Introduction to Methods of Process Safety Hazard Assessment

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Randy Freeman

- 30+ years of industrial process safety experience
- 25 years experience in design and application of instrument systems to prevent accidents
- Author of over 30 technical papers
- Committee member or technical reviewer of approximately 20 CCPS guideline books
- Member ISA S84 Committee
- AIChE Fellow, Emeritus Member Loss Prevention Symposium Planning Committee and Emeritus Member of CCPS, CCPS Fellow
- Past Chairman of AIChE Safety and Health Division
- BS, MS, PhD Chemical Engineer - Univ of MO - Rolla
- Founder of S&PP Consulting
AGENDA

• Why Process Safety Reviews?
• Hazard Assessment Methods
  – HAZOP
  – What If
  – Checklists
• Advanced Techniques
  – LOPA
  – Consequence Analysis
A Few Examples

Photos from US Chemical Safety Board

1. Propane fire at Valero McKee Refinery
2. BP Texas City ISOM unit explosion kills 15 workers (2 photos)
3. Dust explosion in Kinston, NC
4. Solvent explosion at a Boston area ink blending plant damages local houses
Process Hazards Analysis

• A Process Hazards Analysis (PHA) is a systematic method for looking for potential process safety concerns before they become actual incidents

• A PHA is normally completed by a team
PHAs Per OSHA PSM Standard 29 CFR 1910.119

• A PHA is required for covered process systems
• Allowable PHA methods are:
  – What-If;
  – Checklist;
  – What-If/Checklist;
  – Hazard and Operability Study (HAZOP);
  – Failure Mode and Effects Analysis (FMEA);
  – Fault Tree Analysis; or
  – An appropriate equivalent methodology
Typical Events of Concern

- Fire
- Explosion
- Toxic material release
- Significant environment impact
- Release to a flare system
- Vessel Overpressure
- Runaway reaction
## Typical PHA Team

<table>
<thead>
<tr>
<th>Team Participant</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHA Team Leader</td>
<td>Lead and document the PHA sessions. Primarily a facilitator of the team meetings</td>
</tr>
<tr>
<td>Process Engineer</td>
<td>Provides process chemistry knowledge to the PHA team</td>
</tr>
<tr>
<td>Control Systems Engineer</td>
<td>Provides control system knowledge to the PHA team</td>
</tr>
<tr>
<td>Production operator</td>
<td>Provides hands-on operations knowledge of how the system operates. For a new facility, the production operator may be chosen from a sister production unit or from a similar process system. A senior operator is normally assigned to this function.</td>
</tr>
<tr>
<td>Production supervision</td>
<td>Provides management and operating policy input to the team</td>
</tr>
<tr>
<td>Safety advisor</td>
<td>Provides knowledge of plant safety policies and risk toleration</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Provides knowledge on how the system will be maintained</td>
</tr>
</tbody>
</table>
What If

• Creative Brainstorming Method
• Based on experience and knowledge of PHA Team
• Can be used to define emergency actions:
  – What if we have a fire in XYZ Department?
  – What if we spill a drum of 2, 3 DMD?
  – What if we overpressure TK-101?
Check Lists

• Used to evaluate a system with a predefined list of questions
• Easy to use
• Can be used where no accident scenario is known
• Often used to verify that a system complies with a design specification or practice
• “mother of all check lists” in CCPS Guideline Book HEP, 3rd Ed, pages 477-518
Check List Example

10. Are discharges from vents, relief valves, rupture disks, and flares located to avoid hazards to equipment and personnel? Could liquids be sprayed into the air? Are vents from relief devices (e.g., between rupture disks and relief valves, between balanced bellows, and between weep holes in discharge piping) also routed to a safe location? Are flame arresters installed?

11. Are relief devices located so that when they open, the process flow will continue cooling critical equipment (e.g., steam superheaters)?

12. What are the impacts of a flare, incinerator, or thermal oxidizer trip or flameout? What would happen if the flare gas recovery compressor tripped?

HAZOP

• Directed Creative Brainstorming Method
• Based on experience and knowledge of PHA Team
• Use Guide Words to Control the PHA Team Discussions
• Focuses on one small part of the system at a time
• Very Widely Used in Process, Chemical, Refining and Pharmaceutical Industries
<table>
<thead>
<tr>
<th>Guide Words</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO / NOT</td>
<td>Complete negation of design intent</td>
</tr>
<tr>
<td>Less</td>
<td>Quantitative decrease</td>
</tr>
<tr>
<td>More</td>
<td>Quantitative increase</td>
</tr>
<tr>
<td>Part of</td>
<td>Only a portion of design intent achieved</td>
</tr>
<tr>
<td>As Well As</td>
<td>In addition to design intent</td>
</tr>
<tr>
<td>Reverse</td>
<td>Opposite to design intent</td>
</tr>
<tr>
<td>Other Than</td>
<td>Complete substitution</td>
</tr>
</tbody>
</table>
## Typical Process Parameters

<table>
<thead>
<tr>
<th>Flow</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Time</td>
</tr>
<tr>
<td>Temperature</td>
<td>Reaction</td>
</tr>
<tr>
<td>Level</td>
<td>Mixing</td>
</tr>
</tbody>
</table>
# Process Deviations

- Found by combinations of Guide Word and Process Parameters as Applied to Design Intent

<table>
<thead>
<tr>
<th>Design Intent</th>
<th>Transfer oil at 100 F from TK-101 to TK-102</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Guide Word</strong></td>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>No</td>
<td>Flow</td>
</tr>
<tr>
<td>More</td>
<td>Temperature</td>
</tr>
<tr>
<td>Other Than</td>
<td>TK-102</td>
</tr>
</tbody>
</table>
Design Intent: Transfer Oil at 100 F from TK-101 to TK-102

<table>
<thead>
<tr>
<th>Item</th>
<th>Deviation</th>
<th>Cause</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>More Level In TK-102</td>
<td>Failure of LT 102-1 on TK-102</td>
<td>Overflow TK-102 resulting in a release of 1000 barrels of oil to dike</td>
<td>None</td>
<td>Install a redundant level device on TK-102</td>
</tr>
</tbody>
</table>

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Advanced PHA Techniques

Other methods of identification of accident scenarios
Spectrum of Risk Decision Methods

Qualitative Analysis
(100% of scenarios are analyzed using qualitative methods)

Simplified-quantitative Analysis
(10-20% of the scenarios go on to simplified-quantitative methods)

Quantitative Analysis
(1% go to QRA)

Techniques:

- HAZOP
- What-if/Checklist
- FMEA

Quantified FMEA
F&E
CEI

LOPA

Rough estimate with event tree
Event tree
Fault tree
HRA

Applicability to simple issues:

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Good</th>
<th>Good</th>
<th>Good</th>
<th>Overkill</th>
<th>Gross overkill</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZOP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What-if/Checklist</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMEA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Applicability to complex issues:

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Poor</th>
<th>Poor</th>
<th>Usually good</th>
<th>Occasionally poor</th>
<th>Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZOP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What-if/Checklist</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMEA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What is LOPA

• A systematic method for looking at the protective features of your plant
• Semi-quantitative method for evaluation of the risk of an incident
• Method for documenting the justification for risk reduction recommendations
Layers of Defense

COMMUNITY EMERGENCY RESPONSE

PLANT EMERGENCY RESPONSE

PHYSICAL PROTECTION (DIKES)

PHYSICAL PROTECTION (RELIEF DEVICES)

AUTOMATIC ACTION SIS OR ESD

CRITICAL ALARMS, OPERATOR SUPERVISION, AND MANUAL INTERVENTION

BASIC CONTROLS, PROCESS ALARMS, AND OPERATOR SUPERVISION

PROCESS DESIGN
Swiss Cheese View of Layers

Bad Things Happen

Protective Layers 1, 2, 3

Holes in Cheese are weaknesses in each layer
GOAL: Keep the holes from alignment
Swiss Cheese View of Layers

Bad Things Happen

Protective Layers 1, 2, 3

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GOAL: Keep the holes from alignment
Swiss Cheese View of Layers

Bad Things Happen

Protective Layers 1, 2, 3

Holes in Cheese are weaknesses in each layer
GOAL: Keep the holes from alignment
Bad Things Happen

IPL_1

success

IPL_2

success

failure

IPL_3

success

failure

failure

Fire, Explosion, Toxic Release

Safe outcome
Undesired, but tolerable outcome

Worst Case Consequences

Key:
Thickness of arrow represents frequency of the consequence if later IPLs are not successful
Steps in a LOPA Study

1. Define the system to be studied (Scope)
2. Define the reason for the study (Why or what question are you trying to answer)
3. Organize the Team
4. Define Scenarios
5. Define Possible Protective Layers
6. Define Initiating Events
7. Determine Consequences
8. Evaluate Risk
9. Develop Recommendations for Improvement
Independent Protective Layers Must Be

• Capable of preventing the undesired event of concern
• Be independent of other safeguards to be counted as an IPL
• Be auditable
Generic Types of IPLs

• Procedural Control (With Qualifications)
• Passive Mechanical Device
• Active Mechanical Device
• Basic Process Control System
• Safety Interlock (With Qualifications)
Procedural Control IPLs

- Procedure must be capable of preventing consequence of concern
- Clear indication of event and need to complete procedure
- People must be trained
- Tools and equipment must be available
- Written procedure must exist
- People must have time to act (> 10 min)
- Must be able to complete procedure before event of concern occurs
- Only one procedural control normally allowed as an IPL (special considerations apply for more than one)
### Initiating Event Frequencies

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency, Events/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure of BPCS</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Pump seal failure</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Pressure regulator failure</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Large fire of an entire process unit</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Small Fire in a process unit</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Pressure vessel rupture</td>
<td>$1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Human operator error – routine task performed frequently</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Spurious opening of a relief valve</td>
<td>$1 \times 10^{-2}$</td>
</tr>
</tbody>
</table>
# LOPA Risk Matrix

<table>
<thead>
<tr>
<th>Severity -&gt; Frequency (event/yr)</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.E+00</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>1.E-01</td>
<td>I</td>
<td>I</td>
<td>M</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>1.E-02</td>
<td>I</td>
<td>I</td>
<td>M</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>1.E-03</td>
<td>I</td>
<td>M</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>1.E-04</td>
<td>M</td>
<td>M</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>1.E-05</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>1.E-06</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>
Consequence Scale

1. Very Low Consequence
   • So small that we don’t care
2. Low Consequence Events
   • minor injuries in plant
3. Medium Consequence Events
   • Up to $1M damage to facility
4. High Consequence Events
   • Off site public injuries
5. Very High Consequence Events
   • Fatalities in plant, serious injuries (death) to public
# Generic LOPA Credits

<table>
<thead>
<tr>
<th>Protective Layer</th>
<th>LOPA Credit (Probability of Failure on Demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Process Control System</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Procedural control with more than 10 minutes to complete the task</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Procedural Control with more than 40 minutes to complete the task</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>Active mechanical safeguard (relief valve, rupture disk, etc.)</td>
<td>$1 \times 10^{0}$ to $1 \times 10^{-3}$ depending upon process conditions and history of the device</td>
</tr>
<tr>
<td>Passive mechanical safeguard (dike)</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>Safety interlock (Safety Instrumented Function implemented in an Safety Instrumented System) at a Safety Integrity Level 1</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>Safety interlock (Safety Instrumented Function implemented in an Safety Instrumented System) at a Safety Integrity Level 2</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>Safety interlock (Safety Instrumented Function implemented in an Safety Instrumented System) at a Safety Integrity Level 3</td>
<td>$1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Communication of LOPA Results

- Identification data
- Reference Data
- Hazard Description
- Existing Safeguards
- Existing Hardware
- Desired Safety Function
- Additional Safeguards needed
- Use a standard format
Consequence Evaluation Techniques

How bad will the scenario be?
Consequence Evaluation Tools

• Simple hand calculations or spreadsheets (See CCPS Guidelines on Consequence Evaluation)

• Public Source Software (For example, NOAA ALOHA air dispersion model)

• Proprietary Software (For example, PHAST by DNV)
The following examples are a work of fiction. Equipment, locations and chemicals are either the product of the authors imagination or are used fictitiously. Any resemblance to an actual chemical plant or process is entirely coincidental.
Example - Chlorine Release

Accidental Release of Chlorine from a small storage cylinder. Release rate of 1 kg/s at 100 F. Compute downwind distance to concentration isopleth of 20 ppm (by volume in air)
Spreadsheet Calculation
Ref: Example 2.16 of CCPS CPQRA book

• Wind speed of 1.5 m/s
• Chlorine release rate of 1 kg/s
• Concentration of concern 20 ppm
Spreadsheet Results

Distance Crosswind vs. Distance Downwind, m
Calculation using ALOHA

- Pressurized cylinder (2000 lb) of chlorine at 100 F
- Hole size is ¼ inch diameter
- Wind speed is 1.5 meter/sec ( mph)
ALOHA Results

<= 20 ppm = A EGL-3 (60 min)

<= 2 ppm = A EGL-2 (60 min)

<= 0.5 ppm = A EGL-1 (60 min)

Confidence Lines
Calculation Using PHAST

• Pressurized cylinder (2000 lb) of chlorine at 100 F
• Hole size is ¼ inch diameter
• Wind speed is 1.5 meter/sec ( mph)
PHAST Results
Center for Chemical Process Safety

References

• CCPS, *Guidelines for Consequence Analysis of Chemical Releases, 1999*
• CCPS, *Layer of Protection Analysis*, 2001
Consequence Analysis
Software References

• DNV, PHAST Software Package, Version 6.53
• US EPA, Office of Emergency Management, ALOHA, Version 5.4.1.2
Government References

• US EPA, Risk Management Plan Rule, 40 CFR 68
  http://www.epa.gov/oem/content/rmp/


• US Chemical Safety Board,
  http://www.chemsafety.gov/
QUESTIONS