Technically Speaking

Explosion

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We will be discussing three kinds of explosions.

- Detonation of an explosive device producing blast or shock waves
- Vapor cloud and dust cloud explosions in an unconfined or partially confined space
- Explosion produced by sudden rupture of a container under pressure

Sometimes explosions are classified as (1) thermal explosions and (2) non-thermal explosions. A thermal explosion is one which burns suddenly (detonates) resulting in a violent expansion of gases with great disruptive force and a loud noise. The detonation of an explosive device made up of ammonium nitrate/fuel oil is an example of a thermal explosion. A non-thermal explosion describes a sudden bursting because of buildup of pressure within a container. An example is the filling of a tank with air under pressure, and the tank suddenly bursts producing an explosion. Detonation of an Explosive Device

An explosive device involves the use of a solid or liquid that explodes if ignited, shocked, or subjected to heat or friction. Examples are nitroglycerine, ammonium nitrate/fuel oil mixtures, PETN, TNT, dynamite, lead azide, RDX, gunpowder, and dynamite.

Whether something will explode requires investigation on a case-by-case basis. Some materials such as copper azide will detonate at the slightest shock or movement whereas others such as TNT or RDX may require another explosive (called a primary explosive, or a blasting cap) to detonate the material. There is no easy way of predicting whether a particular material is explosive; a case-by-case investigation is required. However if an oxidizing material (e.g. ammonium perchlorate, potassium permanganate, ammonium nitrate, etc.) can be placed in intimate contact with a fuel source (almost any organic material which burns) this is a basic recipe for an explosive material. If the oxidizing part can be incorporated into the molecule itself (e.g. nitric acid plus glycerin to yield nitroglycerine), a powerful explosive is produced. Another example is trinitrotoluene, also called 2,4,6-trinitrotoluene, or "TNT" for short, which is manufactured from toluene (toluene is the fuel part of the molecule, three "nitro-" groups are the oxidizing part). If certain combustible metal powders such as aluminum can also be mixed in with the material, the explosive capability may be enhanced. Many explosive chemicals have nitrogen in the form of nitrate (a nitrogen atom linked to three oxygen atoms) or nitro- (a nitrogen atom linked to two oxygen atoms) or azide (two nitrogen atoms linked together) incorporated as part of the organic molecule.

Dynamite is a detonating explosive containing a liquid explosive ingredient (usually nitroglycerine or a similar organic nitrate ester or both) that is uniformly mixed with an adsorbent material such as wood pulp and usually contains materials such as nitrocellulose, sodium and/or ammonium nitrate (definition from United States 40 CFR 173.59).

All of these fall into the general category of thermal explosions.

One of the current technological challenges is to build non-evasive equipment able to detect 'signatures' of explosive materials that might be in airport baggage or in vehicles.

When an explosive material detonates, the violence and speed of the reactions taking place produce a blast or shock waves (a thin shell of highly compressed air which rapidly expands in all directions from the point that the explosion is initiated). The speed of the wave can exceed the speed of sound. The strength of the wave is measured in terms of overpressures, or peak overpressures (maximum pressure in the wave in excess of normal atmospheric pressure).

The blast effects of one explosive, TNT, have been very well studied. All other explosives are compared to TNT in terms of TNT equivalents. Even nuclear explosions are rated in terms of TNT equivalents.

The following equation relates the distance from the point of a ground-level explosion to peak overpressure.

$$X = M^{1/3} \exp[3.5031 - 0.7241\ln(P) + 0.0398 (\ln(P))^2]$$

here, X = Distance in feet to a given overpressure P

M = TNT equivalent mass, lbs

P = overpressure, psi (psi = pounds per square inch)

This equation is from Lees, F. (1980), Loss Prevention in the Process Industries, Butterworth Press. It is the equation used in the ARCHIE model and also used by EPA in Risk Management studies (EPA uses P = 1 psi). The equation is also used in the PEAC tool in predicting Protective Action Distances. The equation is valid for an explosion at ground level at 20°C ignoring any redirection of the overpressure by structures and terrain. If the explosion occurred up in the air (unconfined in all directions), the distance X would be reduced by a factor of 1.26.

The expected damage that is expected to occur for a given overpressure is listed in table 1.
p class=MsoNormal>Table 1. Explosion Overpressure Damage Estimates

Overpressure, psi	Expected Damage
0.04	Very loud noise (143 dB); sonic boom glass failures
0.1	Breakage of small windows under strain
0.15	Typical pressure of glass failure
0.30	10% of windows broken
0.5	Windows shattered, limited minor damage to house structures
0.7	Upper limit for reversible effects on humans
1.0	Partial demolition of houses; corrugated metal panels fail and buckle; skin lacerations from flying glass
2.0	Partial collapse of walls and roofs of houses
2.4	Eardrum rupture of exposed populations
2.5	Threshold for significant human lethality
3.0	Steel frame building distorted and pulled away from foundation
5.0	Wooden utility poles snapped
10	Probable total building collapse. Lungs hemorrhage
20	Total destruction. 99% fatality due to direct blast effects

The Bureau of Alcohol, Tobacco and Firearms (ATF) has published (once available on line at www.atf.treas.gov/pub/fire-explo_pub/i54001.htm, now must be ordered at the address given at the ATF website) Lethal Air Blast Range and Minimum Evacuation Distance values for vehicles carrying explosives as in a terrorist threat. Table 2 compares these distances with the overpressure formula listed above, assuming that the explosive is TNT or equivalent. A possible explosive used by a terrorist is ANFO, prepared by soaking ammonium nitrate prills in fuel oil (94% ammonium nitrate, 6% fuel oil) and detonated by an high explosive booster or a blasting cap. ANFO has an explosive power (by weight) approaching that of TNT, or even greater if the ANFO is enhanced with aluminum powder.

Table 2. Comparison of Formula Calculations with ATF Distances for Vehicles Carrying Explosives

Vehicle	Explosive Capacity, lbs	ATF Lethal Air Blast Range, ft.	Equation calc. At P = 3 psi	ATF Minimum Evac. Dist, ft.	Equation calc. At P = 0.12 psi.
Compact Sedan	500	100	125	1500	1464
Full Size Sedan	1000	125	157	1750	1840
Cargo Van	4000	200	250	2750	2928
14-ft Box Van	10000	300	339	3750	3974
Fuel Truck	30000	450	489	6500	5753
Semi-Trailer	60000	600	615	7000	7220

At P = 0.15 psi, glass failure may occur. At 0.3 psi, 10% of the windows in buildings may be broken. The upper limit for reversible effects on humans is at P = 0.7 psi. At P = 2.4 psi, eardrum rupture may occur. P= 2.5 to 10 and higher is in the range of lethality to humans. At P = 3 psi, a steel frame building may become distorted and pulled away from its foundation. At P = 10 psi, there will be probable total building destruction. There are differences of opinion in the literature as to what overpressure should be used for a Protection Action Distance. The 0.12 psi number is suggested based on the ATF information.

In the PEAC tool, both the ATF information and Protective Action Distances based on overpressure calculations are displayed.

EXAMPLE : Terrorist with small package containing an explosive

A terrorist has a small package, which appears to measure approximately 4x3x5 inches. It could be a hoax, but what are the consequences if the package contains a plastic bonded explosive and it detonates?

Using the PEAC tool. The PEAC user selects “plastic bonded explosive” and the package dimensions. The PEAC tool internally calculates a TNT equivalent (about 6 lbs). The user enters several overpressure values, including 0.12 psig (minimum safe evacuation distance), 1 psig (possible serious injury due to flying glass and missiles; partial demolition of houses), and 5 psig (nearly complete destruction of houses; vehicle demolished). The

PEAC tool calculates internally 320 feet, 60 feet, and 20 feet for the respective overpressures using the equation listed above.

Discussion. If the incident occurs in a bus, the explosion may blow apart the bus possibly killing most people aboard and blowing out the windows of nearby vehicles. If the incident occurs in a shopping mall, shrapnel may fall at a distance up to about 320 feet and with serious injury at 60 feet. A terrorist would probably position himself or place the explosive for maximum possible impact (as in a bus, an aircraft, near a fuel storage tank, or corridor where many people are present), which must be taken into consideration.

Vapor Cloud or Dust Cloud Explosions in an Unconfined or Partially Confined Space

By unconfined or partially confined space we mean out in the open or inside a building or a silo as opposed to inside a tank or some other sealed container.

You have seen numbers, "Lower Explosive Limit" and "Upper Explosive Limit listed with many chemicals. For example, propane has a lower explosive limit of 2.7% and an upper explosive limit of 9.5%. If the concentration of propane in air is between 2.7 and 9.5% by volume, and there is an ignition source (e.g. a spark generated by friction, a lighted cigarette) an explosion will occur. If the concentration of propane is less than 2.7%, the mixture is too lean for the propane to ignite. If the concentration is above 9.5%, the mixture is too rich.

Last month we talked about concentration fluctuations in the air resulting from air circulation patterns. Even though the average concentration measured might be outside the explosive range, localized concentrations may be within the range, resulting in detonation if a ignition source occurred.

Many materials will self-ignite if heated to a high enough temperature. This is the auto-ignition temperature . This temperature is listed in the PEAC tool for many chemicals. This is of particular concern if there is a nearby fire, and the radiant heat from this fire heats nearby structures and their chemical contents. The heat can volatilize the chemicals which may self ignite without the original fire coming into contact with the chemicals.

Two things may happen when the vapor cloud or dust cloud is ignited. The first is a vapor cloud explosion. This may be followed (almost instantaneously) by a fire as the flammable vapor burns. It is common practice in a vapor cloud explosion to express the energy released as a TNT-equivalent charge, and then utilize the overpressure data for TNT explosions. The overpressure data from TNT explosions are used to relate overpressure to distance from the vapor cloud explosion. However, only a fraction of the energy in the chemical contributes to the explosion. The rest of the energy may contribute to an accompanying fireball. The equation for calculating the equivalent mass of TNT is

$M = m_c\ [\ H_c / 1155]\ Y$

where M = TNT equivalent mass, lbs

H_c = lower heat of combustion of chemical, kcal/kg

Y = yield factor (the fraction of the mass of chemical that contributes to the explosion)

The number 1155 is the heat of detonation of TNT in kcal/kg.

(kcal/kg = kilocalories per kilogram).

The heat of combustion is a number that can be looked up in a reference table for a particular chemical. By convention the reference tables in chemistry handbooks usually give the "high value" for the heat of combustion and must be corrected to give the lower value (this is a simple mathematical correction). For example, the lower heat of combustion for ethylene is 11,272 kcal/kg, and the high value is 12,022 kcal/kg (from the 4^{th} edition of the Chemical Engineer's Handbook).

The yield factor is probably the biggest unknown. If we have an explosive device, essentially 100% of the material contributes to the explosion. For vapor cloud explosions, the numbers are much less, usually Y is between 0.02 and 0.20 (2 to 20% of the energy in the chemical contributes to the explosion). The U.S. EPA when performing Risk Management calculations suggest using Y = 0.1 for all chemical forming vapor clouds, but the ARCHIE model assigns different yield factors for different chemicals.

Once the mass of equivalent TNT is calculated, the equation relating distance to overpressure can be used. The ARCHIE model cites a Health and Safety Executive board (England) recommendation that the overpressure P should be less than 15 psi when using the equation to calculate distances.

This is not the only methodology available for computing vapor cloud explosions. A discussion of the TNO yellow book model is in J. R. Taylor's book titled "Risk Analysis for Process Plant Pipelines and Transport", 1994, published by E&FN Spon, London (England). The TNO yellow book model was developed by the Bureau of Industrial Safety of the Netherlands, and originally published in 1980

EXAMPLE : Ethylene oxide gas escapes from a cylinder into a room

The entire contents of a 15-lb (net weight) 4B240 cylinder of ethylene oxide escapes into a room overnight. The room is closed and the ventilation system is turned off. No other flammable liquids or gases are in the room . The room measures 10 by 15 feet and is 9 feet high. The temperature is 68^{o}F (20^{o}C). What are the consequences if the escaped gas ignites?

Discussion: From the PEAC tool, ethylene oxide is seen to have a boiling point of 51^{o}F, a molecular weight of 44.1, a lower explosive limit of 3%, and an upper explosive limit of 100%. There are also toxicity concerns as ethylene oxide has an IDLH of 800 ppm (parts per million). The same information can be looked up in the NIOSH pocket guide to chemical hazards. Ethylene oxide is heavier than air (air has an average molecular weight of 29) so at least initially the escaping gas will settle close to the floor. Eventually the gas will diffuse and mix throughout the room. The volume of the room is 1350 cubic feet. The volume of 15 lbs of ethylene oxide at 68^{o}F is 131 cubic feet. If all of the ethylene oxide remained inside of the room, the volume percent of ethylene oxide in the room could reach 9.7% (131 x 100% / 1350). This number is well above the lower explosive limit.

Ethylene oxide is a molecule that contains its own oxygen. The "fuel" and "oxidant" are part of the same molecule. It is explosive even at a vapor concentration of 100%.

The ARCHIE model suggests using a yield factor of 0.19 (Y = 0.19) for ethylene oxide in vapor/gas explosions. The heat of combustion of ethylene oxide is 6380 kcal/kg (from the CHRIS Manual). The numbers work out such that 15 pounds of ethylene oxide in an explosive gas mixture is roughly equivalent to 15 lbs of TNT.

Of course it can be argued that some ethylene oxide will seep under the door or through vents so the amount explosive mixture inside the room may be less than 15 pounds. Also the algorithm for TNT overpressure is known to over-predict the overpressure at very close distances to the center of the vapor cloud explosion. But we are looking at the worst case.

Using the PEAC tool, distances corresponding to 0.12 psi, 1 psi, and 5 psi overpressure are calculated for 15 lbs of TNT. These are 455, 82, and 28 feet. The force of the explosion could knock down the walls of the room. There could be serious injury from flying debris at 82 feet. The calculations predict a minimum safe evacuation distance of about 455 feet. Because of uncertainties of how the blast/shock waves may be directed in the building and to the outside, the entire building probably should be evacuated, and probably an additional safety factor for evacuation outside the building.

Example: Case Study of an ethylene mixture vapor cloud explosion in Texas

In an accident in Pasadena, Texas, 85,000 lbs of a mixture containing primarily ethylene was released through a valve at 700 psi producing a vapor cloud ignited. The damage produced by the explosion was equivalent to 10 tons of TNT. How does this accident compare with results predicted by the ARCHIE model?

<u>Discussion</u>: Ten tons of TNT produces approximately 5 psi overpressure at a distance of about 320 feet which was consistent with the damage which occurred. The ARCHIE model suggests a yield factor of 0.06 for ethylene. The CHRIS manual uses 11,272 kg/kg for the heat of combustion of ethylene. Using the formula for TNT equivalents, 85000 lbs (42.5 tons) of ethylene is equivalent to 25 tons of TNT. Apparently only a little less than half the ethylene mixture contributed to the vapor cloud explosion.

<u>Explosion produced by sudden rupture of a container under pressure</u>

An over-pressurized container can explode even without involvement of a combustible or explosive material. The pressurized vessel can be filled with air or some other inert gas; it does not have to be filled with a combustible gas or flammable vapor. Also a nearly empty pressurized container of gas can be of a more of an explosion hazard than a container nearly filled with liquid that ruptures at the same pressure. A sudden rupture of a container under pressure is an example of a non-thermal explosion, but a secondary thermal explosion can occur if the escaping container contents are flammable and ignite.

A BLEVE (<u>B</u>oiling <u>L</u>iquid <u>E</u>xpanding <u>V</u>apor <u>E</u>xplosion) occurs when a liquid that is contained under pressure and at a temperature significantly above its normal (atmospheric) boiling point is suddenly released from the container (as in a container rupture). When this happens the liquid vaporizes almost instantaneously and expands to several times its original volume with explosive force. If the BLEVE involves a flammable liquid or a liquefied flammable gas, the initial explosion often will be followed by the instantaneous ignition of the released vapors, resulting in a massive fireball and increased explosive force.

BLEVEs have been known to hurl debris weighing a hundred pounds or more for more than a half-mile from the explosion. There can be a trail of flaming vapor as a portion of the exploded tank or container flies through the air. The blast wave from a BLEVE can destroy structures several hundred feet from the incident. These incidents makes BLEVEs particularly dangerous.

Let us recap. Several things happen here:

- There is an initial pressurized tank or container failure, which may produce an initial explosion.

- If the tank or container contained a pressurized liquid which is normally a gas under ambient temperatures, the sudden release of pressure caused by tank failure may result in a BLEVE. The secondary explosion from the BLEVE can destroy nearby structures and can hurl debris far from the tank location.

- If the BLEVE involves a flammable liquid or liquefied flammable gas, there can be a massive fireball and increased explosive force.

Liquefied natural gas and propane are common examples of a liquefied flammable gas.

What can cause failure of a pressurized container, and possible resulting BLEVE?

Pressurized vessels used in industry should contain safety valves, or pressure release valves, designed to vent excessive pressure before vessel failure occurs. But sometimes pressure can buildup suddenly, or a nearby explosion takes place, or there may be direct flame impingement above the liquid level of the tank causing the tank metal to fail.

Two situations that can cause initial failure of a tank is (1) buildup of pressure inside the tank because of fire impinging on the tank, and (2) failure of a tank because of shrapnel damage from a nearby explosion.

Example: BLEVE at an Illinois refinery in 1984 killing 17 people.

A propane tank associated with monoethanolamine absorber tower failed at 200 psi and 100°F at an Illinois refinery. The explosion and ensuing fireball killed 17 people including 10 members of a standby fire brigade, which had been earlier called to the site when an operator observed a 6-inch crack in the absorber tower. It was later determined that a weld in the propane vessel shell catastrophically failed due to inadequate heat treatment following a weld repair made ten years earlier.

(reference: S.W. Haines, Workshop: Preventing Boiling Liquid Expanding Vapor Explosions, International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, Sept. 26-29, 1995, New Orleans, LA, presented in a book [page 87] published by American Institute of Chemical Engineers, N.Y., N.Y.; the Pasadena Texas , ethylene explosion example was also cited from the same book [page 966]).