CAUSES AND EFFECTS OF FIRES AND EXPLOSIONS

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1.0 SCOPE

This data sheet is designed to provide information useful to those evaluating fires and explosions. It does not include recommended safeguards.

Refer to Data Sheet 7-42, *Guidelines For Evaluating the Effects of Vapor Cloud Explosions Using a Flame Acceleration Model,* for specific details on outdoor vapor cloud explosions and methods to evaluate the blast effects on property.

1.1 Changes

April 2013. Minor editorial changes and additional guidance for using TNT equivalence methods for estimating the effects of explosions (overpressure) involving energetic materials.

2.0 GENERAL

With fire, two factors are of major importance. These are the cause or ignition source and the development of the fire. Determination should be made as to how fire could start and how it could develop, spread, be controlled, and extinguished.

In an explosion, events prior to explosion are important. An explosion is a rapid transformation of potential physical or chemical energy into mechanical energy. It is important to determine how the potential energy can be accumulated or prepared for sudden transformation and how this transformation can be triggered. The effects of an explosion may be explored to evaluate its magnitude.

3.0 BASIC DEFINITIONS AND PRINCIPLES—FIRE

3.1 Combustion

Combustion is an exothermic chemical reaction usually involving oxidation of a fuel by atmospheric oxygen. Glowing combustion involves direct oxidation of a solid or liquid fuel, such as charcoal or magnesium. Flaming combustion involves a gas phase or volatile matter driven off by heat.

3.2 Ignition Temperature

Ignition temperature is the minimum temperature to which a substance must be heated to initiate self-sustained combustion in whatever atmosphere is present. To start the chemical reaction between fuel molecules and oxygen molecules, sufficient energy must be imparted into the mix. If the fuel is a solid or liquid, some of it usually is turned into a gas (unless the oxidizer is also a solid or liquid) so that there is intimate mixing of molecules. The ignition temperature can vary, depending on the fuel or oxygen concentration, the rate of air flow, rate of heating, the size and shape of the solid or space involved, the temperature of the ignition source, and possible catalytic or inhibiting effect of other materials present.

For less volatile solids, such as wood, or paper, the ignition temperature is greatly dependent on the time necessary to volatilize the fuel to form an ignitable mix at the surface. Artificial heating can also initiate self-heating, which may bring the fuel up to its ignition temperature. The normally accepted minimum self-ignition temperature of wood, paper, cotton, wool, and combustible fiberboards is 400° to 500°F (200° to 260°C). Ignition can occur at lower temperatures if the material is contaminated with oils or if charcoal is formed followed by ensuing self-heating.

4.0 IGNITION SOURCES

An ignition source is normally energy in the form of heat which brings fuel up to its ignition temperature. Since fires are unusual in most occupancies, an ignition source usually involves some unusual circumstance not otherwise present. Ignition sources are classified based on the origin of the heat involved.

4.1 Electrical

Electrical energy produces heat when electric current flows through a conductor or jumps an air gap. The heat produced is proportional to the resistance and to the square of the current. Excessive heat, sufficient to start a fire, can be generated by: (1) a high current, (2) a high resistance, or (3) impaired cooling or removal of normal heat.

1. High current can be the result of:

   a. Short circuits caused by breakdowns in insulation or accident. Continuous overload causing a short before the fire will exhibit beads of metal and fusing of the copper wire conductors. There will also be decomposition and carbonization of insulation on both sides where the short occurred. Shorts caused during the heat of the fire may show beading. However, decomposition and carbonization of insulation will be found only on the side exposed to the fire.

   b. Single phasing in three-phase motors. (See Data Sheet 5-18, *Protection of Electrical Equipment*.)

   c. Loss of field in synchronous motors. (See Data Sheet 5-13, *Synchronous Motors*.)

   d. Lightning. (See Data Sheet 5-11, *Lightning Surge Protection*.)

2. High resistance can be the result of loose or oxidized electrical connections.

3. Impaired cooling can be the result of:

   a. Failure of fans in transformers or enclosed equipment.

   b. Plugging of air passageways.

   c. Coatings on bare wires, bus bars, lighting fixtures, and heating elements.

   d. Dropping of oil or other coolant levels away from heating elements.

   e. Combustibles too close to light bulbs or heating elements.

When electric current jumps an air gap, the resistance is so high that even a small current produces significant energy. In the case of static sparks, minute currents can ignite flammable vapors or gases. Strong currents arcing across air gaps can melt metal, which in turn can start fires.

If electric motors are found in the area of origin, check the interior of the motor windings to see if the fire was deep seated; the wire coating at the interior would probably not burn away unless the wiring was heated electrically.

In any electrical appliance having a thermal control, sticking or fusing of the contact points would signify overheating of the device.

4.2 Static Electricity

Fires and explosions are often attributed to static electricity after other possible causes have been eliminated. If a fire or explosion is caused by static electricity, it is important to understand and explain the specific mechanism so that repetition can be prevented.

For static electricity to be a source of ignition, four conditions must be fulfilled:

1. There must be an effective means of static generation.

2. There must be a means of accumulating the charges and maintaining a suitable electrical potential difference.

3. There must be a spark discharge of adequate energy.

4. The spark must occur in an ignitable mixture.

Static is normally generated by movement of dissimilar substances involving the making and breaking of contact of surfaces. A poor conductor of electricity must be involved. Examples are a rapidly moving rubber belt; paper or cloth unwinding or passing over rollers; nonconducting fluids flowing through pipes or being agitated in tanks; or the movement of dust or stock, as in grain handling.

A free charge on an ungrounded conductive body is mobile, and the entire charge can be drawn off by a single spark. On the other hand, the charge on a nonconductive body is relatively immobile so that a spark from its surface can release the charge from only a limited area and will usually not involve enough energy to produce ignition. Thus, nonconductors, the bodies most directly involved in charge generation, are usually not directly involved in the sparks which initiate fires and explosions.

For example, if a person walks across a fur rug, static electricity will be generated by the nonconductor, the rug, and accumulated in the body of the person, a nongrounded conductor. When the person touches a grounded object, a spark will jump at that point.

A static spark is a relatively weak ignition source. The most common ignitable mixture is a mixture of a flammable vapor or gas with air. A liquid involved normally must be above its flash point. Combustible dust mixtures may possibly be ignited by static electricity, but it requires a very high energy spark. Static sparks do not normally have sufficient energy to ignite dusts.

4.3 Hot Surfaces—Nonelectrical

Combustible or flammable material may be ignited by contact with or by radiant heat from surfaces heated by means other than electrical energy. These hot surfaces are most often produced by: (1) friction, (2) heating equipment, and (3) molten substances.

1. Friction can be caused by improperly lubricated bearings, broken or misaligned machine parts, choking or jamming of materials, and poor adjustment of conveyors or machine drives. Frictional heating may cause noncombustible parts to become hot and ignite nearby combustibles. A typical example is a hot paper machine bearing igniting oil or paper lint. In some instances, the combustible material may be heated directly, as with a rubber conveyor belt slipping on a pulley.

Friction, as a fire cause, will be indicated if the point of damage to the motor belts is worse where it passes over pulleys. In fires from outside sources, belts are damaged most between pulleys.

2. Heating equipment located too close to combustible construction or storage can result in ignition. The top or bottom of a furnace or heater, a hot flue or duct, or an exposed steam pipe may ignite combustibles in contact with the heated surface or where nearby clearances, insulation, or air circulation is adequate.

The ordinary ignition temperature of wood is 400° to 500°F (200° to 260°C), but when wood is exposed to prolonged heat, it undergoes a chemical change and becomes pyrophoric carbon with an ignition temperature as low as 300°F (150°C). Heat will greatly reduce the time required for ignition. For instance, long leaf pine will ignite when subjected to: 356°F (180°C) for 14.3 minutes; 392°F (200°C) for 11.8 minutes; 437°F (225°C) for 8.7 minutes; 482°F (250°C) for 6.0 minutes; 572°F (300°C) for 2.3 minutes; 662°F (350°C) for 1.4 minutes; and 752°F (400°C) for 0.5 minutes.

3. Molten substances, such as metal or glass escaping from a furnace or container, can ignite any combustible material in the vicinity.

4.4 Sparks and Open Flames—Hot Work

Open flames may be fixed or portable. Fixed open flames, such as in ovens, furnaces, water heaters, and boilers, may ignite moving combustibles, such as flammable vapors or gases. Portable flames, such as portable burners or welding torches, can ignite combustible material any place in a building. Hot sparks or molten globules from cutting or welding or from mechanical grinding operations are common ignition sources. Metal introduced into textile or grain processing machinery can generate hot sparks that can ignite lint, dust, or other easily ignitable material.

4.5 Smoking

Smoking is a leading cause of fires. This conclusion is often determined by a process of elimination. Direct evidence is seldom found which proves that a cigarette, cigar, or match was specifically the ignition source.

Studies have been made of the mechanisms by which cigars and cigarettes start fires. Temperatures in a glowing cigarette range from 550° to 1400°F (290° to 760°C). Test conclusions were:

1. Cigars and cigarettes start fires in solid fuels (except explosives, matches, and other highly flammable chemicals) by first initiating glowing combustion. Therefore, in order to be ignitable by a cigarette, a solid must be capable of supporting flameless combustion. Such materials are virtually all of cellulosic origin and include paper, fabric, textile fibers, and dry vegetation. Materials which melt when heated, such as rubber, plastic, and most synthetic fibers, cannot sustain glowing combustion, possibly because the heat applied is absorbed as heat of fusion during the melting stage.

2. Conditions favoring ignition include a good supply of finely divided, fairly compact fuel and a good air supply or draft to promote flaming combustion.

3. Flammable vapors and gases are surprisingly difficult to ignite with a cigar or cigarette, but not impossible.

Cigarettes are an unreliable source of ignition, but their widespread use and careless handling make them significant as a fire cause. Of course, flames from matches or lighters are much stronger and more reliable ignition sources.

4.6 Incendiarism

An incendiary fire is often characterized by a conscious attempt to insure that the fire is severe. Ignitable liquids or ‘‘trailer’’ devices are often used to help spread the fire. Strong ignition sources are used, usually with a timing mechanism such as a candle or clock. More than one fire is often started at once. Fire protection systems may be shut off. In accidental fires, chance plays an important part. In intentional fires, chance is minimized.

Witnesses to the fire in its early stages can often give helpful information concerning the material initially involved in the fire. If incendiarism is suspected, the type of smoke or flame initially observed is often of interest.

Color of smoke is often the first clue to the combustibles involved in the fire (Table 1).

Table 1. Color of Smoke Produced by Burning Combustibles

Combustible	*Color of Smoke*
Hay/Vegetable compounds	White
Cooking oils	Brown
Phosphorus	White
Nitrocellulose	Yellow-Brownish-Yellow
Sulfur	Yellow-Brownish-Yellow
Sulfuric, nitric, or hydrochloric acid	Yellow-Brownish-Yellow
Gunpowder	Yellow-Brownish-Yellow
Chlorine gas	Greenish-Yellow
Petroleum products	Black
Wood	Gray-Brown
Most plastics	Black
Paper	Gray-Brown
Cloth	Gray-Brown

The absence of flames or comparatively small flames indicate a lack of air. More flames than smoke indicate well-ventilated burning of dry substances. Erratic flames indicate the presence of gases, while sparks in large quantities indicate that powdery substances are burning.

A trailer (a line of paper rags or ignitable liquid designed to cause a fire to spread) often leaves residue, or a fire spreads in ways other than its usual upward direction.

4.7 Spontaneous Ignition

Spontaneous heating can occur in many types of materials including solids (wood chips, coal, foam rubber, rags, fiberboard, and metal powders) and liquids (animal and vegetable oils). Materials that spontaneously heat will increase in temperature without taking heat from the surrounding environment. Heat generations is generally due to one or a combination of the following exothermic reactions (reactions that liberate heat): oxidation (chemical combination of a material with oxygen), decomposition (material breaks down into its elements), polymerization (combination of low molecular weight molecules into a single high molecular weight compound), or biological action (bacterial caused decomposition). These reactions often occur normally (at a slow rate) without heat build-up. An increase in material temperature occurs when heat loss to the surroundings is reduced. The conditions that will affect spontaneous heating include: the geometry of the material, the available surface area and insulation from the surrounding environment. Various arrangements of the above reactions and other conditions will permit spontaneous heating to occur and lead to the ignition of the material producing either flaming or smoldering combustion.

In agricultural crops, bacteria can promote oxidation and heat generation. This can be promoted by a high moisture content. The bacteria tends to die at temperatures above 160° to 175°F (71° to 80°C); heating beyond that point is normally due to oxidation accompanied by chemical decomposition.

The following materials are most subject to spontaneous heating:

1. *Animal and Vegetable Oils.* These oils contain unsaturated bonds, having greater tendency for oxidation at lower temperatures. The greatest danger occurs if they impregnate rags or other absorbent, insulating organic materials.

2. *Agricultural and Animal Products.* These may contain animal or vegetable oils, or may be subject to bacterial oxidation. If heated, or if already charred, the oxidation tendency is increased.

3. *Wood Chips.* See Data Sheet 8-27, *Storage of Wood Chips* and Data Sheet 7-10, *Wood Processing and Woodworking Facilities.*

4. *Coal and Charcoal.* See Data Sheet 8-10, *Coal and Charcoal Storage*.

5. *Fiber Products.* These products are most hazardous when heated and stored before cooling, or when impregnated or contaminated with animal or vegetable oils.

6. *Paint and Paint Scrapings.* The most hazardous are paints which are not fully dry and contain linseed oil or drying agents. High gloss paint designed to dry at room temperature contains drying agents. These oxidizing catalysts strongly promote spontaneous heating when arranged so that heat cannot readily dissipate as in stored scrapings. See Data Sheet 7-27, *Spray Application of Ignitable and Combustible Materials.*

Table 2, Materials Subject to Spontaneous Heating, lists additional materials that should be evaluated.

Table 2. Materials Subject to Spontaneous Heating[1]
(Originally prepared by the NFPA Committee on Spontaneous Heating and Ignition which has been discontinued. Omission of any material does not necessarily indicate that it is not subject to spontaneous heating.)

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Alfalfa Meal	High	Bags, bulk	Avoid moisture extremes. Tight cars for transportation are essential	Many fires attributed to spontaneous heating probably caused by sparks, burning embers, or particles of hot metal picked up by the meal during processing. Test fires caused in this manner have smoldered for 72 hours before becoming noticeable.
Burlap Bags “Used”	Possible	Bales	Keep cool and dry.	Tendency to heat dependent on previous use of bags. If oily would be dangerous.
Castor Oil	Very slight	Metal Barrels, Metal Cans in Wooden boxes	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Possible heating of saturated fabrics in badly ventilated piles.
Charcoal	High	Bulk, Bags	Keep dry. Supply ventilation.	Hardwood charcoal must be carefully prepared and aged. Avoid wetting and subsequent drying.
Coal, Bituminous	Moderate	Bulk	Store in small piles. Avoid high temperatures.	Tendency to heat depends upon origin and nature of coals. High volatile coals are particularly liable to heat.
Cocoa Bean Shell Tankage	Moderate	Burlap Bags, Bulk	Extreme caution must be observed to maintain safe moisture limits.	This material is very hygroscopic and is liable to heating if moisture content is excessive. Precaution should be observed to maintain dry storage, etc.
Coconut Oil	Very slight	Drums, Cans, Glass	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Only dangerous if fabrics, etc., are impregnated.
Cod Liver Oil	High	Drums, Cans, Glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated organic materials are extremely dangerous.

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Colors in Oil	High	Drums, Cans, Glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	May be very dangerous if fabrics, etc., are impregnated.
Copra Corn-Meal Feeds	Slight High	Bulk Burlap Bags, Paper Bags, Bulk	Keep cool and dry. Materials should be processed carefully to maintain safe moisture content and to cure before storage.	Heating possible if wet and hot. Usually contains an appreciable quantity of oil which has rather severe tendency to heat.
Corn Oil	Moderate	Barrels, Tank Cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Dangerous heating of meals, etc., unlikely unless stored in large piles while hot.
Cottonseed Cottonseed Oil	Low Moderate	Bags, Bulk Barrels, Tank Cars	Keep Cool and Dry. Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Heating possible if piled wet and hot. May cause heating of saturated material in badly ventilated piles.
Distillers' Dried Grains with oil content (Brewers' grains)	Moderate	Bulk	Maintain moisture 7 percent to 10 percent. Cool below 100°F (38°C) before storage.	Very dangerous if moisture content is 5 percent or lower.
(Ditto) No oil content	Moderate	Bulk	Maintain moisture 7 percent to 10 percent. Cool below 100 °F (38°C) before storage.	Very dangerous if moisture content is 5 percent or lower.
Feeds, various	Moderate	Bulk, Bags	Avoid extremely low or high moisture content.	Ground feeds must be carefully processed. Avoid loading or storing unless cooled.
Fertilizers Organic, inorganic, combination of both matter	Moderate	Bulk, Bags	Avoid extremely low or high moisture content.	Organic fertilizers containing nitrates must be carefully prepared to avoid combinations that might initiate heating.
(Ditto)Mixed, Synthetic containing nitrates and organic	Moderate	Bulk, Bags	Avoid free acid in preparation.	Insure ventilation in curing process by small piles or artificial drafts. If stored or loaded in bags, provide ventilation space between bags.
Fish meal	High	Bags, Bulk	Keep moisture 6 percent to 12 percent. Avoid exposure to heat.	Dangerous if over dried or packaged over 100°F (38°C).
Fish Oil	High	Barrels, Drums, Tank Cars	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Impregnated porous or fibrous materials are extremely dangerous. Tendency of various fish oils to heat varies with origin.
Fish Scrap	High	Bulk, Bags	Avoid moisture extremes.	Scrap loaded or stored before cooling is extremely liable to heat.
Foam Rubber in Consumer Products	Moderate	Bulk, Bags	Where possible remove foam rubber pads, etc. from garments to be dried in dryers or over heaters. If garments containing foam rubber parts have been artificially dried, they should be thoroughly cooled before being piled, bundled, or put away. Keep heating pads, hair dryers, other heat sources from contact with foam rubber pillows, etc.	Foam rubber may continue to heat spontaneously after being subjected to forced drying as in home or commercial dryers, and after contact with heating pads and other heat sources. Natural drying does not cause spontaneous heating.

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Grain (various kinds)	Very slight	Bulk, Bags	Avoid moisture extremes	Ground grains may heat if wet and warm.
Hay	Moderate	Bulk, Bales	Keep dry and cool	Wet or improperly cured hay is almost certain to heat in hot weather. Baled hay seldom heats dangerously.
Hides	Very slight	Bales	Keep dry and cool.	Bacteria in untreated hides may initiate heating.
Iron Pyrites	Moderate	Bulk	Avoid large piles. Keep dry and cool.	Moisture accelerates oxidation of finely divided pyrites.
Istle	Very slight	Bulk, Bales	Keep cool and dry.	Heating possible in wet materials. Unlikely under ordinary conditions. Partially burned or charred fiber is dangerous.
Jute	Very slight	Bulk	Keep cool and dry.	Avoid storing or loading in hot wet piles. Partially burned or charred material is dangerous.
Lamp Black	Very slight	Wooden Cases	Keep cool and dry.	Fires most likely to result from sparks or included embers, etc., rather than spontaneous heating.
Lanolin	Negligible	Glass, Cans, Metal Drums, Barrels	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Heating possible on contaminated fibrous matter.
Lard Oil	Slight	Wooden Barrels	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Dangerous on fibrous combustible substances.
Lime, unslaked (Calcium Oxide, Pebble Lime, Quicklime)	Moderate	Paper Bags, Wooden Barrels, Bulk	Keep dry. Avoid hot loading.	Wetted lime may heat sufficiently to ignite wood containers, etc.
Linseed	Very slight	Bulk	Keep cool and dry.	Tendency to heat dependent on moisture and oil content.
Linseed Oil	High	Tank, Cars, Drums, Cans, Glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Rags or fabrics impregnated with this oil are extremely dangerous. Avoid piles, etc. Store in closed containers, preferably metal.
Manure	Moderate	Bulk	Avoid extremes of low or high moisture contents. Ventilate the piles.	Avoid storing or loading uncooled manures.
Menhaden Oil	Moderate to high	Barrels, Drums, Tank Cars	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Dangerous on fibrous product.
Metal Powders*	Moderate	Drums, etc.	Keep in closed containers.	Moisture accelerates oxidation of most metal powders.
Metal Turnings*	Practically none	Bulk	Not likely to heat spontaneously.	Avoid exposure to sparks.
Mineral Wool	None	Pasteboard Boxes, Paper Bags	Noncombustible. If loaded hot may ignite containers and other combustible surroundings.	This material is mentioned in this table only because of general impression that it heats spontaneously.
Mustard Oil, Black	Low	Barrels	Avoid contact of leakage with rags, cotton or other fibrous combustible materials.	Avoid contamination of fibrous combustible materials.
Oiled Clothing	High	Fiber Boxes	Dry thoroughly before packaging.	Dangerous if we material is stored in piles without ventilation.

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Oiled Fabrics	High	Rolls	Keep ventilated. Dry thoroughly before packing.	Improperly dried fabrics extremely dangerous. Tight rolls are comparatively safe.
Oiled Rags	High	Bales	Avoid storing in bulk in open.	Dangerous if we with drying oil.
Oiled Silk	High	Fiber Boxes, Rolls	Supply sufficient ventilation.	Improperly dried material is dangerous in form of piece goods. Rolls relatively safe.
Oleic Acid	Very slight	Glass Bottles, Wooden Barrels	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated.
Oleo Oil	Very slight	Wooden Barrels	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	May heat on impregnated fibrous combustible matter.
Olive Oil	Moderate to Low	Tank Cars, Drums, Cans, Glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Paint containing drying oil	Moderate	Drums, Cans, Glass	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Fabrics, rags, etc. impregnated with paints that contain drying oils and driers are extremely dangerous. Store in closed containers, preferably metal.
Paint Scrapings	Moderate	Barrels, Drums	Avoid large unventilated piles.	Tendency to heat depends on state of dryness of the scrapings.
Palm Oil	Low	Wooden Barrels	Avoid contact of leakage form containers with rags, cotton or other fibrous combustible materials	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Peanut Oil	Low	Wooden Barrels, Tin Cans	Avoid contact of leakage form containers with rags, cotton or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Peanuts, “Red Skin”	High	Paper Bags, Cans, Fiber Board Boxes Burlap Bags	Avoid badly ventilate storage.	This is the part of peanut between outer shell and peanut itself. Provide well ventilated storage.
Peanuts, shelled	Very slight or Negligible	Paper Bags, Cans, Fiber Board Boxes, Burlap Bags	Keep cool and dry.	Avoid contamination of rags, etc., with oil.
Perilla Oil	Moderate to High	Tin Cans, Barrels	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Pine Oil	Moderate	Glass, Drums	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Powdered Eggs	Very slight	Wooden Barrels	Avoid conditions that promote bacterial growth. Inhibit against decay. Keep cool.	Possible heating of decaying powder in storage.
Powdered Milk	Very slight	Wooden and Fiber Boxes, Metal Cans	Avoid conditions that promote bacterial growth. Inhibit against decay. Keep cool.	Possible heating by decay or fermentation.
Rags	Variable	Bales	Avoid contamination with drying oils. Avoid charring. Keep cool and dry.	Tendency depends on previous use of rags. Partially burned or charred rags are dangerous.

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Red Oil	Moderate	Glass Bottles, Wooden Barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated porous or fibrous materials are extremely dangerous. Tendency varies with origin of oil.
Roofing Felts and Papers	Moderate	Rolls, Bales, Crates	Avoid over-drying the material. Supply ventilation.	Felts, etc., should have controlled moisture content. Packaging or rolling uncooled felts is dangerous.
Sawdust	Possible	Bulk	Avoid contact with drying oils. Avoid hot, humid storage.	Partially burned or charred sawdust may be dangerous.
Scrap Film (Nitrate)	Very slight	Drums and Lined Boxes	Film must be properly stabilized against decomposition.	Nitrocellulose film ignites at low temperature. External ignition more likely than spontaneous heating. Avoid exposure to sparks, etc.
Scrap Leather	Very slight	Bales, Bulk	Avoid contamination with drying oils.	Oil-treated leather scraps may heat.
Scrap Rubber or Buffings	Moderate	Bulk, Drums	Buffings of high rubber content should be shipped and stored in tight containers.	Sheets; slabs, etc. are comparatively safe unless loaded or stored before cooling thoroughly.
Sisal	Very slight	Bulk, Bales	Keep cool and dry.	Partially burned or charred material is particularly liable to ignite spontaneously.
Soybean Oil	Moderate	Tin Cans, Barrels, Tank Cars	Avoid contact with rags, cotton, or fibrous materials.	Impregnated fibrous materials may heat unless well ventilated.
Sperm Oil -See Whale Oil				
Tankage	Variable	Bulk	Avoid extremes of moisture contents. Avoid loading or storing while hot.	Very dry or moist tankages often heat. Tendency more pronounced if loaded or stored before cooling.
Tung Nut Meals	High	Paper Bags, Bulk	Material must be very carefully processed and cooled thoroughly before storage.	These meals contain residual oil which has high tendency to heat. Material also susceptible to heating if over-dried.
Tung Oil	Moderate	Tin Cans, Barrels, Tank Cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Turpentine	Low	Tin, Glass, Barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Has some tendency to heat but less so than the drying oils. Chemically active with chlorine compounds and may cause fire.
Varnished Fabrics	High	Boxes	Process carefully. Keep cool and ventilated.	Thoroughly dried varnished fabrics are comparatively safe.

Table 2. Materials Subject to Spontaneous Heating[1]
(Originally prepared by the NFPA Committee on Spontaneous Heating and Ignition which has been discontinued. Omission of any material does not necessarily indicate that it is not subject to spontaneous heating.)

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Wallboard	Slight	Wrapped Bundles, Pasteboard Boxes	Maintain safe moisture content. Cool thoroughly before storage.	This material is entirely safe from spontaneous heating if properly processed.
Waste Paper	Moderate	Bales	Keep dry and ventilated.	Wet paper occasionally heats in storage in warm locations.

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Whale Oil	Moderate	Barrels and Tank Cars	Avoid contact of leakage from containers with rags, cotton or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Wool Wastes	Moderate	Bulk, Bales, Etc.	Keep cool and ventilated or store in closed containers. Avoid high moisture.	Most wool wastes contain oil, etc. from the weaving and spinning and are liable to heat in storage. Wet wool wastes are very liable to spontaneous heating and possible ignition.

* Refers to iron, steel, brass, aluminum, and other common metals, for information on magnesium, sodium, zirconium, etc.

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The ignition source for a recent large loss was directly attributed to the spontaneous ignition of used rags. The plant had recently switched from a chlorofluorocarbon (CFC) based solvent to a terpene based solvent. The terpene solvent resolved several environmental concerns, however, it also introduced a combustible liquid into a process that previously had none. Used clean-up rags containing terpene solvent were discarded into open top plastic trash barrels where the fire started.

Sources of terpenes are turpentine and other basic oils. Terpene solvents are used as a CFC solvent replacement because they are considered environmentally safe (used for circuit board cleaning). The material safety data sheet for the solvent involved indicated the liquid could polymerize. Chemically, terpenes can have unsaturated bonds which would suggest spontaneous heating tendencies (confirmed by the example loss). Proper disposal (normally closed metal containers) and prompt removal (empty drums at end of shift) of the terpene soaked rags would have eliminated the ignition source and prevented this loss.

The potential for spontaneous heating needs to be considered as a possible ignition source in many occupancies. Recognition of a material that may spontaneously heat, allows the initiation of preventative measures designed to eliminate or control the potential ignition source. Changes in manufacturing materials to comply with new codes and laws must be fully reviewed to assure a clear understanding of any new hazards that are introduced by the changes.

Spontaneous ignition can also take place by other exothermic chemical action, sometimes sudden and violent if highly reactive materials are mixed. Examples are water and sodium, strong oxidizing materials, and organic matter. NFPA 491M, *Manual of Hazardous Chemical Reactions*, gives many specific examples.

5.0 INDICATORS OF SLOW OR FAST—BURNING FIRES

Uniform overhead damage usually indicates a slow and smoldering fire, whereas extensive damage in one place on the ceiling indicates an intense, rapid buildup beginning below this spot. A wide angle ‘‘V’’ pattern indicates a slow-burning fire. A narrow angle ‘‘V’’ indicates a fast-burning fire.

In glass, large cracks and a heavy smoke film generally indicate slow burning, while irregularly shaped cracks and slight smoke film generally indicate rapid burning. A fast, intense fire will cause heavy alligatoring and shiny, smooth blisters on exposed wood surfaces, while a long, low heat source will produce flat alligatoring. In a cross-section of a piece of wood found near the point of origin, a distinct line between charred and uncharred portions of the wood indicates a fast, intense fire. A gradation in charring and an overall baked appearance usually indicate a long, slow fire.

6.0 EFFECTS OF FIRE ON STEEL

Steel has three characteristics that are of concern under fire conditions:

1. Steel expands substantially when heated.

2. Steel loses strength substantially when heated to temperatures in excess of 900° to 1000°F (480° to 540°C).

3. Steel transmits heat readily.

6.1 Thermal Expansion

If the ends of a steel member are free to move, the increase in length is approximately 0.065 percent for each 100°F rise in temperature (0.125 percent for each 100°C rise in temperature). For example, a 100 ft (30 m) long steel beam heated uniformly to 1000°F (556°C) above ambient will increase in length by almost 8 in. (200 mm). If the ends are fixed, the applied stress will change by about 19,000 psi for each 100°F temperature change (240 MPa [2400 bars] for each 100°C). Uniform heating of long horizontal beams can push over masonry walls or cause shear failure in connections for structural steel members.

Analysis of fire-induced stresses in horizontal cylindrical tanks containing liquefied gas indicates that failure of such tanks under fire conditions is not due to overpressurization nor to weakening of the unwetted shell, but to stresses produced by the axial expansion of the unwetted portion of the shell. As the unwetted portion is heated, it tends to expand, while the immediately adjacent wetted portion of the shell remains cool and restrains the expanding portion. As a result, tensile stress in excess of the ultimate strength of the metal is produced just below the liquid level. The metal starts to rip circumferentially at that point. The tank separates into (usually two) sections which rocket parallel to the axis of the tank.

6.2 Loss of Strength

The strength of mild steel actually increases up to about 600°F (315°C). Beyond that temperature, a decrease in strength occurs until about 1100°F (600°C) when the strength of steel is reduced to a point where it is not sufficient to carry the dead load, and the steel member fails.

Loss of strength is often the result of localized heating due to shielding or obstruction of the water spray from a few sprinklers or due to missing sprinklers. Bar joists and steel trusses are particularly subject to failure due to rapid overheating of thin steel members. The consequences in the case of bar joists may not be serious because large supporting beams that are protected can maintain the overall structural integrity of the building. However, localized overheating of a small section of a large steel truss system can cause major building collapse.

6.3 Thermal Conductivity

Heat can be transmitted through steel to combustible material that is otherwise unexposed to fire, such as steel deck roof insulation and contents of tanks and bins.

6.4 Evaluating Structural Damage

Mild structural steel building members often show no change in physical properties as a result of fire exposure. Many instances have been reported where straightening of distorted structural steel members has been both feasible and economical. Connections between members should be checked for cracks around holes.

Steel which has been exposed to temperatures of 1600°F (870°C) or higher may have a roughened appearance due to excessive scaling and grain coarsening. The steel will usually have a dark gray color, although other colors may be present. Steel so modified is commonly called ‘‘burnt’’ steel. Its suitability for further use is a matter for careful evaluation and judgment.

Steel with a higher carbon content than mild structural steel often has special characteristics determined by heat treating. Fire exposure may significantly change its physical properties and affect its suitability for continued use.

7.0 EFFECTS OF FIRE ON CONCRETE AND MASONRY

Fire alone seldom causes failure of concrete or masonry structural components. Failure is more often due to loss of support or stresses indirectly resulting from the fire. For example:

Masonry walls can be pushed over by expanding concrete or steel members, toppling or expanding storage, or explosion pressures.

Exposed steel-supporting trusses, beams, or columns can fail if not protected by water spray or insulation.

Floors can be overloaded by water-soaked storage.

Spalling can occur due either to expansion of moisture or to thermal expansion of the outer surface in concrete under compression as in columns, walls, or prestressed structural members.

7.1 Evaluating Structural Damage

Damage to concrete is usually superficial in fires with automatic sprinkler protection or in fires lasting less than two hours without sprinklers. If exposure is more severe, a careful study of structural damage is needed.

A waiting period of several weeks will allow damage to concrete to be more discernible from cracking, layering, calcination, or discoloration. The natural gray color changes to pink or brown indicating exposure to temperatures in excess of 450°F (232°C). Unsound concrete will be more or less soft and friable when chipped with a pick or hammer. Core samples of concrete and samples of reinforcing steel for load tests give more accurate quantitative measurements of structural strength. Such tests and examination should be performed under the supervision of a registered structural engineer.

Loss of tension in prestressed concrete-reinforcing tendons should be investigated where these members have been heated above 300°F (150°C). Ordinary reinforcing steel should be restored to its depth of cover where spalling has occurred to preserve its protection against future fire exposure and corrosion.

8.0 EFFECTS OF FIRE ON WOOD

Although wood is combustible, it has some positive properties from a fire exposure standpoint. For example, it does not expand significantly when heated, it does not lose strength except as it is burned away, and it is much less conductive than steel or concrete.

Thin members, such as boards and joists, burn through or lose strength much more rapidly than planks or plain or laminated timbers. The average rate of penetration of char when flame is impinged upon a wood member is about 1½ in. (40 mm) per hour. This is often useful in tracing the origin of a fire in an area of wood construction or occupancy.

Fire tends to sweep upward until its progress in this direction is blocked by some obstacle. If no holes, cracks, or outlets are present, the flames mushroom out horizontally until they bend around the obstruction and continue upward. Fire does not spread nearly so rapidly in a horizontal direction unless there are favorable ventilation conditions or some fast-burning material present. Fire should not spread downward significantly except in the case of falling, burning material. This also may be useful in tracing the origin of a fire.

Charring of the top surface of a wood floor is usually not evident because flames tend to rise away from the surface, and water from fire fighting readily protects the surface. However, localized charring is often evident. This can indicate the presence of either a combustible surface just above the floor such as a skid radiating heat downward or a thin ignitable liquid layer burning on the floor with some soaking-in to increase the volatility of the wood. It can also indicate a fire near the floor where water cannot penetrate to the floor because of shielding above or absorption by material above such as tissue or plastic foam.

8.1 Evaluating Structural Damage

Except for the volume of wood lost to charring, the strength of a wood structural member is affected very little by fire exposure. After the charred volume has been deducted, the remaining strength can be determined through structural analysis. However, metal-connecting members such as bolts and screws may lose strength or lose their connecting ability due to the burning away of wood.

9.0 EFFECTS OF FIRE ON SPRINKLER SYSTEM

The effect of the fire on the automatic sprinkler system can furnish useful information. This involves two factors: the number of sprinklers that operate, and the damage done to the sprinkler system by the fire.

The operation of an unusually high number of sprinklers can be due to a variety of causes:

1. A water supply too weak for the hazard.

2. The water supply to the sprinklers shut off, either at the start of the fire or during the fire. This may be due to:

   a. a closed valve,

   b. broken pipe,

   c. obstructed pipe,

   d. a dry pipe or deluge valve that failed to open or which was delayed,

   e. impairment of a water supply.

3. Shielded sprinklers
4. Fire that spread ahead of the sprinkler operation due to:
   a. dust, oil, or lint deposits, usually near the ceiling;
   b. fast-burning construction such as plastic foam, usually at the ceiling;
   c. an explosion or ‘‘puff’’ of vapor or dust;
   d. sprinklers located too far below the ceiling.

Damage to sprinklers, piping, or valves indicates that the equipment damaged did not receive water at some time during the fire. The extent of the damage should correspond to the extent of the impairment. A few damaged sprinklers may mean a plugged branch line. A damaged dry-pipe valve may mean an entire system was shut off and drained.

10.0 BASIC DEFINITIONS AND PRINCIPLES—EXPLOSIONS

10.1 Explosion

An explosion is a rapid transformation of potential physical or chemical energy into mechanical energy and involves the violent expansion of gases. This gas expansion creates a blast wave, with an overpressure and duration depending on the type of explosion. The two parameters of the blast wave that are important for evaluation of its damage potential are the maximum overpressure (P_{max}) and the impulse (I) of the positive phase of the pressure-time curve. Figure 1 illustrates the different pressure time profiles of deflagration and detonation waves.

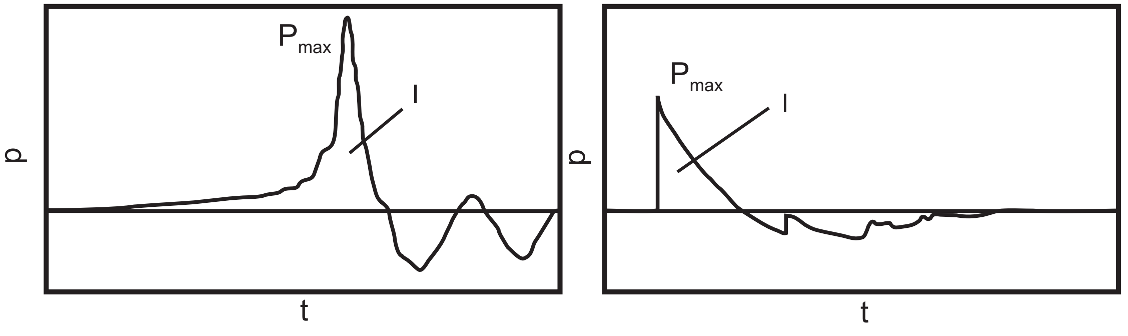

Fig. 1. Examples of pressure & impulse profiles from deflagration (left) and detonation

10.2 Physical Explosion

A physical explosion originates from purely physical phenomena, such as rupture of a boiler or pressurized container, or from interaction between water and molten metal or black liquor smelt.

Flash vaporization, the rapid vaporization of a superheated liquid when the pressure has been suddenly released, is an example of a physical explosion. This phenomenon often occurs when water is trapped under hot oil.

10.3 Chemical Explosion

A chemical explosion originates from a chemical reaction such as a flammable vapor air explosion, a dust explosion, or detonation of an explosive or blasting agent.

10.4 Thermal Explosion

A thermal explosion is the result of an exothermic reaction occurring under conditions of confinement with inadequate cooling. As the temperature rises, the reaction rate and heat generation accelerate until the container falls due to overpressure. See Data Sheet 7-49, *Emergency Venting of Vessels*.

10.5 BLEVE

A BLEVE (boiling liquid expanding vapor explosion) results from the rupture of a vessel containing a liquid substantially above its atmospheric boiling point. It may be a physical explosion or a thermal explosion. Energy is produced by the expanding vapor and boiling liquid. If the vapor is flammable and is ignited, a fireball ensues. Since the vapor is not premixed with air, if ignition is immediate, the main effect of the combustion is fire and radiant heat rather than explosive force (overpressure effects). A BLEVE can occur with a nonflammable liquid as with a rupturing hot water heater.

10.6 Deflagration

A deflagration is an exothermic reaction that propagates from the burning gases to the unreacted material by conduction, convection, and radiation. The combustion zone progresses at a rate that is less than the velocity of sound in the unreacted material. The unreacted material may be compressed by the force exerted by the deflagration, and the reaction rate may increase as a result. If this continues for a sustained time, as in a pipeline, the reaction rate may increase to sonic velocity, and a detonation may result.

10.7 Detonation

A detonation is an exothermic reaction propagating at greater than sonic velocity in the unreacted material. A shock wave is established and maintains the reaction. Detonations usually take place in solid or liquid materials such as explosives or blasting agents, and on rare occasions, explosions in gases can reach detonation velocity if confined for considerable distances as in pipelines.

10.8 The Mechanism of Explosion

Since an explosion is the rapid transformation of potential physical or chemical energy into mechanical energy, a common sequence of events takes place in all explosion processes.

1. Preceding the explosion, there is a buildup period during which the potential physical or chemical energy accumulates in a manner in which it may be suddenly transformed.

2. At the instant of the explosion, a triggering agent is introduced into the system which initiates the energy transformation.

3. During the buildup period, the triggering agent must be absent.

10.9 The Buildup Period

The buildup period may be anything from a fraction of a second to hours or days. During this time, ‘‘the stage is being set’’ for the explosion. Examples are:

1. A cloud of flammable gas or vapor mixes with air, leading to a gas or vapor/air explosion.
2. A cloud of dust mixes with air, leading to a dust explosion.
3. Pressure builds up in a tank, leading to a vessel rupture.
4. Molten metal or black liquor smelt accumulates, leading to a molten substance/water explosion.
5. A charge of explosive material is placed, leading to a blasting explosion.
6. A chemical reaction in a vessel ‘‘runs away’’, leading to a thermal explosion.

10.10 The Triggering Agent

The triggering agent may be introduced into the system, or the buildup period may spread or travel to encompass the triggering agent.

1. An ignition source, such as a spark or flame, may be introduced into an enclosure after a cloud of flammable vapor or gas is mixed with air, or the vapor/air cloud expands or moves to encompass the ignition source.

2. A dust/air cloud contacts a spark or flame sufficient for ignition.

3. The walls of a vessel rupture, transforming the potential physical energy into the expanding mechanical energy of the gas.

4. Water contacts a hot molten material converting the heat energy into expanding vapor.

5. A detonator or other shock-producing device detonates an explosive material.

6. Failure of a vessel wall converts the thermal chemical energy into a BLEVE or vessel-rupture explosion. The thermal explosion process itself may have been initiated by sudden mixing of two chemicals.

10.11 Explosion Prevention

The explosion may be prevented or transformed into a controlled release of energy by preventing the buildup period or the triggering agent, or by insuring that the triggering agent is present during the buildup period:

1. A vapor/air explosion can be prevented by excluding the flammable vapor from the system, by keeping air out of the system, by preventing any chance of ignition, or by insuring that an ignition source is present when air and fuel are first introduced, as at the burner of a furnace.

2. A dust explosion can be averted by preventing the formation of dust/air clouds, by keeping ignition sources away from dust/air clouds, or by (in the case of a pulverized fuel burner) insuring that an ignition source is present when pulverized fuel is dispersed.

3. A vessel rupture explosion can be averted by preventing a pressure buildup beyond safe limits, by insuring that the vessel walls do not fail below the maximum allowable pressure, and by releasing the energy by opening the vessel (through a relief valve or rupture disk) before excessive pressure buildup takes place.

4. A water/molten material explosion can be prevented by excluding molten material, by keeping water from contacting molten material, or by introducing the molten material in very small quantities to absorb the energy gradually, as in the dissolving tank of a black liquor boiler.

5. A blasting explosion may be prevented by keeping explosives out of the area, or by keeping detonating agents away from the explosives.

6. A thermal explosion can be prevented by controlling the exothermic reaction, by adequate cooling or other reaction suppression devices and by the gradual release of energy by venting devices.

11.0 EFFECTS OF EXPLOSIONS

Explosion effects are from the sudden release of mechanical energy in the form of pressure as a blast wave. Buildings can be destroyed or damaged by the pressure as well as the duration of the pressure.

11.1 Detonations

Detonations release a very large amount of energy within a relatively small volume. Extremely high pressures are produced in the immediate vicinity of the detonating material and the explosion occurs too quickly for venting to have any effect. As a result, there is usually shattering or pulverizing of steel or concrete, and a crater may be formed. Detonations can occur in some explosives, highly reactive gases (e.g., hydrogen) or even less-reactive gas-air mixtures in piping systems.

11.1.1 Energetic Materials

Energetic materials, such as TNT, dynamite, rocket propellants, and ammonium nitrate, etc., can accidentally explode during manufacture or storage causing widespread damage. TNT equivalence is an appropriate way to evaluate the effects of energetic material explosions and is discussed in Data Sheet 7-28, *Energetic Materials.*

11.1.2 Blast Waves and Overpressures

Blast waves are a major consequence of all explosions and move outward in a spherical shape like the ripple of a stone dropped in a pool of water. The amplitude (overpressure) and duration are related to the amount of energy released and how quickly it is released. The blast wave energy (overpressure and duration) decays at a rate proportional to the cube root of the distance from the explosion (Hopkinson-Cranz Scaling Law).

The common practice in predicting effects of explosion has been to translate the energy released into TNT equivalent. Most common explosives have TNT equivalents. Other references are available for estimating the TNT equivalence of other phenomena (Lees, Stephens).

Using the scaling law (Equation 1) it is then possible to predict blast effects in terms of overpressure.

$$R_g = Z_g \, (W_e)^{1/3} \qquad \text{(Eq. 1)}$$

Where:
R_g = Radial distance from energy release epicenter (expressed in feet or meters), at some overpressure
Z_g = Scaled ground distance (ft/lb$^{1/3}$ [m/kg$^{1/3}$]) from Table 3a or 3b for a defined overpressure
W_e =TNT equivalent mass, expressed in pound or kilograms

Table 3a. Scaled Ground Distance at Overpressures (English)

Overpressure, P (psig)	Scaled Ground Distance, Z ft/lbs $^{1/3}$
15	8
10	9.8
6	13
5	14.5
3	19.5
2	26
1	45

Table 3b. Scaled Ground Distance at Overpressures (Metric)

Overpressure, P (barg)	Scaled Ground Distance, Z m/kg $^{1/3}$
1.03	3.2
0.69	3.89
0.41	5.2
0.34	5.75
0.21	7.7
0.14	10.0
0.07	17.9

After calculating the distance to the selected overpressure the overpressure rings can be plotted on a plan view of the site centered on the explosion.

Damage tables based on overpressure are available from a number of sources (Lees, Stephens). There are also effects related to the duration (impulse), but for most property loss evaluations this was generally not considered. More recently, evaluations have been done considering both overpressure and impulse.

11.1.3 Craters

If a detonation takes place near the surface of the ground, a crater may be produced. The size of the crater can vary widely, but an approximation can be made for dry soil by using the formula $D = 1.5\ W^{1/3}$ where D is the crater diameter in feet, and W is the charge weight in pounds of TNT. In metric units, $D = 0.6\ W^{1/3}$ where D is the crater diameter in meters, and W is the charge weight in kilograms of TNT. The depth of the crater is normally about one-quarter of the diameter.

11.2 Deflagrations

Deflagrations release energy more slowly and the combustion occupies a larger volume. The overpressures developed are less than those from a detonation, and venting of the building or vessel can often reduce the damage effects to an acceptable level. Damage is more likely to involve tearing of materials into relatively large pieces. Craters are usually not produced.

11.3 Vapor Cloud Explosions (VCE)

In most deflagrations, the overpressures produced in the explosion are confined to process equipment or a building. In some cases, such as at petrochemical plants or refineries, a large cloud of flammable vapor can be released outdoors into a partially confined and/or congested open process structure. The resulting VCE can produce severe damage over a wide area, sometimes even beyond the plant boundaries. Refer to Data Sheet 7-42, *Vapor Cloud Explosions, for additional information.*

TNT equivalence methods have been used in the past to predict blast effects of vapor cloud explosions but are no longer widely used for hazard evaluations. Energy release effects from explosives, blast wave and impulse, are different from that caused by flammable vapor clouds and pressure vessel ruptures, and using TNT equivalents can overestimate near field effects and underestimate the far field effects.

Flame acceleration models (FAM) for prediction of outdoor gas clouds are more accurate and have been implemented by FM for property loss evaluation. Details are covered in Data Sheet 7-42.

11.4 Vessel Ruptures and BLEVES

When a vessel containing a gas under pressure ruptures, the mechanical energy released is proportional to the volume of gas times the pressure, assuming that is the only energy available. If the vessel comes apart completely so that all the energy is released at once, a shock wave may be produced. However, if the pressure buildup is relieved, for example by a manhole cover coming off, the vessel may remain largely intact and the energy is released over a longer period. Damage may be limited to that done by the flying cover or rocketing tank.

If the material in a vessel is noncombustible, the effects of the overpressure will be a blast wave proportional to the mechanical energy released plus fragments from the vessel. If the material in the vessel is corrosive, in addition to blast and fragment effects, widespread damage to process areas from later corrosion might occur. If the material is an ignitable liquid or flammable gas, a number of ″add on″ events could occur, such as a fire ball with radiant heat effects and subsequent fires.

If the vessel contains liquid well above its atmospheric boiling point, a portion of the liquid instantly vaporizes when the pressure is released. The unvaporized liquid is carried with the expanding vapors and the event is often called a BLEVE (boiling liquid expanding vapor explosion). The liquid doesn’t have to be flammable to be considered a BLEVE.

Historically, a number of scenarios have resulted in pressure vessel ruptures in process equipment and mobile storage vessels, including the following:

- Process vessels operating in corrosive conditions
- Process vessels with potential for internal hidden corrosion such as lined, clad, or overlaid construction
- Process vessels with external hidden corrosion, such as under exterior insulation
- Vessels with known metallurgical defects
- Chemical reactors running exothermic reactions with incorrectly sized, plugged, or impaired pressure relief devices
- Vessels with the potential to be connected to high-pressure services (e.g., air, steam, or process lines) where the pressure is significantly greater than the ultimate failure pressure of the vessel (MAWP plus design safety factors)
- Process vessels weakened by exposure to an uncontrolled fire

11.4.1 Pressure Vessel Rupture Failure Pressure

The pressure at which a vessel fails can vary depending on operating conditions, defects, and overpressure scenarios. Pressure vessels typically have an ultimate failure pressure with a safety margin above the design maximum allowable working pressure (MAWP). For ASME code vessels this margin can be 3.5 to 4 times the MAWP, depending on the version or section of the code that applies. European design codes typically have smaller safety margins, such as 2.4 times MAWP for carbon steel without corrosion or fabrication allowances. Determine the pressure at vessel failure based on one of the criteria below:

A. Use the highest normal operating pressure of a vessel
  - in corrosive service or environment.
  - with known metallurgical defects.

B. Use the ultimate failure pressure (MAWP plus design safety factors) of a vessel
  - containing highly reactive systems (exothermic reactors).
  - that can be accidentally exposed to pressure exceeding the ultimate failure pressure.

11.4.2 Pressure Vessel Rupture Energy Release

If energy contained in a pressurized vessel is released by sudden failure of the shell, the effects can be estimated using pressure-volume (bursting pressure vessel) calculation models. There are a number of models to estimate the energy release from a bursting pressure vessel. An isothermal expansion model was previously suggested to tie in with the TNT equivalent method. FM has developed proprietary software, BlastCalc, which will be used by FM engineers for pressure vessel rupture evaluations. The energy release is based on Brode’s constant volume energy addition approach tied in with pressure wave parameters from bursting vessels.

Chapter 7 of the CCPS Guideline book on vapor cloud explosions (see 12.2) provides some guidance on calculation methods as well as worked examples for evaluating blast effects produced by these events.

11.4.3 Loss Examples

11.4.3.1 Kaiser Aluminum and Chemical Corporation, Gramercy, Louisiana, USA

On July 5, 1999 an explosion occurred at an alumina refinery. The incident occurred in a high-pressure alumina ore processing system that had been weakened by corrosion and reportedly had impaired pressure relief systems. The accident caused the rupture of all five digesters in the process. Four of the five digesters had volumes of 68,000 gal (260 m^3), and one had a capacity of 180,000 gal (690 m^3). The design temperature was 600°F (315°C) and the MAWP was 600 psig (41 barg). Records show the failure pressure of the vessels was between 600 and 633 psig (41 and 44 barg).The ruptures essentially destroyed the processing plant. There were no ensuing fires. The gross loss estimate was over US$500 million. This incident was investigated by the US Mine Safety and Health Administration (MSHA) and a report was issued.

12.0 REFERENCES

12.1 FM

Data Sheet 7-12, *Mining and Ore Processing Facilities*
Data Sheet 7-28, *Energetic Materials*
Data Sheet 7-42, *Vapor Cloud Explosions*
Data Sheet 7-55, *Liquefied Petroleum Gas (LPG) in Stationary Installations*
Data Sheet 7-64, *Aluminum Smelting*
Data Sheet 7-89, *Ammonium Nitrate and Mixed Fertilizers containing Ammonium Nitrate*

12.2 Others

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Center for Chemical Process Safety (CCPS). *Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards.* Second Edition. 2010.

Fig. 2. Damage after the explosion.

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Stephens, M.M. *Minimizing Damage to Refineries from Nuclear Attack, Natural, and Other Disasters.* US Dept. of the Interior, Office of Oil and Gas, Prepared for the Department of the Army, Series Report No. AD-773-048. February 1970.

US Department of Labor, Mine Safety and Health Administration (MSHA). *Nonfatal Exploding Vessels Accident, Gramercy Works, Kaiser Aluminum and Chemical Corporation.* ID No. 16-00352. July 5, 1999.

APPENDIX A GLOSSARY OF TERMS

Ignitable Liquid: Any liquid or liquid mixture that is capable of fueling a fire, including flammable liquids, combustible liquids, inflammable liquids, or any other reference to a liquid that will burn. An ignitable liquid must have a fire point.

Ultimate failure pressure: Internal pressure at which a vessel will fail catastrophically. For ASME code vessels this pressure can be 3.5 to 4 times the MAWP, depending on the version or section of the code that applies. European design codes typically have smaller safety margins, such as 2.4 times MAWP for carbon steel without corrosion or fabrication allowances.

MAWP: maximum allowable working pressure is the maximum pressure to which a vessel may be subjected during operation. It is code limited and determined by either the manufacturer or by analysis. The value is usually stamped on the vessel nameplate.

APPENDIX B DOCUMENT REVISION HISTORY

April 2013. Minor editorial changes and additional guidance for using TNT equivalence methods for estimating the effects of explosions (overpressure) involving energetic materials.

October 2012. References to the use of TNT equivalence to evaluate the effects of vapor cloud explosions were replaced with the use of flame acceleration modeling and pressure-impulse effects. Additional guidance was provided for estimating the effects of pressure vessel rupture using pressure-impulse methods to evaluate the explosion effects.

January 2012. Terminology related to ignitable liquids has been revised to provide increased clarity and consistency with regard to FM Global's loss prevention recommendations for ignitable liquid hazards.

April 1994. Revised to remove guidance on vapor cloud explosions to new 7-0S.

July 1981. First publication.