The ExCEED facility for beryllium dust explosions

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Dust explosions- a long standing safety issue

- Dust explosions became an issue when large scale milling of grain began in the 1700s; the earliest known: a flour warehouse explosion in Turin, Dec. 14, 1785.

- They continue to be a problem: three incidents involving metal dust and hydrogen explosions killed five and injured three at the Hoeganaes facility in Gallatin, TN in 2011.

- Legislation (H.R.522) was (re)introduced last week to compel OSHA to issue a standard on dust explosions.

- We know dust is created by plasma-surface erosion in tokamaks; this safety concern has to be addressed for devices that may generate large quantities of dust.
Relevant questions

• Is the dust explosive?
  – This is the “explosibility” - established by igniting dust clouds over a wide range of concentrations - the dust is not explosive if it fails to ignite

• In what concentrations is it explosive?
  – The Lower Explosion Limit (LEL) identifies the minimum concentration necessary for an explosion

• How much oxygen is needed to permit a dust explosion?
  – The Limiting Oxygen Concentration (LOC) is that below which a dust explosion cannot occur

• How violent is the explosion?
  – The explosion indices \( (P_{\text{max}}, K_{\text{max}}) \) are the maximum pressure and maximum rate of pressure rise for a particular dust
Kühner 20 liter sphere

- Standard device for determination of explosion indices (cf. ASTM E1226)
- 0.6 liter, 21 atm dust/air mixture combines with:
  - 20 liter, 0.4 atm air volume
- Timed ignition with 2 chemical igniters (5 kJ each for measurement of the explosion indices)
- Pressure rise measured and recorded as function of time
- Double walled vessel has a water jacket for rapid cooling, constant initial temperatures
**Explosion Indices of Combustible Dust**

- Explosion indices are determined by conducting a series of explosions at increasing dust concentrations in air under standardized conditions.

- Each explosion has a maximum pressure ($P_m$) and maximum rate of pressure rise ($dP/dt_m$) identifiable on the pressure trace.

- Plotting $P_m$ and $dP/dt_m$ for each explosion versus the dust concentration identifies the $P_{\text{max}}$ and $dP/dt_{\text{max}}$ characteristic of that dust.

- $dP/dt_{\text{max}}$ is further corrected to be volume independent: $K_{\text{max}} = V^{1/3} \left( \partial P / \partial t \right)_{\text{max}}$.

- $P_{\text{max}}$ and $K_{\text{max}}$ are the explosion indices of the dust in question.

- $K_{\text{max}}$ is an indication of the explosion violence and is grouped into the classes:
  - St 1: $0 < K_{\text{max}} < 200$ [m·bar/s] (Weak)
  - St 2: $201 < K_{\text{max}} < 300$ [m·bar/s] (Strong)
  - St 3: $K_{\text{max}} > 300$ [m·bar/s] (Very Strong)
KIT facility - DUSTEX

• To address the explosion risk for fusion, KIT has carried out numerous tests (also with a Kühner sphere) on graphite and tungsten dusts

• These were found to be at most weakly explosive (class St 1)

<table>
<thead>
<tr>
<th>Dust</th>
<th>$P_{\text{max}}$ (bar)</th>
<th>$K_{\text{max}}$ (bar·m/s)</th>
<th>Class</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>6.6</td>
<td>68</td>
<td>St 1</td>
<td>Weak Explosion</td>
<td>Denkevits, Fus. Eng. Des. 75-79 (2005) 1135</td>
</tr>
<tr>
<td>W</td>
<td>4.7</td>
<td>71</td>
<td>St 1</td>
<td>Weak Explosion</td>
<td>Denkevits, Fus. Eng. Des. 75-79 (2005) 1135</td>
</tr>
<tr>
<td>Wood</td>
<td>9.4</td>
<td>208</td>
<td>St 2</td>
<td>Strong Explosion</td>
<td>Bartknecht 1989</td>
</tr>
<tr>
<td>Niacin</td>
<td>8.1</td>
<td>243</td>
<td>St 2</td>
<td>Strong Explosion</td>
<td>Kühner report</td>
</tr>
<tr>
<td>Al</td>
<td>10-12.5</td>
<td>500-650</td>
<td>St 3</td>
<td>Very Strong Explosion</td>
<td>Numerous</td>
</tr>
</tbody>
</table>
Beryllium data is needed

• Beryllium oxidation is more energetic than tungsten or graphite, may dominate explosion risk if present as a PFC

• To address this need, we have commissioned the Experimental Chamber for Evaluation of Exploding Dust (ExCEED)

• Testing in the Kühner sphere requires ~100s of grams of material

• This is a real challenge considering that exposure to as little as 0.2 µg/m^3 can cause chronic beryllium disease

• Our Kühner sphere is housed in a glovebox for complete containment of beryllium
Safety Analysis and Controls

• Pressure vessel analysis
  – Kühner sphere has a MAWP of 30 bar; tested to 42 bar
  – Established Code equivalency between European Pressure Equipment Directive 97/23/EC and ASME section VIII for the sphere
  – Installed ASME section VIII U-stamped safety relief valve

• Glovebox integrity
  – Inert (N₂) atmosphere for fire and explosion prevention
  – Pressure relief and HEPA filtration
  – Pressurization scenarios considered; no threat to the glovebox is evident

• Igniter handling
  – Anti-static controls include pulsed DC ion bar, grounded mats and wrist straps, grounding of all devices, anti-static glovebox gloves
  – Accidental ignition not a threat to glovebox integrity
Igniters

- We use Simex igniters because of their superior safety characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard 5kJ Igniters</th>
<th>New SiMEX NPI® 5kJ Igniters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content of Toxic Compounds</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>ESD Sensitivity</td>
<td>10-20 mikro J</td>
<td>10-20 milli J</td>
</tr>
<tr>
<td>Friction Sensitivity</td>
<td>200 gms</td>
<td>4000 gms</td>
</tr>
<tr>
<td>Safety Current</td>
<td>0,18 Amps</td>
<td>0,4 Amps</td>
</tr>
<tr>
<td>Function time delay and accuracy</td>
<td>7,5 ± 2,5ms</td>
<td>1,5 ± 0,5ms</td>
</tr>
<tr>
<td>Calculated Combustion Temperature</td>
<td>3800 ± 200 °C</td>
<td>3800 ± 200 °C</td>
</tr>
<tr>
<td>Results of P&lt;sub&gt;max&lt;/sub&gt; and K&lt;sub&gt;max&lt;/sub&gt; Evaluation (CaRo-07, Al, Coal, Lycopodium etc.)</td>
<td>Mean value ± 10%</td>
<td>Mean value ± 10%</td>
</tr>
<tr>
<td>Caloricty</td>
<td>5 kJ</td>
<td>5 kJ</td>
</tr>
<tr>
<td>Ballistic output (20lt)</td>
<td>0,9 to 1,3 Bar</td>
<td>0,9 to 1,3 Bar</td>
</tr>
</tbody>
</table>
Calibration Testing

• Kühner provides a powder (Niacin, a.k.a. vitamin B₃, C₆NH₅O₂) and test protocol for calibration of the sphere

• Purpose is to compare results for a standard dust against all other facilities

• Results within 10% of mean are acceptable

• 3 test series are required; each series consists of explosions at 60, 125, 250, 500, 750... g/m³ (1.2, 2.5, 5, 10, 15... g in the 20 liter sphere) continuing until the peak in the curve P_max (or K_max) vs. concentration is identified

• This testing has been completed in ExCEED
  – We were able to do so without the glovebox sealed as there is no need for strict confinement of niacin
**Niacin Calibration**

\[ P_{\text{max}} = 8.6 \text{ bar} \]

\[ K_{\text{max}} = 236 \text{ bar} \cdot \text{m/s} \]

**70 different facilities**

\[ P_{\text{max}} = 8.1 \text{ bar} \]

\[ K_{\text{max}} = 243 \text{ bar} \cdot \text{m/s} \]
Beryllium Testing – Powder Specifications

- Powder representative of tokamak dust has been purchased from Materion Brush Beryllium and Composites (1 kg) and is well characterized
  - Size distribution contains primarily <10 µm and some < 1 µm particles
  - BET surface area: 4.67 m²/g


Status and Future Work

- Explosion Indices of beryllium dust have been measured
- Some possible future work:
  - Standard tests for Limiting Oxygen Concentration, Minimum Ignition Energy, or Lower Explosion Limit
  - Testing of larger beryllium particle sizes
  - Identification and testing of surrogates for beryllium with similar explosion characteristics (for larger scale tests)
  - Explosion indices of mixed dusts (e.g. including beryllium, tungsten, and/or others)
  - Inclusion of hydrogen in the gas mixture (some additional safety reviews and equipment will probably be required)
  - Analysis of product gases (e.g. oxygen content) for benchmarking of combustion models