**FIRE TRIANGLE**

- **FUEL** - Liquid (vapor or mist), gas, or solid capable of being oxidized. Combustion always occurs in the vapor phase; liquids are volatized and solids are decomposed into vapor prior to combustion.

- **OXIDANT** - A substance which supports combustion – Usually oxygen in air.

- **IGNITION SOURCE** - An energy source capable of initiating a combustion reaction.
DUST EXPLOSION PENTAGON

- IGNITION SOURCE
  - In absence of confinement
    - Deflagration or flash fire

- Lofting of fuel into air - DUST CLOUD
- FUEL - DUST
- OXIDANT - AIR
- SUSPENSION
- CONFINEMENT
CONDITIONS FOR A DUST EXPLOSION

1. Dust must be explosible (flammable, combustible)
2. Dust must be airborne
3. Concentration must be within explosible range
4. Particle size distribution capable of propagating flame
5. The atmosphere must support combustion
6. An ignition source must be present
   - Conditions 1-5 often exist at some point during the handling, processing, and packaging operations
   - In the presence of an incendive ignition source a flash fire or explosion will occur
Appearance of an Explosible Dust Cloud

A cloud of 40g/m³ of coal dust in air is so dense that a glowing 25W light bulb can hardly be seen through a dust cloud of 2m thickness (Eckhoff)
Range of explosible dust concentrations in air at normal temperature and atmospheric pressure for a typical natural organic dust (maize starch), compared with typical range of maximum permissible dust concentrations in the context of industrial hygiene, and a typical density of deposits of natural organic dusts (Eckhoff).
Is the Particle Size Distribution Capable of Propagating Flame?

- Powders include pellets, granules, and dust particles.
- Pellets have diameters greater than 2mm [0.1”], granules have diameters between 0.42mm [1/64”] and 2mm, and dusts have diameters of 0.42mm (420µm) or less. Pellets and granules are not likely to be explosible, with typical ignition sources.
- The finer the particles, the greater the surface area, and thus the more explosible [faster burning] a given dust is likely to be. Thus, in general, the smaller the particles, the greater the explosion hazard.
DUST PARTICLE SIZES

Four Sheets Copy Paper ~ 400 microns

Note:
1/32 inch ~ 8 sheets of paper = 794 microns
Also: 1/32 inch ~ thickness of a paper clip

75 micron particle

420 micron particle
Why Housekeeping is Important
Formation of Explosible Dust Cloud

Illustration of the potential hazard of even thin dust layers. A 1mm (0.040 in.)
layer of a dust of bulk density 500 Kg/m³ (31.2 lb/ft³) will generate a cloud of
average concentration 100 g/m³ (0.10 oz/ft³) if dispersed in a room of 5 m (16.4
ft) height. Partial dispersion up to only 1 m (3.3 ft) gives 500 g/m³ (0.5 oz/ft³)
(Eckhoff)

\[ C = P_{\text{bulk}} \times \frac{h}{H} \]

- \( C \) is dust cloud concentration
- \( P_{\text{bulk}} \) is powder bulk density
- \( h \) is dust layer thickness
- \( H \) is dust cloud height in the room
An Accumulation of Fine Dust in a High Place

Or an accumulation of 0.0013 mil lofted into suspension
HAZARDS OF SECONDARY EXPLOSIONS

Illustration of how the blast wave from a primary explosion entrains and disperses a dust layer, which is subsequently ignited by the primary dust flame (Eckhoff)

a. PRIMARY EXPLOSION

b. BLAST WAVE

DUST CLOUD FORMED

c. EXTENSIVE SECONDARY EXPLOSION RESULTS
Basis(Bases) of Safety

• Anything you can do to remove one or more legs of the Fire Triangle or Explosion pentagon is a Basis of Safety.

• The more bases of safety you have the lower becomes your risk.
Typical Steps Involved in a Dust Hazard Analysis

• Opening meeting with client to discuss expectations
• Review of P&IDs, EFDs, printed kkjidrawings, combustible dust test information
• Detailed discussion with plant personnel to understand specific equipment and process operations, administrative controls, etc.
• Walk around inside plant to observe, examine, and inspect housekeeping, equipment, engineering controls.
• Conduct the DHA
Each piece of Equipment that Handles particulate/dust

- Is the particulate deflagrable?
- Is the particulate inside small enough to propagate a deflagration flame front?
- Is there a means of suspending or dispersing the particulate?
- Is there a sufficient quantity of particulate to achieve MEC?
- Is there a competent source of ignition?
TYPICAL STEPS INVOLVED IN A DHA

● Close out meeting with client to discuss preliminary findings.

● Development of a comprehensive report that discusses areas of noncompliance and provides practical recommendations to achieve compliance. This report can be prioritized, if required.
Two Important Dust Explosibility/Ignitibility Tests (Explosion Severity and Minimum Ignition energy of a Dust Cloud) and How they Can Used to Assess Risk

Risk = Severity * Likelihood

• Explosion Severity is a Predictor of explosion Consequences

• MIE along with MEC and MIT cloud and layer is a predictor of explosion Likelihood
Combustibility of Fly Ash

• Fly ash is the by-product of combustion of fuel inside the boilers.
• Depending upon the efficiency of combustion, there can be very little or a significant amount of unburned carbonaceous material in the ash.
• Depending upon the amount of carbonaceous material, an explosibility hazard may exist.
• A test known as “loss on Ignition” or LOI provides a crude measure of the organic content of the ash.
• LOI represents unburned carbon that was part of the original fuel entering the power boiler. DEKRA has seen LOI values as high as 56% (Grated boilers burning bark)
• DEKRA’s experience is that the actual ash content of the fly ash must be at least 90% in order to prevent an explosion hazard. This would translate to an LOI value of no greater than 10%.
• DEKRA database shows fly ash samples with $K_{st}$ values up to 114 bar·meters/sec.
• Explosions have occurred in fly ash dust collectors and silos.
Activated Carbon

- Can burn and can present a fire and explosion hazard.
- Typically difficult to ignite with MIE > 10 Joules

SECTION 5 – FIRE FIGHTING MEASURES

Fire:
As with most organic solids, fire is possible at elevated temperatures or by contact with an ignition source. Activated carbon is difficult to ignite and tends to burn slowly (smolder) without producing smoke or flame.

Wet activated carbon depletes oxygen from the air. Materials allowed to smolder for long periods in enclosed spaces, may produce amounts of carbon monoxide which may reach the lower explosive limit for carbon monoxide of 12.5% in air.

Contact with strong oxidizers such as ozone or liquid oxygen may cause rapid combustion.

Explosion:

Fine dust dispersed in air in sufficient concentrations, and in the presence of an ignition source is a potential dust explosion hazard. Minimum explosible concentration 0.140 g/l.

Fire Extinguishing Media:
Water spray, dry chemical, alcohol foam, or carbon dioxide.

Special Information:
In the event of a fire, wear full protective clothing and NIOSH-approved self-contained breathing apparatus with full facepiece operated in the pressure demand or other positive pressure mode.
For a dust explosion hazard to exist particles must be sufficiently small, generally smaller than about 0.5 mm (500 um).

Insects are organic in nature and thus probable will present a fire/explosion hazard. The latter depending upon attrition of the insect, particle size wise.
Coal

- All US Bituminous Coals are explosible (VR > 12)
- Some sub bituminous coals are explosible
- PRB coals can present special challenges in Handling, Self – heating, for example
- Anthracite coal burns but is not Explosible, (low in Volatile matter high in fixed carbon
- Some Petroleum coke is explosible some not, difficult to predict must test.
## MIE OF DUST SUSPENSIONS

<table>
<thead>
<tr>
<th>Dust</th>
<th>Minimum Ignition Energy mJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous Coal</td>
<td>50 - 120</td>
</tr>
<tr>
<td>Anthracite</td>
<td>Nonexplosible</td>
</tr>
<tr>
<td>Coke</td>
<td>30</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>Varies from NE to &gt; 1000</td>
</tr>
<tr>
<td>Wheat Grain Dust</td>
<td>30</td>
</tr>
<tr>
<td>Activated Carbon</td>
<td>&gt; 10,000</td>
</tr>
<tr>
<td>Rice Starch</td>
<td>90</td>
</tr>
<tr>
<td>Dextrin</td>
<td>10</td>
</tr>
<tr>
<td>Aluminum</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Zirconium</td>
<td>5</td>
</tr>
</tbody>
</table>
Deflagration Index of a Dust Cloud, $K_{st}$ ASTM E 1226

- An indication of the severity of dust cloud explosion
- Used for the design of deflagration protection (venting, suppression, Containment)
- Determined experimentally in a 20-Liter test sphere per ASTM E1226
- Data produced:
  - Maximum developed pressure, $P_{max}$
  - Maximum rate of pressure rise, $(dP/dt)_{max}$
- Deflagration Index (explosion severity) $K_{st}$ calculated from:
  \[ K_{st} = (dP/dt)_{max} \cdot V^{1/3} \text{ [bar.m/s]} \]
  Where $V$ is the volume of the test vessel (m$^3$)
Explosion Severity

Deflagration Pressure/Time Curve

- Maximum Pressure, $P_{\text{max}}$ [barg]
- Maximum Rate of pressure Rise, $(dP/dt)_{\text{max}}$ [bar/s]
- Deflagration Index, $K_g$ or $K_{\text{st}}$ [bar m/s]

Note: 1 bar = 14.504 psi
## Dust Explosion Hazard Classification

<table>
<thead>
<tr>
<th>Dust Explosion Class</th>
<th>Deflagration Index $K_{st}$ (bar.m/s)</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>St 0</td>
<td>0</td>
<td>Non-explosible</td>
</tr>
<tr>
<td>St 1</td>
<td>0 &lt; $K_{st}$ &lt; 200</td>
<td>Weak to moderately explosible</td>
</tr>
<tr>
<td>St 2</td>
<td>200 &lt; $K_{st}$ &lt; 300</td>
<td>Strongly explosible</td>
</tr>
<tr>
<td>St 3</td>
<td>$K_{st}$ &gt; 300</td>
<td>Very strongly explosible</td>
</tr>
</tbody>
</table>

Based on test data using 1m$^3$ and 20-L Vessels and 10KJ Ignition Sources

**Note:**
- Any explosion can cause burn injuries
- Any explosion can cause structural damage if the containment is not strong enough
### Explosion Characteristics of Selected Dusts

<table>
<thead>
<tr>
<th>Dust</th>
<th>Peak Pressure $P_{\text{max}}$ (barg)</th>
<th>Deflagration Index $K_{st}$ (bar.m/s)</th>
<th>Dust Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous Coal</td>
<td>8.0 – 9.0</td>
<td>100 - 150</td>
<td>St1</td>
</tr>
<tr>
<td>Coke</td>
<td>Varies from NE to 6-8</td>
<td>Varies</td>
<td>St 0 - 1</td>
</tr>
<tr>
<td>Anthracite</td>
<td>0</td>
<td>0</td>
<td>St0PRB</td>
</tr>
<tr>
<td>PRB</td>
<td>7.0 – 8.0</td>
<td>100 -150</td>
<td>St1</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>Varies from NE to 6 - 8</td>
<td>25- 75</td>
<td>St1</td>
</tr>
<tr>
<td>Activated Carbon</td>
<td>7.4</td>
<td>80 - 140</td>
<td>St1</td>
</tr>
<tr>
<td>Rice Starch</td>
<td>10</td>
<td>190</td>
<td>St1</td>
</tr>
<tr>
<td>Dextrin</td>
<td>8.7</td>
<td>200</td>
<td>St2</td>
</tr>
<tr>
<td>Aluminum</td>
<td>11.5</td>
<td>555</td>
<td>St3</td>
</tr>
</tbody>
</table>
Tools Used by DPS

- Practical experience gained as a result of conducting combustible dust fire and explosion hazard analyses at over 250 facilities
- NFPA consensus standards for combustible dusts
Outcomes of the DHA

Identification and evaluation of the process or facility areas where fire, flash fire, and explosion hazards exists

Where the hazards exists, identification and evaluation of specific and deflagration scenarios which include

- identification of safe operating ranges
- identification of the safeguards that are in place to manage fire, deflagration and explosion events
- recommendation of additional safeguards, where warranted, including plans for implementation.

A well-documented risk assessment that is acceptable to the authorities having jurisdiction can be used to supplement the DHA to determine what protection measures are to be used. (and also to prioritize the recommendations)
MANAGEMENT SYSTEM REQUIREMENTS
NFPA 652

1. Written Operating Procedures
2. Inspection, Testing and Maintenance
3. Training of employees, contractors, sub-contractors in the hazards of combustible dust
4. Incident investigation and reporting (process safety)
5. Emergency response plans
6. Management of Change
7. Management Systems Review
8. Document Retention
9. Employee participation

• Must be followed if threshold quantity of Chlorine (1500 lb) and/or anhydrous ammonia (10,000 lb) is exceeded.
Ammonia Hazards

Aqueous Ammonia (liquid)

- Typically about 30% ammonia (ammonium hydroxide) in water

- Liquid is much less hazardous than anhydrous ammonia
  - But still very hazardous !!!

- Liquid is:
  - Highly corrosive to skin
  - Causes chemical burns
  - Causes permanent eye damage
  - Vapors can cause lung injury
Ammonia Hazards

Anhydrous Ammonia (gas)

- Exists as Ammonia – near 100% concentration
- Colorless – cannot see a cloud
- Less corrosive than the liquid.
  - Gas is flammable
  - Stored under high pressure
  - Acutely toxic
  - Can travel great distances in harmful concentrations.
- Odor threshold is lower than dangerous concentration limits
  - Provides good warning of release and exposure, allowing escape
- Lighter than air – will help dilute and disperse a gas cloud.
Chlorine Gas

- Like anhydrous ammonia
- Chlorine gas can travel great distances in harmful concentrations.
- Stored under high pressure
- Acutely toxic
- Yellow/green cloud at high concentrations
- Reacts with moisture in air, on skin or inside the lungs to form highly corrosive hydrogen chloride gas
- Chlorine is an oxidizer – promotes fire
- Can be fatal if inhaled
- Causes severe skin and eye burns
DEKRA Top Ten Rules for Process Safety

1. Obtain, understand and maintain all relevant and valid process safety information.
2. Ensure those with PSM responsibilities have the competence to fulfill their roles.
3. Process safety should become a value not simply a compliance topic.
4. Process Safety is the study of accidents, not an account of the accidents that did not occur (Kletz 1993).
5. Things get worse under pressure.
6. Ensure thorough and adequate risk assessments to understand risks and provide a robust basis for prevention and/or mitigation measures.
7. Let no single safeguard lead to disaster.
8. Do not presume a small change is not significant until you have properly assessed it.
9. Maintain a "chronic sense of unease": The absence of evidence of risk is not evidence of the absence of risk.
10. Measure and report PSM performance using meaningful indicators across the whole organization.
Questions ??
Thank you!

MISSION

SAFETY