Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs

CENTER FOR CHEMICAL PROCESS SAFETY
of the American Institute of Chemical Engineers
3 Park Avenue, New York, NY 10016-5901
This page intentionally left blank
Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs
Publications Available from the
CENTER FOR CHEMICAL PROCESS SAFETY
of the
AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

Guidelines for Preventing Human Error in Process Safety
Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs
Guidelines for Implementing Process Safety Management Systems
Guidelines for Safe Automation of Chemical Processes
Guidelines for Engineering Design for Process Safety
Guidelines for Auditing Process Safety Management Systems
Guidelines for Investigating Chemical Process Incidents
Guidelines for Hazard Evaluation Procedures, Second Edition with Worked Examples
Plant Guidelines for Technical Management of Chemical Process Safety
Guidelines for Technical Management of Chemical Process Safety
Guidelines for Chemical Process Quantitative Risk Analysis
Guidelines for Process Equipment Reliability Data, with Data Tables
Guidelines for Vapor Release Mitigation
Guidelines for Safe Storage and Handling of High Toxic Hazard Materials
Guidelines for Use of Vapor Cloud Dispersion Models
Safety, Health, and Loss Prevention in Chemical Processes: Problems for Undergraduate Engineering Curricula
Workbook of Test Cases for Vapor Cloud Source Dispersion Models
CCPS/AIChe Directory of Chemical Process Safety Services
Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs

CENTER FOR CHEMICAL PROCESS SAFETY
of the
American Institute of Chemical Engineers
3 Park Avenue, New York, NY 10016-5901
# CONTENTS

*Acknowledgments*

*A Note on Nomenclature and Units*

*Glossary*

## 1. INTRODUCTION

## 2. PHENOMENA: DESCRIPTIONS, EFFECTS, AND ACCIDENT SCENARIOS

2.1. Vapor Cloud Explosions  
2.2. Flash Fires  
2.3. BLEVEs  
2.4. Historical Experience  
References

## 3. BASIC CONCEPTS

3.1. Atmospheric Vapor Cloud Dispersion  
3.2. Combustion Modes  
3.3. Ignition  
3.4. Blast  
3.5. Thermal Radiation  
References

## 4. BASIC PRINCIPLES OF VAPOR CLOUD EXPLOSIONS

4.1. Overview of Experimental Research  
4.2. Overview of Computational Research  
4.3. Vapor Cloud Explosion Blast Modeling  
4.4. Summary and Discussion  
References

## 5. BASIC PRINCIPLES OF FLASH FIRES

5.1. Overview of Research  
5.2. Flash-Fire Radiation Models  
5.3. Summary and Discussion  
References
6. BASIC PRINCIPLES OF BLEVEs
   6.1. Mechanism of a BLEVE
   6.2. Radiation
   6.3. Blast Effects of BLEVEs and Pressure Vessel Bursts
   6.4. Fragments
   6.5. Summary and Discussion
   References

7. VAPOR CLOUD EXPLOSIONS—SAMPLE PROBLEMS
   7.1. Choice of Method
   7.2. Methods
   7.3. Sample Calculations
   7.4. Discussion
   References

8. FLASH FIRES—SAMPLE PROBLEMS
   8.1. Method
   8.2. Sample Calculation

9. BLEVEs—SAMPLE PROBLEMS
   9.1. Radiation
   9.2. Blast Parameter Calculations for BLEVEs and Pressure Vessel Bursts
   9.3. Fragments
   References

APPENDIX A. VIEW FACTORS FOR SELECTED CONFIGURATIONS
   A-1. View Factor of a Spherical Emitter (e.g., Fireball)
   A-2. View Factor of a Vertical Cylinder
   A-3. View Factor of a Vertical Plane Surface
   References

APPENDIX B. EFFECTS OF EXPLOSIONS ON STRUCTURES

APPENDIX C. EFFECTS OF EXPLOSIONS ON HUMANS
   C-1. Introduction
   C-2. Primary Effects
   C-3. Secondary Effects
   C-4. Tertiary Effects
   References
ACKNOWLEDGMENTS

The Center for Chemical Process Safety of the American Institute of Chemical Engineers owes a great deal of thanks to the dedicated and professional engineers and scientists who served with distinction on the Vapor Cloud Explosion subcommittee during the development of this Guidelines book. They are:

- John A. Davenport (Industrial Risk Insurers), chair
- John V. Birtwistle (Monsanto Chemical Company)
- Stanley S. Grossel (Hoffman-LaRoche, Inc.)
- R. A. Hawrelak (Dow Chemical Canada Inc.)
- Peter D. Hoffman (Hoechst Celanese)
- David C. Kirby (Union Carbide Corporation)
- Robert E. Linney (Air Products and Chemicals, Inc.)
- Robert A. Mancini (Amoco Corporation)
- M. Reid McPhail (Novacor Chemicals Ltd.)
- Larry J. Moore (Factory Mutual Research Corporation)
- Francisco N. Nazario (Exxon Research and Engineering Company)
- Gary A. Page (American Cyanamid Company)
- Ephraim A. Scheier (Mobil Research and Development Corporation)
- Richard F. Schwab (Allied Signal, Inc.)

The task of preparing the text, examples, tables, and figures of the book was entrusted to TNO Prins Maurits Laboratory, Rijswijk, the Netherlands. The principal authors were all members of the Explosion Prevention Department of the Laboratory:

- Kees van Wingerden
- Bert van den Berg
- Daan van Leeuwen
- Paul Mercx
- Rolf van Wees

Their technical expertise is evident in both the characterization of the phenomena that this book explores (Chapters 2–6) and the practical examples that illustrate these phenomena (Chapters 7–9).

The authors and the subcommittee were well served during this transnational effort by Dr. Hans J. Pasman, then Director, Technological Research, and Mr. Gerard Opschoor, Head, Explosion Prevention Department, TNO PML. Likewise, Mr. Thomas W. Carmody, then Director, CCPS, supported this important work. William J. Minges provided CCPS staff help.
ACKNOWLEDGMENTS

Peer review for this important and lengthy volume was provided by:

Philip Comer, Technica, Inc.
R. C. Frey, M. W. Kellogg
T. O. Gibson, Dow Chemical
D. L. Macklin, Phillips Petroleum
S. J. Schechter, Rohm and Haas

Finally, CCPS is grateful to Dr. B. H. Hjertager, Telemark Institute of Technology and Telemark Innovation Centre, Porsgrunn, Norway, for preparing “A Case Study of Gas Explosions in a Process Plant Using a Three-dimensional Computer Code” (Appendix F).

For this second printing, CCPS acknowledges the thoughtful, technical, time-consuming efforts of Dick Hawrelak, now retired from Dow, but a former subcommittee member, who painstakingly reviewed the first printing of this book.

A NOTE ON NOMENCLATURE AND UNITS

The equations in this volume are from a number of reference sources, not all of which use consistent nomenclature (symbols) and units. In order to facilitate comparisons within sources, the conventions of each source were presented unchanged.

Nomenclature and units are given after each equation (or set of equations) in the text. Readers should ensure that they use the proper values when applying these equations to their problems.
GLOSSARY

**Blast:** A transient change in the gas density, pressure, and velocity of the air surrounding an explosion point. The initial change can be either discontinuous or gradual. A discontinuous change is referred to as a shock wave, and a gradual change is known as a pressure wave.

**BLEVE (Boiling Liquid, Expanding Vapor Explosion):** The explosively rapid vaporization and corresponding release of energy of a liquid, flammable or otherwise, upon its sudden release from containment under greater-than-atmospheric pressure at a temperature above its atmospheric boiling point. A BLEVE is often accompanied by a fireball if the suddenly depressurized liquid is flammable and its release results from vessel failure caused by an external fire. The energy released during flashing vaporization may contribute to a shock wave.

**Burning velocity:** The velocity of propagation of a flame burning through a flammable gas-air mixture. This velocity is measured relative to the unburned gases immediately ahead of the flame front. Laminar burning velocity is a fundamental property of a gas-air mixture.

**Deflagration:** A propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance rapidly but at less than sonic velocity in the unreacted material.

**Detonation:** A propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at or greater than sonic velocity in the unreacted material.

**Emissivity:** The ratio of radiant energy emitted by a surface to that emitted by a black body of the same temperature.

**Emissive power:** The total radiative power discharged from the surface of a fire per unit area (also referred to as surface-emissive power).

**Explosion:** A release of energy that causes a blast.

**Fireball:** A burning fuel-air cloud whose energy is emitted primarily in the form of radiant heat. The inner core of the cloud consists almost completely of fuel, whereas the outer layer (where ignition first occurs) consists of a flammable fuel-air mixture. As the buoyancy forces of hot gases increase, the burning cloud tends to rise, expand, and assume a spherical shape.
Flame speed: The speed of a flame burning through a flammable mixture of gas and air measured relative to a fixed observer, that is, the sum of the burning and translational velocities of the unburned gases.

Flammable limits: The minimum and maximum concentrations of combustible material in a homogeneous mixture with a gaseous oxidizer that will propagate a flame.

Flash vaporization: The instantaneous vaporization of some or all a liquid whose temperature is above its atmospheric boiling point when its pressure is suddenly reduced to atmospheric.

Flash fire: The combustion of a flammable gas or vapor and air mixture in which the flame propagates through that mixture in a manner such that negligible or no damaging overpressure is generated.

Impulse: A measure that can be used to define the ability of a blast wave to do damage. It is calculated by the integration of the pressure-time curve.

Jet: A discharge of liquid, vapor, or gas into free space from an orifice, the momentum of which induces the surrounding atmosphere to mix with the discharged material.

Lean mixture: A mixture of flammable gas or vapor and air in which the fuel concentration is below the fuel's lower limit of flammability (LFL).

Negative phase: That portion of a blast wave whose pressure is below ambient.

Overpressure: Any pressure above atmospheric caused by a blast.

Positive phase: That portion of a blast wave whose pressure is above ambient.

Pressure wave: See Blast.

Reflected pressure: Impulse or pressure experienced by an object facing a blast.

Rich mixture: A mixture of flammable gas or vapor and air in which the fuel concentration is above the fuel's upper limit of flammability (UFL).

Shock wave: See Blast.

Side-on pressure: The impulse or pressure experienced by an object as a blast wave passes by it.

Stoichiometric ratio: The precise ratio of air (or oxygen) and flammable material which would allow all oxygen present to combine with all flammable material present to produce fully oxidized products.

Superheat limit temperature: The temperature of a liquid above which flash vaporization can proceed explosively.

Surface-emissive power: See Emissive power.
**Transmissivity:** The fraction of radiant energy transmitted from a radiating object through the atmosphere to a target after reduction by atmospheric absorption and scattering.

**TNT equivalence:** The amount of TNT (trinitrotoluene) that would produce observed damage effects similar to those of the explosion under consideration. For non-dense phase explosions, the equivalence has meaning only at a considerable distance from the explosion source, where the nature of the blast wave arising is more or less comparable with that of TNT.

**Turbulence:** A random-flow motion of a fluid superimposed on its mean flow.

**Vapor cloud explosion:** The explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure.

**View factor:** The ratio of the incident radiation received by a surface to the emissive power from the emitting surface per unit area.
INTRODUCTION

The American Institute of Chemical Engineers (AIChE) has been involved with process safety and loss control for chemical and petrochemical plants for more than thirty years. Through its strong ties with process designers, builders, operators, safety professionals, and academia, AIChE has enhanced communication and fostered improvements in the safety standards of the industry. Its publications and symposia on causes of accidents and methods of prevention have become information resources for the chemical engineering profession.

Early in 1985, AIChE established the Center for Chemical Process Safety (CCPS) to serve as a focus for a continuing program for process safety. The first CCPS project was the publication of a document entitled Guidelines for Hazard Evaluation Procedures. In 1987 Guidelines for Use of Vapor Cloud Dispersion Models was published and in 1989 Guidelines for Chemical Process Quantitative Risk Analysis and Guidelines for Technical Management of Chemical Process Safety were published. The present book has evolved from the eighth CCPS project.

This text is intended to provide an overview of methods for estimating the characteristics of vapor cloud explosions, flash fires, and boiling-liquid-expanding-vapor explosions (BLEVEs) for practicing engineers. The volume summarizes and evaluates all the current information, identifies areas where information is lacking, and describes current and planned research in the field.

For the novice, this volume provides a starting point for understanding the phenomena covered and presents methods for calculating the possible consequences of incidents. It also offers an overview and resource reference for experts. It should provide managers with a basic understanding of the phenomena, methods of calculation to estimate consequences, and the limitations of each method. The authors also hope that this volume can be taken as a starting point for future research.

This volume consists of two parts: Chapters 1–6 and Chapters 7–9. Chapters 1 through 6 offer detailed background information. They describe pertinent phenomena, give an overview of past experimental and theoretical research, and provide methods for estimating consequences. Chapter 2 describes the phenomena covered, identifies various accident scenarios leading to each of the events, and describes actual accidents. In Chapter 3, principles such as dispersion, deflagration, detonation, blast, and radiation are explained.

Each event treated requires a different approach in estimating effects. Therefore, each type of event is covered in a separate chapter. Chapters 4, 5, and 6 give background information, including experimental and theoretical research and conse-
quence modeling techniques, on vapor cloud explosions, flash fires, and BLEVEs, respectively.

Chapters 7, 8, and 9 demonstrate the consequence modeling techniques for vapor cloud explosions, BLEVEs, and flash fires, respectively, by presenting sample problems. These problems contain sufficient detail to allow an engineer to use the methods presented to evaluate specific hazards.

The authors have not attempted to describe all experimental and theoretical research in the field. Rather, the most important activities and their results are covered in order to offer an adequate understanding of the basic physical principles.

This volume does not address subjects such as toxic effects, explosions in buildings and vessels, runaway reactions, condensed-phase explosions, pool fires, jet flames, or structural responses of buildings. Furthermore, no attempt is made to cover the frequency or likelihood that a related accident scenario will occur. References to other works are provided for readers interested in these phenomena.
Accidents involving fire have occurred ever since man began to use flammable liquids or gases as fuels. Summaries of such accidents are given by Davenport (1977), Strehlow and Baker (1976), Lees (1980), and Lenoir and Davenport (1993). The presence of flammable gases or liquids can result in a BLEVE or flash fire or, if sufficient fuel is available, a vapor cloud explosion.

The likelihood of such occurrences can be reduced by process design and reliability engineering which meet or exceed established codes of practice. These codes include well-designed pressure relief and blowdown systems, adequate maintenance and inspection programs, management of human factors in system design and, perhaps most important, a full understanding and support by responsible managers of risk management efforts. Nevertheless, despite all of these precautions, accidents may still occur, sometimes resulting in death, serious injury, damage to facilities, loss of production, and damage to reputation in the community.

Mathematical models for calculating the consequences of such events should be employed in order to support efforts toward mitigation of their consequences. Mitigating measures may include reduction of storage capacity; reduction of vessel volumes; modification of plant siting and layout, including location of control rooms; strengthening of vessels and other plant items; and reinforcing of control rooms.

Knowledge of the consequences of vapor cloud explosions, flash fires, and BLEVEs has grown enormously in recent years as a result of many international efforts. Insights gained regarding the processes of generation of overpressure, radiation, and fragmentation have resulted in the development of reasonably descriptive models for calculating the effects of these phenomena.

This chapter describes the main features of vapor cloud explosions, flash fires, and BLEVEs. It identifies the similarities and differences among them. Effects described are supported by several case histories. Chapter 3 will present details of dispersion, deflagration, detonation, ignition, blast, and radiation.

2.1. VAPOR CLOUD EXPLOSIONS

A vapor cloud explosion may be simply defined as an explosion occurring outdoors, producing a damaging overpressure (Factory Mutual Research Corporation, 1990).
It begins with the release of a large quantity of flammable vaporizing liquid or gas from a storage tank, process or transport vessel, or pipeline. Generally speaking, several features need to be present for a vapor cloud explosion with damaging overpressure to occur.

First, the released material must be flammable and at suitable conditions of pressure or temperature. Such materials include liquefied gases under pressure (e.g., propane, butane); ordinary flammable liquids, particularly at high temperatures and/or pressures (e.g., cyclohexane, naphtha); and nonliquefied flammable gases (e.g., methane, ethylene, acetylene).

Second, a cloud of sufficient size must form prior to ignition (dispersion phase). Should ignition occur instantly, a large fire, jet flame, or fireball may occur, but significant blast-pressure damage is unlikely. Should the cloud be allowed to form over a period of time within a process area, then subsequently ignite, blast pressures that develop can result in extensive, widespread damage. Ignition delays of 1 to 5 minutes are considered the most probable for generating vapor cloud explosions, although major incidents with ignition delays as low as a few seconds and greater than 30 minutes are documented.

Third, a sufficient amount of the cloud must be within the flammable range of the material to cause extensive overpressure. A vapor cloud will generally have three regions: a rich region near the point of release, a lean region at the edge of the cloud, and a region in between that is within the flammable range. The portion of the vapor cloud in each region depends on many factors, including type and amount of the material released; pressure at time of release; size of release opening; degree of confinement of the cloud; and wind, humidity, and other environmental effects (Hanna and Drivas 1987).

Fourth, the blast effects produced by vapor cloud explosions can vary greatly and are determined by the speed of flame propagation. In most cases, the mode of flame propagation is deflagration. Under extraordinary conditions, a detonation might occur.

A deflagration can best be described as a combustion mode in which the propagation rate is dominated by both molecular and turbulent transport processes. In the absence of turbulence (i.e., under laminar or near-laminar conditions), flame speeds for normal hydrocarbons are in the order of 5 to 30 meters per second. Such speeds are too low to produce any significant blast overpressure. Thus, under near-laminar-flow conditions, the vapor cloud will merely burn, and the event would simply be described as a large flash fire. Therefore, turbulence is always present in vapor cloud explosions. Research tests have shown that turbulence will significantly enhance the combustion rate in deflagrations.

Turbulence in a vapor cloud explosion accident scenario may arise in any of three ways:

- by turbulence associated with the release itself (e.g., jet release or a catastrophic failure of a vessel resulting in an explosively dispersed cloud);
2.2. FLASH FIRES

- by turbulence produced in unburned gases expanding ahead of a flame propagating through a congested space;
- by externally induced turbulence from objects such as ventilation systems, finned-tube heat exchangers, and fans.

Of course, all mechanisms may also occur simultaneously, as, for example, with a jet release within a congested area.

These mechanisms may cause very high flame speeds and, as a result, strong blast pressures. The generation of high combustion rates is limited to the congested area, or the area affected by the turbulent release. As soon as the flame enters an area without turbulence, both the combustion rate and pressure will drop.

In the extreme, the turbulence can cause a sufficiently energetic mixture to convert from deflagration to detonation. This mode of flame propagation is attended by propagation speeds in excess of the speed of sound (2 to 5 times the speed of sound) and maximum overpressures of about 18 bar (260 psi). Once detonation occurs, turbulence is no longer necessary to maintain its speed of propagation. This means that uncongested and/or quiescent flammable portions of a cloud may also contribute to the blast. Note, however, that for a detonation to propagate, the flammable part of the cloud must be very homogeneously mixed. Because such homogeneity rarely occurs, vapor cloud detonations are unlikely.

Whether a deflagration or detonation occurs is also influenced by the available energy of ignition. Deflagration of common hydrocarbon–air mixtures requires an ignition energy of approximately $10^{-4}$ Joules. By contrast, direct initiation of detonation of normal hydrocarbon–air mixtures requires an initiation energy of approximately $10^6$ joules; this level of energy is comparable to that generated by a high-explosive charge. A directly initiated detonation is, therefore, highly unlikely.

An event tree can be used to trace the various stages of development of a vapor cloud explosion, as well as the conditions leading to a flash fire or a vapor cloud detonation (Figure 2.1).

2.2. FLASH FIRES

A flash fire results from the ignition of a released flammable cloud in which there is essentially no increase in combustion rate. In fact, the combustion rate in a flash fire does increase slightly compared to the laminar phase. This increase is mainly due to the secondary influences of wind and surface roughness.

Figure 2.1 identifies the conditions necessary for the occurrence of a flash fire. Only combustion rate differentiates flash fires from vapor cloud explosions. Combustion rate determines whether blast effects will be present (as in vapor cloud explosions) or not (as in flash fires).

The principal dangers of a flash fire are radiation and direct flame contact. The size of the flammable cloud determines the area of possible direct flame contact
Figure 2.1. Event tree for vapor cloud explosions and flash fires.

effects. Cloud size, in turn, depends partially on dispersion and release conditions. Radiation effects on a target depend on its distance from flames, flame height, flame emissive power, local atmospheric transmissivity, and cloud size.

Until recently, very little attention has been paid to the investigation of flash fires. Chapter 5 summarizes results of investigations performed thus far.

2.3. BLEVEs

A BLEVE is an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure. In contrast to flash fire and vapor cloud explosions, a liquid does not have to be flammable to cause a BLEVE. In fact, BLEVE, which is an acronym for "boiling-liquid-expanding-vapor explosion," was first applied to a steam explosion. Nonflammable liquid BLEVEs produce only two effects: blast due to the expansion of the vapor in the container and flashing of the liquid, and fragmentation of the container.

BLEVEs are more commonly associated with releases of flammable liquids from vessels as a consequence of external fires. Such BLEVEs produce, in addition to blast and fragmentation effects, buoyant fireballs whose radiant energy can burn exposed skin and ignite nearby combustible materials. A vessel may rupture for a
different reason and not result in immediate ignition of its flammable contents. If the flammable contents mix with air, then ignite, a vapor cloud explosion or flash fire will result.

A BLEVE’s effects will be determined by the condition of the container’s contents and of its walls at the moment of container failure. These conditions also relate to the cause of container failure, which may be

- an external fire,
- mechanical impact,
- corrosion,
- excessive internal pressure, or
- metallurgical failure.

The blast and fragmentation effects of a BLEVE depend directly on the internal energy of the vessel’s contents—a function of its thermodynamic properties and mass. This energy is potentially transformed into mechanical energy in the form of blast and generation of fragments.

Fluid in a container is a combination of liquid and vapor. Before container rupture, the contained liquid is usually in equilibrium with the saturated vapor. If a container ruptures, vapor is vented and the pressure in the liquid drops sharply. Upon loss of equilibrium, liquid flashes at the liquid–vapor interface, the liquid–container–wall interface, and, depending on temperature, throughout the liquid.

Depending on liquid temperature, instantaneous boiling may occur throughout the bulk of the liquid. Microscopic vapor bubbles begin to form and grow. Through this process, a large fraction of the liquid can vaporize within milliseconds. Instantaneous boiling will occur whenever the temperature of the liquid is higher than the homogeneous nucleation temperature or superheat limit temperature. The liberated energy in such cases is very high, causing high blast pressures and generation of fragments with high initial velocities, and resulting in propulsion of fragments over long distances. If the temperature is below the superheat limit temperature, the energy for the blast and fragment generation is released mainly from expansion of vapor in the space above the liquid. Energy, based on unit volume, from this source is about one-tenth the energy liberated from a failing container of liquid above the superheat limit.

The pressure and temperature of a container’s contents at the time of failure will depend on the cause of failure. In fire situations, direct flame impingement will weaken container walls. The pressure at which the container fails will usually be about the pressure at which the safety valve operates. This pressure may be as much as 20 percent above the valve’s setting. The temperature of the container’s contents will usually be considerably higher than the ambient temperature.

If a vessel ruptures as a result of excessive internal pressure, its bursting pressure may be several times greater than its design pressure. However, if the rupture is due to corrosion or mechanical impact, bursting pressure may be lower
than the design pressure of the vessel. Temperatures in these situations will depend
on process conditions.

Internal energy prior to rupture also affects the number, shape, and trajectory
of fragments. Ruptures resulting from BLEVEs tend to produce few fragments, but
they can vary greatly in size, shape, and initial velocities. Large fragments, for
example, those consisting of half of the vessel, and disk-shaped fragments can be
projected for long distances. Rocketing propels the half-vessel shapes, whereas
aerodynamic forces account for the distances achieved by disk-shaped fragments.

A BLEVE involving a container of flammable liquid will be accompanied by
a fireball if the BLEVE is fire-induced. The rapid vaporization and expansion
following loss of containment results in a cloud of almost pure vapor and mist.
After ignition, this cloud starts to burn at its surface, where mixing with air is
possible. In the buoyancy stage, combustion propagates to the center of the cloud
causing a massive fireball.

Radiation effects due to the fireball depend on

- the diameter of the fireball as a function of time and the maximum diameter
  of the fireball;
- the height of the center of the fireball above its ignition position as a function
  of time (after liftoff);
- the surface-emissive power of the fireball;
- the duration of combustion.

The distance of the fireball to targets and the atmospheric transmissivity will
determine the consequences of radiation.

Investigations of the effects of BLEVEs (Chapter 6) are usually limited to the
aspect of thermal regulation. Blast and fragmentation have been of less interest to
researchers and, hence, not studied in as much detail.

2.4. HISTORICAL EXPERIENCE

Selection of incidents described was based on the availability of information, the
kind and amount of material involved, and severity of damage. Accidents occurring
on public property generally produce better published documentation than those
occurring on privately owned property.

The vapor cloud explosion incidents described below cover a range of factors:

- Material properties: Histories include incidents involving hydrogen (a highly
  reactive gas), propylene, dimethyl ether, propane, cyclohexane (possibly partly
as a mist), methane (generally classified as a low-reactivity gas), and natural gas liquids.

- **Period of time covered**: Explosions occurring over the period between the years 1948 and 1989 are reported.
- **Quantity released**: Releases ranged in quantity from 110 kg (240 lb) to 70,000 kg (150,000 lb);
- **Site characteristics**: Releases occurred in settings ranging from rural to very congested industrial areas.
- **Availability of information**: Very well-documented incidents (e.g., Hixborough) as well as poorly documented incidents (e.g., Ufa) are described.
- **Severity**: Death tolls and damage from pressure effects vary widely in cases presented.

Most incidents discussed occurred several years ago, but it should be emphasized that such incidents still occur. More recent incidents include Celanese (1987), Shell (1988), Phillips (1989), and Exxon (1989).

Documentation of flash fires is scarce. In several accident descriptions of vapor cloud explosions, flash fires appear to have occurred as well, including those at Flixborough, Port Hudson, East St. Louis, and Ufa. The selection and descriptions of flash fires were based primarily on the availability of information.

![Figure 2.2. Damage at Phillips, 1989.](image-url)
2.4.1. Vapor Cloud Explosions

**Flixborough, UK: Vapor Cloud Explosion in Chemical Plant**

On June 1, 1974, a cyclohexane vapor cloud was released after the rupture of a pipe bypassing a reactor. In total, approximately 30,000 kg of cyclohexane was released. The cyclohexane formed a cloud which ignited after a period of approximately 30 to 90 seconds. As a result, a very strong explosion occurred which caused the death of 28 people and injured 36 people. The plant was totally destroyed and 1821 houses and 167 stores and factories in the vicinity of the plant were damaged.

Parker (1975), Lees (1980), Gugan (1978), and Sadée et al. (1976, 1977) have described extensively the vapor cloud explosion that occurred in the reactor section of the caprolactam plant of the Flixborough Works on June 1, 1974. The Flixborough Works is situated on the east bank of the River Trent. The nearest villages are Flixborough [800 meters (one-half mile) away], Amcotts [800 meters (one-half mile) away], and Scunthorpe [4.9 km (approximately three miles) away].

The cyclohexane oxidation plant contained a series of six reactors. The reactors were fed by a mixture of fresh cyclohexane and recycled material. The reactors were connected by a pipe system, and the liquid reactant mixture flowed from one reactor into the other by gravity. Reactors were designed to operate at a pressure of approximately 9 bar (130 psi) and a temperature of 155°C (311°F). In March, one of the reactors began to leak cyclohexane, and it was, therefore, decided to remove the reactor and install a bypass. A 20-inch diameter bypass pipe was installed connecting the two flanges of the reactors. Bellows originally present between the reactors were left in place. Because reactor flanges were at different heights, the pipe had a dog-leg shape (Figure 2.3).

On May 29, the bottom isolating valve on a sight glass on one of the vessels began to leak, and a decision was made to repair it. On June 1, start-up of the process following repair began. As a result of poor design, the bellows in the bypass failed and a release of an estimated 30 tons of cyclohexane occurred, most of which formed a flammable cloud of vapor and mist.

After a period of 30 to 90 seconds following release, the flammable cloud was ignited. The time was then about 4:53 P.M. The explosion caused extensive damage and started numerous fires. The blast shattered control room windows and caused the collapse of its roof. It demolished the main office block, only 25 m from the explosion center. Twenty-eight people died, and thirty-six were injured. The plant was totally destroyed (Figures 2.4 and 2.5), and 1821 houses and 167 shops and factories in the vicinity of the plant were damaged.

Sadée et al. (1976–1977) give a detailed description of structural damage due to the explosion and derived blast pressures from the damage outside the cloud.
Several authors estimated the TNT mass equivalence based upon the damage incurred. Estimates vary from 15,000 and 45,000 kg.

Estimates of pressures inside the cloud vary widely. Gugan (1978) calculated that the forces required to produce damage effects observed, such as the bending of steel, would have required local pressures of up to 5–10 bar.

**Ludwigshafen, Germany: Rupture of Tank Car Overheated in Sun**

On July 28, 1948, a rail car containing liquefied dimethyl ether ruptured and released its entire contents. The rupture was due to the generation of excessive pressures created by long solar exposure following initial overfilling. The gas was ignited after 10 to 25 seconds. The ensuing vapor cloud explosion caused the death of 207 people and injured 3818.

Marshall (1986) describes the accident at BASF in Ludwigshafen drawing extensively on original data. On July 28, 1948, a railway tank car suffered a catastrophic failure and discharged its entire contents of 30,400 kg of dimethyl ether. The
Figure 2.4. Area of spill showing removed reactor.

Figure 2.5. Damage to congested area of Flixborough works.
Figure 2.6. Blast–distance relationship outside the cloud area of the Flixborough explosion. (Vertical bars were drawn based on observed damage.)

catastrophic failure was, according to the original data, due to overfilling of the car. On the day of the explosion, the ambient temperature reached approximately 30° to 32°C (86° to 90°F). Heating and consequent expansion of its contents resulted in hydraulic rupture.

An alternative explanation, proposed by Marshall (1986) is that there was a defect in the construction of the tank car. The increase in vapor pressure caused
by the higher temperature resulted in the tank car failure. The failure had taken place principally along a welded horizontal seam. Witnesses claim to have seen a brownish-white cloud appearing from the tank car, accompanied by a whistling sound, before the car ruptured completely.

According to Giesbrecht et al. (1981), there was a delay of 10 to 25 seconds between the moment of the initial large release and the moment of ignition. The explosion must have been very violent in view of the extensive structural damage to the plant. The high death toll was due to the high population density in the vicinity of the point of release.

The TNT equivalence of the blast was estimated to be 20–60 tons (Davenport, 1983). The area of total destruction was 430,000 ft² (40,000 m²) and the area of total destruction plus severe damage was 3,200,000 ft² (300,000 m²) (Figures 2.7–2.9). The main cause of the explosion was the turbulence generated by the release itself. The release did, however, occur in a very congested area.

Port Hudson, Missouri, USA: Vapor Cloud Explosion after Propane Pipeline Failure

On December 9, 1970, a liquefied propane pipeline ruptured near Port Hudson. About 24 minutes later, the resulting vapor cloud was ignited. The pressure effects were very severe. The blast was equivalent to that of 50,000 kg of detonating TNT.

Figure 2.7. Remains of exploded tank car.
Burgess and Zabetakis (1973) describe the Port Hudson explosion, which took place on December 9, 1970. At 10:07 p.m., an abnormality occurred at a pumping station on a liquid propane line 24 km (15 miles) downstream from Port Hudson. At 10:20 p.m., there was a sudden increase in the throughput at the nearest upstream pumping station, indicating a major break in the line. During the first 24 minutes, an estimated 23,000 kg (50,000 lb) of liquid propane escaped. The noise of escaping propane was noticed at about 10:25 p.m. A plume of white spray was observed to be rising 15 to 25 m (50 to 80 ft) above ground level. The pipeline was situated in a valley, and a highway ran at about one-half mile (800 m) from the pipeline. Witnesses standing near a highway intersection observed a white cloud settling into the valley around a complex of buildings. Weather conditions were as follows: low wind (approximately 2.5 m/s [8 ft/s]) and near-freezing temperature (1°C; 34°F). At about 10:44 p.m., the witnesses saw the valley "lighting up." No period of flame propagation was observed. A strong pressure pulse was felt and one witness was knocked down.

After the valley was illuminated, a flash fire was observed, which consumed the remainder of the cloud. After the explosion and flash fire, a torch fire resulted at the point of the initial release. Buildings in the vicinity of the explosion were damaged (Figures 2.10 and 2.11).
The cloud was probably ignited inside a concrete-block warehouse. The ground floor of this building, partitioned into four rooms, contained six deep-freeze units. Gas could have entered the building via sliding garage doors, and ignition could have occurred at the controls of a refrigerator motor.

Damage from the blast in the vicinity was calculated to be equivalent to a blast of 50,000 to 75,000 kg of TNT. According to Burgess and Zabetakis (1973), the Port Hudson vapor cloud detonated. As far as is known, this is the only vapor cloud explosion that may have been a detonation.

Enschede, The Netherlands: Release and Explosion from a Propane Tank

On March 26, 1980, a power shovel was relocating a tank containing 1500 l (750 kg; 1650 lb) liquid propane. During maneuvering, the tank fell from the shovel; a portion of its contents was released as a result. After a delay of 30 seconds, the ensuing vapor cloud was ignited. The explosion caused substantial blast and fire damage. There were no casualties.