CHAPTER 17

EXPLOSIONS AND EXPLOSIVES

17-1 EXPLOSIONS

General Characteristics

The term *explosion* is difficult to define precisely. In general, it refers to a group of phenomena in which there is a sudden expansion or a bursting effect. One definition is a rapid increase of pressure or an excessively high pressure in a confined space followed by its sudden release resulting from rupture of the container. In some explosions, there are visible flames and a flash of light. In others, one observes matter flying in many directions. Explosions produce a noticeable sound described as a "crack" or "boom," depending on the location of the person relative to the source and other conditions.

Controlled explosions can be very useful. For example, explosions regularly occur in internal combustion engines. Accidental or uncontrolled explosions can have disastrous effects. Spectacular explosions of various types gain widespread attention. One of the most notable was the space shuttle Challenger explosion on live television in 1986. Others are grain elevator explosions and explosions of railroad tank cars and storage vessels containing liquid petroleum gas (LPG) and other materials. Although the visible effects appear similar, the phenomena are not exactly alike.

Kinds of Explosions

There are various schemes for classifying explosions. For the relatively common explosions produced by exothermic chemical reactions (sometimes called combustion explosions), there are two main types: deflagration and detonation.

A deflagration is an exothermic reaction that expands rapidly from the burning gases to the unreacted material by conduction, convection, and radiation. The combustion zone progresses through the material at a rate that is less than the velocity of sound. A deflagration may not always produce sufficiently rapid increases in pressure to produce an explosion.

A detonation is an exothermic reaction characterized by the presence of a shock wave in the material that establishes and maintains the reaction. A detonation usually results in sufficiently rapid increases in pressure to produce an explosion. The reaction zone expands at a rate greater than the speed of sound in the unreacted material.

A more detailed classification scheme considers a variety of phenomena. Classifications differ somewhat among sources.

Condensed Phase Detonations Condensed phase materials are high explosives and propellants. Detonation of such materials has occurred during manufacturing, transporta-

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tion, storage, and use. Certain compounds decompose almost instantly in a violent reaction. Most produce hot gases. Rapid decomposition can occur with acetylene, hydrogen, and certain metallic azides. For example, in 1947 in Texas City, Texas, *S. S. Grandcamp*, packed with well over 1,400 tons of ammonium nitrate fertilizer, accidentally ignited, exploded, and killed 400 people outright. People more than one mile away were injured and all houses within 0.9 miles were destroyed. Explosives are discussed further in the ensuing text.

Combustion Explosion of a Gaseous or Liquid Fuel in an Enclosure These explosions can be divided into two groups based on the length-to-diameter ratio (L/D) of the container. Many buildings, ship holds, and boilers fall into this group. For containers with an L/D ≈ 1, there is a relatively slow rise in pressure. The overpressure causes the container to rupture.

In containers with large L/D ratios, such as pipes, certain buildings, or tanker ships, the dynamics of the flame front and the turbulence of the gases in front of it are important. As a flame propagates, it creates turbulence in front of it, and this turbulence improves mixing and expands the flame area and speed of travel. Pressures can increase very rapidly by as much as 20 times, achieving pressures of 15 to 20 atm. Damage often is greatest at points distant from the source of ignition. If the rapidly accelerating flame front and pressure wave are reflected from a surface, pressures may double again. This type of explosion can occur in compressed-air lines, where fuel from compressor lubricants and enriched oxygen usually are present.

Combustion Explosions of Dusts in an Enclosure Dust explosions most often occur in containers where the dust is distributed in the atmosphere. They also can occur when some activity suddenly creates a cloud of airborne dust and a source of ignition is present. Similar to gas and vapor explosions, dust explosions show effects related to the L/D ratio of the container.

Boiling Liquid-Expanding Vapor Explosions When a container holding a liquid at a temperature well above its boiling point ruptures, the liquid will evaporate or boil rapidly into a vapor state. The sudden expansion, a physical phenomenon, can throw parts of the container considerable distances. This phenomenon includes sudden releases of pressurized steam and may be accompanied by fire if the material is combustible, thereby producing thermal as well as physical effects. The heat of the fire can increase the rate of pressure rise and the pressure achieved. Boiling liquid-expanding vapor explosions (BLEVEs) involving LPG produce spectacular fireballs.

Explosions of Pressure Vessels Containing Nonreactive Materials This type of explosion is closely related to a BLEVE. It is typical for a pressure vessel with a weak structure that will fail at quite low pressures (less than 2 lb/in^2 [gauge]). Materials are not thrown as violently as in a BLEVE. The pressure vessel itself may have severe damage from the rapid expansion of steam or from a combustion explosion within the vessel.

Unconfined Vapor Cloud Explosions Unconfined vapor clouds are open-air concentrations of fuels in vapor form. The cloud can dissipate to a harmless condition (from a flammability viewpoint) in which the concentration is too low to burn or it can be ignited as it is released from a container, thereby burning off the fuel at a somewhat controlled rate, with little overpressure resulting. However, if the cloud is ignited and the flame accelerates rapidly enough, a dangerous blast wave can result.

Deflagrations of Mists If fuels are dispersed in air in the form of a fog or mist and concentrations fall within flammable limits, ignition can produce violent deflagrations.

Chemical Reactor Runaway Chemical reactions may create too much pressure for the container they are in. Inadequate cooling, insufficient stirring, too much catalyst, and other factors may cause the reaction to go out of control. In a sealed container, pressure increases may result from the reaction itself and from temperature increases following the Boyle-Charles law (see Chapter 19).

Nuclear Reactor Runaway or Nuclear Detonations A nuclear detonation occurs when the structure of nuclei is rapidly rearranged by either fission or fusion. In an air detonation of a nuclear device, energy is converted into a blast wave, thermal radiation, and nuclear radiation. In the event of a nuclear reactor runaway, the rate of decomposition is much less than that of a weapon. The likelihood of a runaway reactor is very low because control systems included in the reactor prevent such an occurrence. However, the Chernobyl reactor explosion on April 26, 1986, was a runaway event for one type of reactor design. The explosion was caused by heat from the reaction, not from a nuclear explosion, such as that in a bomb.

17-2 EXPLOSION HAZARDS

There are three main causes of damage and injury from explosions. The most common cause of damage or injury is a blast wave or pressure wave that radiates from the explosion. Another cause of damage or injury is thermal radiation from combustion. A third source of damage and injury stems from projectiles (flying metal, glass, wood, etc.) created by the explosion. A blast wave impacting on a secondary object may produce additional projectiles.

Blast Wave Effects

A blast wave emanating from an explosion is called a free-field blast wave until it reaches an object and interacts with it. Sources of explosions that have very high energy and power densities produce ideal blast waves that have predictable properties. The blast wave decays with distance from the source. For high explosive materials, the distance for a blast wave is related to the cube root of the charge weight. In some cases, one can estimate the forces involved in an explosion from the fragment distribution pattern.

The interaction of a blast wave with an object is complex. The reflections can produce local pressures that are much higher than that of the blast wave itself. The object struck may bend or break. The damage produced is related to pressure, impulse (duration), and drag force. Table 17-1 lists typical damage resulting from various overpressures.

Thermal Effects

A combustion explosion produces a fireball. Radiation damage from the fireball is related to the size of the ball and its duration. Most fireballs reach a temperature on the order of 2,400°F. The radiant energy dissipates in relation to the distance squared, but accurate prediction of thermal damage is quite difficult.

TABLE 17-1 Blast Wave Effects Resulting from Overpressure

Approximate Overpressure (lb/in^2)	Effect
0.5–1.0	Shatter glass
1.0	Knock a person down
2–3	Shatter 8–12 in block or concrete wall
5	Snap utility pole
7	Overturn loaded railroad car
11	Threshold for lung damage
15	50% of eardrums are ruptured

Scatter of Fragments

Fragment damage is also difficult to predict. The scatter depends on the size of the explosion and failure modes for materials. It is known that glass will fragment quite easily and scatter, whereas tougher, more ductile materials may not scatter as much. However, tougher materials may be thrown farther because they do not fragment. The orientation of a container (building, tank, etc.) can affect the likely points for failure. An internal pressure wave is likely to be greater along a long axis or orientation. Damage will be greatest at the ends of the axis, and fragments are likely to move in the direction of the internal pressure wave. The presence of venting and pressure relief devices can affect the degree of fragmentation and the scatter pattern. In some cases, the release of gases in an explosion can cause a container, such as a cylinder or tank, to act like a missile, particularly when there is a failure at one end of the container.

17-3 DUST EXPLOSIONS

Description

Dust explosions result when fine particles are dispersed in air and ignited. A flame front spreads rapidly through the contaminated air and pressure and temperature increase. Virtually all organic dusts, some inorganic dusts, and certain metallic dusts are combustible in air and can explode. Inert dusts, like limestone, are sometimes used as extinguishing agents.

Dust must be airborne to burn readily. Dusts can become airborne from some operation, or dust that has settled on equipment in ducts or on parts of structures can become airborne if disturbed. Dust explosions frequently occur as a sequence of explosions. A first explosion may cause accumulated dust to become airborne and result in a second explosion. A fire may start in a pile of dust on a hot piece of equipment, and a fire hose or extinguisher may throw the dust into the air, producing an explosion.

The severity of dust explosions is a function of the material. Compared with combustible dusts, oxidizing dusts can accelerate the combustion process. If oxidizing agents are mixed with combustible dust, the resulting explosion will be even more severe. Some materials will burn more readily than others, producing higher rates of pressure and temperature buildup.

Other properties of dusts that affect the likelihood of ignition and the severity of combustion include panicle size, concentration, oxygen presence, presence of impurities, moisture content, and air turbulence. Small particles tend to be easier to ignite, and fine dusts tend to produce higher rates of pressure rise during combustion. Similar to flammable gases and vapors, certain concentrations of dusts are combustible. Particle size affects the concentration required for combustion, and if a concentration is too low, combustion is not likely. The presence of inert material in a dust tends to reduce its ability to burn. As the moisture content of dust increases, the ignition temperature of the dust increases. The rate of combustion increases with partial pressure of oxygen. Therefore, the presence of inert gas can help reduce the likelihood of dust explosions. Combustion will be faster and an explosion more violent when a combustible dust and air are mixed turbulently.

Indices of Dust Explosion Hazard

Explosion properties of dusts are available in tables, such as those found in the *National Fire Code* and the *Fire Protection Handbook*. The Bureau of Mines developed some indices to represent the relative hazard of various dusts. There are three indices: ignition sensitivity, explosion severity, and explosibility index. The latter is the product of the first two. Ignition sensitivity and explosion severity are derived from laboratory tests in comparison with a standard Pittsburgh coal dust. The ignition sensitivity is a function of ignition temperature, minimum energy of ignition, and minimum concentration. Explosion severity is a function of maximum explosion pressure and maximum rate of pressure rise. The rating scale in Table 17-2 classifies the relative hazard of a dust. Table 17-3 lists the explosion properties of a few dusts.

17-4 CONTROLS FOR EXPLOSIONS

The appropriate controls for preventing an explosion or reducing the damage vary with each application. In the following text, controls are summarized. Training, procedures, and enforcement are also important. Today, one can also use specialized software to analyze the impact of explosion or the risk of damage to surrounding buildings and structure resulting from explosions of various types.

Limit Quantities of Materials

If the amount of materials that can explode is minimized in any location, the likelihood and degree of damage will be small should an explosion occur. The likelihood of an explosion also will be reduced in many cases, because there is less opportunity for ignition. Many examples could be given. OSHA and NFPA have rules about the amount of flammables and combustibles stored in work areas. Large amounts should be stored in remote areas. As detailed later in this chapter, standard reference tables prescribe limits on the amounts of explosive materials in one place. In locations where dust can accumulate, regular cleaning can reduce dangers of explosions. The design of such locations also can

TABLE 17-2 Relative Explosion Hazard of Dusts

Type of Explosion	Ignition Sensitivity	Explosion Severity	Explosibility Index
Weak	<0.2	<0.5	<0.1
Moderate	0.2–1.0	0.5–1.0	0.1–1.0
Strong	1.0–5.0	1.0–2.0	1.0–10
Severe	>5.0	>2.0	>10

TABLE 17-3 Explosion Properties of Selected Dusts

Dust Type	Explosibility Index	Ignition Sensitivity	Cloud Explosion Severity	Ignition Temperature (°C)	Minimum Cloud Ignition Energy (J)	Minimum Explosion Concentration (oz/ft^2)
Aluminum fines	>10	1.4	7.7	760	0.05	0.045
Benzoic acid	>10	5.4	2.1	620	0.02	0.03
Cellulose	2.8	1.0	2.8	480	0.08	0.055
Cellulose acetate	>10	8.0	1.6	420	0.015	0.04
Charcoal (hardwood mixture)	1.3	1.4	0.9	530	0.02	0.14
Cinnamon	5.8	2.5	2.3	440	0.03	0.06
Coal (Pittsburgh)	1.0	1.0	1.0	610	0.06	0.055
Corn	6.9	2.3	3.0	400	0.04	0.055
Grain dust	9.2	2.8	3.3	430	0.03	0.055
Magnesium (milled)	>10	3.0	7.4	560	0.04	0.03
Nylon polymer	>10	6.7	1.8	500	0.02	0.03
Peanut hull	4.0	2.0	2.0	460	0.05	0.045
Polystyrene molding compound	>10	6.0	2.0	560	0.04	0.015
Polyurethane foam, not fire retardant	>10	6.6	1.5	510	0.02	0.03
Rubber, crude, hard	7.4	4.6	1.6	350	0.05	0.025
Rubber, synthetic, hard, contains 33% sulfur	>10	7.0	1.5	320	0.03	0.03
Salicylanilide	5.8	4.1	1.4	610	0.02	0.04
Sugar, powdered	9.6	4.0	2.4	400	0.03	0.05
Sulfur	>10	20.2	1.2	190	0.015	0.035
Titanium	>10	5.4	2.0	510	0.025	0.045
Vitamin C (ascorbic acid)	2.3	1.0	2.2	460	0.06	0.07
Wheat flour	4.1	1.5	2.7	440	0.06	0.05
Wood flour (white pine)	9.9	3.1	3.2	470	0.04	0.035

help by minimizing places for dust to accumulate. Compressed air lines with traps and accumulators will minimize buildup of flammable oils in lines, and the lines should be cleaned or purged regularly to minimize fire and explosions within the pipes.

Prevent Combustible Concentrations

Processes and operations where flammable mixtures of gases, vapors, and dusts with air could occur should be designed and managed to prevent combustible and explosive mixtures with air. This principle includes reducing oxidizers that add to the explosive energy of a combustible material. For this reason, fuels and oxydizers are stored separately from each other. Monitoring equipment can help detect explosive concentrations and provide warnings or actuate ventilation or other equipment to reduce the hazards.

Eliminate Sources of Ignition

If there is a potential for an explosive atmosphere, sources of heat, flame, and spark must be kept away or carefully controlled. Some companies do not allow workers to carry any kind of smoking material, matches, or lighters on company premises. A hot work permit system is needed. Moving belts and other sources of static electricity must be grounded, and electrical equipment (switches, fixtures, motors, etc.) must be sealed to prevent a dusty atmosphere from reaching sources of sparks. Such equipment must meet electrical code requirements for explosive atmospheres. By itself, this means of prevention is not dependable. In many operations, such as those in grain elevators and factories, it is very difficult to eliminate every source of ignition.

Reduce Oxygen

Some environments that could produce explosive mixtures can be protected by keeping oxygen concentrations low. An inert gas, such as nitrogen, may be used to replace air. However, people cannot enter such environments without an independent source of breathing air. Oxygen concentration above standard atmospheric concentrations and compressed oxygen mixtures that elevate the partial pressure of oxygen and elevate combustion behavior should be avoided to reduce the potential for accelerated rates of burning.

Provide Overpressure Relief

In containers, including tanks and buildings, where there is a potential for explosive mixtures or releases, pressure relief devices should be in place. Venting is a passive means for minimizing damage from an explosion. In some cases, such as pressurized vessels and boilers, venting can prevent an explosion. Pressure relief valves, fusible plugs, and other devices are discussed further in Chapter 19. NFPA 68[1] provides guidance for explosion venting. In buildings, vents to relieve explosive pressures can be built into walls and roofs, and sashes, window panels, and doors also can be designed to relieve explosive pressures. The quantity and design for explosion relief depends on the rate of pressure rise expected, the L/D ratio of the container, the type of explosive material, and other factors.

Install Extinguishing and Suppression Systems

If a fire occurs that could lead to an explosion, extinguishing equipment may put out the fire and prevent an explosion. However, some kinds of extinguishing equipment for certain situations may add to the potential for explosion. For example, equipment that distributes dust into the air in a fire can lead to an explosion. There are some special suppression systems for explosions that are an active means for minimizing damage. They have to act very quickly to detect an explosion and minimize any effects. NFPA 69[2] gives details on explosion prevention systems, including suppression systems.

Use Distance and Barriers

One means to reduce the severity of an explosion is to separate quantities of materials by distance and barriers. A blast wave deteriorates with distance. A barrier that can withstand a blast wave will reduce the energy of the wave and will reduce the impact on objects shielded by the barrier.

Provide Remote Controls

If there are conditions where combustion can lead to explosion, there should be remote controls for valves and equipment. During normal operation, manual controls on equipment may not be hazardous, but if there is a danger of explosion, remote controls will avoid the need for operators to enter dangerous areas and operate valves usually.

17-5 EXPLOSIVES

An explosive is a chemical compound or mixture of substances used or intended for the purpose of creating a rapid self-propagating reaction and explosion. Energy is released in the form of heat and pressure. Explosive materials include explosives, blasting agents, slurries, and detonators.

Depending on the type of substance, there are various ways to initiate a reaction within an explosive. Ignition may be by fire, friction, concussion, percussion, or detonation.

Explosives are classified by the Department of Transportation (DOT) into classes.

Class A. These explosives possess a detonating hazard. They are divided into many types, including black powder, low explosives, high explosives, dynamite, nitroglycerine, picric acid, lead azide, blasting caps, detonating primers, shape charges, and ammunition.

Class B. These are explosives that, in general, function by rapid combustion rather than detonation. Included are fireworks, flash powders, pyrotechnic signal devices, some liquid or solid propellant explosives, some smokeless powders, and certain ammunition.

Class C. These are certain types of fireworks or manufactured articles that contain class A or class B explosives or both as components in restricted quantities and certain types of fireworks.

Many organizations establish standards and regulations for explosives. Besides the DOT, the Bureau of Alcohol, Tobacco, and Firearms (ATF), OSHA, MSHA, and state and local governments have regulations on explosives. Standards are set by the Institute of Makers of Explosives, NFPA, and other organizations. A longstanding reference on explosives and their use is the *Blasters' Handbook*.

Hazards

Explosives are dangerous materials. They create damage from heat and pressure waves. The primary hazard is release of their energy in the wrong place and at the wrong time. The quantity and type of material activated determines the degree of damage for a particular place and time. Release in the presence of people can cause serious injury or death. The injury may be from the heat or pressure wave or from materials thrown by the pressure wave. Properly used, explosives can serve useful functions. They are essential for mining excavation, demolition, and similar activities.

Controls

Minimizing explosive hazards includes applying controls during manufacture, distribution, and use. Controls include training and licensing of handlers, users, and distributors.

Manifesting explosive materials from factory to final use minimizes their getting into the hands of unqualified users or being improperly used. Many states require that those involved in explosives be licensed after adequate training and examination.

Another control is proper storage. Blasting caps and detonating devices are not stored with explosives. Standards limit the quantities in magazines or in daily use and specify the distance certain quantities must be located from transportation routes and buildings. They also specify the distances between stored quantities in magazines. Most quantity-distance tables are based on the American Table of Distances for Storage of Explosives (see Table 17-4) developed by the Institute of Makers of Explosives.

Magazines, storage facilities for explosives, must meet design specifications. Design criteria include fire resistance, impedance to firearms, physical security, location, and other factors. Magazines must meet standards that vary with the quantity of material stored. Distances between magazines or between a magazine and a building, highway, or railway may be lower when there is a proper natural or artificial barricade, such as a mound of earth or wall of timber that will prevent material from an exploding magazine from affecting the adjacent structures, highway, or railway.

Implosions

An implosion is a sudden, inward collapse of a building or closed container when the external pressure is greater than that inside the container sufficient to produce structural failure in some element of the structure. An implosion can also be the inward collapse of a building or structure during controlled demolition using explosive charges that create failure in structural elements (columns, beams, etc.).

If an implosion is planned, humans should be barricaded and removed from any area in which debris could create a hazard. For structures containing hazardous materials, demolition procedure may require removing the hazardous materials before the implosion to reduce risks to surrounding areas.

TABLE 17-4 American Table of Distances for Storage of Explosives (Abbreviated)[a]

Quantity of Explosives (lb) Over-Less Than	Minimum Distance between Magazines (ft)	Distance from Inhabited Building (ft)	Distance from Public Highway (ft)	Distance from Passenger Railways and High-Traffic Highways[b] (ft)
2–5	12	140	60	102
10–20	20	220	90	162
40–50	28	300	120	230
100–125	36	400	160	300
200–250	46	510	210	378
500–600	62	680	270	506
1,000–1,200	78	850	330	636
2,000–2,500	98	1,090	380	816
5,000–6,000	130	1,460	470	1,092
10,000–20,000	164	1,750	540	1,374
20,000–25,000	210	2,000	630	1,752
50,000–55,000	280	2,000	880	2,000
95,000–100,000	370	2,000	1,090	2,000

[a] Distances shown are for unbarricaded magazines. They may be reduced by $^1/_2$ for quantities under 10,000 lb, if properly barricaded. For large quantities, allowable reductions in distance vary.
[b] More than 3,000 vehicles per day.

If a container could experience implosion because of a process failure, changes in the process design, or in the structural elements may be needed to reduce or eliminate risks from release of process materials or damage to surrounding structures or containers.

EXERCISES

1. An industrial plant is 750 ft wide (along the south and north) and 350 ft deep. It is located on a rectangular lot that is 1,750 ft wide (along the south and north) and 1,500 ft deep. The lot is bordered on the south by a highway, on the west by a rail line (passenger service), on the east by a residential area, and the north by an uninhabited flood plain of a stream. The plant sets back 150 ft north of the highway to provide a parking lot and is offset 250 ft from the west lot line for a shipping and receiving area. Fifteen pounds of explosives are to be used daily in the plant and a 60-day supply is to be maintained at the site. Prepare a layout of the site and using the American Table of Distances, show which areas on the site can be used for
   (a) a daily-use magazine
   (b) a 60-day supply
2. Cinnamon dust has an ignition sensitivity of 2.5 and an explosion severity of 2.3. What is its explosibility index?

REVIEW QUESTIONS

1. Briefly describe each class of explosion in the following list. Note any unique characteristics for each class.
   (a) combustion explosion
   (b) deflagration
   (c) detonation
   (d) condensed phase detonation
   (e) combustion explosion of a gaseous or liquid fuel in an enclosure
   (f) combustion explosions for dust in an enclosure
   (g) BLEVE
   (h) explosions of pressure vessels containing nonreactive materials
   (i) unconfined vapor cloud explosions
   (j) deflagrations of mists
   (k) chemical reactor runaway
   (l) nuclear reactor runaway or nuclear detonations
2. What are the three main causes of damage and injury from explosions?
3. Describe factors that contribute to the occurrence and severity of dust explosions.
4. What three indices are used to characterize the explosion hazard of dusts?
5. What controls help prevent explosions?
6. What controls reduce damage resulting from explosions?
7. Describe characteristics of each class of DOT explosives.

(a) Class A
(b) Class B
(c) Class C

8. What are the hazards of explosives?
9. What controls reduce the hazards of explosives?

NOTES

1 NFPA 68, Venting of Deflagrations.

2 NFPA 69, *Explosion Prevention Systems*.

BIBLIOGRAPHY

Bartknecht, W., *Explosions—Course, Prevention, Protection*, H. Burg and T. Almond, transl., Springer, New York, 1981.

Blasters' Handbook, E. I. DuPont de Nemours & Co., Wilmington, DE, current edition.

Conkling, J. A., *Chemistry of Pyrotechnics*, Marcel Dekker, New York, 1985.

Fire Protection Handbook, 19th ed., National Fire Protection Association, Quincy, MA, 1986.

Harris, R. J., *The Investigation and Control of Gas Explosions in Buildings and Heating Plants*, 3rd ed., Methuen, New York, 1983.

Nagy, J., and Verakis, H. C., *Development and Control of Dust Explosions*, Marcel Dekker, New York, 1981.

National Fire Protection Association Codes, National Fire Protection Association, Boston, MA:
NFPA 68 Venting of Deflagrations
NFPA 69 Explosion Prevention Systems
NFPA 77 Static Electricity
NFPA 495 Explosive Materials Code

Natural Gas Safety Handbook for Utility Workers and Contractors, National Safety Council, Itasca, IL, 2003.

Strehlow, R. A., "Accidental Explosions," *American Scientist*, 68:420–428 (1980).