Practical Issues with Marginally Explosible Dusts: Evaluating the Real Hazard

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What is a Combustible Dust?

Sugar

Metal Flake

Creamer

Sawdust
Explosibility Testing

Hartmann Apparatus

1 m³ Sphere

Siwek 20L Sphere
## Comparative Data

<table>
<thead>
<tr>
<th>Material</th>
<th>K\textsubscript{St}, 1 m\textsuperscript{3} (bar-m/sec)</th>
<th>K\textsubscript{St}, 20 L (bar-m/sec)</th>
<th>P\textsubscript{max}, 1 m\textsuperscript{3} (bar)</th>
<th>P\textsubscript{max}, 20 L (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Stearate</td>
<td>140</td>
<td>197</td>
<td>9.1</td>
<td>6.6</td>
</tr>
<tr>
<td>Lignite</td>
<td>138</td>
<td>113</td>
<td>7.3</td>
<td>6.2</td>
</tr>
<tr>
<td>Maltodextrine</td>
<td>205</td>
<td>147</td>
<td>9.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Grinding Dust</td>
<td>36</td>
<td>59</td>
<td>4.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Sodium Monochloroacetate</td>
<td>62</td>
<td>62</td>
<td>0</td>
<td>7.4</td>
</tr>
<tr>
<td>Lixivalt Dust</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.3</td>
</tr>
<tr>
<td>Metco Dust</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.5</td>
</tr>
<tr>
<td>Solid Sewing Residues</td>
<td>65</td>
<td>65</td>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>PVC Dust</td>
<td>64</td>
<td>113</td>
<td>8.7</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**FALSE POSITIVES IN 20-L APPARATUS**

- Consider retesting a marginally explosible dust in larger scale
- Be wary of False Positives and False Negatives
- Read the paper for details

[Proust 2007]
Screening Test

- NFPA654 recommends that determination of dust combustibility be based on a low cost screening test methodology per ASTM E1226 – 2010 edition

- If dust is determined explosible, further testing may be needed to establish the properties needed for the intended protection methods

- E1226-2010 as well as NFPA 654 recommends testing in larger scale (e.g. in 1 m³) if dust is marginally explosible in 20-L apparatus.
How much Dust is too much?

<table>
<thead>
<tr>
<th>Reference</th>
<th>Thickness and Caveats</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFPA-654</td>
<td>1/32” @ 75 lb/ft³, Adjusted for Lower Bulk Density</td>
</tr>
<tr>
<td>NFPA-664</td>
<td>1/8”, Assumes 20 lb/ft³ Bulk Density</td>
</tr>
<tr>
<td>NFPA-484</td>
<td>Does Not Allow Accumulation, Infers Daily Cleaning Schedule</td>
</tr>
<tr>
<td>NFPA-61</td>
<td>Remove Concurrently with Operations, Refers to 654</td>
</tr>
<tr>
<td>OSHA Grain Dust</td>
<td>1/8”</td>
</tr>
<tr>
<td>OSHA Dust NEP</td>
<td>1/32”</td>
</tr>
</tbody>
</table>

- Current allowances are based on layer thickness

\[
\text{Allowable Thickness} \leq \frac{1/32''}{75 \text{ lb/ft}^3} \times \frac{75 \text{ lb/ft}^3}{\text{bulk density}}
\]

- Layer thickness is not the primary parameter

- Explosible Cloud mass decides the consequences
Where did 1/32” allowance come from?

According to NFPA 654-06 Annex D

- Using a bulk density of 75 lb/ft³ and a cloud concentration of 350 g/m³, it has been calculated that a dust layer averaging 1/32 in. thick and covering the floor of a building is sufficient to produce a uniform dust cloud of optimum concentration, 10 ft (3 m) high, throughout the building. This situation is idealized; several factors should be considered.

- First, the layer will rarely be uniform or cover all surfaces, and second, the layer of dust will probably not be dispersed completely by the turbulence of the pressure wave from the initial explosion. However, if only 50 percent of the 1/32 in. thick layer is suspended, this material is still sufficient to create an atmosphere within the explosible range of most dusts.
According to NFPA 654-06 Annex D

• Consideration should be given to the proportion of building volume that could be filled with a combustible dust concentration. The percentage of floor area covered can be used as a measure of the hazard. For example, a 10 ft 10 ft room with a 1/32 in. layer of dust on the floor is obviously hazardous and should be cleaned. The same 100 ft² area in a 2025 ft² building is a moderate hazard. The hazardous area represents about 5 percent of a floor area and is about as much coverage as should be allowed in any plant.

\[
\text{Hazard} = 5\% \text{ of Floor Area, } 1/32'', \text{ Bulk Density 75 lb/ft}^3
\]
But, not All Dusts are the Same

<table>
<thead>
<tr>
<th></th>
<th>Bulk Density (Kg/m³)</th>
<th>$P_{\text{max}}$ (bar)</th>
<th>$c_w$ (Kg/m³)</th>
<th>MEC (gm/m³)</th>
<th>$K_{\text{St}}$ (bar-m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE-1</td>
<td>485</td>
<td>6.3</td>
<td>1.25</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>PE-2</td>
<td>560</td>
<td>8.8</td>
<td>0.25</td>
<td>10</td>
<td>168</td>
</tr>
</tbody>
</table>

- Particle Size and shape are important
- Chemical composition is important
- Explosibility Parameters can quantify the hazard and prevention/protection requirements
New Methodologies for the next edition of NFPA 654

• The Committee has long known that a single layer thickness is inadequate to represent all possible applications

• The Committee formulated the concepts in Annex D of the 2006 edition into simple equations

• New equations
  - Recognize different buildings and enclosures can tolerate different amounts of dust accumulations
  - Recognize some dusts are more hazardous than the others, and should be cleaned more frequently

• Methodology gives credit for appropriate protection measures
New Criteria

- **Structural integrity - Room or enclosure should not collapse (Explosion Criterion)**
  - NFPA 68 provides a simple algebraic methodology which was used to calculate maximum quantity of combustible dust a given enclosure can tolerate in the absence or presence of deflagration vents.

- **95% occupant survivability (Flash Fire Criterion)**
  - Achieved either by controlling the quantity of dust accumulations or by protective garments
NFPA-68 Partial Volume Methodology

\[ A_{v4} = A_{v3} \cdot X_r^{-1/3} \sqrt{\frac{X_r - \Pi}{-\Pi}} \]

- \( X_r \) is the fraction of the volume filled with an optimum dust concentration

- When \( X_r \leq \Pi \), no venting is required

\[ X_r \leq \frac{P_{red}}{P_{max}} \leq \frac{P_{es}}{DLF \cdot P_{max}} \]

- This means the amount of dust will not cause failure of the building – one of the goals
What is Fill Fraction?

- Fill Fraction is the largest portion of the enclosure that could be at the optimum dust concentration for explosion

\[ X_r = \frac{M \cdot \eta_D}{A_{floor} \cdot H \cdot c_w} \]

- It is the ratio of the volume of the optimum dust cloud to the total enclosure volume
Simplified Explosion Criterion

- Maximum Allowable Dust Accumulation in the Absence of any Deflagration Vents:

\[ M_{exp} = \left( \frac{P_{es}}{DLF} \right) \cdot \left( \frac{C_w}{P_{max}} \right) \cdot \left( \frac{A_{floor} \cdot H}{\eta_D} \right) \]

Even simpler screening formula:

\[ M_{basic-exp} = 0.004 \cdot A_{floor} \cdot H, \ A_{floor} \leq 2000 \, m^2, \ H \leq 12 \, m \]
Comparison of PE-1 and PE-2

Square enclosure, 30 ft high 20,000 ft² area

<table>
<thead>
<tr>
<th>Pes/RLF (psf)</th>
<th>Weak Building</th>
<th>Strong Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>144</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Kst (bar-m/s)</th>
<th>PE-1 Low Kst</th>
<th>PE-2 High Kst</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>168</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pmax (bar)</th>
<th>6.3</th>
<th>8.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cw (g/m³)</td>
<td>1250</td>
<td>250</td>
</tr>
</tbody>
</table>

1% Vent, No Limitation on Accumulations

230 Kg, if No Vent
Entrainment Fraction, $\eta_D$

- Fraction of dust layer mass which can become airborne before the flame arrival
- At most, $\eta_D$ can range from 0 to 1
- Appropriate value depends on the application, e.g.
  - Sticky, cohesive dusts resist entrainment
  - Elevated deposits tend to be smaller particle size and more easily entrained
  - Elongated rooms and galleries could have higher entrainment

From Ural 1992

**FIGURE 6.** Dust entrainment under simulated explosion conditions.
Entrainment Fraction, $\eta_D$

• NFPA Research Foundation project is underway

• NFPA-654 Committee picked the value 0.25 mainly to be consistent with the 1/32” layer thickness for selected dust/enclosure combinations.

• Examples for $P_{max} = 7$ bar, $C_w = 0.5$ Kg/m$^3$ and dust layer coverage equivalent to 5% of the floor area:

<table>
<thead>
<tr>
<th>Enclosure Strength (psi)</th>
<th>Enclosure Height (ft)</th>
<th>Layer Bulk Density (lb/ft$^3$)</th>
<th>Allowable Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>16</td>
<td>75</td>
<td>1/32</td>
</tr>
<tr>
<td>0.5</td>
<td>32</td>
<td>75</td>
<td>1/16</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>75</td>
<td>1/16</td>
</tr>
<tr>
<td>0.5</td>
<td>16</td>
<td>19</td>
<td>1/4</td>
</tr>
</tbody>
</table>
Flash-Fire Hazard Criterion

• Desire to limit the probability that an employee could be engulfed in a fire-ball

• The volume of the fire-ball can be related to dust explosibility properties

\[ V_{un\text{-burnt}} = \frac{M_{\text{fire}} \cdot \eta_D}{C_w} \]

\[ V_{burnt} = V_{un\text{-burnt}} \cdot \left[ \frac{P_{\text{initial}} + P_{\text{max}}}{P_{\text{initial}}} \right] \]
\[ M_{\text{fire}} = c_w \cdot \left[ \frac{P_{\text{initial}}}{P_{\text{initial}} + P_{\text{max}}} \right] \cdot \frac{V_{\text{burnt}}}{\eta_D} \]

- 20 People uniformly Distributed on the Floor
- 20 People uniformly Distributed in the Volume
- Burnt Volume - \( V_{\text{burnt}} \)
- 20 People uniformly Distributed on the Floor

2010 GCPS
20 People uniformly Distributed on the Floor

Occupied Volume = \( A_{\text{floor}} \times \text{Nominal Height} \)

20 People uniformly Distributed on the Floor

5% of Occupied Volum
Flash-fire Threshold

\[ M_{\text{fire}} = 0.05 \cdot c_w \cdot \left[ \frac{P_{\text{initial}}}{P_{\text{initial}} + P_{\text{max}}} \right] \cdot \frac{A_{\text{floor}} \cdot D}{\eta_D} \]

- D is a nominal 2 meters
- More dust requires flame-resistant garments
 Threshold Mass without Protections

\[ M = \min \left( M_{\text{exp}}, M_{\text{fire}} \right) \]

- Dust and Building parameters result in one or the other controlling
- Cleanup focus determined based upon operating experience
- Cleanup frequency adjusted to target the allowable limit
Layer Thickness versus Threshold Mass

• For those who are accustomed to layer thickness

\[
\delta_{\text{layer}} = \frac{\min \left( M_{\text{exp}}, M_{\text{fire}} \right)}{\rho_{\text{layer}} A_{\text{layer}}} \cdot 1000
\]

• Note: Allowable layer thickness is inversely proportional to layer bulk density and layer surface area
Example: \( \min[M_{exp}, M_{fire}] = 100 \text{ Kg} \)
A Numerical Example

- Polyethylene dust being handled in a 30 ft high square building, capable of resisting 1 psi internal pressure, which has a floor area of 20,000 ft².

- Dust is being handled in one corner of the building, and the accumulations are limited to a total layer surface area of 400 ft².

- Calculate the maximum allowable accumulated dust mass, and maximum allowable layer thickness if the dust has the following explosibility properties:

<table>
<thead>
<tr>
<th>Bulk Density (Kg/m³)</th>
<th>$P_{\text{max}}$ (bar)</th>
<th>$c_w$ (Kg/m³)</th>
<th>MEC (gm/m³)</th>
<th>$K_{\text{St}}$ (bar·m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>485</td>
<td>6.3</td>
<td>1.25</td>
<td>30</td>
<td>16</td>
</tr>
</tbody>
</table>
A Numerical Example - Solution

A) NO VENTING, NO PROTECTIVE GARMENTS:

\[ M_{\text{exp}} = \sqrt[1.25]{\frac{1.25}{6.3}} \cdot \left[ 10000 \cdot 0.3048^2 \cdot 0.00 \cdot 0.3048 \right] = 930 \text{ Kg} \]

\[ M_{\text{fire}} = 0.05 \cdot 1.25 \cdot \left[ \frac{1}{1 + 6.3} \right] \cdot \left[ 10000 \cdot 0.3048^2 \cdot 2 \right] = 127 \text{ Kg} \]

• Since, \( M_{\text{fire}} \) is smaller than \( M_{\text{exp}} \) in this case, the maximum allowable accumulated dust mass will be limited to 127 Kg.

• Then the maximum allowable layer thickness:

\[ \delta_{\text{layer}} = \frac{127}{485 \cdot 100 \cdot 0.3048^2 \cdot 1000} = 7 \text{ mm} = 0.28 \text{ inch} \]

• This is more than 3.5 times what is allowed in the current edition of NFPA 654, based on bulk density adjustment. Clearly, other examples may result in smaller allowances.
A Numerical Example - Solution

B) NO VENTING, with PROTECTIVE GARMENTS:

\[ \delta_{layer} = \frac{930}{485 \cdot 400 \cdot 0.3048^2 \cdot 1000} = 52 \text{mm} = 2 \text{inches} \]

C) 1% VENTING, with PROTECTIVE GARMENTS:

\[ \delta_{layer} = \text{Unlimited, with Documented Risk Evaluation acceptable to the AHJ} \]
## Unscheduled Cleaning

<table>
<thead>
<tr>
<th>Accumulation on the worst single square meter of surface</th>
<th>Longest Time to Complete Un-scheduled Local Cleaning of Floor-Accessible Surfaces</th>
<th>Longest Time to Complete Un-scheduled Local Cleaning of Remote Surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 1 to 2 times threshold dust mass/accumulation</td>
<td>8 hours</td>
<td>24 hours</td>
</tr>
<tr>
<td>&gt;2 to 4 times threshold dust mass/accumulation</td>
<td>4 hours</td>
<td>12 hours</td>
</tr>
<tr>
<td>&gt;4 times threshold dust mass/accumulation</td>
<td>1 hour</td>
<td>3 hours</td>
</tr>
</tbody>
</table>
Electrical Application – Current OSHA Approach

\[
\text{Explosion\_Severity} = \frac{P_{\text{max}} \cdot \hat{P}}{P_{\text{max}} \cdot \hat{P}^2} \geq 0.5, \text{ or } \frac{P_{\text{max}} \cdot \hat{P}}{P_{\text{max}} \cdot \hat{P}^2} \geq 0.2
\]

\[
\text{Ignition\_Sensitivity} = \frac{\hat{C} \cdot E \cdot M_{c}}{\hat{C} \cdot E \cdot M_{c}^2} \geq 0.2
\]

• Severity Index not relevant to electrical protection methods

• Sensitivity Index confounds relevant layer ignition

• 1 to 4 tests are required: \( K_{St} \), MEC, MIE, and Layer Ignition (roughly $1.5K to $5K)
Electrical Application – Simpler Approach

- Is the dust cloud explosible?
  - Explosible? (E1226)
    - Yes
      - Classify Local Areas
    - No
      - No need for Classification

  1 to 3 tests required: screening, TL and Tc (roughly $250 to $2.5K)

- Is the dust layer or dust cloud susceptible to ignition from GP electrical equipment?
  - TL < 450°C? (E2021)
    - Yes
      - Use T Code Design
    - No
      - Melted before ignited
        - Tc < 450°C? (E1491)
          - Yes
            - No need for T Code Design
          - No
            - No need for T Code Design

Rodgers and Ural
Conclusions

• How much Dust is too much? One thickness allowance does not fit all applications. The answer depends on:
  - Specific dust
  - Specific building/enclosure
  - Personnel Protection Goal
  - Property Protection Goal

• New equations presented portray the real hazard and offer significant flexibility to users by:
  - Allowing differential treatment of marginally explosible dusts
  - Giving credit when due for building design, as well as prevention and protection measures
Conclusions

• Dust explosibility can be test equipment specific. If marginally explosible, test in 1 m³ scale.
  - False positives in OSHA tests

• Unscheduled Risk-based Housekeeping is an effective addition to Scheduled Housekeeping to maintain a safe workplace.

• Determination of Class II applicability per NMAB-353-3 confuses effects with causes. A simpler approach as that proposed for NFPA-499 is more appropriate.
Other Topics in the Paper

• OSHA test methodology differences

• Housekeeping Frequency as relates to Electrical Area Classification
• BACKUP SLIDES
Values in the Basic Equations

\[ \frac{P_{es}}{DLF} = 0.0167 \text{ bar} = 35 \text{ psf} \]
\[ C_w = 500 \text{ g/m}^3 \]
\[ \eta_D = 0.25 \]
\[ P_{max} = 8 \text{ barg} \]
\[ H = 12 \text{ meters} \]
\[ \text{Bulk Density} = 1201 \text{ kg/m}^3 = 75 \text{ lb/ft}^3 \]

\[ M_{basic-exp} = 0.004 \times A_{floor} \times H, A_{floor} \leq 2000m^2, H \leq 12m \]

\[ M_{basic-exp} = 0.048 \frac{kg}{m^2} \times A_{floor} \]

\[ M_{basic-exp} = 0.96 \frac{kg}{m^2} \times 0.05 \times A_{floor} \]

\[ \text{Layer} = \frac{0.96 \frac{kg}{m^2}}{1201 \frac{kg}{m^3}} = 0.0008m = 0.8mm \approx \frac{1}{32} \text{ inch} \]
Values in the Basic Equations

\[ P_{es}/DLF = 0.0167 \text{ bar} = 35 \text{ psf} \]

\[ C_w = 500 \text{ g/m}^3 \]

\[ \eta_D = 0.25 \]

\[ P_{\text{max}} = 8 \text{ barg} \]

\[ H = 12 \text{ meters} \]

Bulk Density = 1201 kg/m\(^3\) = 75 lb/ft\(^3\)

\[
M_{\text{basic–fire}} = 0.02 \cdot A_{\text{floor}}, A_{\text{floor}} \leq 2000m^2
\]

\[
M_{\text{basic–fire}} = 0.40 \frac{kg}{m^2} \cdot \phi 0.05 \cdot A_{\text{floor}}
\]

\[
Layer = \frac{0.40 \frac{kg}{m^2}}{1201 \frac{kg}{m^3}} = 0.00033m = 0.33mm \approx \frac{1}{64} \text{ inch}
\]
Quantifying the Accumulation

NFPA-68 conservatively assumes all of the dust accumulation can enter the cloud

\[ X_r = \frac{M_f}{A_{fs} \cdot c_w \cdot H} + \frac{M_s \cdot A_{sur}}{A_{ss} \cdot V \cdot c_w} + \frac{M_e}{V \cdot c_w} \]

- Each deposit would, in reality, be entrained to a different extent

\[ X_r = \frac{M_f \cdot A_{floor} \cdot \eta_{Dfloor}}{A_{fs} \cdot A_{floor} \cdot H \cdot c_w} + \frac{M_s \cdot A_{sur} \cdot \eta_{Dsur}}{A_{ss} \cdot A_{floor} \cdot H \cdot c_w} \]

\[ + \frac{M_e \cdot \eta_{De}}{A_{floor} \cdot H \cdot c_w} \]