densities of 0.0249 g/cc (explosives) and 0.0390 (propellant and explosives). These values are between Joachim's Tests 3 and 4, and lower than all of Allain's tests with HD 1.3 gun propellants. The vent area for the miniature magazine test was 0.587. This was extremely high. The high vent area ratio was the design of the miniature magazine but also allowed sufficient air to burn the wood in the bon-fire. The loading density and very high vent area ratio ensured that flow through the door and vents was unchoked flow with minimal pressure rise in the magazine.

This comparison between the tests with HD 1.2 and HD 1.3 is shown in Figure 181.

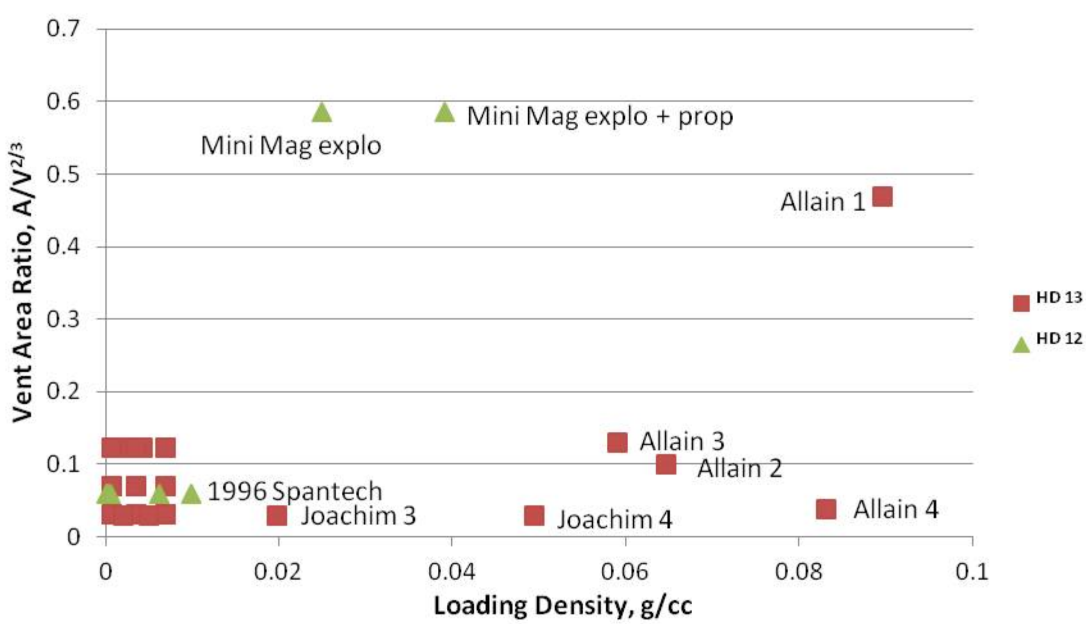


FIGURE 181. Plot of Vent Area Ratio and Loading Density for Various Tests.

The Joachim Tests 1 through 4 were with HD 1.3 M-1 gunpowder and all of the Allain tests were with 1.3 gun propellant with composition very similar to M1 gun propellant. The grouping at lower left includes Joachim Tests 1 and 2 with HD 1.3, and the Herrera et al tests with HD 1.3 M1 gun propellant. The loading densities for the Spantech tests were very low and would not have resulted in the choked flow that was responsible for the rapid pressurization of the Joachim Test 4 and the Allain Tests 3 and 4: tests that resulted in violent rupture of the confining structure. [Note: Allain Tests 1 and 2 were no-tests because the confining structure actually rose into the air and released reaction gases—essentially vastly increasing the venting and vent area ratio.]

Figure 181 plots the vent area ratio-loading density data for various tests with HD 1.2 and HD 1.3. How does this compare to conditions with magazines? Table 29 provides maximum loading density (assuming 500,000 NEW for the contents of the magazine) and vent area rations for several types of magazines.

TABLE 29. Maximum Loading Densities and Vent Area Ratios for Various Types of Magazines.

Magazine Type and Dimensions	Maximum Loading Density Assuming 500,000 lb. NEW	Vent Area Ratio $A/V^{2/3}$
RC Box 421-80-06	0.364 g/cc	0.316
RC Circular Arc, NAVFAC 1404310-1404324		
80 ft long, door area 100 sq.ft.	0.43	0.1423
80 ft long, door area 160 sq.ft.	0.43	0.228
RC Arch 421-80-05		
90 ft. long, door area 64 sq.ft.	0.3	0.0725
90 ft. long, door area 100 sq.ft.	0.3	0.113
80 ft.long, door area 64 sq.ft.	0.338	0.0785
80 ft. long, door area64 sq.ft.	0.338	0.122
60 ft. long, door area 64 sq.ft.	0.45	0.0951
60 ft. long, door area 100 sq.ft.	0.45	0.148
Steel Arch 421-80-01		
89 ft. long, door area 64 sq.ft.	0.309	0.073
89 ft. long, door area 100 sq.ft.	0.0309	0.114
Lone Star, 60' x 26'6" x 12'9"	0.252	0.0299
Indian Head 82' x 25' x 11'	0.226	0.0691
Radford 82'2" x 25' x 13'	0.191	0.0299

The maximum loading densities and vent area ratios of three of these magazines [Note: Two of the magazines types had two different door sizes as indicated in the figure legend.], together with the data from the tests with HD 1.2 propellants and HD 1.3 propellants, are plotted in Figure 182.

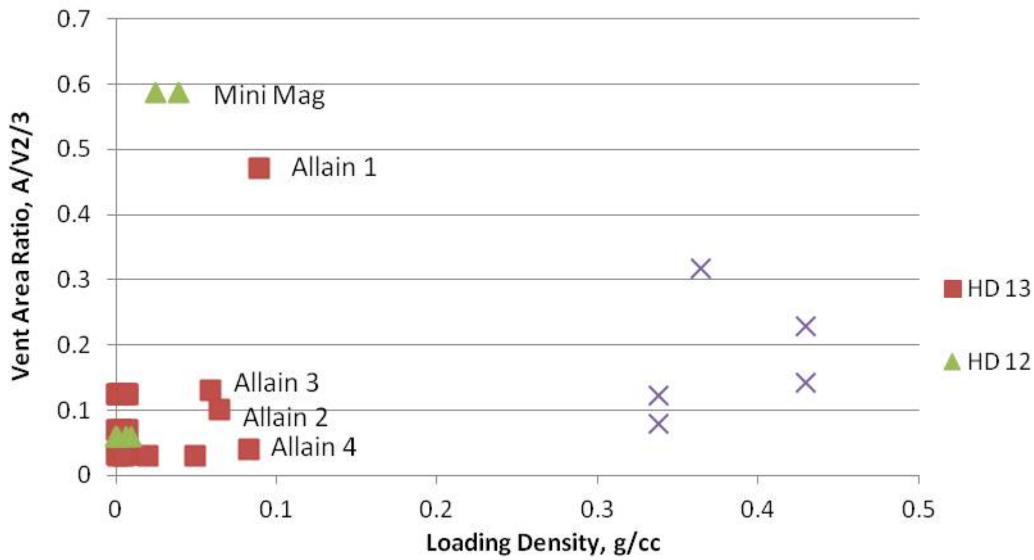


FIGURE 182. Vent Area Ratios and Maximum Loading Densities for Three of the Magazines from Table 29, With Data Points From the Previously Presented Tests. (Left to right, RC Arch 421-80-05 80 ft long and either 64 or 100 sq. ft. doors, RC Box 421-80-06, and RC Circular Arch NAVFAC with either 100 or 160 sq. ft. doors.)

Figure 182 shows that the maximum loading densities of the magazines are clearly much higher than the conditions tested for the HD 1.2 and HD 1.3 materials, although it must be remembered that these are the maximum loading densities based on 500,000 lbs NEW in the representative magazines. Often magazines are not loaded to this maximum level, so the loading densities would be lower. The vent area ratios are equal to or higher than most of the test conditions. The implication is that depending on what is stored in the magazines, the loading density almost guarantees that fire in the magazine with HD 1.3 propellants having a high surface area such as gun propellants (similar to the materials tested in Joachim's Test 4 and Allain's Tests 3 and 4 [again, Allain's Tests 1 and 2 were no tests because the magazine rose in the air and allowed much of the reaction products to vent relieving the pressure]), will experience choked flow and catastrophic rupture of the magazine will result when the internal pressure exceeds about 10 bars. The catastrophic rupture can occur without any explosion or detonation, simply due to rapid pressurization that cannot be sufficiently vented. If the experience of Joachim's Test 4 and Allain's Tests 3 and 4 are any indication the secondary debris from the failing magazine can be very large.

ANALYTICAL MODELING

Swisdak and Montanaro (Reference 53) also made the following argument:

> "…The effects of burning HD 1.3 material inside a closed structure can range from benign to catastrophic. If adequate venting is not provided, the pressure can build up at such a rapid rate that it can overwhelm the structure. This explains why it is safest to store HD 1.3 materials in structures that provide large amounts of venting [emphasis added]. In above ground structures, this venting is provided through frangible walls and/or roofs. When HD 1.3 materials are stored in hardened structures or any other structure that provides structural confinement, extra care should be taken to provide adequate venting. The amount of venting required varies with the volume of the storage chamber, the weight of the [energetic] material being stored, and its [mass] burn rate. These phenomena are not adequately addressed in the current versions of the explosive safety standards—either from the standpoint of safe-separation distance or asset protection."

[Note: In addition to the weight of energetic material, its thermochemistry/ energy content is also an important consideration. The author inserted mass into burning rate because the term burning rate is often construed to mean surface regression rate while mass burning rate, which is an important determinant of the pressure–time history of the event, considers not only the surface regression rate but also burning area and density.]

These words from 1996 are just as true today as they were then.

Swisdak and Montanaro (Reference 53) based the above on calculated results and experimental results.

The calculated results were obtained using the computer code BlastX and based on the following:

- Gun propellant type material with an outside diameter of 0.059 inch and 0.394 inch length and having a single perforation with 0.020 inch diameter.
- Propellant burning rate given by r (inches/second) = 0.00161 p (psi)$^{0.741}$.
- Burning inside a chamber of 1,000 cubic feet.
- Charge weight was varied between 100 and 5,000 pounds.

- Vent area varied between 10 and 200 ft^2.

The results are presented in Figures 183 through 186. The abscissa and ordinates were presented in arbitrary units because the parameters selected for the calculations do not represent any real situations of propellants.

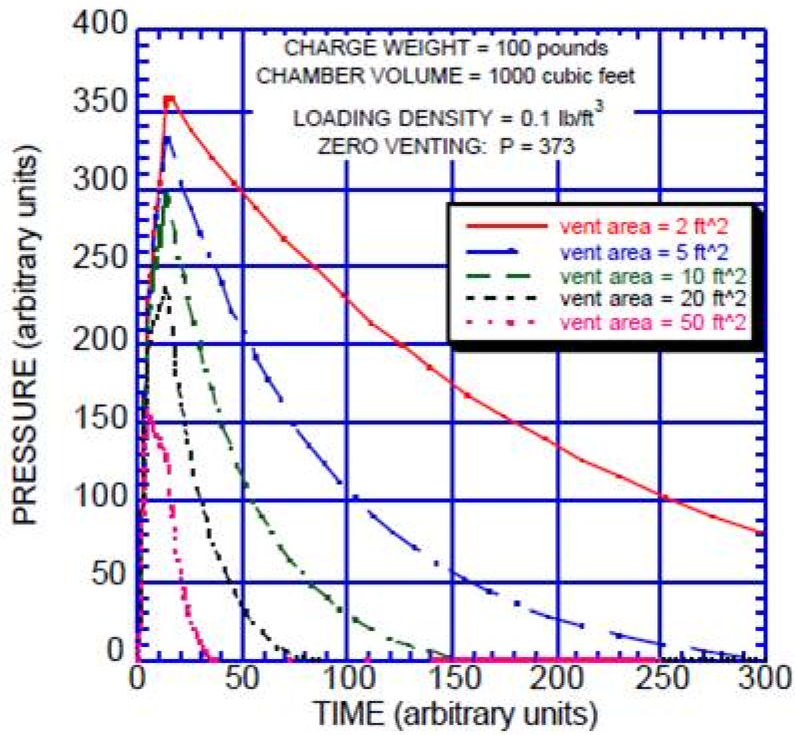


FIGURE 183. Pressure–Time for Various Amounts of Venting and 100 Pounds Burning (Reference 53).

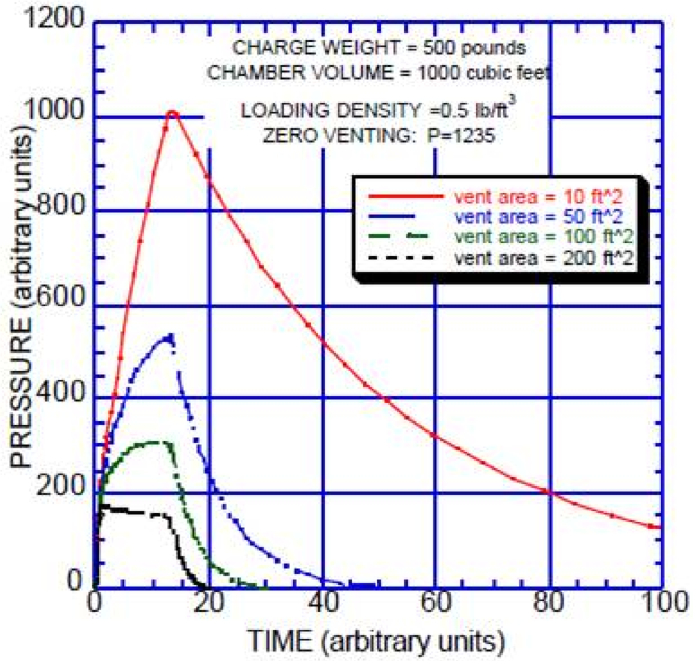


FIGURE 184. Pressure–Time With Various Amounts of Venting for 500 Pounds Burning (Reference 53).

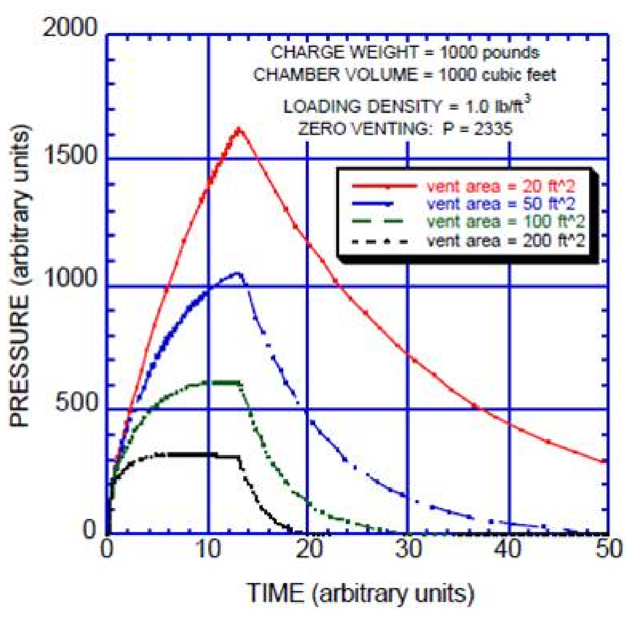


FIGURE 185. Pressure–Time With Various Amounts of Venting for 1,000 Pounds Burning (Reference 53).

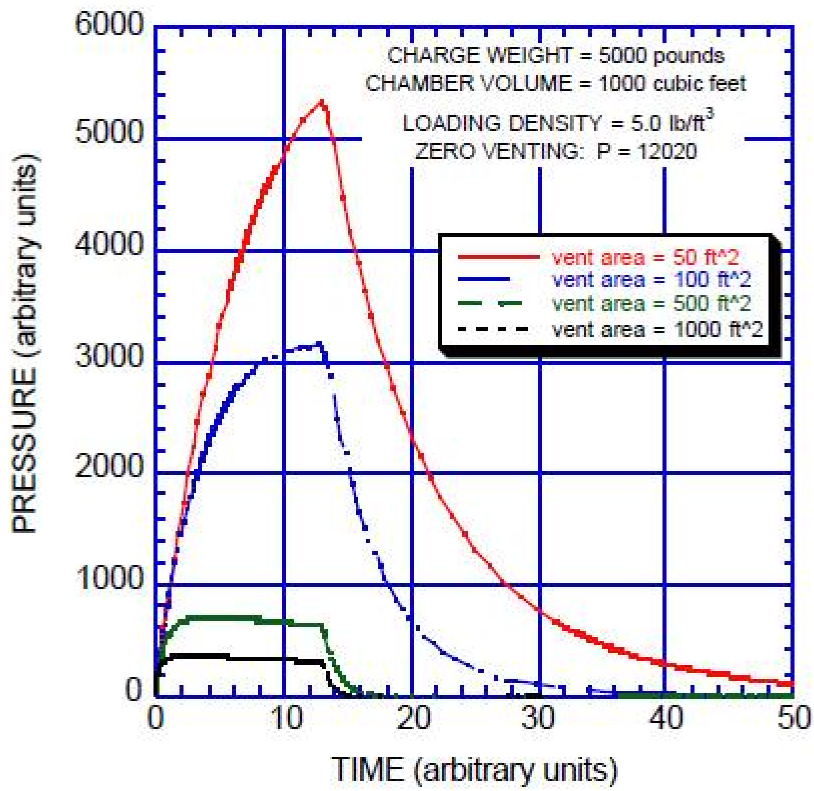


FIGURE 186. Pressure–Time for Various Amounts of Venting for 5,000 Pounds Burning (Reference 53).

The authors used these figures to communicate the following information:

- The larger the vent area, the lower the pressure.
- The larger the vent area, the shorter duration of the pressurization event.
- The appropriate vent area is related to both the volume of the chamber and the weight of the energetic material involved.
- The pressures shown on each plot for zero vent area would have caused the chamber to fail catastrophically given the conditions. Some of the other small vent areas—those that would cause choked flow through the vent—would also result in catastrophic rupture. Joachim (Reference 47) and Allain (Reference 48) estimated that their test structures ruptured with about 10 bars internal pressure.

References 67 and 68 present the results of calculations for an example facility schematically illustrated in Figure 187.

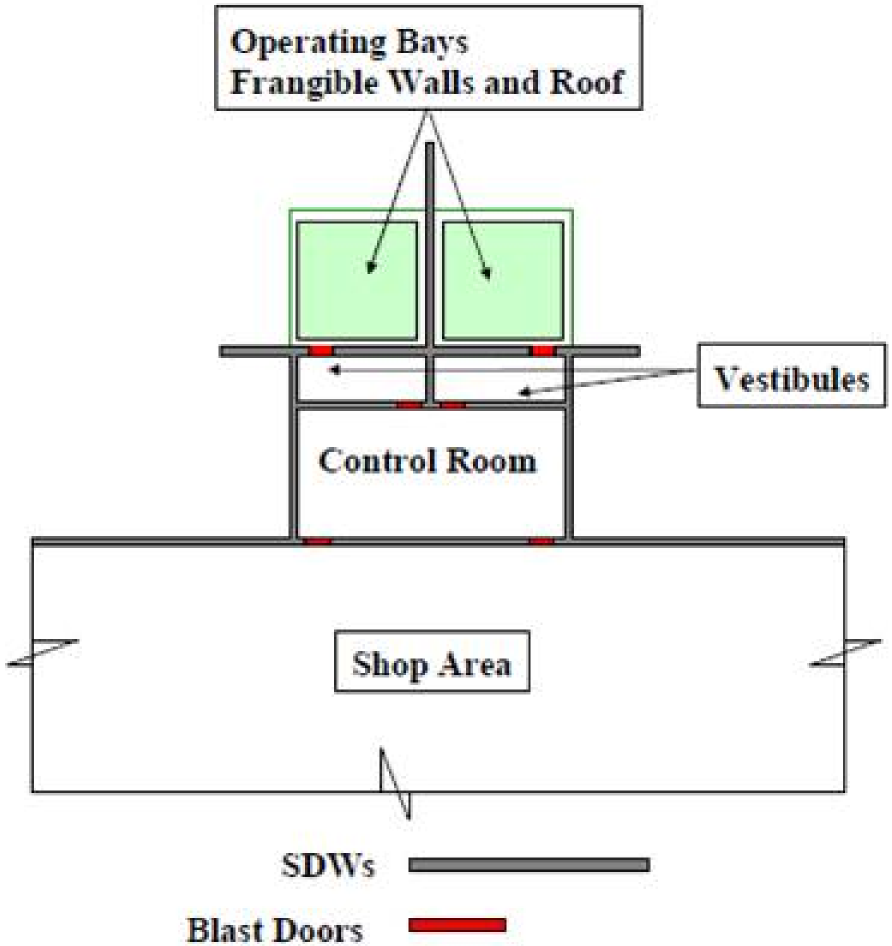


FIGURE 187. Schematic of Facility Considered in References 67 and 68.
(SDW: Substantial Dividing Wall.)

Reference 68 presents the methodology developed for the calculation of gas loading inside a room resulting from the ignition and combustion of HD 1.3 materials. The methodology includes consideration of venting and time-dependent removal of frangible walls along with thermodynamic submodels for the burning munition producing products, radiation heat loss to wall and venting to connected enclosure such as the vestibule shown in Figure 187. The methodology was implemented in an Excel spreadsheet that calculates the time-dependent pressure and temperature inside the room as a function of the energetic material burn rate and the amount of venting initially present and dynamically created as frangible walls are pushed outward. The results were compared to results calculated using BlastX and Flame Acceleration Simulator (FLACS) (a computational fluid dynamics [CFD] code). The energetic material used in the calculation was a combination of AP and aluminum.

[Note: This is not a real propellant. Propellants have a polymeric binder, on the order of 10% by weight, to encapsulate the AP and aluminum and produce a solid propellant.]

While the paper discusses mass flow rates with un-choked and choked flow, it does not discuss projection of material outside the cell during un-choked flow (see previous discussions of experimental results. Several studies, with gun propellants, showed that during un-choked flow the gun propellants were expelled from the cell and burned outside the structure.) That is, the paper assumes that all of the material is combusted inside the cell. The method used in this paper produces more conservative pressure results than BlastX and when compared to results from FLACS resulted in similar results for the frangible roof case and very good agreement for fixed panels, constant vent case.

Reference 67 used the method of Knight et al. for calculations based on a 20- x 20- x 10-foot cell, with frangible panels having weight/area (wf) of 10 pounds per square foot (psf) and a burn rate of 50 pounds per second (lb/s). [Note: The energetic material in these calculations was simple AP—no binder, no aluminum.] Results are shown in Figures 188 through 190.

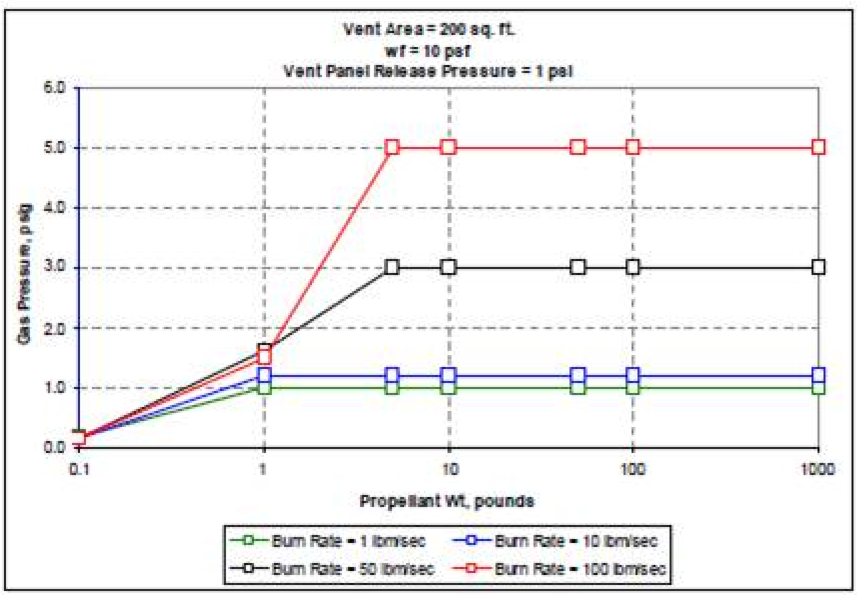


FIGURE 188. Pressure Variation With Burn Rate (Figure 5 of Reference 67).

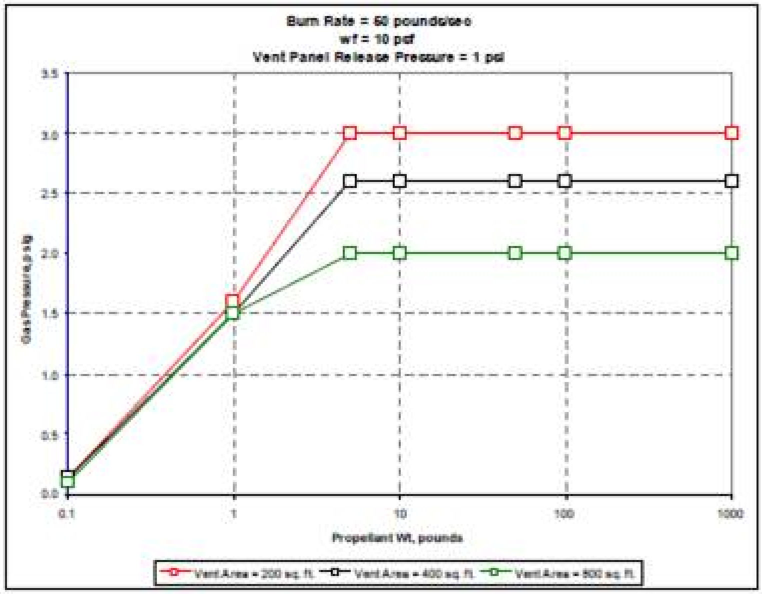


FIGURE 189. Pressure Variation With Vent Area (Figure 6 of Reference 67).

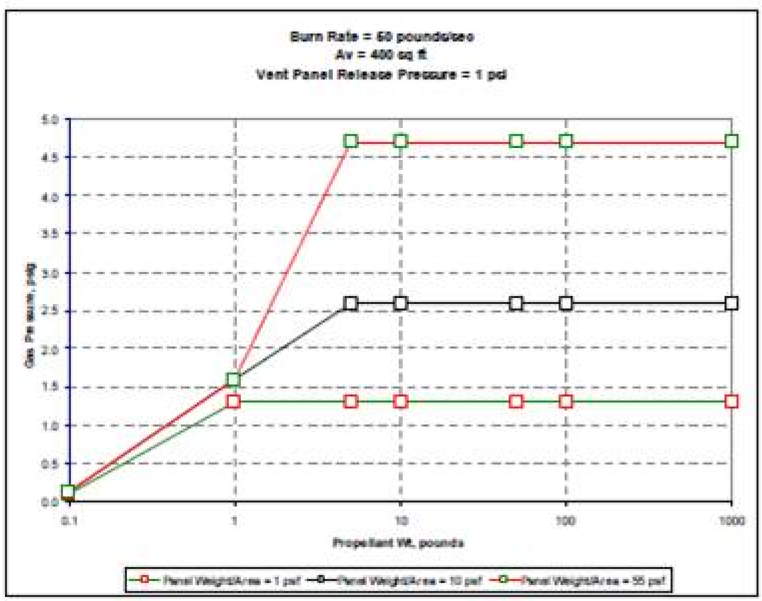


FIGURE 190. Pressure Variation With Panel Weight/Area (Figure 7 of Reference 67).

The paper also mentions that a very important aspect of predicting design loading from HD 1.3 events is the need to have data on burn rate and the burn scenario. In the calculations presented in the paper, it did not appear that a pressure-dependent burn rate was used in the calculations and the possible expulsion of materials during un-choked flow was not considered.

Probably the most extensive modeling of determining safe-separation from a mass fire event was with determination of safe-separation distance from the VAB at KSC with almost 11.6 million pounds of AP/aluminum/binder propellant. The following is a brief description of that effort described in Reference 45.

The VAB at the KSC was originally designed for use in the Apollo Program. In more recent times, it has been used to assemble the segments of the reusable solid rocket boosters, and to mate the boosters with the other components of the Space Shuttle. Figure 191 shows the VAB and surrounding buildings.

FIGURE 191. VAB at KSC and its Immediate Environment.

Figure 192 shows a plan view of the VAB. The Space Shuttle Program used Bays 1 and 3 to assemble the Space Shuttle on the mobile launch platform (MLP) and store the assembled Space Shuttle. Figure 192 shows the four high bays, the 16-story tall masonry walls, and the transfer aisle. The booster assembly process entailed the following:

- Motor segments were brought into the VAB via the transfer aisle.
- Check-out of the segment while in the transfer aisle.
- The first segment of each booster was lifted by crane and transferred into the appropriate bay and placed on the MLP.
- Successive segments were brought in, checked, and lifted via crane and stacked one atop another, and joined.
- The last segment was the forward end cap.

Each Space Shuttle assembly had two booster motors, each comprised of four segments. Each segment contained approximately 300,000 pounds of HD 1.3 propellant. The existing Q-D arc for the approximately 4.44 million pounds of propellant (two four-segment boosters in Bays 1 and 3) as determined using the DOD weight-based approach ($D = KW^{1/3}$) was two circles centered in each of Bays 1 and 3 with a 1,310-foot radius. Tangents connected the two circles and formed the Q-D footprint.

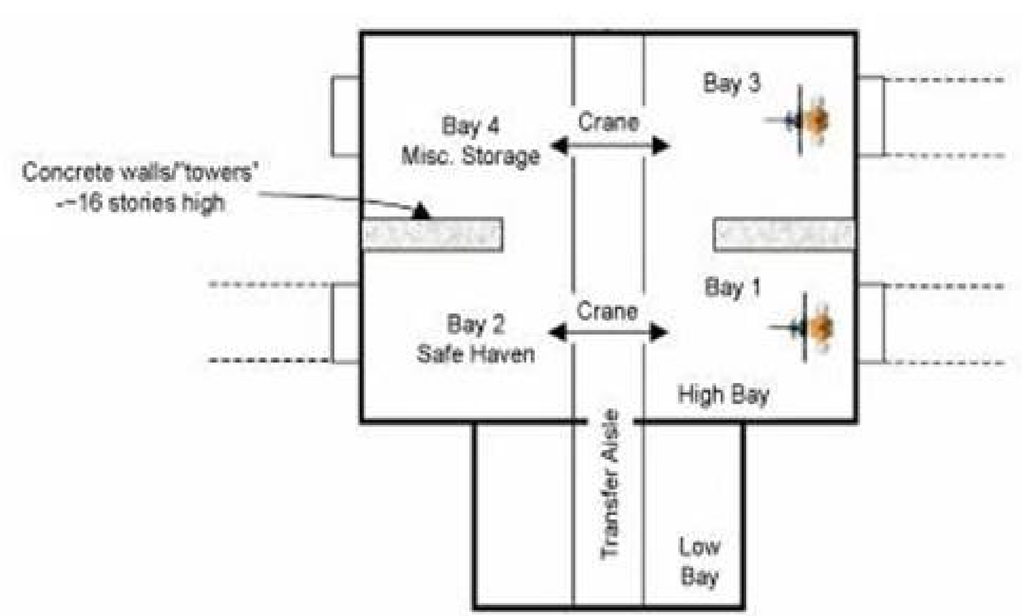


FIGURE 192. VAB High Bay and Transfer Aisle Locations.
Space Shuttle uses Bays 1 and 3.

With the advent of the Constellation program, the proposed launch schedule could require assembly and storage of units having approximately 11.6 million pounds (5.3 million kilograms) of HD 1.3 propellant (eight 5-segment boosters) within the VAB. If the DOD weight-based approach were used to determine safe-separation distances for these 11.6 million pounds of propellant, the hazard arc would be on the order of 1,831 feet (558 meters) radius. This arc would encompass a number of existing buildings including a five-story office building and adjacent cafeteria. The NASA Engineering and Safety Center (NESC) report, *Review of the Test Plan to Update KSC VAB Propellant Safety Siting Methodology for the Exploration Program* (Reference 69) concluded that the DOD weight-based approach may be inappropriate for solid propellant boosters with a HD 1.3 classification, and recommended that an alternate approach based on calculating the actual threats from mass fire (due to exhaust plumes and radiative heat flux from the plumes) be evaluated.

To address this recommendation, the NESC assembled a team of experts to develop an alternative heat flux-based methodology and apply it to determine the safe-separation distances from the VAB containing eight five-segment boosters. The NESC team focused on quantifying the thermal threat from burning five-segment boosters, or four segments in the process of stacking a booster, to individuals in proximity to the VAB and establishing the appropriate safe-separation distances.

At the initial Technical Interchange Meeting held at KSC on 27 February 2007, several important aspects of a comprehensive VAB hazard study were discussed. Several of the items, while certainly a hazard concern, were deemed out of scope for the thermal flux-based safe-separation analyses. Analysis of the boosters going propulsive within the VAB or toppled from their original locations was one of the items considered out of scope. The team was instructed to consider the boosters in their original locations on the MLPs in the four bays.

Preliminary scoping calculations using spreadsheet techniques and a number of conservative, worst-case assumptions were used to bound the problem. The scoping calculations showed:

- To determine the energy release rate and the respective burn times, the configuration of the energetic materials (booster segment versus partially completed stack versus complete booster), not just the weight of energetic materials, must be considered.
- The heat flux-based approach is a viable alternative to the weight-based approach.

To move from preliminary scoping calculations to more detailed analyses, the assembly operations that take place in the VAB were studied and various scenarios were proposed to represent the vehicle considerations that may exist within the VAB.

The calculations started with the inadvertent ignition within one High Bay, determined the heat and mass flow from the burning boosters in that one bay to adjacent bays, and predicted time to ignition of the boosters in the other bays. Scenario 1, each bay containing two five-segment boosters, was initially assumed to be the worst case in determining safe-separation distance.

In performing the analyses of the various scenarios, several NESC teams were involved and different analytical codes were used. Reference 45 (Section 6.3) describes the methodology that was established, the codes used, the sequence of considerations, and the handoffs from one NESC team to another. These analyses required the NESC team to consider the exhaust plumes from the boosters that were inadvertently ignited, the flow of the exhaust plumes, and subsequent ignition of boosters in adjacent bays. Flow of the exhaust plumes was influenced by failure of internal cinder block masonry walls in the VAB, and failure of VAB exterior wall panels was considered. Two ignition methods were considered:

- Hot exhaust gases impinging on adjacent boosters, failure of the booster nozzle plugs, hot gases entering the booster bore through the nozzle, and ignition of exposed propellant in the bore.
- Hot exhaust gases impinging on the exterior of boosters and/or radiation from hot exhaust plumes to the booster casing: transient heat conduction through the booster casing, insulation and liner into the propellant; and ignition of the propellant at the propellant-liner interface.

[Note: The flow of the exhaust plumes was down through the opening in the MLP with subsequent impingement on the floor of the VAB. The massive MLP also guided the flow of the plume and partially shielded the boosters from being in contact with the plume and "partially shielded boosters from seeing the plume" (Reference 45 Sections 7.3 through 7.5)].

Scenario 1 was studied in detail with analysis of four sub-scenarios.

- Scenario 1a—the cinder block walls between High Bays 1 and 3 and between Bays 2 and 4, and the VAB external walls were assumed to remain intact. This is the scenario that was addressed in previous studies of inadvertent ignition of motors within the VAB.
- Scenario 1b—same as Scenario 1a, but accounting for failure of the lower halves of internal cinder block walls between High Bays 1 and 3 and between Bays 2 and 4, and the VAB external walls largely remaining intact.

[Note: The external walls were allowed to fail in this scenario, but the failure criterion used in this scenario was conservative and resulted in less failure of wall panels than was subsequently demonstrated in later analyses.]

- Scenario 1c—same as Scenario 1b, but with more realistic analysis for failure of VAB external wall panels to allow venting of booster plume exhaust using a different failure criterion. The failure of the external walls occurred within seconds after the ignition of the first boosters and so this scenario was terminated and Scenario 1d was initiated.
- Scenario 1d—this scenario started with the lower half of the interior cinder block walls and the full external walls of the VAB removed to reduce computational complexity and time before inadvertent ignition of the first boosters.

The determination of the timing and sequence of booster ignition and combustion within the VAB was a major focus of the NESC Modeling Team, since it is the first step in correctly predicting heat flux to areas surrounding the VAB. The Modeling Team reviewed available historical propellant ignitability data. This review revealed the need to perform experiments to generate data on the ignitability of TP-H1148 propellant at the relatively low heat flux and long exposure times characteristic of accident scenarios. The Modeling Team chose this propellant for study because it is used in the Space Shuttle solid propellant booster motors, and because it or a similar formulation was likely be used in the Ares I and Ares V boosters. Experimental data on TP-H1148 ignitability over much of the heat flux range of interest to this study was generated by ATK Space Systems in a separately funded effort and by the Naval Air Warfare Center Weapons Division (NAWCWD), China Lake.

Preliminary analyses for through-the-case ignition was completed for Scenario 1d (see Reference 45 Section 7.5) and predicted that adjacent boosters would not ignite due to conduction through the casing due to the original boosters burning; these analyses have been validated by experiment (Reference 70) where ignition occurred but only after 3 to 4 minutes of direct heating at 200 to 300 kW/m^2. Since the burn time of the boosters was approximately 130 seconds, it was concluded that the boosters in adjacent bays would not ignite through the casing from the burning of the first boosters.

An NESC Human Exposure Sub-team was convened and managed by the NASA Office of Safety and Mission Assurance. The Human Exposure Sub-team was tasked to determine the acceptable levels of human exposure to radiative heat flux. The Human Exposure Sub-team concluded that prevention of second-degree burns (and the potential for fatalities associated with such burns) should be the criterion used for determining safe-separation distances between the VAB and inhabited buildings and personnel in the open.

The results for the various sub-scenarios are summarized in the following paragraphs. More detailed discussions are available in Reference 45.

The pressures calculated from Scenario 1a indicate that the interior walls separating the High Bays would not survive a booster burning for more than a few seconds. From these results, the NESC Modeling Team determined that calculations of Scenario 1b should be initiated. At the request of KSC, the calculations for Scenario 1a (interior walls remaining intact) were run until the ignition of the boosters across the transfer aisle occurred (at 52.5 seconds).

Scenario 1b calculations show that removal of these internal walls significantly changes the exhaust plume flow dynamics and ignition time line of boosters in the VAB. Once ignited, each booster burns for approximately 2 minutes. By 112 seconds after ignition of the first pair of boosters, all eight boosters are burning. In addition, the Scenario 1b calculations showed that a significant number of the VAB external wall panels are also likely to fail. Given these results, the Modeling Team decided to start calculations of Scenario 1c.

Scenario 1c calculations account for external wall panel failure and show that the exterior wall panels fail within a few seconds after the first two boosters ignite. Because the failure occurred so quickly, this calculation was stopped and the calculations of Scenario 1d were started.

The calculations of Scenario 1d, the most likely portrayal of Scenario 1, show a different situation than the ones addressed in previous analyses performed by other investigators. Because the exhaust plumes of the first two boosters are not confined to within the VAB, the exhaust plume quickly spreads outside the original VAB boundaries, because it is effectively channeled by the floor on the bottom and the bottom-portion of the MLP. As a result, the boosters in the other High Bays are not predicted to ignite while the originally ignited boosters are burning (130 seconds). The rapid flow of the exhaust plumes produces temperatures higher than 1,000°Kelvin (K) (1,340°F) at distances greater than 200 meters (656 feet) from the VAB center. Figures 193 through 197 show the temperatures 66 inches above the floor (roughly the height of a human). The magenta color area represents temperatures 1,073°K and above. The succession of figures with advancing time shows the rapid expansion of the plume out of the original outline of the VAB. Exposure of humans to these temperatures would cause fatalities, and the rapid expansion precludes most humans "out running" the plume. Figures 193 through 197 show the results of inadvertent ignition of the boosters in High Bay 3. The probability of an inadvertent ignition is equal for each High Bay, so that the results of Figures 193 through 197 would have to be reflected across the axes of symmetry to represent the probability that the boosters in the other three quadrants could just as easily ignite.

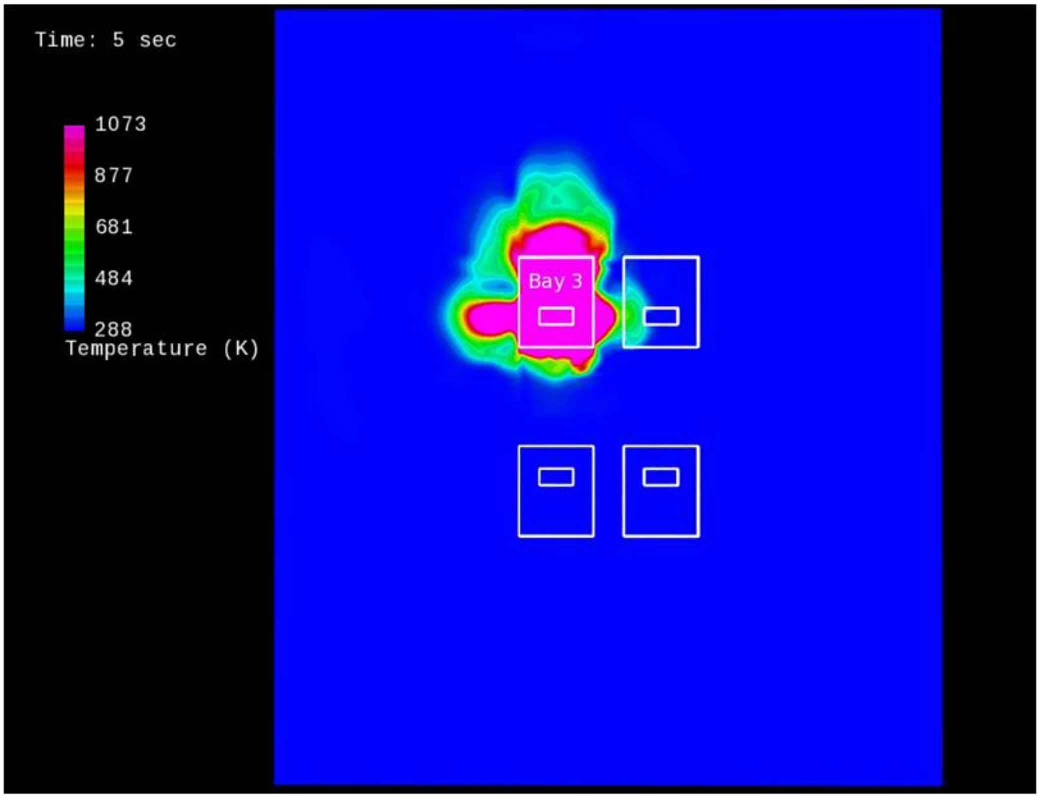


FIGURE 193. Plan View of Temperatures of Exhaust Plumes at 1.68 Meters (66 Inches) Above the VAB Floor 5 Seconds After Ignition of Boosters in High Bay 3 for Scenario 1d (Reference 45).

[Note: The calculation domain (the blue area) was approximately 400 x 400 meters (1,312 x 1,312 feet).]

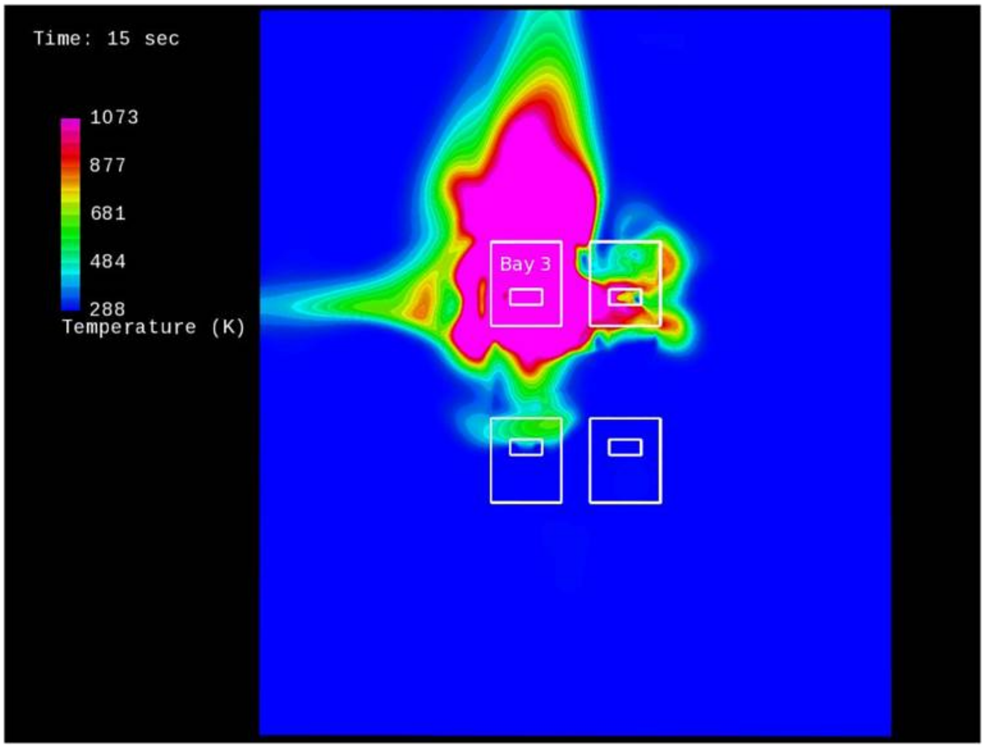


FIGURE 194. Temperatures of Exhaust Plumes at 1.68 Meters (66 Inches) Above the VAB Floor 15 Seconds After Ignition of Boosters in High Bay 3 for Scenario 1d (Reference 45).

[Note: The calculation domain (the blue area) was approximately 400 x 400 meters (1,312 x 1,312 feet).]

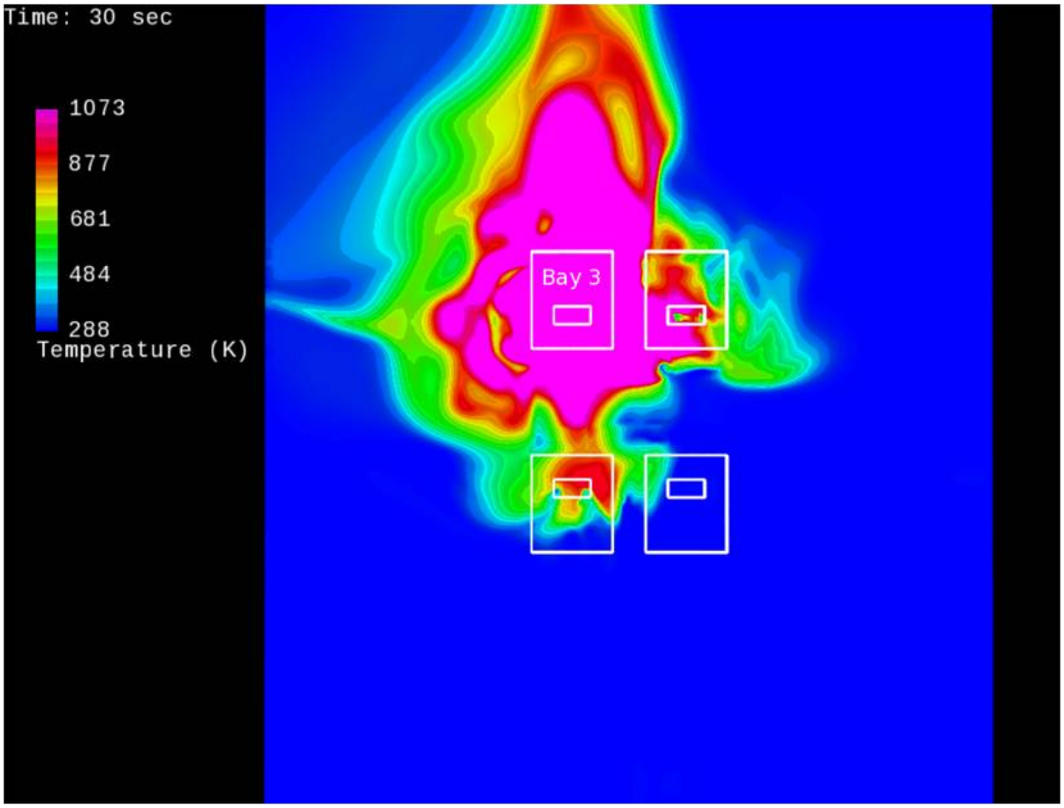


FIGURE 195. Temperatures of Exhaust Plumes at 1.68 Meters (66 Inches) Above the VAB Floor 30 Seconds After Ignition of Boosters in High Bay 3 for Scenario 1d (Reference 45).

[Note: The calculation domain (the blue area) was approximately 400 x 400 meters (1,312 x 1,312 feet).]

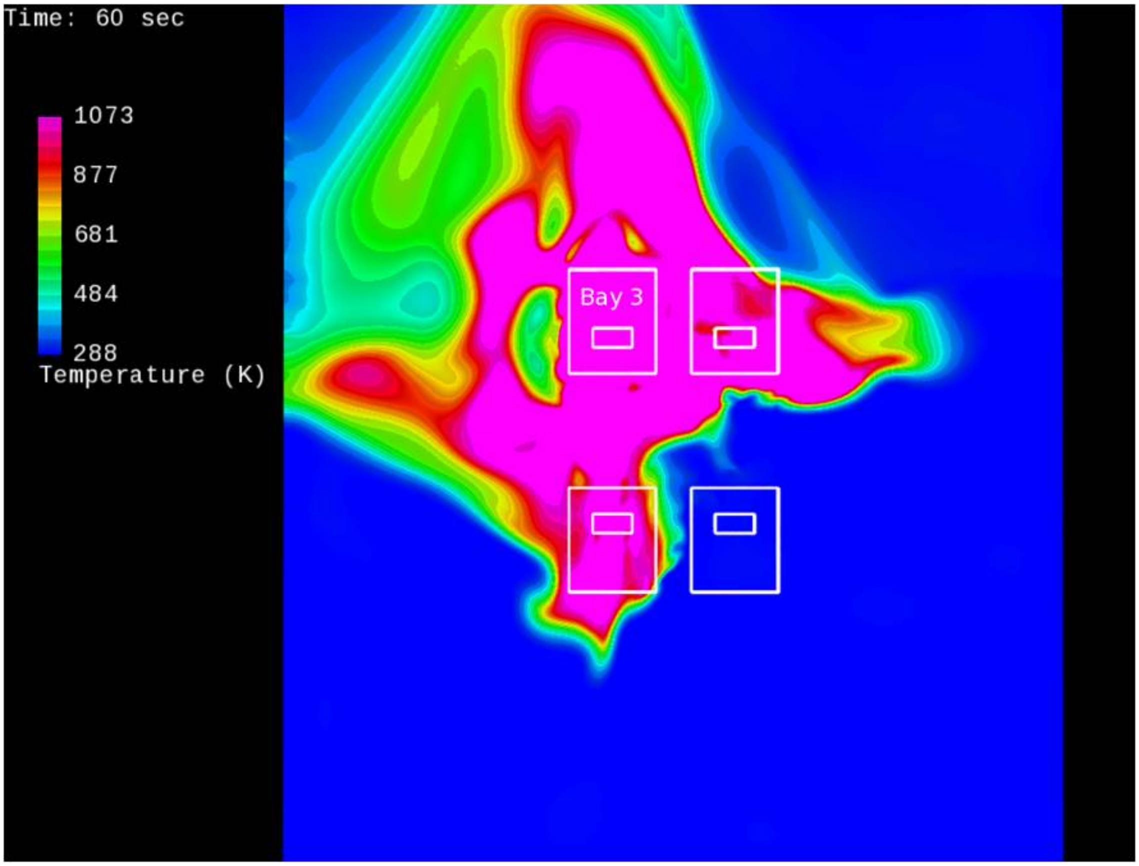


FIGURE 196. Temperatures of Exhaust Plumes at 1.68 Meters (66 Inches) Above the VAB Floor 60 Seconds After Ignition of Boosters in High Bay 3 for Scenario 1d (Reference 45).

[Note: The calculation domain (the blue area) was approximately 400 x 400 meters (1,312 x 1,312 feet).]

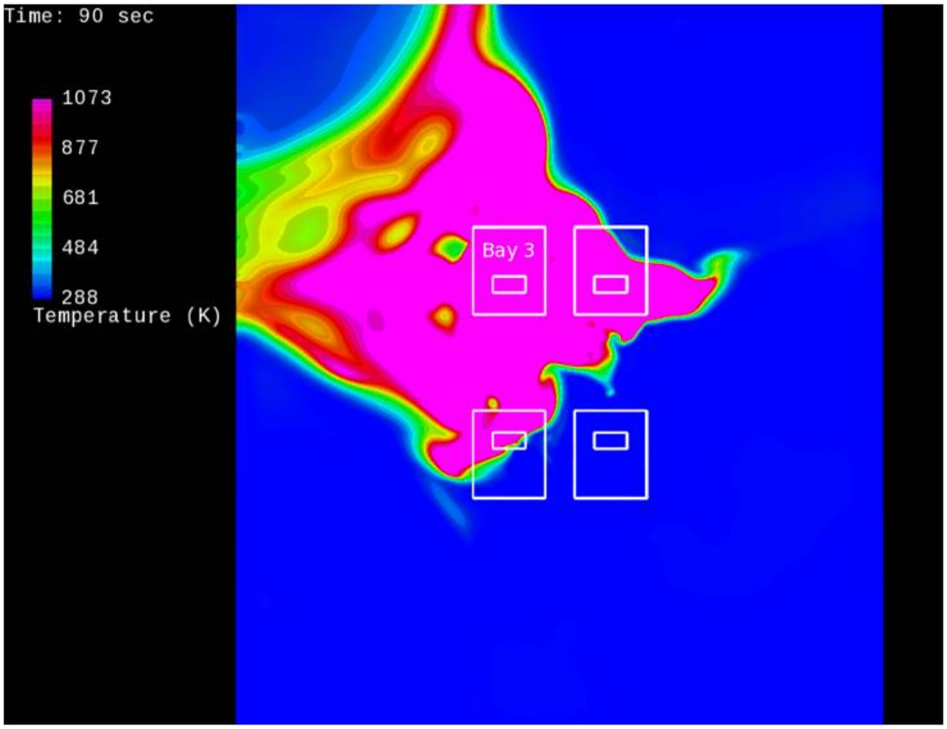


FIGURE 197. Temperatures of Exhaust Plumes at 1.68 Meters (66 Inches) Above the VAB Floor 90 Seconds After Ignition of Boosters in High Bay 3 for Scenario 1d (Reference 45).

[Note: The calculation domain (the blue area) was approximately 400 x 400 meters (1,312 x 1,312 feet).]

The radiation-to-distance from these exhaust products was determined using two approaches:

- The Fire Dynamics Simulator (FDS) code predicted fluxes at various distances from the VAB. Burn injuries were determined as a function of distance from the VAB to determine safe-separation distances.
- The Star-CCM+ program was used in conjunction with extrapolated plume locations to determine radiation exposure limit contours and safe-separation distances from the VAB.

The safe-separation distances, as determined by the FDS approach, fell within the existing Q-D arcs, which were set for the two Space Shuttle units in the VAB using the DOD weight-based approach (see Figure 198 for Scenario 1d distances). Safe-separation distances are defined as the distance to the transition point where second-degree burns become more likely than first-degree burns. In Figure 198, the transition between first- and second-degree burns is shown by the transition from green to yellow. The existing Q-D arc is shown by the thin blue-black circle inside the green area. The dark purple rectangle in the center is the outline of the VAB High Bays. This shows that the heat flux-based approach gives a smaller safe-separation footprint for 11.6 million pounds of propellants than does the $kW^{1/3}$ approach for only 4.44 million pounds of propellant.

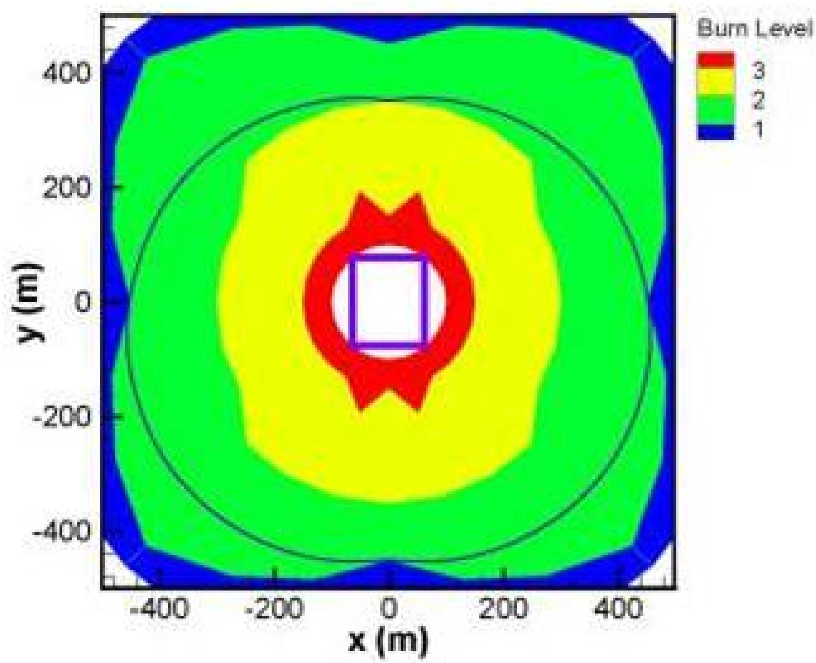


FIGURE 198. Scenario 1d Contour Map of Burn Level Due to Radiation as a Function of Position Around VAB for One Motor Pair (Burning in Same Bay) (Including Safety Factor and Solar Isolation) as Determined Using FDS Code (Reference 45).

The FDS approach was also used to predict what the safe-separation distance might be with four, six, and all eight boosters burning. The result for all eight boosters burning is shown in Figure 199.

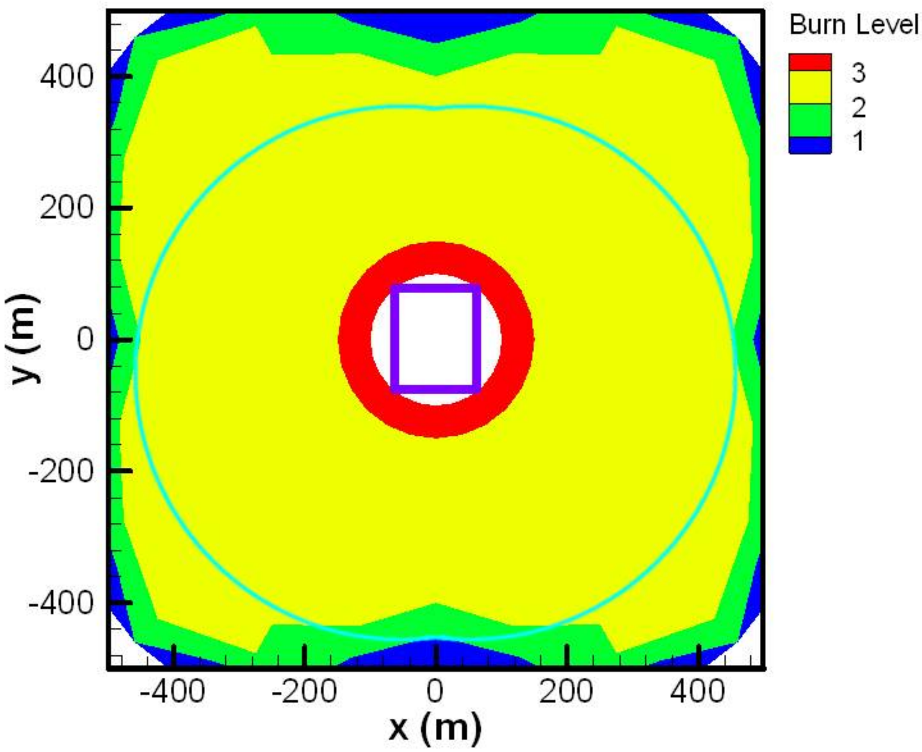


FIGURE 199. Scenario 1d Contour Map of Burn Level Due to Radiation as a Function of Position Around VAB for All Eight Boosters Burning (Including Safety Factor and Solar Isolation) as Determined Using FDS Code (Reference 45).

The safe-separation distance determined by the Star-CCM+ approach, was also located largely within the existing arc determined for the two Space Shuttle units (Figure 200). However, there was one region where the safe-separation distances were outside the arc determined for the SSP. This area is shown at the bottom of Figure 200. It should be noted that this region is in an area where buildings are inside the arc determined for the SSP.

Because the Star-CCM+ approach produced the larger safe-separation distance that distance was recommended as the safe-separation distance, giving an even more conservative safe-separation distance.

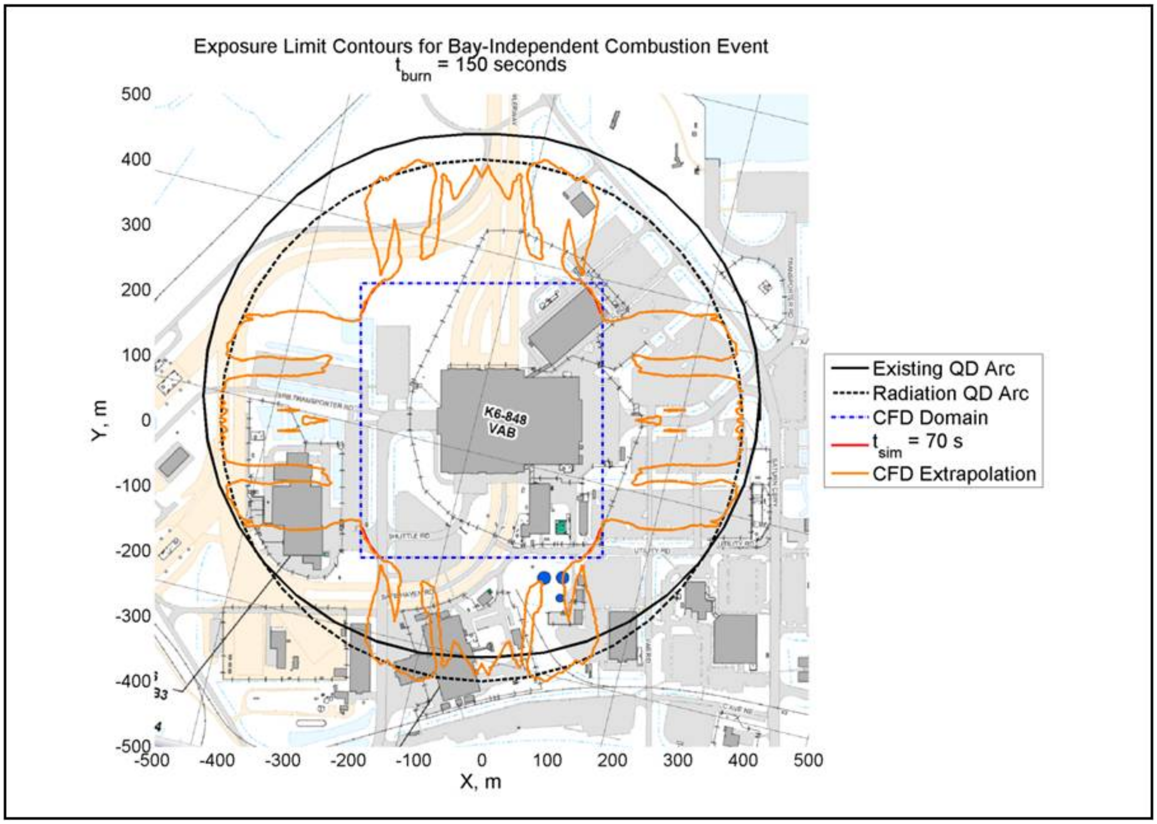


FIGURE 200. Contour Map Showing One Region Where Safe-Separation Distances, Using Radiation Method, Were Slightly Outside Arc Determined for SSP (Reference 45).

Conclusions and lessons learned from the NASA VAB study were as follows.

1. **General Conclusions and Lessons Learned.** A heat flux-exposure time-based model was developed and applied to determine safe-separation distances from the VAB for inadvertent ignition of booster motors.

The results showed that while providing a more realistic assessment of the mass fire event than would the DOD weight-based approach, the new analytical technique also allowed for significantly smaller safe-separation distances than would be determined from the weight-based approach. This translates into a significant difference in footprint (125 acres versus 236 acres, a difference of 111 acres). Another way of looking at this, the heat flux-exposure time method gave almost the same safe-separation distance for 11.6 million pounds of 1.3 propellant as the weight-based approach did for 4.44 million pounds of the same propellant.

The configuration of the items (single segment versus four-segment, uncapped stack versus full five-segment capped stack) is much more important than the corresponding weight because the configuration (closed vessel with nozzle versus open vessel) determines energy release rate and level, and burn time.

Two methods of ignition of adjacent boosters were considered:

- Hot exhaust gases contacting adjacent boosters, failure of the booster nozzle plugs, hot gases entering the booster bore, and ignition of exposed propellant in the bore.
- Hot exhaust gases impinging on the exterior of boosters and/or radiation from hot exhaust plumes to the booster casing: transient heat conduction through the booster casing, insulation and liner into the propellant; and ignition of the propellant at the propellant-liner interface.

In the scenarios considered in the VAB study, the first ignition method prevailed in part because of the position of the MLP.

Confinement or lack of confinement of exhaust plumes is a critical consideration as discussed below.

2. **Conclusions Based on Comparing Scenarios 1b and 1d.** In Scenario 1b, the external VAB wall panels were allowed to fail but at a rate much slower than in either Scenario 1c (where the external wall panels failed within 3 seconds) or Scenario 1d (where the external wall panels were non-existent at the beginning of the calculation for ease in calculations). As a result, there was significant difference in confinement of exhaust plumes and products between Scenarios 1b and 1d. As a result, in Scenario 1b, where the exhaust products were largely confined, the energy confined to within the VAB ignited the boosters in adjacent bays so that at some time all eight boosters were burning. In contrast, where there were no external walls in Scenario 1d, only the two boosters that were initially assumed to be burning were calculated to burn—the other boosters did not ignite. While having only two boosters burning, rather than eight boosters burning, was "good news," the lack of confinement allowed the high temperature exhaust plumes to rapidly expand out to over 200 meters. Anyone within the area of the hot exhaust plume would perish from exposure to hot gases (some regions of over 1,000°K).

3. **Conclusions From Scenario 1d.** The conclusions from the analysis of Scenario 1d—the most likely portrayal of the events—showed a different situation than considered in previous studies. These conclusions are listed as follows:

- Because the external wall panels failed, the exhaust plumes and associated energy quickly expanded outside the VAB confines.
- This expansion and release of energy was such that the other boosters did not ignite. Only the original two boosters were consumed.

- Large areas of the exhaust plumes expanded beyond 200 meters (656 feet), as measured from the VAB center. Within this region, exposure to the elevated temperatures would result in fatalities.
- Temperatures and heat fluxes within the plumes are sufficient to ignite combustible materials.
- The safe-separation distance, determined as the distance within which personnel are likely to suffer second-degree burns with fatalities due to exposure to radiation, is largely within the existing Q-D arcs originally established for two Space Shuttle units in the VAB.
- Based on the results of this study, the VAB may be used to process and store eight five-segment boosters for Constellation, as long as the propellant has similar ignition characteristics to TP-H1148, the booster segment design is similar to that used in the Shuttle program, and the VAB has a similar configuration.

[Note: Unfortunately, the Constellation program was cancelled due to budget cuts to NASA.]

LESSONS LEARNED FROM ACCIDENTS, TESTS, AND ANALYSES

The preceding sections presented:

- A review of accidents in storage, transportation and operational use, and lessons learned.
- A review of tests and lessons learned.
- A review of analytical modeling and lessons learned.

Some of the lessons learned are not new, but it may be beneficial to re-emphasize some of these lessons. For example, we know that accidents are probabilistic in that you can do the same operation over and over with no serious consequence but that does not mean that there is no hazard involved. The accident involving ammonium nitrate at Oppau, Germany in September 1921 is a good case in point. AN is hygroscopic and when water is absorbed the material clumps together into a plaster-like cake. The standard practice was to deconsolidate the cake by placing small charges of dynamite in the cake and detonating the dynamite. Reports from that time said that this was the common practice and that it had been performed 20,000 times without mishap. Unfortunately, a mishap occurred when they used this technique on 21 September 1921 that resulted in approximately 560 fatalities and 1950 injuries. About 80% of the buildings in Oppau were destroyed. This accident followed one two months earlier in Kriewald, Germany where the same technique was used to de-consolidate AN that had set up in a railroad tank car. That accident involved detonation of the caked AN resulting in 19 fatalities.

In the descriptions of accidents in this report, we often used the simple equation

$$\text{sample} + \text{stimulus} + \text{environment} \rightarrow \text{reaction}$$

Unfortunately many accidents are attributed to “human error” without describing the attributes of sample, stimulus, and environment that led to the unwanted resulting mishap. This often occurs because you can see the consequences of the accident but it is much harder to “swim upstream” and determine the attributes of sample, stimulus, and environment that caused the accident. And it does not help that many of the first-hand witnesses to the event were also the first fatalities. In this report, we went to great effort in trying to determine, as best we could, the attributes of sample, stimuli, and environment as well as simply reporting the unwanted reaction. And again, it is difficult because accidents are probabilistic.

Another old lesson that was re-learned many times from the accidents was that while policies, regulations, and standard operating procedures are necessary, these tools cannot replace trained operators who are aware of the hazards and are constantly thinking about ways to mitigate the risks. It is often said that the lessons learned were often at the cost of lives and were written in blood. One of the purposes in writing this document was to hopefully prevent many of these lessons being learned the hard way by the new generation working with propellants and explosives and ordnance using these energetic materials.

Another old lesson that was re-learned is that HD 1.3 cannot just be considered to be a “wooden round” meaning that they are “safe.” If depleted, these materials, especially ammonium perchlorate (AP) based missile propellants and single- and double-base gun propellants as stabilizer, may be relatively easy to ignite as compared to explosives. Not only are they relatively easy to ignite, they burn well at one atmosphere. The AP based propellants also burn well in oxygen free environments. The danger is from burns either from direct plume impingement or from heat flux radiation exposure (and exposure time) leading to second-degree burns or worse. Often fatalities occur after painful suffering over time. A victim of a flash fire that occurred in September 2010 suffered burns over 80% of her body and was in critical condition on a feeding tube and respirator a year later. She passed away 29 September 2011. It has been said that in the propellant R&D and propellant formation/missile motor manufacturing/testing industries more people have been lost due to fire than explosion/detonation.

Another old lesson that needs to be re-emphasized is that fires that burn for long durations may attract people for a closer look. Often traffic gridlock occurs. This results in additional fatalities when the fire transitions to detonations as was the case at the

Texas City accident in 1947, and the Enschede fireworks accident in 2000, and Mihăileşti, Buzău, Romania, accident in 2004.

Some of the other lessons learned include:

- Most of the accidents started with fire.
- The fires often burned for minutes and even hours before the next significant reaction, if any.
- In a fire, obviously all of the energetic material is not consumed instantly or simultaneously. Even in the tests where the choked flow caused pressure rupture of the confining chamber to occur at about 10 bars of internal pressure, the energetic material continued to burn in a fireball after rupture. This is in marked contrast to a mass detonation where all, or almost all, of the material is consumed extremely quickly and essentially simultaneously.
- Mass fire can transition to mass explosion/mass detonation. The next significant reaction following fire was often explosion(s) that in turn was sometimes followed by detonation.
- While in many of the accidents the fire burned for a significant time, in some instances over-pressure due to combustion resulted in catastrophic rupture of the confining structure and projection of large pieces of structural debris occurred very quickly. For example, in Test 4 (discussed in Reference 48), fire resulted in overpressure and rupture of an ECM in 1 second after ignition of the gun propellant. This was not a detonation, there was no blast overpressure and no crater was formed, but five huge fragments were produced and thrown significant distance. This was caused by burning of HD 1.3 material.
- One of the accidents (Milan 2004) also produced huge fragments that traveled great distances (outside the IBD arcs).
- One of the major determinants in whether burning leads to significant debris being thrown great distances is the race between pressurization due to combustion versus the venting of reaction products from the confining chamber. Of critical importance is whether the flow through the vent(s) was either un-choked or choked. Choked flow occurs when the pressure inside the chamber is approximately 1.7 to 1.9 times (or greater) the outside pressure. Choked flow can rapidly lead to rapid pressurization and rupture of the confining structure and spreading of secondary fragments/debris.
- If the flow was un-choked, unburned energetic material was often expelled and burned outside the chamber not inside the chamber.
    - Reports on some of the accidents reported plumes extending several hundred feet outside the chamber after the magazine doors, or head wall, were blown open.

  - The tests also showed plumes out a significant distance from the chamber. When the plumes from 1/10th scale test were scaled by analysis to full scale, the calculated plume was out 250 feet.
  - Direct exposure to the hot plumes will cause fatalities.
  - There was significant heat flux radiated from the plumes. Radiation from the hot plume can cause fatalities at a distance if the heat flux levels and exposure times are sufficient.

- It is not sufficient simply to mention irradiance or heat flux. The flux levels and exposure time must be considered.
- The heat flux level decreases with distance from the plume roughly with $1/d^2$.
- Heat flux (q)-exposure times (t) below the combinations given by the equation

$$t = 200\ q^{-1.46}$$

  are insufficient to cause the onset of second-degree burns.

  Distances where the flux has decreased to less than approximately 5 kW/m^2 requires about 19 seconds exposure time before the onset of second-degree burns. This time allows for recognition of the threat and time to take some preventive measures such as getting behind an obstacle or "duck-and-cover". These distances represent a safe-separation distance from a mass fire event.

- Using such a heat flux exposure time-based approach may offer significant advantages over the conventional $D = kW^{1/3}$ approach as demonstrated in the NASA analysis of the VAB at KSC presented in the previous section.

The above lessons learned have implications for determining safe-separation distances from mass fires and indicate that it is time that DDESB consider methods other than $D = kW^{1/3}$ and table look-up Q-D tables for mass fire events.

Before discussing the need for change in determining safe-separation distances for mass fire reactions, it should be mentioned that HD 1.3 is a large class of varied materials ranging from gun propellant grains with high surface area available for combustion; to large rocket motors with high internal pressure, high thrust, and large high temperature plumes when burning; to flares with high radiation. Each of these varied materials have different compositions, thermochemistry, burning rates, burning surface areas, and combustion products leading to different pressurization rates in confinement. Reference 71 discusses these differences.

There is sometimes a disconnect between assignment of HD and the hazard and resulting determination of safe-separation distance associated with burning of energetic material.

In the U.S., the process leading to assignment of a HD classification is described in TB 700-2 (Reference 2). This is based largely on UN Series 6 tests. A major deficiency in the process is that it does not consider the role of confinement and venting of storage structures. Materials classified as HD 1.3 stored in heavy confinement with insufficient venting can cause catastrophic rupture of the confinement when burning and throw debris significant distances, as attested by lessons learned from accidents and testing that was reported earlier. The CHAF effort (described in Reference 27) provided excellent examples of how the assignment of HD based on the UN Series 6 tests did not sufficiently predict the hazard effects of the fireworks stored in ISO containers. Some of the fireworks that were classified as HD 1.1 in the UN tests displayed mass fire behavior when ignited in the ISO container, while some of the items classified as HD 1.3 displayed mass explosion behavior in the ISO container tests.

Hazard division assigned based on UN Series 6 tests can change with time and conditions. For example, the gunpowder stored at the Evangelos Florakis Naval Base in Cyprus may have been HD 1.3 when the ISO containers containing the gunpowder were first stored at the naval base. However sitting in stacked ISO containers in the hot and humid conditions of Cyprus for 2½ years increased the hazard sensitivity of the energetic material. The mass fire transitioned into explosions followed by mass detonation a couple of hours after the onset of fire. There were several other accidents where materials that were originally classified as HD 1.3 started to burn and ended with detonations some time later. The fires in several of the accidents were with gun propellants with the fire starting due to stabilizer depletion in the gun propellant occurring over time.

CURRENT WEIGHT-BASED SITING METHODS ARE INADEQUATE FOR MASS FIRE HD 1.3

As mentioned earlier, current safe-separation distances for HD 1.3 are presented in DoDM 6055.09-M (Reference 1). Safe-separation distances for HD 1.3, like Q-D for HD 1.1, are based on weight of energetic material using the simple equation:

$$D = kW^{1/3}$$

where:

D = safe-separation distance, or Q-D arc
k = factor as defined in Reference 1
W = weight of energetic material

There are many k factors for HD 1.1 materials reflecting such considerations as

- air blast and fragments resulting from the mass explosion/mass detonation

- whether spacing from a potential explosive source is considering distance to inhabited building (IBD), to public transportation route (PTRD), from magazine to adjacent magazines (IMD), or intraline distance from operating buildings performing like operations
- construction type such as ECM
- orientation of potential explosive source to receptor (side versus back versus front/entry)
- whether barricades are in place or not

The many k factors for HD 1.1 ranging from k = 1.1(inter magazine distance from barricaded modules or cells) to k = 50 (distance between front or side of ECM with greater than 250,000 pounds NEW to IBD.

There are almost 13 pages of tables for HD 1.1; the situation with HD 1.3 is much simpler. There are no primary fragments and blast considerations to deal with. (Again, there may be secondary fragments and blast resulting from pressurization of a confining structure.) There are only two considerations, either IBD/PTRD and IMD/intraline distance (ILD), with k factors of eight and five respectively, and a one page table (and one page of footnotes and formulae), but again, it is still essentially $D = kW^{1/3}$. Essentially, the same methodology is used for HD 1.3 and HD 1.1, just with different k factors.

The current weight-based approach, with the multitude of k factors, has served the DOD community relatively well for HD 1.1 materials, but maybe it is time to explore other siting options for HD 1.3 (and perhaps 1.2.3 and 1.4 materials). While the weight-based approach is applicable to 1.1 materials, it is not be applicable for materials where the primary threat is fire not primary fragments or blast, and may result in overly conservative safe separation distances with concomitant excess real estate requirements.

Recent studies have shown that use of the weight-based approach may be overly conservative in some aspects but also may not be considering the real hazards in other cases.

- The current weight-based siting methods are appropriate for mechanical shock initiation of HD 1.1 but are inadequate for HD 1.3 for several reasons. One reason is there are very different initiation methods, time scales, and resultant hazards. These are shown in Table 30.

TABLE 30. Fundamental Differences Between HD 1.1 and 1.3.

Consideration	Mass Detonation/ Mass Explosion	Mass Fire
Input stimuli	Fire or shock wave	Ignition
Initiation time	Microseconds after shock	Up to several minutes
Event time	Milliseconds to seconds	Minutes to several minutes to hours
Stores/time participation	Almost all react simultaneously	Time delays, some unreacted
Reaction output	Blast and fragments secondary debris	Fireball and radiation, throw secondary debris if choked flow
Cause of fatalities	Crush, dismemberment, fragment penetration	Second- and third-degree burns

- For HD 1.1, the weight-based approach is acceptable because the reaction times are very quick, as are the event times, and almost all of the explosive mass is rapidly and almost simultaneously consumed. In contrast, for HD 1.3 the initiation and reaction times are spread over minutes to tens of minutes, and all of the mass is not reacting simultaneously. In some cases, some of the mass may not react at all. In a detonation or explosion, the reaction from unreacted solid to reacted gaseous products can almost be represented by a step function in time (and is often modeled simply as a discontinuity) while the ignition and combustion are very time dependent.
- Fires may have burned for some time, so part of the original weight has been consumed.

What are the hazards associated with HD 1.3 systems? The principal concerns are as follows:

- Direct contact with exhaust plumes or fireballs. The exhaust temperatures of rocket motors are in the range of 2,000 to 2,300°C. Obviously, structures and walls can channel the flow of plumes. Exhaust plumes, with temperatures over 1,000°K, rapidly expand and in some instances to distances of 200+ meters from the source as determined in the analyses from the NASA KSC VAB presented in previous sections of this report. The accidents and tests described in Reference 31 mentioned plumes out to 250 feet or more. Direct exposure to these temperatures will result in fatalities.
- These hot gases and, in the case of some solid missile propellant exhausts, hot metal oxides (such as Al_2O_3) can radiate to distance, providing radiation heat fluxes in the multiple kW/m^2 range at 400 meters from the reactions.

In addition to these principal concerns, the following also need to be considered:

- If there is not sufficient venting of the hot combustion gases, pressure can build up and cause catastrophic rupture of the building and produce very large debris fragments. Again, the accidents and tests described in this publication clearly showed this. HD 1.3 systems are often treated as HD 1.1 when stored in underground chambers.
- If the HD 1.3 stores are rocket motors, inadvertent ignition can cause the motors to go propulsive and spread burning reactions. Again, the exhaust plumes are in the 2,000 to 2,300°C range and can cause sympathetic ignition of adjacent stores.

The current weight-based method for siting mass fire is not based on the following:

- Human health risks/consequences based on direct exposure to flame or to radiative heat flux exposure time relationships.
- Consideration of time dependent heat flux based on what is actually burning at any given time.
- Consideration of confinement in determining what is actually burning. The confinement can be provided by motor casings, shipping containers, and the building itself.
- Consideration of venting to prevent pressure buildup.
- Consideration of propulsive reactions and subsequent consequences.

Given that the fatalities associated with HD 1.3 materials are largely caused by direct exposure to fire and radiative heat flux, determination of safe-separation distance for HD 1.3 should reflect the above considerations. Due to the above reasons, treating HD 1.3 siting using a weight-based methodology is not a realistic approach or a conservative assumption.

Other considerations for mass fire include:

- Ignition sequence—what is burning at what times, which in turn is determined by:
  - The energetic materials,
  - The stimulus,
  - The environment, including confinement.
- The heat flux produced as a function of time.
- Heat flux roughly diminishes with distance ($1/d^2$) and obstacles.

The inadequacy of the current weight-based approach has been advanced by others in previous DDESB seminars and other documents. Tinkler (Reference 72) stated that:

> "In the writer's opinion this concept of relating the radius for a certain degree of (acceptable) hazard to the explosive quantity by a simple mathematical relationship is justified only when blast is the predominating effect producing the hazard. This implies that it is essentially wrong in principle for other than HD 1.1 mass exploding explosives."
>
> "In contrast with the blast and projection effects of HD 1.1 and HD 1.2 explosives, the fiery behavior of HD 1.3 explosives has hardly been studied at all. This is in spite of the large quantities of propellants which are used, particularly in military ammunition."

The document also reported on tests conducted in the UK in the 1970s and mentioned "a roaring flame jet swept for 200 feet (60 meters) horizontally along the ground" after discharging from the open end of the room. This is similar to the fireballs described in Phases 2 and 3 of the DDESB program described in References 44 and 46. Tinkler (Reference 72) concluded:

> "Consideration of some HD 1.3 quantity distances show many anomalies and imply that the level of protection they afford may be inadequate compared to HD 1.1 and 1.2 explosives whose effects are better understood. It is the strongly held view of the writer that the behavior in a fire of boxed propellants, and the various types of rocket motor classified as HD 1.3, does not lend itself to theoretical study nor modeling. Large-scale test firings should therefore be carried out to confirm, or otherwise, the presently accepted quantity distances. More immediately, large quantity HD 1.3 storage facilities should be surveyed to ensure any probable jetting effects from buildings do not produce an unacceptable communication hazard."

Crockart (Reference 73) also championed the need for a heat flux-based approach for HD 1.3 mass fires and for programs to address this need, as stated below:

> "A careful review of the causes of death and injury in 81 accidents in the explosives and propellant industries over the 1959 through 1968 period, reported in Reference A, showed that primary blast (overpressure) damage did not cause a single death but projected fragments and the effects of exposure to the searing radiant heat accounted for 77 of the 78 fatalities covered by the review. The great majority of these accidents involved a fire that eventually led to a mass detonation."

> [Note: This was also illustrated by Table 1 of Reference 3 (found in Reference 73) where more fatalities were produced by fire that blast and fragments.]

Crockart continued:

> "Although there have been studies undertaken over recent years to understand the hazard mechanism and devise more effective protection for blast and projected fragment injury, the subject of protection from radiant heat has not been well studied."

The Statement of Work for the DDESB program from the late 1970s and 1980s (References 43, 44, and 46) included:

> "A program of research and testing has been undertaken to correct the deficiencies in the safety standards for articles and substances of Class 1, Divisions 3 and 4."

Some of the deficiencies listed included:

> "*It has been observed that, while cube-root scaling [of the weight of explosive material] applies to the blast overpressures from explosions, thermal radiation incident on a surface exposed to a burning source does not scale in this manner. Furthermore, source parameters other than the total weight of combustible material present, such as geometry, affect the irradiance from the source*. [Italics added in this paper for emphasis.]

IF THE CURRENT WEIGHT-BASED APPROACH IS INAPPROPRIATE WHAT SHOULD BE USED TO DETERMINE SAFE-SEPARATION DISTANCES FOR HD 1.3?

Any other method should reflect that the risks from mass fire are direct exposure to plumes (almost certain death) and exposure to thermal radiation. As previously mentioned, the plumes associated with un-choked flow can carry hundreds of feet from the magazine.

Obviously, the consequence of burns to personnel needs to be quantified. Direct exposure to flame is sometimes referred to as near-field while radiation to distance is sometimes referred to as far-field.

Direct exposure to exhaust plumes or fireballs in the near-field with the high temperatures (and often toxic products such as moist hydrochloric acid [HCl]) will result in fatalities.

As an ironic side note, DOD 6055.09M-STD presents an equation to estimate the diameter of fireballs associated with HD 1.3.

$$D_{fire} = 10\ W_{EFF}^{1/3}$$

where:

D_{fire} = diameter of the fireball (feet)
W_{EFF} = 1.2 weight of HD 1.3 material involved (pounds)

Table 31 presents the fireball diameter calculated for various weights of HD 1.3 using the above equation.

TABLE 31. Fireball Diameter Calculations.

Weight, lb	Calculated Fireball Diameter, ft
10,000	229
100,000	493
250,000	669
500,000	843

Now compare the diameter of the fireballs with the Q-D presented in DoDM 6055.09-M. For example, it would allow siting of 500,000 pounds of HD 1.3 (Q-D is 569 feet for IBD/PTRD; and 372 feet for ILD by Table C9.T13, or 635 feet if using k = 8 for IBD in $kW^{1/3}$) without any restrictions. However, as seen in Table 31, the fireball diameter is calculated to be 843 feet and not considered in the siting limitations. So in this example, a person could be standing at 650 feet and be outside the Q-D arc and yet still be within the fireball diameter and die.

Fatalities can also be caused in the far-field by exposure to thermal radiation. The primary considerations for thermal radiation are heat fluxes and exposure times. Certain combinations of heat flux and exposure times can cause second-degree burns and the possibility of fatalities. The onset of second-degree burns is a function of many variables including the following:

- Radiative heat flux levels and exposure times are the primary variables but there are secondary considerations such as age—generally older people are more susceptible to radiation than younger men and women.

- Geographic location and time of year—people in the southern and southwest states, especially in the summertime when the attire may be short-sleeved shirts and shorts are more susceptible to radiation than someone in the northern states bundled up in the winter.

HUMAN RESPONSE TO MASS FIRE

As mentioned earlier, the hazards from mass fire are primarily the plume/fireball itself and radiation from the plume/fireball. Anyone in the plume or fireball has very little chance of survival because of the extreme temperature and chemical species such as moist HCl. The hazard from the radiation is due to the heat flux and exposure time that produce second- and third-degree burns. Another concern is debris fragments produced by pressure burst of structures when internal pressures reach on the order of 10 bars. Previous sections discussed un-choked flow from structures that can result in plumes and radiation and the debris that result from pressurization of robust structures such as earth covered magazines. This section will discuss the hazards from human response to radiation from the plumes and fireballs.

This is not a new concern. In the U.S., DDESB had programs in the 1980s addressing fire hazards (see for example, References 43, 44, and 46), while the UK and Australia also had programs. In the UK, Q-D was based on an approximate model of skin burns based on heat radiating from nuclear explosions (References 74 and 75). Unfortunately the thermal radiation from nuclear white body emitters (temperature ≈ 7000K) is unlike that from explosive fires with their black body emitters (temperature ≈ 1500K) because the wavelengths are significantly different, and explosive fires last for seconds or more as opposed to nuclear flash. Henriques produced a skin burn model by modifying the Arrhenius equation for heat induced chemical reaction (Reference 76). This model was used by Stoll and Green and Perkins et al. to predict tissue damage caused by black body radiation (References 77 and 78). Unfortunately the two approaches give very different results because Perkins et al. used high temperature and short wave-length source that penetrates the skin about 3 mm before being absorbed and requires a much larger heat dose to produce skin damage, while Stoll and Greene used low temperature and longer wavelength source that does not penetrate the skin so that the entire heat dose is absorbed by the surface cells that are more readily destroyed. Lawton modified Henriques theory to allow penetration of radiation before absorption giving accurate predictions of skin temperature and burn damage regardless of the nature of the heat source. Reference 79 introduced Lawton's model and preliminary characterization progress. Characterization was completed in 1995. Reference 80 presented the results of Phases 1 through 3:

- Phase 1. The burning of loose propellant in the open to produce unmasked radiation from large flames.

- Phase 2. The burning of boxed propellant in the open.
- Phase 3. The burning of loose and boxed propellant in a confining structure with a vent opening to induce horizontal jetting.

The propellant was a slow burning triple base slotted tube stick MNLF 2P/S 168-048. This propellant was chosen because it is one of the slowest burning (longest exposure) propellants in the UK at that time. Tests were conducted with ½, 1, 2, 4, and 8 tonnes. Heat flux sensors were positioned at 0.6R, 0.8R, 1.0R, and 1.2R away from the center of the fires where R was the predicted pain threshold distance. The areas under the heat flux-time curves were used to calculate heat doses. The model predicted the onset of pain, and the thresholds for first-, second-, and third-degree burns. The results for open burn are shown in Figure 201.

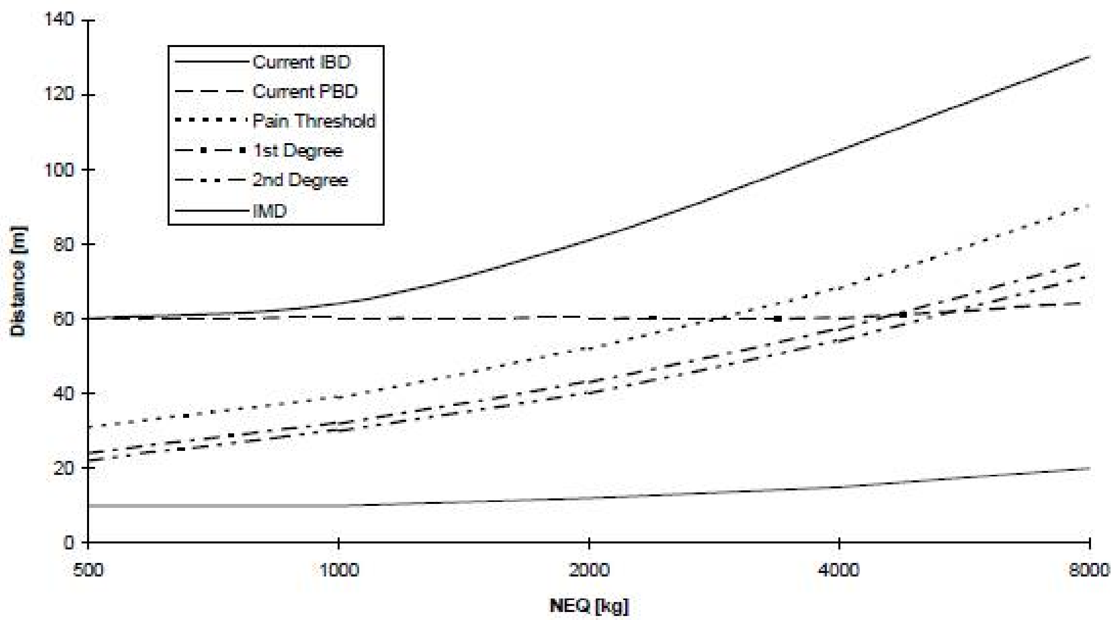


FIGURE 201. Results of Lawton's Calculations for Open Burning of Propellant MNLF2P Compared to Current Inhabited Building Distance IBD and Process Building Distance PBD.

Obviously, using the prevention of second-degree burns significantly would reduce the safe separation distance from the IBD distance based on $D = kW^{1/3}$. It also reduces the distance for processing building distance up to about 6,000 kg.

Lawton also investigated plume jetting from buildings with various venting schematically shown in Figure 202.

The results of Lawton's calculations for jetting schematically shown in Figure 202 is given in Table 32.

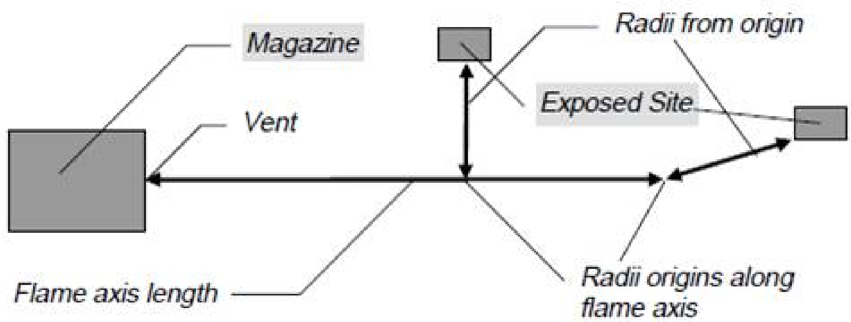


FIGURE 202. The Jetting Parameters Used by Lawton.

TABLE 32. Distances From Jet Center Line for Various NEQ, Vent Openings, and Distance From Magazine That Would Produce Pain and First- and Second- Degree Burns. Burn time of 20 seconds with MNLF2P propellant.

NEQ, kg	Min. Vent, m^2	Flame Length,	Origin Along Flame	Radius From Origin		
				Pain, m	1st Burn, m	2nd Burn, m
500	1.8	37	0.25	16	13	12
			0.5	16	13	12
			0.75	15	12	11
			1	10	8	7
1,000	3.6	34	0.25	16	14	13
			0.5	16	14	13
			0.75	15	13	12
			1	11	9	8
2,000	7	47	0.25	23	19	18
			0.5	24	20	18
			0.75	21	18	16
			1	16	13	12
4,000	14	67	0.25	33	27	26
			0.5	34	28	26
			0.75	30	25	23
			1	23	18	16
8,000	28	94	0.25	41	38	36
			0.5	48	40	37
			0.75	43	36	33
			1	32	26	24
10,000	35	104	0.25	52	43	40
			0.5	53	45	42
			0.75	49	40	38
			1	36	29	26

Table 32 shows loose MNLF2P propellant in the open and in confinement. Table 32 was for vents that would produce un-choked flow. Willcox and Lawton recognized that choked flow would lead to building failure due excess internal pressure. When the propellant was contained in boxes and then burned in the open or confined in a vented building, no vertical or horizontal mass flames ensued. That was because only one or two boxes were burning at any given time. In these instances, the observed heat fluxes never warranted Q-Ds greater than the distance for HD 1.4—a fixed distance of 10 meters.

Unfortunately, we were unable to retrieve any publication that had the heat flux-exposure time (or the heat dose that was defined as the area under the heat flux-time curve) data that Lawton used. We wanted these data so that we could compare with information below. Obviously, Lawton was calibrating his model with the slowest burning propellant (longest exposure) in the UK inventory as the worst case, and as mentioned earlier was able to significantly decrease the IBD safe separation distance.

The results of many studies were plotted in exposure time versus heat flux in a Society of Fire Prevention Engineers study (Reference 28). A line that encompassed all the results for second-degree burns was determined (all of the results were to the right of the line). The equation for that line was

$$t = 300\ q^{-1.46}$$

where

t = exposure time, seconds

q = heat flux, kW/m^2

To account for variability and provide conservatism, a factor of safety of 1.5 was applied to the time giving:

$$t = 200\ q^{-1.46}$$

This is shown in Figure 203.

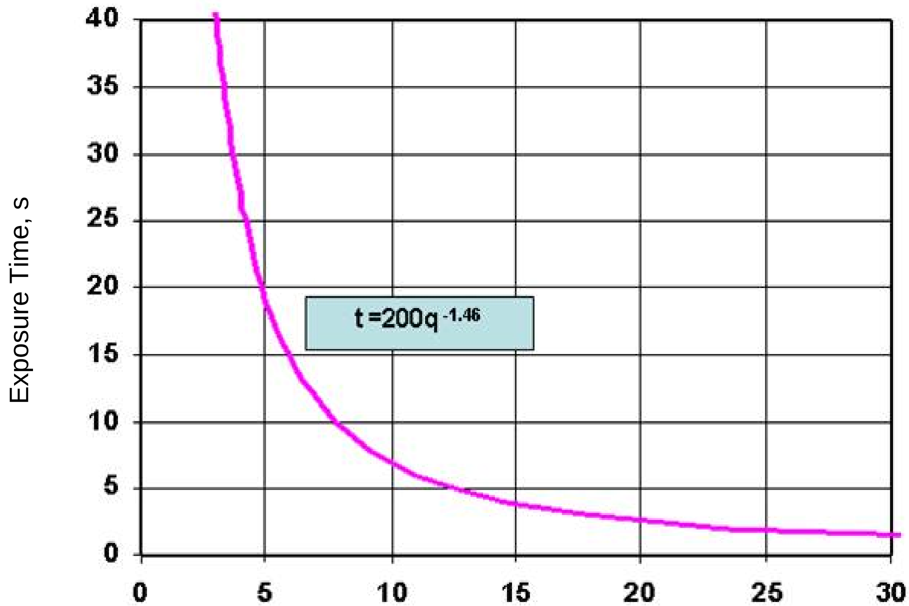


FIGURE 203. Heat Flux and Exposure Times for Onset of Second-Degree Burns (Reference 28).

The NASA program to determine safe-separation distance from the KSC VAB discussed earlier (Reference 45) addressed both the near-field and far-field effects. The near-field effects were addressed by calculating plume locations and temperatures. For example the temperatures at 66 inches off the ground (roughly the height of a human when standing) were mapped. The plumes extended 200+ meters from the fire source. Personnel within these areas were assumed to perish from exposure to the high temperatures (greater than 1,000 K). The far-field effects were addressed by calculating heat flux exposure time profiles at locations and using prevention of second-degree burns using the Society of Fire Protection Engineers (SFPE) equation as the criterion for determining safe-separation distances for radiation from the mass fire.

On 25 January 2011, the DDESB approved recommended changes to DoDM 6055.09-M. It was recommended that DDESB adopt the prevention of second-degree burns as a criterion for determining safe-separation distances from mass fires, and revise DoDM 6055.09-M (Reference 1), sections V1.E9.3.1.2, V1.E9.3.2.4, and V1.E9.4.5, to use both heat flux and exposure time, and use the SFPE plot and equation presented in Figure 203.

Previously, DoDM 6055.09-M, sections V1.E9.3.1.2 and V1.E9.4.5 presented a heat flux of 0.3 cal/cm^{2}sec (12.56 kW/m^2) as a limiting factor but did not present an exposure time. A heat flux of 12.56 kW/m^2 only gives an exposure time of about 5 seconds before the onset of second-degree burns, with the concomitant possibility of fatalities, would ensue. When DoDM 6055.09-M did present both heat flux and exposure time (V1.E9.3.2.4), it linked the two by the equation presented below.

$$q = 0.62\ t^{-0.7423}$$

where
q = heat flux (cal/cm^2sec)
t = exposure time (seconds)

Use of this equation gives t = 2.66 seconds for a heat flux of 0.3 cal/cm^2sec (12.56 kW/m^2), and t = 12.4 seconds for a heat flux of 0.0956 cal/cm^2sec (4 kW/m^2).

The International Ammunition Technical Guideline, Reference 65 on page 9, states:

"For explosives of HD 1.3, the IBD is based on a thermal dose of 62.8 kJ/m^2." The thermal dose has units of heat flux x exposure time. How does this number compare with the previous discussion? Table 33 presents heat-flux-exposure time pairs for the 62.8 kJ/m^2 and from the SFPE equation for onset of second-degree burns presented earlier. The heat flux of 12.56 kW/m^2 is included because in the past it has been called a "critical heat flux," but as shown there is only about 5 seconds to recognize the threat and take evasive action.

TABLE 33. Comparison of Heat Flux-Exposure Times.

Heat Flux, kW/m^2	62.8 kJ/m^2 Dose Time, sec	SFPE Time to Second-Degree Burns, sec
3	20.9	40.2
5	12.56	19.1
10	6.28	6.93
12.56	5.00	4.97
15	4.19	3.84

As shown in Table 33, the heat dose method underestimates the time available to recognize the threat and take evasive action as compared to the SFPE time to onset of second-degree burns at the lower fluxes. Obviously, a safe separation distance needs ample time to recognize the threat and take evasive action such as getting behind shelter. Table 33 indicates that the flux level that provides ample time is about 5 kW/m^2.

HOW DOES THIS COMPARE WITH OTHER INDUSTRIES?

The liquefied natural gas (LNG) industry has studied heat fluxes produced by accidental fires and explosions of LNG on land and water that are governed by federal and industry regulations. References 81 through 85 present summaries of these regulations and code, and some of the work is summarized as follows. The National Fire Protection Association's (NFPA's) LNG Standard NFPA 59A (2006) (Reference 86) lists various thermal radiation fluxes for different exposure conditions. These include (from Reference 85) the following:

- 5 kW/m^2 for persons at the proposed fence line of the facility or for the nearest point where groups of 50 or more people are in an outdoor assembly area outside the fence line.
- 9 kW/m^2 for the nearest point of building used for assembly, education, health care, detention and correction, or residential occupancy for a fire in an impounding area.
- 30 kW/m^2 for a property line that can be built upon over an impounding area.

The U.S. Department of Transportation's regulation 49 CFR 193 (Reference 87), also specifies the 5 kW/m^2 thermal radiation exposure at the LNG facility fence line and for groups of 50 or more people outside the fence line.

In addition, there is a European standard for the installation and equipment for LNG (Reference 88). This standard gives three flux levels: 13 kW/m^2 for persons at a fence line in a remote area, 5 kW/m^2 for persons at a fence line in an urban area, and 1.5 kW/m^2 for plant personnel who must remain in an unshielded area without protective clothing or an urban area with more than 20 people per square kilometer or a place difficult or dangerous to evacuate on short notice (e.g., hospital, retirement home, sports stadium, school). Similarly the Canadian Standards Association uses the 5 kW/m^2 criterion for persons at the fence line and for groups of 50 or more outside the proposed fence line (Reference 89).

While the above give the acceptable radiation heat flux, they do not specify the duration of acceptable exposure. However, some of the documents indicate approximately 30 seconds of exposure time before fatalities would occur and imply that within that time interval personnel should be able to find shelter; however, mention is made of susceptible groups such as young children and the elderly who are perhaps not as ambulatory as the rest of the population.

[Note: The SFPE curve, Figure 200, gives 20 seconds exposure time before second-degree burns for 5 kW/m^2 heat flux but that includes a 1.5 factor of safety for the exposure time.]

As pointed out in Reference 90, the 5 kW/m^2 limiting criterion does not adequately represent the risks presented by an LNG facility to sensitive populations like young children or the elderly and/or critical areas and buildings. Melhem et. al. mention that the most widely recognized and used methods for establishing the impact of thermal radiation on people are those developed by TNO and published in the Green Book (Reference 91). These methods are referred to as thermal radiation probits or vulnerability models.

A probit (probability unit, Y) is a normally distributed random variable with a mean of five and a standard deviation of one. The mortality response (percent fatality) is expressed as follows:

$$P = 1/2 + \tfrac{1}{2} \operatorname{erf} \{(Y-5)/1.414\} \tag{2}$$

Probit analysis can also be applied to thermal radiation hazards by

$$Y = A + B\ln(tI^{-4/3}) \tag{3}$$

where

A and B are probit parameters established from measurements and/or critically evaluated scientific data

I = the radiation intensity in W/m^2

t = exposure time in seconds

The TNO Green Book (Reference 91) gives the probits for first- and second-degree burns, fatality for persons unprotected by clothing, and fatality protected by clothing. For example, the probit in the form of Equation (3) for second-degree burns is A = -43.14 and B = 3.02. The probit values from the Green Book (Reference 91) are used to generate a plot of incident heat flux versus exposure times leading to a 1% probability of injury (first- or second-degree burns) or fatality. From Figure 3 of Reference 91, the following exposure times would occur for an incident heat flux of 5 kW/m^2

- First-degree burns would occur in approximately 14 seconds exposure time.
- Second-degree burns would occur in approximately 45 seconds.
- A 1% chance of fatality without proper clothing would occur in approximately 50 seconds.
- A 1% chance of fatality with proper clothing would occur in approximately 70 seconds.

The above discussion has been for the LNG industry. The petroleum refining industry has also considered radiation heat flux, primarily from "flaring" operations for safe disposal of flammable waste gases. Various flux levels are specified in the American Petroleum Institute standard API 521 (Reference 81). These include (1) 15.97 kW/m^2 for heat flux on structures where operators are not likely to be performing duties and where shelters from radiant heat is available, (2) 9.46 kW/m^2 for any location where people have access (but exposure should be limited to a few seconds), (3) 6.31 kW/m^2 for areas where emergency actions lasting up to 1 minute may be required by personnel without shielding but with appropriate clothing, (4) 4.73 kW/m^2 for areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing, and (5) 1.58 kW/m^2 for any locations where personnel with appropriate clothing may be continuously exposed to design flare release conditions.

Reference 82 presents the results of a worst-case consequence analysis for process unit modifications and additions to BP Carson (CA) Refinery. Flash fire hazards, radiation hazards, overpressure hazard, and toxic product hazards were considered. For the radiation hazard analysis, they used the 5 kW/m^2 level, noting "When people see a fire, it is easy for them to determine which direction they should move to increase the distance between them and the fire and thus lower the impact of the fire on them, or they can find a building or other solid structure to go behind to reduce or eliminate the radiant impact. If a person is already inside a building, they will be protected from the radiant impact. [This radiant level is not high enough to ignite a building.]"

The recent change to DoDM 6055.09-M brings DOD consideration of the hazards associated with mass fire more in line with other industries also concerned with mass fire events.

To prevent mass fire transitioning to mass explosion/detonation, choked flow must be prevented. As presented earlier, Reference 53, also made the argument:

> "… the effects of burning HD 1.3 material inside a closed structure can range from benign to catastrophic. If adequate venting is not provided, the pressure can build up at such a rapid rate that it can overwhelm the structure. <u>This explains why it is safest to store HD 1.3 materials in structures that provide large amounts of venting</u> [emphasis added]. In above ground structures, this venting is provided through frangible walls and/or roofs. When HD 1.3 materials are stored in hardened structures or any other structure that provides structural confinement, extra care should be taken to provide adequate venting. The amount of venting required varies with the volume of the storage chamber, the weight of the [energetic] material being stored, and its [mass] burn rate. These phenomena are not adequately addressed in the current versions of the explosive safety standards—either from the standpoint of safe-separation distance or asset protection."

> [Note: In addition to the weight of energetic material, its thermochemistry/ energy content is also an important consideration. We inserted mass into burning rate above because the term burning rate is often construed to mean surface regression rate while mass burning rate, which is an important determinant of the pressure–time history of the event, considers not only the surface regression rate but also burning area and density.]

These words from 1996 are just as true today as they were then.

MIXED STORAGE OF HD 1.1, 1.2, AND 1.3

Reference 71 presents the differences in ignitibility and burn rates for HD 1.1 and 1.3 energetic materials, with HD 1.3 propellants being easier to ignite and burning well at one atmosphere, whereas many HD 1.1 materials burn poorly at one atmosphere. When storing HD 1.1 and 1.3 together in the same facility or structure, problems may be encountered because the HD 1.3 materials may serve as the "match" that start the mass fires that may, or may not, transit to mass explosion/detonation. There is the desire to have robust storage such as ECMs to protect HD 1.1 from incoming blast and fragments because of the detonability of HD 1.1 materials, but perhaps separate frangible storage for 1.3 materials is also desirable. As mentioned previously from Reference 53 and in Reference 31, burning of HD 1.3 in a choked flow situation can easily result in rupture of heavy confinement very quickly (in one instance, 1 second after ignition) with debris thrown to great distances, especially if the rupture is very quickly followed by a detonation.

One suggested possibility is to store HD 1.3 in buildings having frangible blow-out panels in the roof and selected walls to ensure that choked flow does not occur and to direct the flame/plume into desired directions.

While the probability of an inadvertent reaction is usually not part of the safe-separation issue (a reaction is simply assumed), there has been increased interest in including probability into the discussion, especially in storage and transportation scenarios. While it is often assumed that HD 1.1 is the worst case, it often is not when probability of reaction is included.

A consideration that is often not addressed in considering safe-separation distance in storage and transportation scenarios is the probability of initiating a reaction. As was presented earlier, initiation of mass detonation/mass explosion of HD 1.1 materials usually is the result of shock-to-detonation reaction or to cookoff reaction resulting from a fire. To initiate a shock-to-detonation reaction in HD 1.1 materials, the majority of HD 1.1 materials must be subjected to shocks of tens of kilobars. Shocks of these magnitudes are unlikely to occur in storage or transportation scenarios. For example, a munition on a truck that was traveling at 60 mph that then struck a freeway abutment might experience a shock loading of a few kilobars against concrete and approximately 9 kilobars against pointed steel barrier (References 92 and 93). In contrast, HD 1.3 materials with their large critical diameters and high shock thresholds are very unlikely to experience a shock-to-detonation reaction even given extremely high shock levels, levels considerably above those that could occur in storage and transportation scenarios. So it might be argued that the probability of DOD munitions undergoing a shock-to-detonation reaction in storage or transportation scenarios is very low for HD 1.1 materials and almost totally improbable for HD 1.3 materials.

As mentioned earlier in discussing accidents, fires are much more prevalent, and in some instances the fires can lead to mass explosion reactions. However, if the fire could have been prevented in the first place, the probability of deaths or loss of property would have decreased markedly.

Since, in general, HD 1.3 substances ignite easier and burn better than HD 1.1 substances at atmospheric condition, and since fire is the first major reaction in many of the accidents, the probability of an inadvertent accident is greater for HD 1.3 systems when compared to HD 1.1. These phenomenological differences are not captured in risk-based tools such as Safety Assessment for Explosives Risk (SAFER) (Reference 94) and Automated Safety Assessment Protocol–Explosives (ASAP-X) (Reference 95). In all risk assessment methodologies, the probability of the event occurring is not modified based on the probability of accident for one HD relative to another.

Many countries have significant efforts to develop what are called insensitive munitions. These programs have been successful in decreasing the violence of reaction from detonations and explosions to burning. So the probability of inadvertent detonation is decreased further but the probability of inadvertent fire may be increased. This issue may become more acute in the future given the emphasis of insensitive munitions programs to move from inadvertent detonation and explosions reactions to fire-type reactions.

RECOMMENDED NEW TESTS AND MODELING

As mentioned by several others, there is a need to have tests where fire is the initial stimulus with flame spread to adjacent stores. As mentioned earlier, HD 1.3 encompasses many very different materials. Most of the testing has been done with granular gun propellants having high surface area. So far, there has been little, if any, testing with rocket motors other than 2.75-inch rocket motors that were open at both ends. Tests with different configuration of materials are also needed. The configuration, as well as the material type, is important in determining un-choked versus choked flow, and in determining plume extent, fluxes, and reaction durations. Packaging also needs to be considered. Some studies showed that even cardboard containers can play a key role. One study (Reference 52) recommended metal boxes that remain airtight to 100 kPa can play a key role for safely storing gun propellants. Other packaging options ought to be explored. Different configurations of surrounding confinement, for example frangible construction versus robust confinement such as an earth-covered reinforced concrete structure, should be investigated. All tests should be well instrumented, especially to determine intense plume location and heat flux from the plumes.

Modeling efforts should be used in designing tests as well as interpreting the results. For example, what happens when choked flow results in extreme pressure buildup in an ECM that in turn causes rupture of the structure, and what might happen if immediately following the rupture detonation of the remaining energetic material occurred? How might the detonation accelerate the large pieces of debris that had just been formed by the overpressure driven rupture?

SUMMARY AND CONCLUSIONS

1. While the current weight based approach, $D = kW^{1/3}$ (where D = safe separation distance, k = factor, and W = weight of explosive material), is adequate for determining safe separation distance from mass explosion/mass detonation where the threat is blast and fragments, it is inadequate for mass fire reactions where the threat is direct impingement of hot plumes and exposure to heat flux from the fire. This has been the conclusion of other authors as well.
2. There is a disconnect between assignment of hazard division and determination of safe separation distance distances for HD 1.3. Mass fires (HD 1.3) may, or may not, transition to mass explosion/mass detonation (HD 1.1). Many of the accidents clearly showed that the next significant reaction from mass fire was often explosion(s), which was sometimes followed by mass detonation.
3. But even if mass fire did not transition to mass explosion or mass detonation, mass fire if confined by a robust structure (for example, an earth covered magazine) and if the flow of combustion products from the structure is choked, internal pressure in the structure can quickly accelerate resulting in rupture of the structure and projection of large pieces of debris to significant distances, especially if the rupture is very quickly followed by detonation of the rest of the explosive material. Tests (for example Test 4 from Joachim [Reference 47], and Tests 3 and 4 from Allain [Reference 48]) resulted in rupture of the structure seconds after the gun propellant was ignited and projection of large fragments. For example, in Allain's Test 4 (discussed in Reference 48), fire resulted in over-pressure and rupture of an earth-covered magazine one second after ignition of the gun propellant. This was not a detonation, there was no blast over-pressure and no crater was formed, but several huge fragments (in Allain's test the fragments were the entire walls and roof of the

structure. The head wall produced two large concrete and two large steel fragments that were thrown significant distance. This was caused by burning of HD 1.3 material.

4. One of the accidents (Milan 2004) also produced very large fragments (several feet x several feet) that were projected considerable distances (some as far as 3,100 feet and many found at greater than 2,700 feet from the magazine compared to the 1,250-foot IBD for the 22,353 pounds of explosive that was in the magazine before the accident).
5. One of the major determinants in whether or not burning leads to significant debris being thrown great distances is the race between pressurization due to combustion versus the venting of reaction products from the confining chamber. Of critical importance is whether the flow through the vent(s) was either un-choked or choked. Choked flow occurs when the pressure inside the chamber is approximately 1.7 to 1.9 times (or greater) the outside pressure. Choked flow can rapidly lead to rapid pressurization (in Joachim's Test 4 and Allain's Test 4 the structure ruptured in seconds after ignition) and rupture of the confining structure (they estimated that the internal pressure was approximately 10 bars at rupture) and spreading of secondary fragments/debris as described above in item 3.
6. If the flow was un-choked, unburned energetic material was often expelled and burned outside the chamber not inside the chamber.
7. Reports on some of the accidents reported plumes extending several hundred feet outside the chamber after the magazine doors, or headwall, were blown open.
8. The tests also showed plumes out a significant distance from the chamber. When the plumes from $1/10^{th}$ scale test were scaled by analysis to full-scale, the calculated plume was out 250 feet.
9. Detailed review of the accidents revealed that most of them started with fire. For example, fire was the initial reaction in over 75% of the accidents involving storage of munitions.
10. The fires often burned for minutes and even hours before the next significant reaction, if any, occurred.
11. In a fire, obviously all of the energetic material is not consumed instantly or simultaneously. Even in the tests where the choked flow caused pressure rupture of the confining chamber to occur at about 10 bars of internal pressure, the energetic material continued to burn in a fireball after rupture. This is in marked contrast to a mass detonation where all, or almost all, of the material is consumed extremely quickly and essentially simultaneously.
12. A new method for determining safe separation distances from fires is needed, one that is based on risk and consequence. It needs to address:
    a. Any personnel within the plume boundaries will probably succumb due to the extreme temperatures.
    b. Those that are not within the plume boundaries may also perish due to radiation (heat flux) from the fire if the exposure time is long enough.

13. The consideration of radiation from the fire must include the heat flux and exposure time. A conservative criteria has been proposed by the SFPE, and is based on heat flux (q)-exposure times (t) below. The combinations given by the equation

$$t = 200q^{-1.46}$$

are the threshold for onset of second-degree burns. The distance from a mass fire event that results in the heat flux-exposure times given by this threshold represents a safe separation distance. DDESB has recently adopted this criterion in DOD 6055.09. These changes put the DDESB more in line with the practices of other industries where fire is a significant hazard.

14. Using such a heat flux-exposure time based approach may offer significant advantages over the conventional $D = kW^{1/3}$ approach as demonstrated in the NASA analysis of the Vehicle Assembly Building at Kennedy Space Center summarized in this document.

15. It is imperative that choked flow be prevented in order to prevent rapid pressurization from burning reactions that can cause catastrophic rupture of containing structures and significant debris throw. Construction of buildings with frangible panels to allow proper venting to minimize choked flow should be considered for storage of HD 1.3 materials.

16. Studies should be performed to determine the hazards of mixed storage of HD 1.1, 1.2 and 1.3, given that HD 1.3 materials are generally easier to ignite and burn more readily at one atmosphere than do HD 1.1 materials—the HD 1.3 provides the "match" that starts the fires and may lead to a transition from mass fire to mass explosion/detonation.

17. New tests and trials are proposed to study the hazards with fire as the initial stimulus.

18. Analytical models should be used to help design the tests and to help interpret the test results.

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Appendix A

VARIOUS K FACTORS FOR DETERMINING QUANTITY-DISTANCE (Q-D) FOR HD 1.1 MATERIALS

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This appendix is presented to illustrate the number of k factors needed to address the diversity of situations covered for hazard division (HD) 1.1. Obviously, a great deal of research and development was required to address this diversity. In contrast, HD 1.3 only has two k factors, eight for inhabited building distance (IBD) and public transportation route (PTRD), and five for intraline distance (ILD) and magazine to adjacent magazine (IMD). It may be time to invest in research and development to address the diversity of HD 1.3, a family that spans bulk gun propellant to rocket motors to flares to specialty devices.

k factor	Example Where Used
Air Blast Considerations	
9	IBD, 12 pounds per square inch (psi) air blast overpressure with barricade
18	IBD, 3.5 psi air blast overpressure
24	IBD, 2.3 psi air blast overpressure, remote operation
24-30	IBD, 2.3 to 1.7 psi air blast overpressure
30	1.7 psi air blast overpressure, aircraft parking area with explosives near
40-50	IBD, 1.2 to 0.9 psi air blast overpressure for IBDs, administration and housing areas
Fragment Considerations	
25	IBD from rear of earth-covered magazine (ECM), net explosives weight (NEW) QD <100,000 IBD from front or side of ECM, 45,000 <NEW QD <100,000 pounds
40	IBD from other potential explosive site (PES) (not ECM), 30,000 <NEW QD <100,000 pounds
50	IBD from front or side of ECM, 250,000 pounds<NEW QD
50	IBD from other PES (not ECM), 250,000 pounds <NEW QD
ILD from ECMs considerations, see Table C9-T4 in DOD 6055.09-STD, 29 February 2008	
6	ILD from ECM, NEW QD<300,000 pounds, barricaded, rear exposure
7	ILD from ECM, NEW QD<300,000 pounds, barricaded, side exposure
9	ILD from ECM, NEW QD>400,000 pounds, barricaded, side exposure
9	ILD from ECM, NEW QD>400,000 pounds, barricaded, rear exposure
10	ILD from ECM, NEW QD<300,000 pounds, barricaded, front exposure
12	ILD from ECM, NEW QD<100,000 pounds, unbarricaded, rear exposure
16	ILD from ECM, NEW QD<300,000 pounds, unbarricaded, side exposure
18	ILD from ECM, NEW QD>400,000 pounds, unbarricaded, side exposure
18	ILD from ECM, NEW QD<500,000 pounds, unbarricaded front exposure
18	ILD from ECM, NEW QD>400,000 pounds, unbarricaded, rear exposure
For General ILD	
9	ILD general, barricaded
18	ILD general, unbarricaded

k factor	Example Where Used
Inter-magazine distance considerations from Table C9.T6, DOD 6055.09-STD. This table is a 10-column giving PES x 17-row matrix giving exposed sites (ES). The following are just a few examples taken from the matrix of the table.	
1.1	IMD from barricaded modules or cells (PES) to either barricaded or unbarricaded modules or cells (ES) or from unbarricaded modules or (PES) to barricaded modules or cells (ES)
2	IMD from barricaded or non-barricaded front ECM (PES) to rear of adjacent ECM (7-bar) (ES)
2	IMD from rear of ECM (PES) to front of non-barricaded ECM (7-bar) (ES)
2.75	IMD from barricaded front of ECM (PES) to side of ECM (7-bar) (ES)
4.5	IMD from barricaded above ground magazine (AGM) (PES) to barricaded front of ECM (7-bar) (ES)
6	IMD from non-barricaded AGM (PES) to front of barricaded ECM (3-bar) (ES)
11	IMD from front of high performance magazine (PES) to unbarricaded AGM (ES)

Appendix B

ACCIDENTS INVOLVING FIREWORKS AND LINKS TO ARTICLES DESCRIBING THE ACCIDENTS

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References and links to other accidents associated with fireworks were found, but unfortunately, there was not enough detail in the articles to assess what caused the accidents and discern lessons learned. These accidents and links are presented below.

- Benton, Tennessee, 27 May 1983. Illegal fireworks manufacturing plant. 11 fatalities, 1 injured.
  http://www.burnsfireworks.com/disasters-36.htm
  http://tennesseeencyclopedia.net/imagegallery.php?EntryID=D031

- Aerlex Corp. factory, Hallett, Oklahoma, 25 June 1985. 21 fatalities.
  http://www.tulsaworld.com/TWPDFs/2007/Final/W_061407_A_4.pdf

- Independence Professional Fireworks plant, Osseo, Michigan, 11 December 1998. Seven fatalities, 13 injured. Blast heard for at least 20 miles.

- Independence Professional Fireworks plant, Osseo, Michigan, 29 March 1999. Five fatalities.
  http://www.wsws.org/articles/1999/mar1999/fire-m30.shtml
  http://www.burnsfireworks.com/disasters-26.htm

- Hermanos Borreda factory, Rafelcofer, Spain, 15 May 2000. Seven killed, eight injured. Destroyed 12 buildings on site.
  http://news.bbc.co.uk/2/hi/europe/749609

- Tuqu factory, Jiangmen, China, 30 June 2000. 29 fatalities, 200 injured.
  http://news.bbc.co.uk/2/hi/asia-pacific/813436

- Liborio Fernandes (Lanhelas), Portugal, 2 July 2000. Nine injured, two buildings destroyed on site and several in adjacent town caused by fire that then led to explosions. M. Wood and S. Duffield, "Pyrotechnic and Explosives Substances and the Seveso II Directive," Seminar Proceedings, 27 September 2000, Marseille, France and 28-30 March 2001, Ispra, Italy.

- Fougueyrolles, France, 8 June 2000. Fire followed by explosion in a pyrotechnic workshop destroyed the building and scattered debris along a 90-meter trajectory from the site. M. Wood and S. Duffield, Ibid.

- Jiangxi province, China, 5 August 2000. Two tonnes of illegally stored fireworks killed 21 people and injured 25.
  http://news.bbc.co.uk/2/asia-pacific/867079

- Caldelas, Portugal, 10 August 2001. Five fatalities.
  http://news.bbc.co.uk/2/hi/europe/1484432.stm

- Fanglin village school, Wanzai, Jiangxi province, China, 7 March 2001.
  41 fatalities (possibly 60).
  http://news.bbc.co.uk/2/hi/1494204.stm
  http://wwww.china-labour.org.hk/en/node/3172
  http://news.bbc.co.uk/2/hi/asia-pacific/1206665.stm
  (The above link also lists other incidents but gives sparse details.)

- Linli, Hunan province, China, 20 January 2003. Seven fatalities, nine injured.
  http://www.breakingnews.ie/print/explosion-in-chinese-fireworks-factory-kills-seven-84943.html
  http://www.burnsfireworks.com/disasters-35.htm

- Luoding city, Guangdong Province, China, fireworks shop, 1 February 2003. Seven fatalities, 21 injured.
  http://www.abc.net.au/news/newsitems/200302/s774793.htm

- Nangoku Fireworks Co., Kagoshima, Japan, 11 April 2003. 10 fatalities, four injured with one seriously injured.
  http://search.japantimes.co.jp/print/nm20030412a3.html
  http://shippai.jst.go.jp/en/Detail?fn-0&id=CC1300009

- Bonita Springs, Florida, U.S., 3 July 2003. Truck packed with explosives exploded killing five workers that were unloading.
  http://www.burnsfireworks.com/disasters-13.htm
  http://www.foxnews.com/printer_friendly_story/0,3566,91083,00.html
  http://www.sptimes.com/2003/07/03/State/Truck_packed_with_fir.shtml
  sonjabjelland.com/web.../fireworks_explosion_leaves_four_dead.pdf

- Lamb Entertainment warehouse, Kilgore, Texas, U.S., 4 July 2003. Five fatalities.
  http://www.cbsnews.com/stories/2003/07/04/national/main561726.shtml
  http://www.foxnews.com/story/0,2933,91083,00.html
  http://amarillo.com/stories/2003/07/04/usn_threemissing.shtml
  http://www.foxnews.com/printer_friendly_story/0,3566,91083,00.html

- Guoxi Fireworks Factory, Xinji City, Hebei Province, China, 28 July 2003.
  29 fatalities, at least 141 injured.
  http://www.cbsnews.com/stories/2003/07/29/world/main565603.shtml
  http://wwww.china-labour.org.hk/en/node/3172

- Jingxi fireworks Factory, Munhou County, Fujian Province, 31 July 2003. At least four fatalities, 36 injured.
  http://wwww.china-labour.org.hk/en/node/3172

- Tonglu Fireworks Factory, Zhejiang province. No fatalities, 10 injured. http://wwww.china-labour.org.hk/en/node/3172

- Dongguan, Dafang County, Guizhou Province, 3 August 2003. Fireworks factory. Two fatalities, 10 injured. http://wwww.china-labour.org.hk/en/node/3172

- Rawalpindi, Pakistan, 27 December 2003. Five fatalities. Fire started from sparks from an electric pole that crashed into building when struck by a truck. http://www.tribuneindia.com/2003/20031228/world.htm

- Tieling, Liaoning Province, China, 30 December 2003. 38 fatalities, 30 injured. Chairman of the board of directors was sentenced to death. http://www.burnsfireworks.com/disasters-1.htm http://www.fireworkshk.com/FireworksNews/index.htm

- Changsha, Hunan province, China, 10 December 2004. Railway car carrying fireworks. 18 injured. Http://www.burnsfireworks.com/disaters-35.htm

- Anyang, Henan province, China. 36 fatalities (many praying at nearby temple), 48 injured (some critically), 29 January 2006. http://news.bbc.co.uk/2/hi/4661070.stm

- Festival fireworks, East Essex, UK, 4 December 2006. Two firefighters died when a metal container containing firework exploded, 12 injuries. http://www.independent.co.uk/news/uk/this-britain/two-firefighters-killed-in-explosions-at-f

- St. Helena fireworks factory, Ghargur, Birkirara, Malta, 27 June 2007. Five fatalities, one injured. The plant in an abandoned quarry was completely destroyed by a second explosion that occurred 20 minutes after the first explosion. http://www.epicfireworks.com/blog/2010/03/malta-fireworks-factory-explosion-photograph/ http://www.stop-fireworks.org/unfaelle_malta.htm

- Chongqing, China, 22 October 2007. 16 fatalities, 15 injured. http://www.abc.net.au/news/stories/2007/10/222066825.htm

- Wallerawang, Australia, 8 December 2007. Series of explosions over a 90-minute period completely destroyed 20 buildings and damaged 30 others. No fatalities. http://news.bbc.co.uk/2/hi/asia-pacific/7134964.stm

- Istanbul, Turkey, 31 January 2008. 17 fatalities, 40 injured by two explosions 5 minutes apart.
  http://news.sky.com/skynews/Home/World-News/Turkey-Fireworks-Explosion-In-Factory-Kills-17-People/Article/20080141303
  http://www.nytimes.com/2008/02/01/world/europe/01turkey.html

- Foshan City, Guangdong Province, China, February 2008. 15,000 cartons of fireworks stored in 20 warehouses exploded over a 5-hour period, steel structural debris was found 1,000 meters away on a highway. No fatalities.
  http://www.china.org.cn/english/China/242709.htm

- Dubai, India, 26 March 2008. Fireworks warehouse. Two fatalities.
  http://www.bloomberg.com/apps/news?pid=20670001&sid=az79uRXya97c

- Xinxin Fireworks Plant, Hohhot, Sijiazi Township, Inner Mongolia Autonomous Region, China, 30 August 2008. 15 fatalities, 6 injured.
  http://www.cnn.com/2008/WORLD/asiapcf/08/31/china.fireworks.blast/index.html

- Dianbai, China, 17 November 2008. Four fatalities.
  http://www.thaindian.com/newsportal/uncategorized/four-killed-in-china-firework-plant-bla

- Weifang city, Shandong Province, China, 3 January 2009. 13 fatalities, two injured.
  http://www.zeenews.com/printstory.aspx?id+495956

- Star maker fireworks plant, Trece Martires City, Cavite, the Philippines, 29 January 2009. At least 8 fatalities, more than 70 injuries. Several craters with one being 200 meters wide.
  http://www.abs-cbnnews.com/nation/regions/01/29/09/fireworks-factory-explodes-cavite-sc
  http://en.wikinews.org/wiki/Philippine_fireworks_factory_explosion_kils_at_least_8,_injur

- Fuhao Fireworks Plant, Tanbu town, Wanzai County, Jiangxi province, China, 7 May 2009. Three fatalities, 4 injured.
  http://blog.shogun.com.hk/2009/05/wanzai-county-fireworks-plant-blast.html?utm_source=feedburner&utm_medium+feed&utm

- Jinan, China, May 2009. At least 13 fatalities.
  http://www.upi.com/Top_News/2009/05/02/13-die-in-Chinese-fireworks-plant-blast/UPI-62

- Ocracoke, North Carolina, U.S., 4 July 2009. A truck carrying fireworks was being unloaded when the fireworks exploded. Four fatalities.
http://www.wral.com/news/local/story/5502082/
http://www2.insidenova.com/isn/news/locaql/article/fireworks_accident_kills_four_on_ocrac

- Muridke, Punjab, Pakistan, 15 July 2009. Four fatalities, eight critically injured.
http://www.thaindian.com/newsportal/south-asia/pakistan-fireworks-factory-blast-kills-four

- Shri Krishna Fireworks factory, Namaskarichanpatti/Sivakasi, Tamil Nadu, India. Fire led to a series of explosions that resulted in eight fatalities and 45 injured. 20 July 2009.
http://www.topnews.in/eight-dead-explosion-fireworks-unit-tamil -nadu-2191422

- Ghaxaq St. Joseph Fireworks Factory, Malta, 24 September 2009. No fatalities because no one was present at time of explosion.
http://www.timesofmalta.com/articles/view/20090925/local/ghaxaq-fireworks-factory-explodes

- Pallipat, Tamil Nadu, India, 17 October 2009. 33 fatalities, 10 injured.
http://www.euronews.net/2009/10/17/32-die-in-indian-fireworks-blast/
http://www.stagesafe.co.uk/news/2009/november/index.html

- Anhui Province, China, 11 January 2010. 4 fatalities.
http://www.topnews.in/4-killed-fireworks-blast-china-2251625

- Hohhot, Inner Mongolia, China, 27 January 2010. Explosion at illegal fireworks factory. Five fatalities, 10 injured.
http://www.straitstimes.com/BreakingNews/Asia/Story/STIStory_482882.html

- St. Sebastian fireworks Factory, Handaq, Qormi, Malta, 23 February 2010. Two fatalities, two injured (minor).
http://forum.vuurwerkcrew.nl/showthread.php?t=15203

- Puning, Guangdong, China, 27 February 2010. 21 fatalities, 48 injured.
http://english.ntdt.com/ntdv_en/ns_china/2010-03-01/040965832541.html

Obviously there have been many accidents in many countries, with associated fatalities, injuries, and property damage.

> [Note: While the author was performing the literature search, one source of accident information appeared relatively late in the effort. The stop-fireworks organization has a website that lists fireworks related accidents in over 60 countries, listed by country.
> http://www.stop-fireworks.org/accidents.htm#list_e.
> The author wishes this website had been found earlier.]

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