Lessons Learned on Surviving Worst-Case Reactivity Hazards

Explosion Consequence Assessment

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Outline

• Purpose

• Design Basis Scenario

• Potentially Relevant Explosion Scenarios
  ▪ Condensed phase explosion
  ▪ Bursting pressure vessel
  ▪ Vapor cloud explosion
  ▪ Combustible dust explosion

• Consequence Assessment Methods
  ▪ Blast loads (primary focus)
  ▪ Fragments
  ▪ Structural response

• Results from example evaluation
Purpose

• Provide Overview of
  ▪ Potentially relevant explosion scenarios
  ▪ Consequence assessment methods
• Not comprehensive or in-depth
• Emphasis on blast load assessment
• Contact Robert Shumate (P&G) or Kelly Thomas (BakerRisk) if need additional information
Design Basis

• Relevant explosion scenarios and scenario definition must be specified “up front”
  ▪ Scenarios that structures will be designed to
  ▪ Design basis scenarios

• Owner/operator must “own” design basis

• May not be able to completely rule out very low probably events, but may choose not to design for them
  ▪ Excluded from design basis
  ▪ Asteroid strike
  ▪ Can utilize risk analysis to place in context
Potentially Relevant Scenarios

- Condensed phase explosion
- Bursting pressure vessel (BPV)
  - At normal operating pressure (degradation)
  - At bursting pressure (overpressure)
  - Entire vessel or fitting
- Internal vapor cloud explosion (VCE)
  - Deflagration
  - Detonation
- Internal combustible dust explosion
Condensed Phase Explosion (1 of 4)

- Uncontrolled runaway leading to detonation of condensed phase within vessel
- Pressurization rate so high vessel cannot respond
- Can treat as high explosive (e.g., TNT)
- Consequence assessment methods
  - Internal blast loads
  - External blast loads
Internal blast loads
- TNT blast charts (e.g., TM5-1300)
  - Must account for reflections (pressure and impulse)
  - Must account for reverberations (primarily impulse)
- Quasi-static pressure during venting
- Simplified computer codes
- Computational fluid dynamics (CFD) codes (e.g., BakerRisk’s BWTI simulation package)

External blast loads
- Simplified design guides (e.g., TM5-1300)
- CFD codes (e.g., BWTI)
Bursting Pressure Vessel (1 of 4)

- At normal operating pressure
  - Degradation of vessel (e.g., corrosion)
- At bursting pressure
  - Overpressure
  - Inadequate pressure relief
  - Beyond design basis event (e.g., explosion)
- Consequence assessment methods
  - Internal blast loads
  - External blast loads
Internal blast loads
- BPV blast charts (e.g., BakerRisk, CCPS)
  - Must account for reflections (pressure and impulse)
  - Must account for reverberations (primarily impulse)
- Quasi-static pressure during venting
- Computational fluid dynamics (CFD) codes (e.g., BakerRisk’s BWTI simulation package)
  - Routinely use for high pressure test enclosures

External blast loads
- Simplified design guides, treating BPV as equivalent HE charge (e.g., TM5-1300)
- CFD codes (e.g., BWTI)
Internal VCE (1 of 8)

- VCE combustion mode
  - Release of flammable gas/spray/liquid from a vessel or supply line filling portion of enclosure and then being ignited
  - Deflagration (subsonic, “normal”)
  - Detonation
    - Direct initiation, requires high energy source
    - Deflagration-to-detonation transition (DDT), which is normally the only detonation case of interest

- Consequence assessment methods
  - Potential for DDT
  - Internal blast loads
  - External blast loads
Assessment of potential for DDT
- Concern primarily for high reactivity fuels (e.g., \( \text{C}_2\text{H}_2, \text{C}_2\text{H}_4, \text{H}_2, \) etc.)
- Judgment
- CFD based assessment (FLACS)
  - BakerRisk’s Explosion Research Cooperative (ERC)

Internal blast loads
- NFPA 68 standard (2013)
  - \( A_v = f(P_{\text{max}}, A_{s\text{obst}}, A_{s\text{encl}}, \text{fuel, L/D}) \)
  - Can account for cloud which partially fills enclosure
  - Cloud volume (bounding, dispersion)
- CFD codes (e.g., FLACS)
External blast loads
  - Some guidance available in NFPA 68
  - CFD codes (e.g., BWTI, FLACS)
Combustible Dust Expl. (1 of 1)

- Concern where have combustible dust deposited within enclosure
- Combustible dust = “dust made of anything that can burn”
- Typically concerned about secondary dust explosion (primary event suspends dust and provides ignition source)
- Internal loads via NFPA 68
- External loads
  - NFPA 68 provides limited guidance
  - External VCE equivalent
    - BakerRisk’s Explosion Research Cooperative
• Condensed phase (high explosive)
  ▪ Cased weapon relationships (e.g., TM5-1300)

• Bursting pressure vessel
  ▪ Simplified design guidance (Baker et al. 1983)

• Fittings/plugs (not vessel failure)

• Penetration evaluation
  ▪ Simplified design guidance (e.g., TM5-1300)
  ▪ Industry testing programs
    ▪ BakerRisk’s High Pressure Joint Industry Program (HP JIP)
    ▪ Made of primarily of down-hole tool companies
    ▪ Focused on defining fitting/plug failure velocity and shield penetration characteristics
Structural Response (1 of 3)

• Differences between assessing buildings for explosion loads and typical loads
  ▪ Consider both blast overpressure and impulse
  ▪ Allow deformation for accident loads
  ▪ Not treated as static elastic load

• Generally consider both internal and vented blast loads

• Methods
  ▪ Single-degree-of-freedom (SDOF)
    ▪ Multiple packages available
  ▪ Multiple-degree-of-freedom (MDOF)
  ▪ Finite element analysis (FEA)
Response criteria set the amount of deformation a component can undergo.

Response criteria per ASCE (and US DOD) in terms of ductility and support rotations:
- High response corresponds to incipient failure
- Normally design to medium or low response levels

Can develop pressure-impulse curves corresponding to response levels, or evaluate for specific load case.
Structural Response (3 of 3)
Example (1 of 3)

- Existing test cell (8’ x 8’ x 10’)
  - 12 in reinforced concrete, reinforced concrete shield wall outside vented wall, one wall vented

- Bursting pressure vessel
  - 5 gallon 1900 psig MAWP
  - 2 gallon 5325 psig MAWP
  - Failure at MAWP per client specification
  - Loads based on BPV blast curves, accounting for reflection and reverberation (see table)

- Penetration evaluation (see table)

- Hydrogen deflagration (see table)
## Example (2 of 3)

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Surface</th>
<th>Pressure (psig)</th>
<th>Impulse (psi-ms)</th>
<th>Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 gal</td>
<td>Wall</td>
<td>110</td>
<td>46</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>19</td>
<td>28</td>
<td>2.9</td>
</tr>
<tr>
<td>2 gal</td>
<td>Wall</td>
<td>140</td>
<td>49</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>23</td>
<td>31</td>
<td>2.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Quasi-static Pressure Load (psig)</th>
<th>Blow-down Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 gal</td>
<td>2.0</td>
<td>11</td>
</tr>
<tr>
<td>2 gal</td>
<td>2.3</td>
<td>12</td>
</tr>
</tbody>
</table>
## Fragment Results (concrete)

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Fragment Velocity (fps)</th>
<th>Thickness to Prevent Perforation (in)</th>
<th>Thickness to Prevent Spall (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 gal</td>
<td>110</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>2 gal</td>
<td>120</td>
<td>7</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$P_{\text{max}}$ (psig)</th>
<th>Duration (ms)</th>
<th>$dP/dt_{\text{max}}$ (psi/ms)</th>
<th>Time to $P_{\text{max}}$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>100</td>
<td>3.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>