Explosion Basics – Screening Level Application

Explosion Definition

"A rapid expansion of gases resulting in a rapidly moving pressure or shock wave. The expansion can be mechanical (by means of a sudden rupture of a pressurized vessel) or it can be the result of a rapid chemical reaction."

Crowl and Louvar, Chemical Process Safety, 4th (2019)

Types of Explosion

- ***Physical Explosion*** – the catastrophic rupture of a pressurized gas/vapor-filled vessel.
- ***Condensed Phase Explosion*** or Chemical Explosion - An explosion that occurs when the material is present in the form of a liquid or solid.
- ***Boiling-Liquid Expanding-Vapor Explosion (BLEVE)*** – A type of rapid phase transition in which a liquid contained above its atmospheric boiling point is rapidly depressurized, causing a nearly instantaneous transition from liquid to vapor with a corresponding energy release. *A BLEVE of flammable material is often accompanied by a large aerosol fireball*.
- ***Building or Confined Space Explosion*** – an explosion of fuel-oxidant mixture *inside a closed system* (e.g. vessel or building). *In a Building Explosion, the walls may fail during the event allowing the blast wave to dissipate in multiple directions.*
- ***Vapor Cloud Explosion*** – the explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure.
- ***Dust Explosion*** – an explosion resulting from rapid combustion of fine solid particles

Explosion Terms

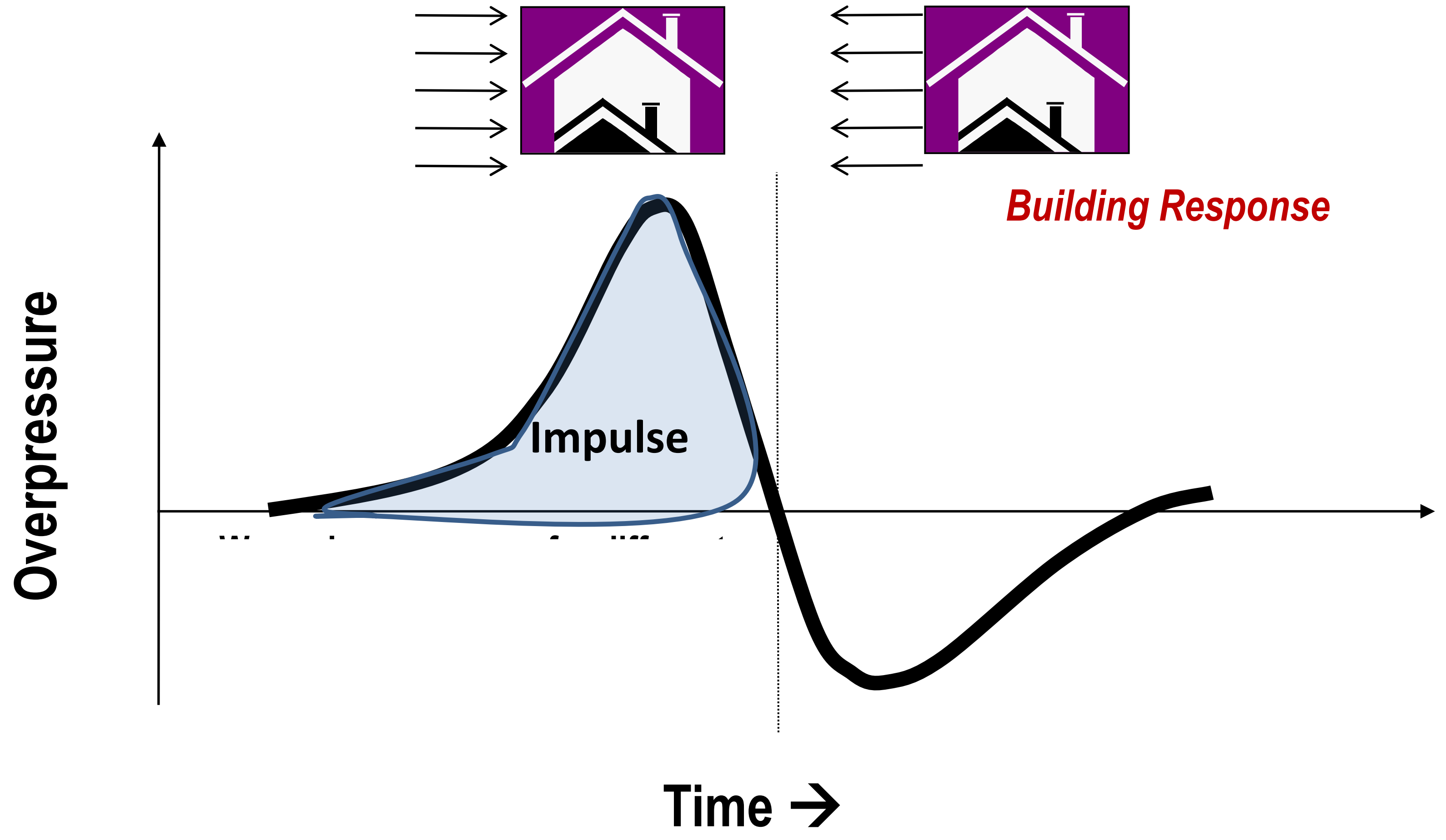
- ***Detonation*** – an explosion in which the reaction front advances into the un-reacted substance at greater than sonic velocity.
- ***Deflagration*** - an explosion in which the reaction front advances into the un-reacted substance at less than sonic velocity.
- ***Blast Wave*** - the overpressure wave traveling outward from an explosion point.
- ***Overpressure*** – the pressure caused by a blast wave over and above normal atmospheric pressure.
- ***Impulse*** - integral of overpressure versus time generally for the positive duration pulse.
- ***Potential Explosion Site (PES)*** – an area within a plant with sufficient congestion and/or confinement that a flammable vapor cloud ignited there could likely develop into an explosion.
- ***Explosion Efficiency*** - The ratio of the mechanical energy released in an explosion to the heat of combustion times the flammable mass in a vapor cloud (net efficiency). Alternately, the ratio of the mechanical energy released in an explosion to the heat of combustion times the total mass of fuel in a vapor cloud (gross efficiency).

Explosion Damage

Overpressure ***(PSI)***	**Damage per NFPA-921**
0.3	"Safe distance" (95% probability of no serious damage)
0.5	Shattering of glass windows
1	Partial demolition of houses
2	Partial collapse of walls and roofs of houses
5	Wooden utility poles snapped/Flying glass serious injury
10	Total destruction of buildings/Heavy machine damage
15	Severe Injury/some fatalities (eardrum rupture/lung damage)
30	Near 100% Fatality from direct blast effects

Simple damage models are based on correlation of damage to peak overpressure assuming a relatively long duration impulse and used for approximate estimates.

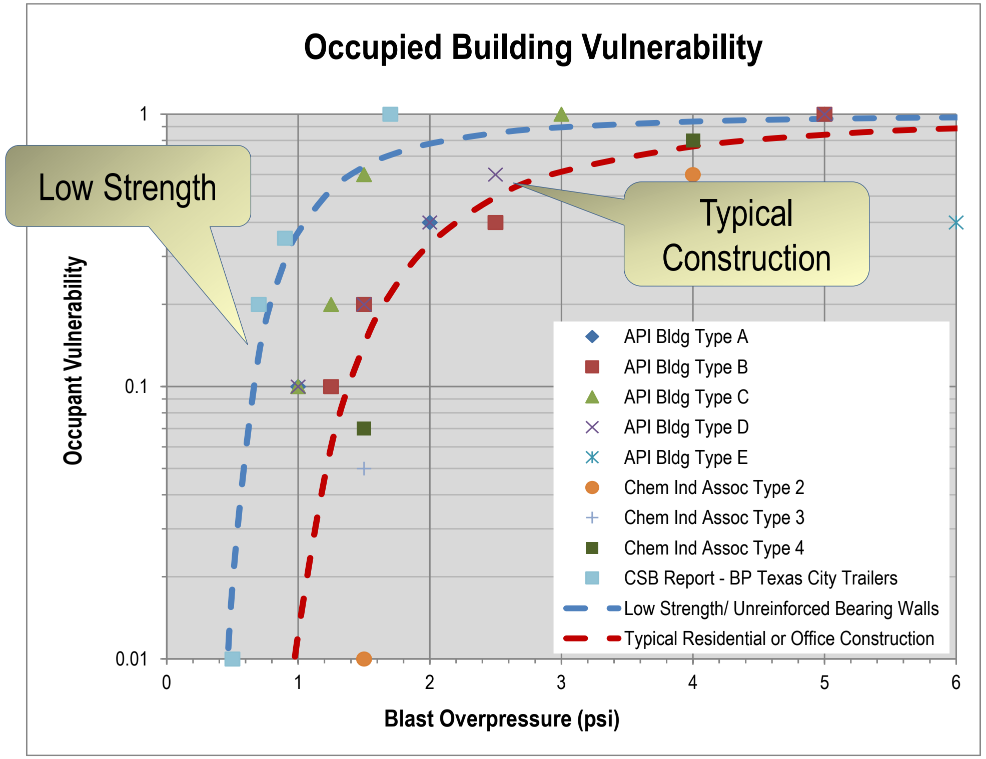
Blast Wave Characteristics



Building Damage from Explosion

Vulnerability of Building Occupants

Most industrial explosion fatalities result from secondary impacts, particularly building failures.



Data compiled from CCPS <u>Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires</u> (1996) page 62

Physical Explosion and BLEVE

Equipment or Vessel Rupture

Stored pressure-volume energy for a gas filled vessel rupture may be estimated as the energy of expansion of an ideal gas per the correlation of Crowl by:

$$Q_{PV} = V\,P_B\,[\,\ln(P_B/P_A) + (P_A/P_B) - 1\,]$$

where V is the vapor volume in the vessel (m^3), Q_{PV} is explosion energy (kJoule), and P_A, P_B are atmospheric and burst pressure (kPa).

The additional energy associated with a Boiling-Liquid Expanding-Vapor Explosion was described by Prugh using an equivalent volume equal to the initial vapor volume plus the volume of vapor generated from instantaneous liquid vaporization or:

$$V^* = V_V + f_V\,M_{Liquid} \,/\, (\,\rho_V - \rho_L\,)$$

where V^* is the equivalent volume (m^3), f_V is the flashed fraction, M_{Liquid} is the mass of liquid within the vessel (kg) and ρ_V is the vapor density while ρ_L is the liquid density at vessel temperature and burst pressure (kg/m^3).

Condensed Phase or Chemical Explosion

During a runaway reaction, the system pressure normally increases due to increasing temperature (and a corresponding increase in vapor pressure) or the formation of volatile or gaseous products. If sufficient reactive material is present, the pressure may increase to the point of vessel or equipment rupture. If the runaway reaction is considered a propagating explosion (capable of deflagration or detonation due to the presence of a high energy molecular structure, or otherwise considered highly energetic), the heat of reaction times an explosion efficiency would be used in estimation of the explosion energy.

$$Q_E = \eta \, Q_{Rx}$$

where Q_{Rx} is the enthalpy of reaction, and η is the explosion efficiency

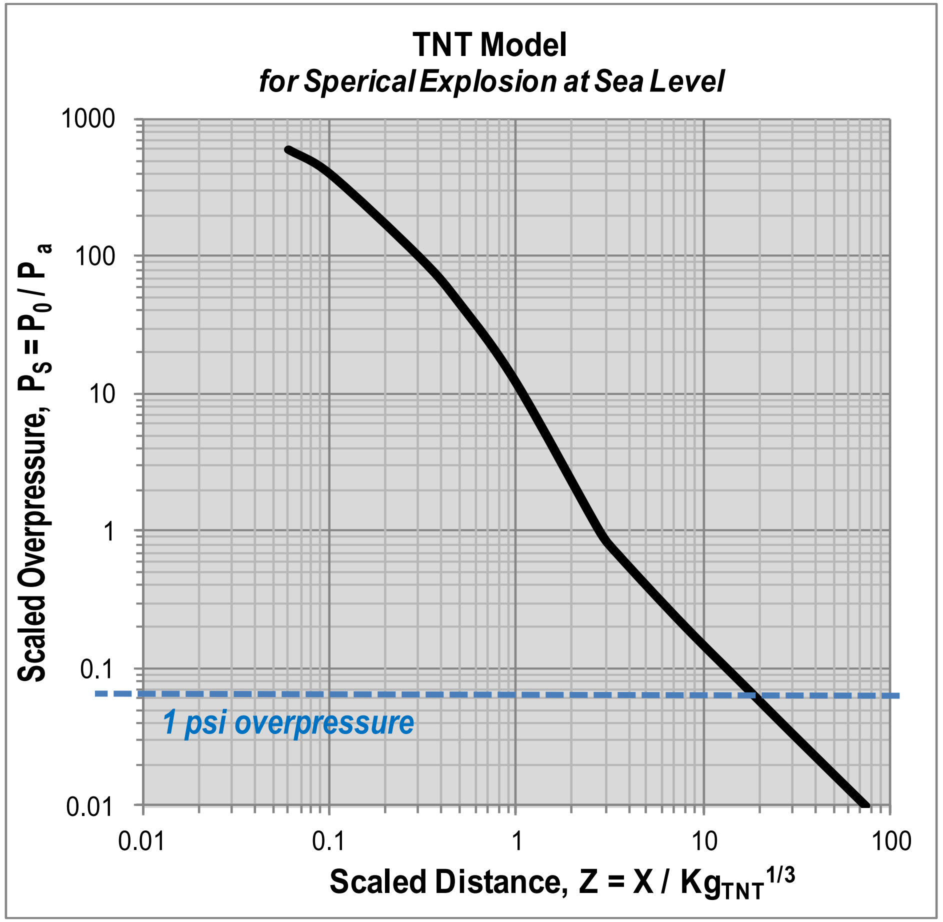
If the reaction does not proceed at a rate fast enough to be considered a propagating reaction a Physical Explosion or BLEVE correlation is used to estimate the explosion energy including any vapor generated from liquid flashing or as a reaction product.

Physical Explosion, BLEVE and Condensed Phase Explosion

Simple TNT Equivalent Model – Equipment Rupture

The simple TNT Equivalent Model correlates Scaled Overpressure (or Overpressure / Atmospheric Pressure) versus Scaled Distance.

- ✓ The TNT equivalent, kg_{TNTeq}, is the explosion energy divided by 4600 kJoule per kg_{TNTeq}.
- ✓ Scaled Distance, Z, is distance from the vessel or equipment divided by TNT equivalent raised to the 1/3 power.



Example Physical Explosion Using the TNT Equivalent Model

Estimate the distance to 1 psi overpressure for rupture of a 10 m^3 (2640 gal) vapor filled vessel at 1000 kPa (145 psia).

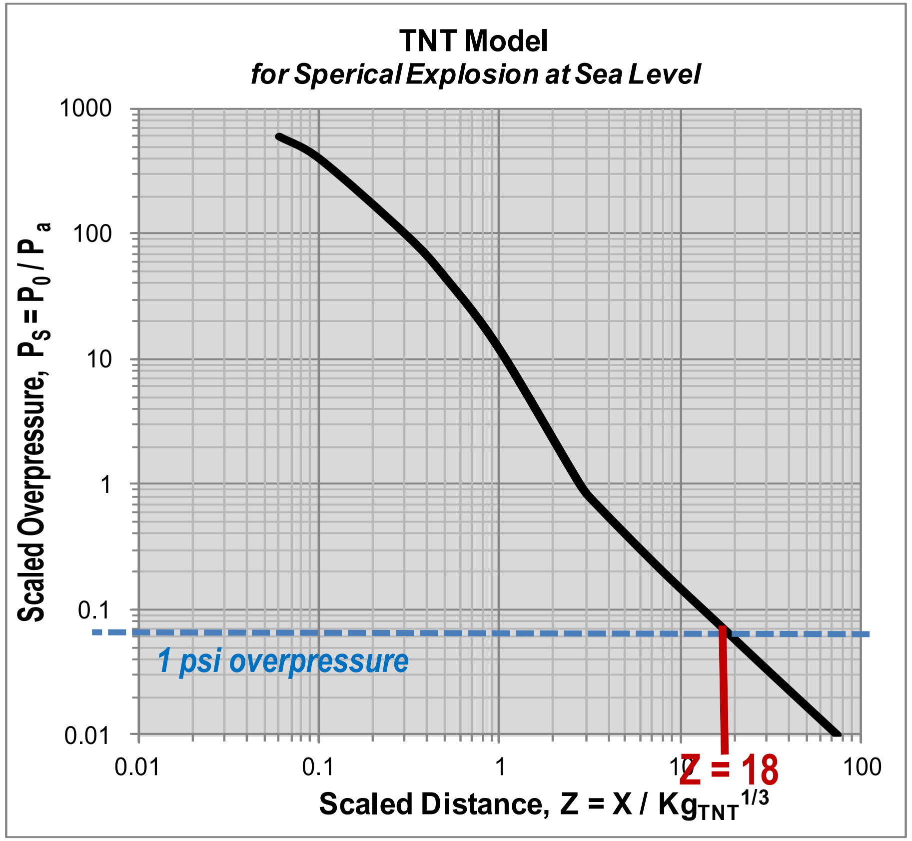
$$Q_{PV} = V^* P_B [\ln(P_B/P_A) + (P_A/P_B) - 1]$$
$$= 10 (1000) [\ln(1000/101.3) + 101.3/1000 - 1] = 1.39 \times 10^4 \text{ kJoule}$$

$$kg_{TNTeq} = 1.39 \text{ X } 10^4 / 4600 = 3.0 \text{ kg}$$

From the graph at 1 psi overpressure,
Scaled Distance, $Z = 18 = X / 3.0^{1/3}$

$$X = 18 (3.0^{1/3}) = 26 \text{ m}$$

Note that 1 psi blast overpressure is often used as a "screening" criteria for estimating significant building damage.



Flammable Vapor or Dust Explosions

Baker-Strehlow-Tang (BST) Model

Correlation of Blast Overpressure for combustion related explosions requires a more complex model than the simple TNT Model. Blast energy is correlated to flame speed (expressed in Mach number units) and related to:

- *Fuel Reactivity* (categorized as high, medium or low) based on fundamental burning velocity.
- *Obstacle Density or Congestion* (categorized as high, medium or low). The presence of obstacles within a flammable cloud generates turbulence and accelerates the flame front.
- *Degree of Confinement* (categorized as 1D, 2D, or 3D) is the presence of surfaces that prevent flame propagation in any one or more of three directions.

Flammable Vapor or Dust Explosions

Fuel Reactivity

High	Medium	Low
Fundamental Burning Velocity > 75 cm/s	*Fundamental Burning Velocity 45-75 cm/s*	*Fundamental Burning Velocity <45 cm/s*
Acetylene, vinyl acetylene, methyl acetylene, ethylene, ethylene oxide, propylene oxide, hydrogen (indoors), cryogenic hydrogen, carbon disulfide, propyne, propadiene and hydrocarbon mixtures with more than 33% hydrogen (molar basis)	Chemicals not listed as high or low reactivity. **Most hydrocarbons are medium reactivity.**	Methane, ammonia, some chlorinated hydrocarbons Class I Dusts

Flammable Vapor or Dust Explosions

Obstacle Density or Congestion

Low – Only 1-2 layers of obstacles. One can easily walk through the area relatively unimpeded.

Medium – 2-4 layers of obstacles. One can walk through an area, but it is cumbersome to do so. Medium Congestion is common for most of our manufacturing facilities.

High – Many layers of repeated obstacles. One could not possibly walk through the area and little light penetrates the congestion .

Flammable Vapor or Dust Explosions

Degree of Confinement

3D – The flame front is free to expand in any direction.

2D – The flame front is free to expand in only two of three directions such as the space beneath platforms, between closely spaced vessels, or between closely spaced cars in a parking lot.

1D – The flame front is free to expand in only one direction such as within a tunnel.

2.5 D Confinement is intermediate between 2 and 3 D.

Flammable Vapor or Dust Explosions

Baker-Strehlow-Tang (BST) Model

Although many combinations of *Fuel Reactivity*, *Obstacle Density or Congestion, and Degree of Confinement are possible,* only the 3-5 most common Flame Speed Mach Numbers are considered for simple screening.

Fuel Reactivity	*Obstacle Density or Congestion*		
	Low	Medium	High
High	0.5	>1	>1
Low-Medium	0.35	0.5	1
Class I Dust		0.35	0.5

Above based on 2.5 D Confinement. 1D Confinement addressed as Mach >1 as transition to detonation is assumed to occur. Note that detonation is also assumed to occur for High Fuel Reactivity and Medium or High Obstacle Density (or congestion).

Flammable Vapor or Dust Explosions

Baker-Strehlow-Tang (BST) Model

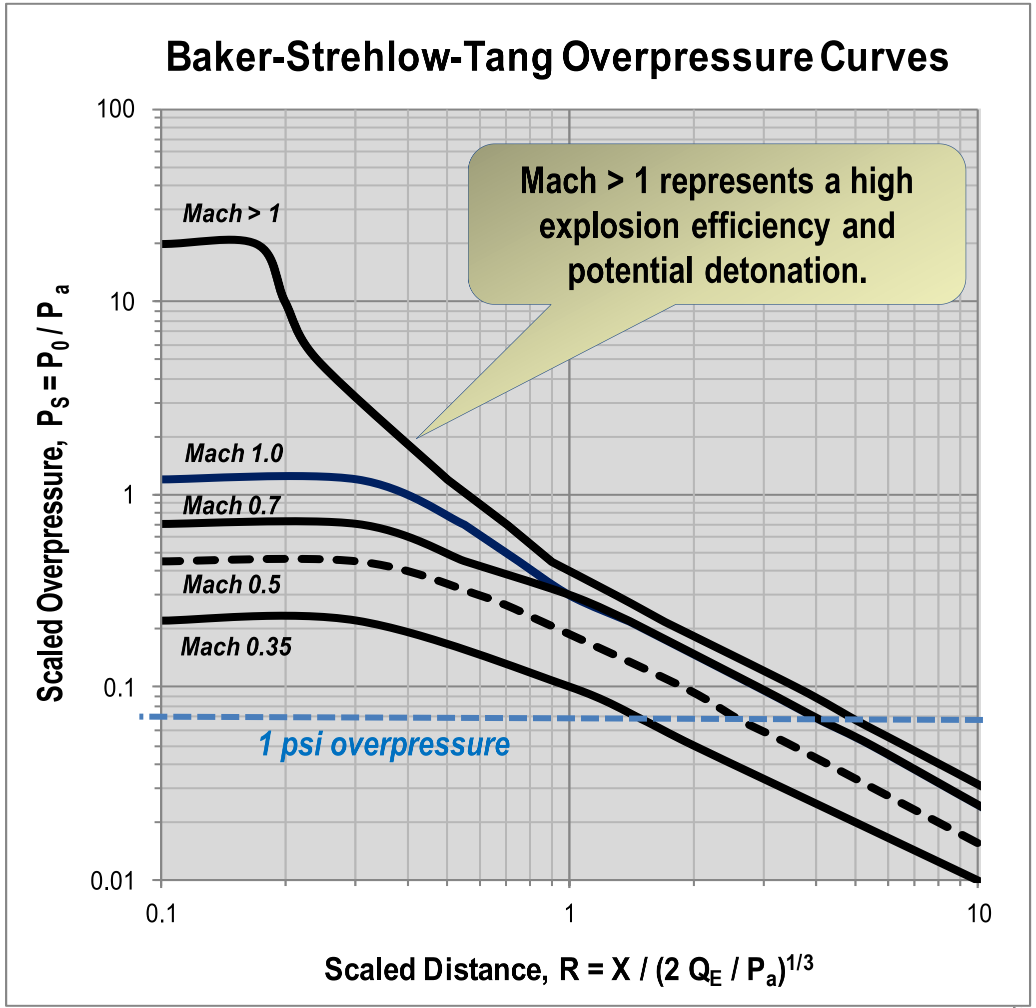
The Explosion Energy is estimated as:

$$Q_E = 3500 \ V_{PES}$$

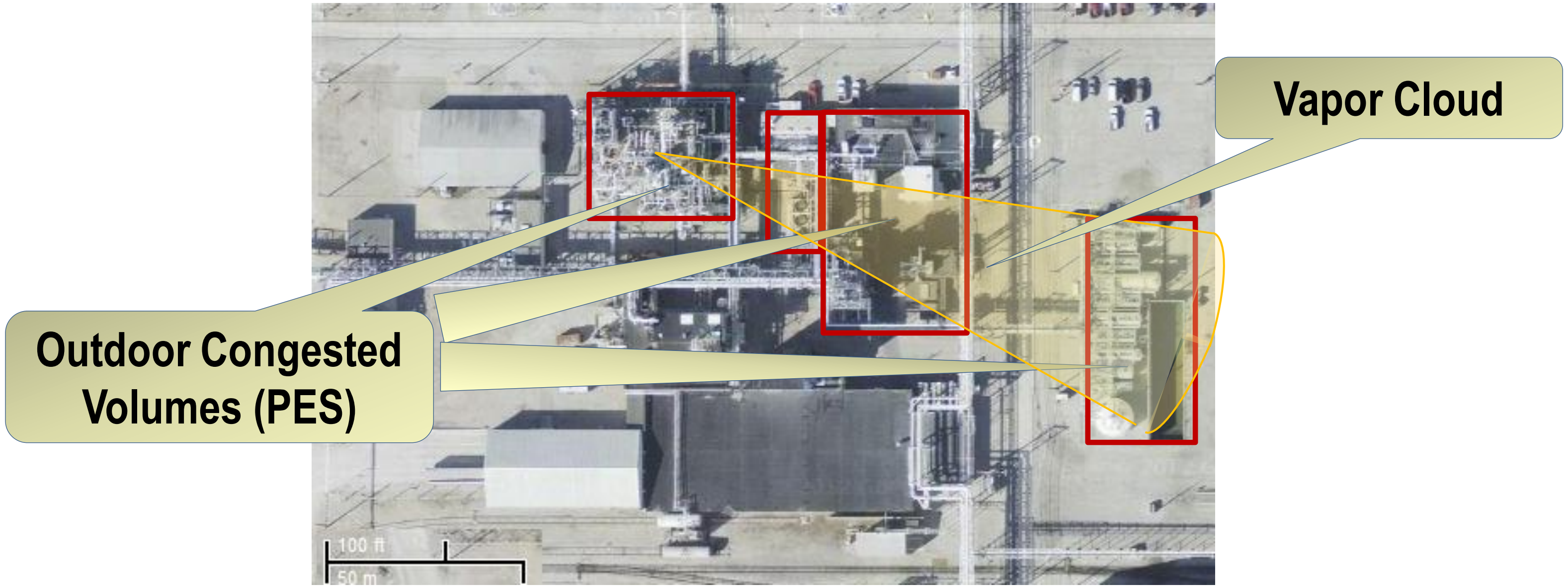
where Q_E is explosion energy in kJoule, *and* V_{PES} *is the Potential Explosion Site volume in* m^3.

Scaled Distance, R, is the distance from the Potential Explosion Site divided by (2 X Explosion Energy in kJoule / 101.3 kPa)$^{1/3}$.

3500 kJ/m³ explosion energy is based on a stoichiometric concentration of fuel and air.



Potential Explosion Site (PES)



- An *indoor* PES is the confined area or building in which a flammable release occurs.
- An *outdoor* congested volume acts as an independent PES if separated from adjacent congested volumes by at least 15 to 20 ft (approximately 5 m) of open space.
- Multiple blast sources (multiple PESs) can emanate from a single outdoor release.

Building Explosion Example

CONFINED SPACE EXPLOSION
Danvers, Massachusetts USA
November 22, 2006

Reference: CSB Report 2007-03-1-MA (May 2008)

Building Explosion Example

Site Layout

The enclosed production area (denoted as C, E, and F) was approximately 12,000 ft^2 (1115 m^2). Areas denoted A and B contained offices and a laboratory. For an average building height of 20 ft. (6.1 m), the enclosed volume is nearly 240,000 ft^3 (6,800 m^3).

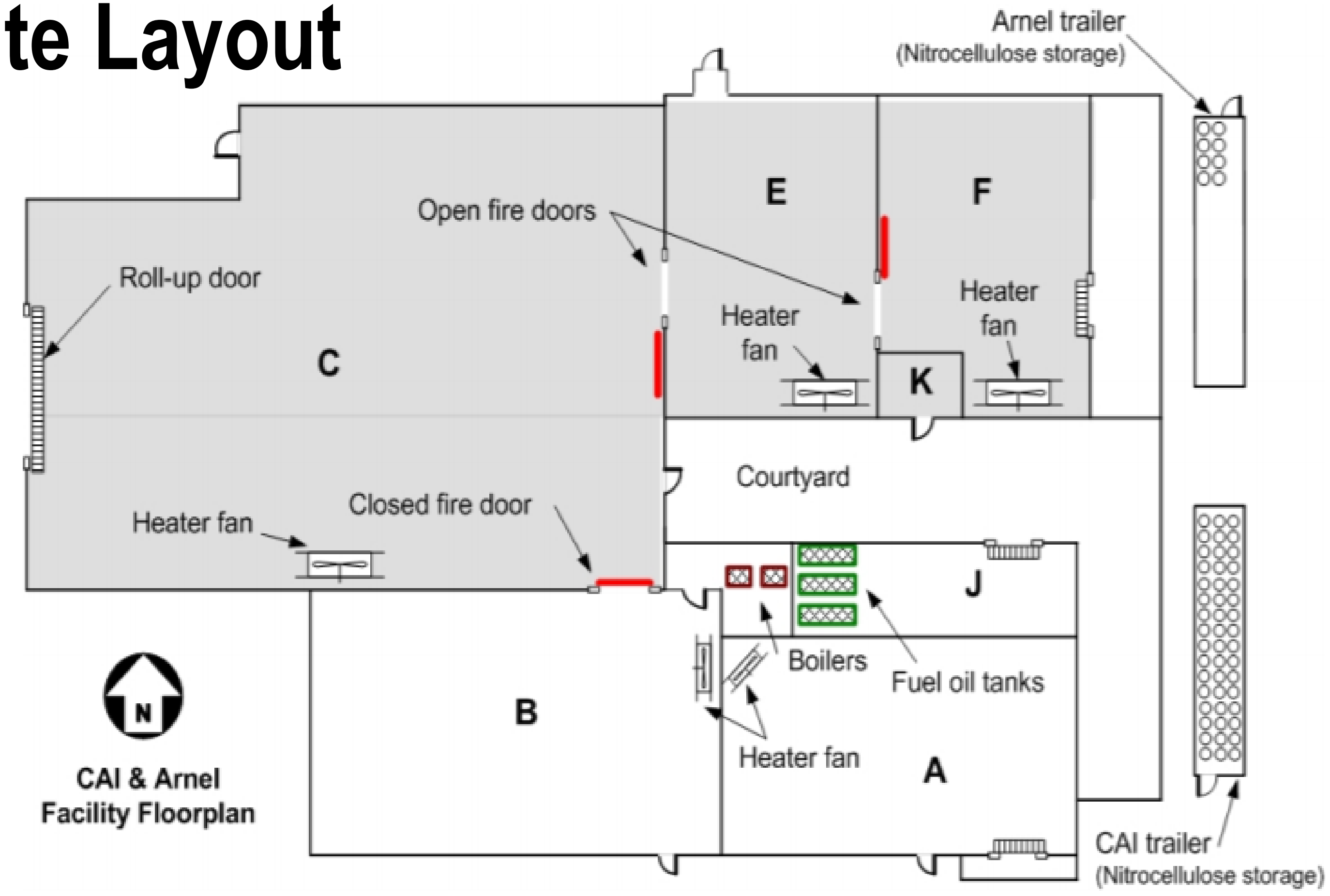


Figure 3. CAI/Arnel building layout. Production areas are highlighted.

Approximately 100 ft.

Building Explosion Example

CAI and Arnel

- Mix Tank #3 was equipped with a 12-inch (30 cm) hatch on the top of the tank for loading solids. The hatch was not sealed such that vapors (from excessive heating and vaporization) could be released from the tank into the enclosed process area.
- As the confined volume of the enclosed process area is roughly 240,000 ft^3 (6,800 m^3), a release quantity of less than *770 lbs (350 kg) could fill this volume to the lower flammable limit* of between 1 (heptane) and 2.1 (propyl alcohol) volume % in a "no ventilation" situation.

Example: For heptane vapor at 25 C, ρ_{Vapor} = 4.1 kg/m³
LFL = 0.01 volume fraction = 0.041 kg/m³
Total volume of 6800 m³ times LFL = 6800 (0.041) = ***279 kg***
Similarly for propyl alcohol vapor at 25 C, ρ_{Vapor} = 2.45 kg/m³
LFL = 0.021 volume fraction = 0.051 kg/m³
Total volume of 5660 m³ times LFL = 6800 (0.051) = ***347 kg***

This concentration (10,000 to 20,000 ppm) may also be sufficient to cause significant health impact from inhalation for those working within this enclosed process area.

Building Explosion Example

CAI and Arnel

The explosion energy for a 6,800 m^3 enclosed area is roughly:

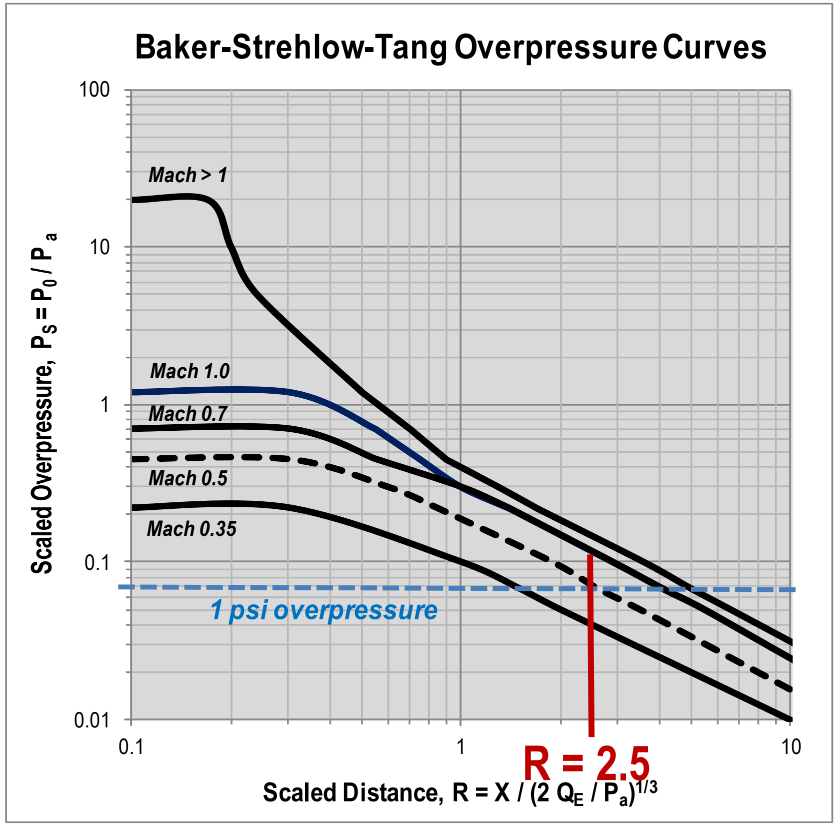
Q_E = 3,500 V_{PES} = 3,500 (6,800) = **2.38 x 10^7 kJoule**

Using medium reactivity fuel and medium congestion, a Mach Number of **0.5** is suggested.

At a scaled pressure of 1 psi / 14.7 psi = 0.068, the Scaled Distance from the Baker-Strehlow-Tang model, **R = 2.5** at Mach Number 0.5.

X_E = R [2 Q_E / 101.3]$^{1/3}$ = 2.5 [2 (2.38 x 10^7) / 101.3]$^{1/3}$

= 194 m (distance to 1 psi)



Case Study – CAI and Arnel

Blast Overpressure

The estimated maximum 194 m (640 ft.) to 1 psi blast overpressure from explosion of the enclosed process area which is in excellent agreement with CSB modeling.

Estimation of the distance to scaled overpressure of 0.15 to 0.16 (or 2.3 psi where significant building damage may occur) yields 87 m (285 ft.) which is also in good agreement with detailed CPB modeling.

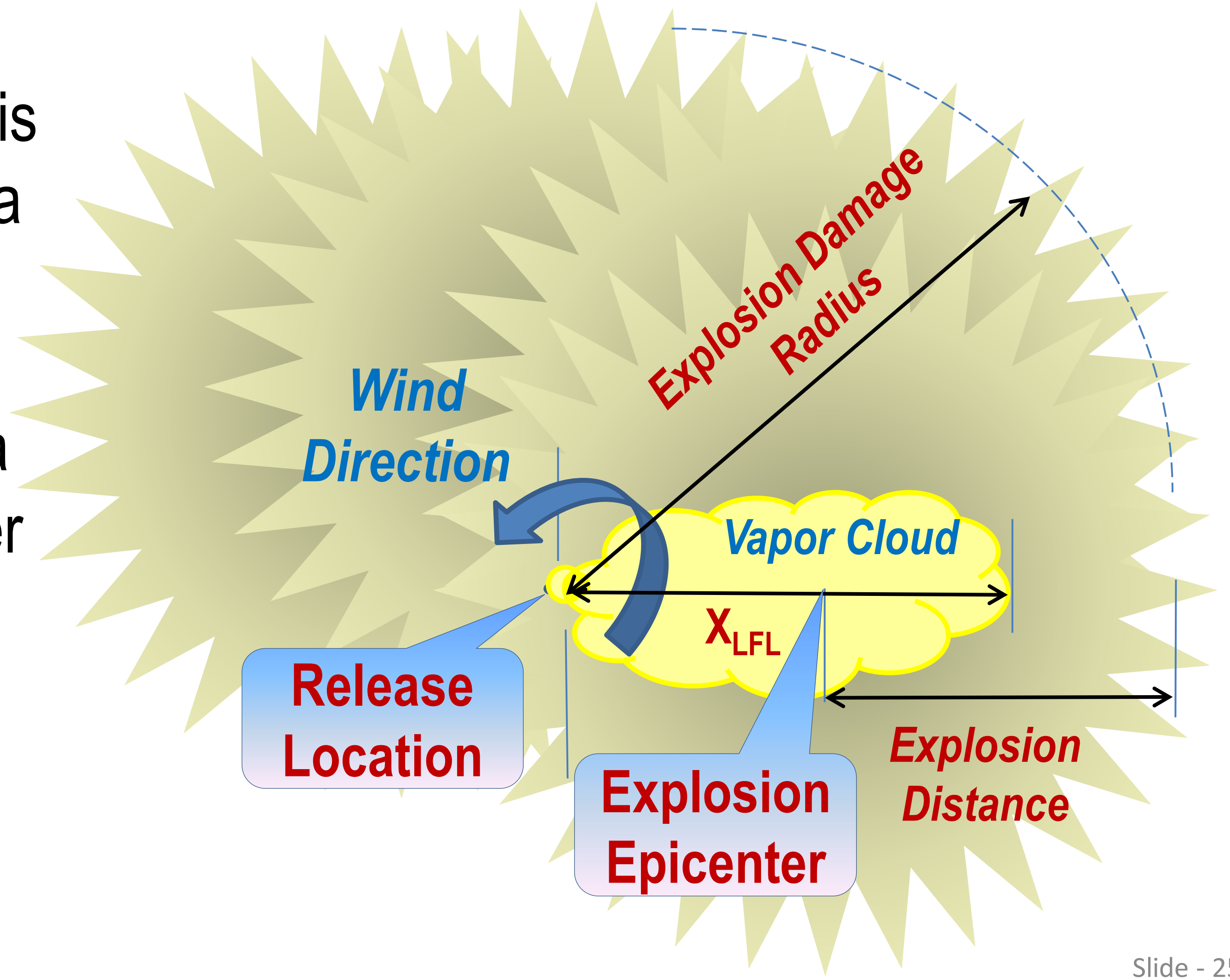
REPORT NO. 2007-03-I-MA , US Chemical Safety Board,
Figure 20. Aerial View showing estimated explosion overpressures

Vapor Cloud Explosion

Simple Model Approach

Although Baker-Strehlow-Tang (BST) is a "multi-source" model (intended that a blast contour for each PES is summed), a simplifying assumption is to consider the entire vapor cloud as a single PES with epicenter at the center of the flammable cloud ($X_{1/2\ LFL}$).

All wind directions are considered in determining a blast contour.



Vapor Cloud Explosion

Simple Model Approach

- The Potential Explosion Site volume is assumed the entire Cloud Volume (based on distance to LFL) *to a maximum which accounts for decreased explosion efficiency (maybe 30,000 m^3) with increase cloud volume.*
- The vapor cloud volume, V_C (m^3), is estimated as:

$$V_C = 2440\ Q\ X_{LFL} / (\phi\ Wind\ Mw\ C_{LFL})$$

where:

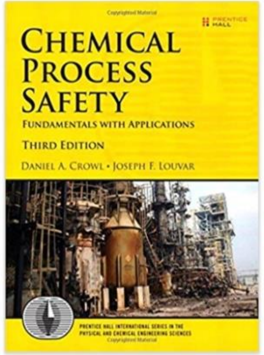
Q is the release rate (kg/sec)
X_{LFL} is distance to LFL (m)
C_{LFL} is the LFL Concentration (vol %)
Wind is wind speed (m/sec)
Mw is molecular weight
ϕ is average concentration / C_{LFL}

- All distances closer to the release point than the epicenter (0.5 X_{LFL}) are assumed at the maximum explosion pressure from the BST plot.

Limitations of Simple Explosion Models

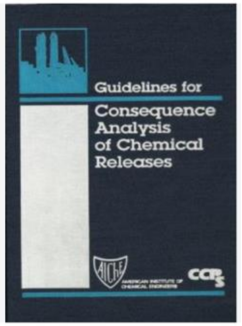
- Confined Space Explosion 1 psi overpressure contours match closely with more advanced models as these represent a well-defined PES.
- Vapor Cloud Explosion overpressure contours may be conservative but may also underestimate distance to high overpressure as they do not account for regions within the LFL cloud that contain higher than "average" congestion or confinement. Evaluation of multiple Potential Explosion Sites within the vapor cloud adds complexity but improves accuracy.
- Simple methods should not be used to estimate damage to blast resistant buildings.
- For "grass roots" facilities, *do not* locate Occupied Buildings close to congested process areas (PESs).

More Information on Explosions



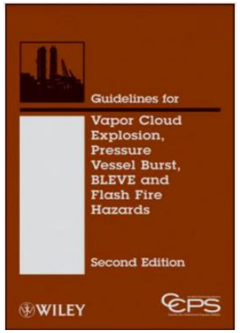
D. A. Crowl and J. A. Louvar, Chemical Process Safety Fundamentals with Applications, 3rd Edition, Prentice Hall, (2011), Prentice Hall, Upper Saddle River, NJ USA

- ✓ Chapter 6 Fires and Explosions, pages 275 – 304



CCPS, Guidelines Consequence Analysis of Chemical Releases, John Wiley and Sons, (1999), Hoboken, NJ USA

- ✓ Chapter 3 Explosions and Fires, pages 127 - 233



CCPS, Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs, 2nd Edition, John Wiley and Sons, (2010), Hoboken, NJ USA

SAChE® Certificate Program – Explosion Hazards ELA964

Questions?