Risk Based Method to Establish Inspection Intervals for Pressure Relief Devices

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Philip A. Henry, P.E.
Principal Engineer
The Equity Engineering Group, Inc.
Shaker Heights, OH

Matthew K. Caserta
Senior Engineer
The Equity Engineering Group, Inc.
Shaker Heights, OH
Risk Based Method to Establish Inspection Intervals for Pressure Relief Devices

- Background
- Methodology
- Probability of Failure
- Consequence of Failure
- Calculation of Risk
- Inspection Planning using Risk Targets
- Refinery Case Study
- Conclusions
Background

- **PRD Inspection Intervals – How do they get established?**
- **API 510 Inspection Code**
  - “pressure relief valves shall be tested at intervals that are frequent enough to verify that the valves perform reliably.”
  - “Intervals between pressure relieving device testing or inspection should be determined by the performance of the devices in the particular service concerned and maybe increased to a maximum of 10 years”
  - Latest version of 510 allows the use of RBI to set intervals
- **Inspection Programs per API 510 and NBIC**
  - Conditioned Based (probability based)
  - Set an Interval, inspect and adjust based on results of inspection
- **API RBI methodology evaluates both probability and consequence, i.e. risk-based**
Background

- API PRD Methodology was included in the 2008 Edition of API RP 581
- Methodology has been incorporated into Version 8 of the API RBI software
- Methodology has been applied at numerous sites with very good results
API RBI PRD Methodology

- Highly Quantitative
- Risk for PRDs are calculated for two failure modes
- Fail to Open (FAIL)
  - PRD does not open on demand during an overpressure scenario (fire, blocked discharge, CV failure, Loss of Cooling, Power failure, etc.)
  - Over pressures can be well over normal operating, for some scenarios burst pressure ($\approx 4 \times$ MAWP)
  - Evaluate loss of containment (leaks or ruptures) from the protected equipment at the overpressure calculated for each applicable overpressure scenario
  - Includes repair costs of equipment, personnel injury, environmental and production losses
- Leakage Failure (LEAK)
  - PRD leaks in-service
  - Considers cost of lost fluid inventory, repair costs, production losses if downtime is required to repair PRD
- RISK = POF x COF + POL x COL, $/year
Probability of Failure

- Probability of Failure

\[ POF = POFOD \times DR \times (GFF \times DF)_{OP} \]

- \( POF \) is probability of PRD failure to open during emergency situations causing an overpressure situation in the protected equipment resulting in loss of containment (failures/year)

- \( POFOD \) is the probability of the PRD failing to open on demand (failure/demand)

- \( DR \) is the demand rate on the PRD or how often an overpressure situation arises that causes a demand on the valve (demands/year)

- \( (GFF \times DF) \) is the probability of failure (loss of containment) from the vessel in its current damaged state
Probability of Failure on Demand (POFOD)

- Uses PRD Failure Database
- Contains about 5000 data points from actual in-shop bench tests, continually adding data as implementations are completed
- Tracks FTO and LEAK data for Conventional, Balanced, Pilot-Operated PRVs and Rupture Disks
- Database for FTO case includes:
  - Stuck or Fails to Open (FTO)
  - Includes Valve Partially Opens (VPO)
  - and Opens Above Set Pressure (OASP)
- FTO is defined as failure to open at 1.3 times the set pressure
- Database for LEAK case includes:
  - Leakage Past Valve (LPV),
  - Spurious/Premature Opening (SPO)
  - and Valve Stuck Open (VSO)
- LEAK is qualified as minor, moderate and stuck open, based on where the PRV started to leak in relation to set pressure on the bench test
- Database tracks effects of temperature, fluid severity, pulsing service, pipe vibration, excessive actuation
Probability of Failure

- Typical Failure Data for Default Mild, Moderate and Severe Services
Probability of Failure

- Probability of Failure on Demand
  - *POFOD* (Failures/demand)
    - Default Weibull failure (*POFOD*) curves are chosen based on the fluid severity (Mild, Moderate, Severe) selected by the user
    - User can supply own Weibull parameters if desired
    - Default curves are then adjusted based on the knowledge gained from the historical inspection records for each PRD
    - Default curves are also modified based on installation factors such as history of valve actuation or pulsing service
**Probability of Failure**

- **PRD Inspection Effectiveness**

<table>
<thead>
<tr>
<th>Inspection Effectiveness</th>
<th>Description of Inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Highly” effective</td>
<td><strong>Pressure Relief Valves</strong></td>
</tr>
<tr>
<td></td>
<td>A bench test has been performed on the PRV in the as-received condition from the unit and the initial leak pressure, opening pressure and the reseat pressure has been documented on the test form. The inlet and outlet piping has been examined for signs of excessive plugging or fouling.</td>
</tr>
<tr>
<td></td>
<td><strong>Rupture Disks</strong></td>
</tr>
<tr>
<td></td>
<td>None Available</td>
</tr>
<tr>
<td>“Usually” effective</td>
<td><strong>Pressure Relief Valves</strong></td>
</tr>
<tr>
<td></td>
<td>A bench test has been performed, however, the PRD was cleaned or steamed out prior to the bench test. Additionally, a visual inspection has been performed where detailed documentation of the condition of the PRD internal components was made.</td>
</tr>
<tr>
<td></td>
<td><strong>Rupture Disks</strong></td>
</tr>
<tr>
<td></td>
<td>The rupture disk is removed and visually inspected for damage or deformations</td>
</tr>
<tr>
<td>“Fairly” effective</td>
<td><strong>Pressure Relief Valves</strong></td>
</tr>
<tr>
<td></td>
<td>A visual inspection has been performed without a pop test, where detailed documentation of the condition of the PRD internal components was made.</td>
</tr>
<tr>
<td></td>
<td>A trevittest or in-situ test has been performed where the actual process fluid was not used to pressurize the system.</td>
</tr>
<tr>
<td></td>
<td><strong>Rupture Disks</strong></td>
</tr>
<tr>
<td></td>
<td>The space between the disk and the PRV is monitored for leakage in accordance with the ASME Code and API RP 520 Part 2.</td>
</tr>
<tr>
<td>Ineffective</td>
<td>No pop test was conducted and no details of the internal component were documented</td>
</tr>
</tbody>
</table>
Probability of Failure

- Demand Rate - \( DR \) (demands/year)
  - The methodology recognizes the fact that the PRD is not needed the majority of the time that is in-service, it is only needed during an overpressure event (fire, loss of power, blocked discharge, etc.)
  - These overpressure events are rare, demand rates are typically on the order of 1/10 years but some are extremely rare, such as fire; 1/250 years
  - Includes a Demand Rate Reduction Factor (\( DRRF \)) to account for factors in the process design that may assist in reducing the Demand Rate on a PRD
    - Process Control Layers of Protection (LOPA)
    - Fire Fighting Facilities
    - Operator Intervention
**Probability of Failure**

- **Demand Rate**
  - User selects applicable overpressure scenarios from choice list
  - Allows User to override demand rate

<table>
<thead>
<tr>
<th>Overpressure Demand Case</th>
<th>Event Frequency</th>
<th>$IEF_i$ (events/year)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire</td>
<td>1 per 250 years</td>
<td>0.004</td>
<td>9.7</td>
</tr>
<tr>
<td>Blocked Discharge with Administrative Controls in Place (see Note 1)</td>
<td>1 per 100 years</td>
<td>0.01</td>
<td>9.11</td>
</tr>
<tr>
<td>Blocked Discharge without Administrative Controls (see Note 1)</td>
<td>1 per 10 years</td>
<td>0.1</td>
<td>9.11</td>
</tr>
<tr>
<td>Loss of Cooling Water Utility</td>
<td>1 per 10 years</td>
<td>0.1</td>
<td>9.7</td>
</tr>
<tr>
<td>Thermal Relief with Administrative Controls in Place (see Note 1)</td>
<td>1 per 100 years</td>
<td>0.01</td>
<td>Assumed same as Blocked Discharge</td>
</tr>
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<td>Thermal Relief without Administrative Controls (see Note 1)</td>
<td>1 per 10 years</td>
<td>0.1</td>
<td>Assumed same as Blocked Discharge</td>
</tr>
<tr>
<td>Electrical Power Supply failure</td>
<td>1 per 12.5 years</td>
<td>0.08</td>
<td>9.7</td>
</tr>
<tr>
<td>Control Valve Failure, Initiating event is same direction as CV normal fail position</td>
<td>1 per 10 years</td>
<td>0.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Control Valve Failure, Initiating event is opposite direction as CV normal fail position</td>
<td>1 per 50 years</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Tower P/A or Reflux Pump Failures</td>
<td>1 per 5 years</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Runaway Chemical Reaction</td>
<td>1 per year</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Liquid Overfilling</td>
<td>1 per 100 years</td>
<td>0.01</td>
<td>9.7</td>
</tr>
<tr>
<td>Heat Exchanger Tube Rupture</td>
<td>1 per 1000 years</td>
<td>0.001</td>
<td>9.5</td>
</tr>
</tbody>
</table>
Probability of Failure

- \((GFF \times DF)\) is the probability of failure (loss of containment) from the vessel in its current damaged state
  - Fixed Equipment RBI is performed at operating pressure
  - Unlike fixed equipment RBI, PRD RBI is performed at much higher overpressures
    - The methodology calculates potential overpressure if the PRD fails to open on demand
    - Overpressure increases release amount and also increases probability of leaks and ruptures (\(GFFs\) are increased as a function of overpressure)
    - Some overpressure scenarios (fire, power failure) will result in rupture, if the PRD fails to open on demand
Probability of Failure

• Direct Link to Fixed Equipment (Vessels and Piping)
  – PRD Protection Database Table links PRDs to their protected equipment
    • Handles equipment protected by multiple PRDs
    • Handles multiple pieces of equipment protected by common PRD(s)
  – Links PRD to the vessel inventory group, operating and design conditions, fluid properties and most importantly to the damage state of the protected equipment
  – PRD RBI can be performed without fixed equipment RBI, in this case a qualitative measure of the damage factor (damage state) of each piece of protected equipment vessel is input
Probability of Failure

• Direct Link to Fixed Equipment
  – Recognizes the fact that damaged vessels are at higher risk to failed PRD than undamaged vessels, current PRD module does not consider the protected equipment damage state.
  – Since the damage factor of the protected equipment increases as a function of time so does the risk associated with the PRD protecting it
  – Allows risk ranking of PRDs versus fixed equipment
• Risk is calculated for EACH piece of equipment or component protected by the PRD
Consequence of Failure

- Calculate impact area (consequence area) of release of hazardous fluids
  - Flammable
  - Toxic
  - Non-flammable (splash, spray, physical explosion, BLEVE)

- Consequence areas are based on damage to equipment and serious injury to personnel

- Impact areas are based on thermal radiation exposure, overpressure from explosion, toxic concentration, and dosage limits

- Financial consequences include
  - Replacement cost of damage equipment
  - Cost of business interruption
  - Potential injuries
  - Environmental clean-up costs
Consequence of Failure

• Consequences associated with loss of containment (leaks and ruptures) from pressurized equipment are calculated

• Equipment is classified into inventory groups for purposes of determining available release mass

• Consequence areas due to the effects of pool fires, jet fires, VCEs, BLEVEs, fireballs, flash fires and toxic releases are calculated

• Embedded Cloud Dispersion Analysis Modeler
  – Calculates component concentrations of vapor clouds as a function of time and distance away from the release point
  – Can analyze instantaneous (puffs) releases and continuous (plume) releases
  – Used to analyze the consequences of release of hazardous (flammable and toxic) releases to the atmosphere
Consequence of Failure

• Possible Event Outcomes
  – Jet Fires
  – Pool Fires
  – Flash Fires
  – Fireballs
  – Vapor Cloud Explosions
  – Non-Flammable Ruptures
    ▪ Physical Explosions (Energy Release)
    ▪ BLEVEs
  – Steam Leaks/Burns
  – Chemical Splashes (Amine/Caustic)
  – Toxic Releases
Figure 3: Event Tree for Rupture Case
Consequence of Failure

- Much more detail on consequence modeler provided in latest edition of API RP 581
- Unlike fixed equipment RBI, the consequence modeler is run at much higher overpressures
  - Overpressure increases release amount and rate
  - Probability of Ignition increases
  - Resultant equipment damage and personnel injury areas increase
- PRD RBI Methodology Accounts for PRD Criticality
  - Recognizes the fact that PRDs may have many different overpressure scenarios, some PRDs more critical than others
  - Enables the criticality of the PRD service to impact Risk, i.e. more critical services result in more risk
  - Links to protected equipment, PRDs protecting damaged equipment get more attention
Consequence of Failure

- Overpressure Demand Cases
  - Fire
    - Most Common
    - Low Demand Rate
    - Minimal Risk

\[
Q = 21,000 \times F \times A^{0.82}
\]

where:
- \(Q\) = heat input, Btu/h
- \(A\) = wetted area, ft\(^2\)
- \(F\) = environmental factor (1.0 for a bare surface)

\[
W = \frac{Q}{LH}
\]

where:
- \(W\) = relief load, lb/h
- \(LH\) = latent heat of vaporization, Btu/#
Consequence of Failure

- Overpressure Demand Cases
  - Blocked Outlet
    - Higher Demand rate related to operator error
  - Upstream Source Pressure
    - Deadhead for Centrifugal
    - Positive Displacement
    - Upstream Process Unit or Tower
- Number of Block Valves
- Administrative Procedures
- Heat Source Type and Temperature can raise overpressure significantly
Consequence of Failure

- Overpressure Demand Cases
  - Control Valve Failure Open
    - Higher demand rate tied to CV reliability
    - Upstream Source Pressure
      - HP/LP Interface
      - Upstream Process
      - Steam Pressure
    - Failure Position affects DR
  - Control Valve Failure Closed
    - Similar to Blocked Outlet
    - Failure Position affects DR
    - Number of CVs affects DR
Consequence of Failure

- Overpressure Demand Cases
  - Loss of Cooling, Loss of Reflux, Electrical Power Failure
    - Typically result in loss of flow
    - Heat source type important
      - Fired Heater
      - Steam Reboilers
    - Heat source temperature can significantly increase overpressure
The calculation of risk for a PRD failing to open upon demand is calculated for EACH applicable demand case using the demand rate, the probability of failure of the PRD and the calculated overall consequence of failure for the demand case as follows:

\[ \text{Risk}_{DC} = POF_{DC} \times COF_{DC} \]

The overall risk is then determined by adding up the individual risks associated with the applicable demand cases as follows:

\[ \text{Risk}_{f_{to}} = \sum_{i=1}^{n} POF_{DC_i} \times COF_{DC_i} \]

where \( i \) represents each of the \( n \) number of applicable overpressure demand cases.

- Accounts for the fact that PRDs may have many different overpressure scenarios, some PRDs more critical than others.
- Enables the criticality of the PRD service to impact Risk, i.e. more critical services result in more risk.
Inspection Planning Using Risk Target

- Consequence of failure is not time dependent
- Probability of failure increases with time
  \[ POF = POFOD \times DR \times (GFF \times DF)_{OP} \]
  - As equipment damage increases, equipment probability of loss of containment \((GFFT \times DF)\) increases
  - Number of Demands on PRD increases \((DR \text{ increases})\)
  - \(POFOD\) increases as PRD condition deteriorates
- Inspection interval for each PRD is determined based on a risk target
- A risk target of $15,000/yr has been successfully used at many sites
  - Balances reduction in risk with reduced inspection costs when compared to conditioned based inspection program (API 510)
  - Typically reduces risk by 60-70% while average inspection interval increase 20%
  - The risk target is ultimately a calibration tool to manage risk
PRD RBI Case Study

- RBI to manage PRD Inspection intervals has been successfully implemented at many sites throughout the US and Canada
- Case Study
  - Midwestern Refinery
  - Fixed equipment RBI implementation throughout the facility
  - Naphtha Hydrotreating Unit
    - 19 PRDs
    - Intervals set according to API 510, typically set at 5 years (60 months)
    - The majority of the risk related to PRDs was concentrated in 6 PRDs
    - Interval reduced on 7 PRDs, increased intervals on the remaining 12 PRDs
    - Average interval increased from 60 to 89 months
    - Risk reduction of 43%, with a overall decrease in inspection costs
- Results are summarized on the next 2 slides
<table>
<thead>
<tr>
<th>PRD Tag</th>
<th>Protected Equipment</th>
<th>Fluid Service</th>
<th>Current Inspection Interval (Years)</th>
<th>Current Risk ($/yr)</th>
<th>RBI Inspection Interval (Years)</th>
<th>RBI Calculated Risk ($/yr)</th>
<th>Total Risk Reduction ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV-001</td>
<td>Nitrogen Reducing Station</td>
<td>Nitrogen</td>
<td>5</td>
<td>13</td>
<td>10.0</td>
<td>37.0</td>
<td>-24</td>
</tr>
<tr>
<td>RV-092</td>
<td>Lube Oil Pump discharge</td>
<td>Lube Oil</td>
<td>5</td>
<td>756</td>
<td>10.0</td>
<td>2,239</td>
<td>-1,483</td>
</tr>
<tr>
<td>RV-093</td>
<td>Lube Oil Pump discharge</td>
<td>Lube Oil</td>
<td>5</td>
<td>756</td>
<td>10.0</td>
<td>2,239</td>
<td>-1,483</td>
</tr>
<tr>
<td>RV-100</td>
<td>Feed Surge Drum</td>
<td>Naphtha</td>
<td>5</td>
<td>22,268</td>
<td>4.0</td>
<td>14,999</td>
<td>7,269</td>
</tr>
<tr>
<td>RV-101</td>
<td>MP Steam Generator - Shell Side</td>
<td>Steam</td>
<td>5</td>
<td>1,670</td>
<td>10.0</td>
<td>2,444</td>
<td>-774</td>
</tr>
<tr>
<td>RV-102</td>
<td>Medium Pressure Steam Header</td>
<td>Steam</td>
<td>5</td>
<td>603</td>
<td>10.0</td>
<td>1,387</td>
<td>-784</td>
</tr>
<tr>
<td>RV-103</td>
<td>MP BFW Piping</td>
<td>BFW</td>
<td>5</td>
<td>547</td>
<td>10.0</td>
<td>1,300</td>
<td>-753</td>
</tr>
<tr>
<td>RV-104</td>
<td>High Pressure Separator</td>
<td>H₂, Naphtha, H₂S</td>
<td>5</td>
<td>45,454</td>
<td>2.1</td>
<td>15,005</td>
<td>30,450</td>
</tr>
<tr>
<td>RV-105</td>
<td>Stabilizer Column</td>
<td>C₄s-C₅s, H₂S</td>
<td>5</td>
<td>39,187</td>
<td>2.6</td>
<td>14,993</td>
<td>24,194</td>
</tr>
<tr>
<td>RV-106</td>
<td>Stabilizer Column</td>
<td>C₄s-C₅s, H₂S</td>
<td>5</td>
<td>60,400</td>
<td>2.0</td>
<td>15,658</td>
<td>44,743</td>
</tr>
<tr>
<td>RV-107</td>
<td>Stabilizer Accumulator</td>
<td>C₄s-C₅s, H₂S</td>
<td>5</td>
<td>9,542</td>
<td>4.6</td>
<td>15,000</td>
<td>-5,458</td>
</tr>
<tr>
<td>RV-108</td>
<td>Reboiler Condensate Pot</td>
<td>Steam</td>
<td>5</td>
<td>1,248</td>
<td>10.0</td>
<td>1,388</td>
<td>-140</td>
</tr>
<tr>
<td>RV-109</td>
<td>Condensate Flash Drum</td>
<td>Steam</td>
<td>5</td>
<td>1,401</td>
<td>10.0</td>
<td>4,246</td>
<td>-2,845</td>
</tr>
<tr>
<td>RV-110</td>
<td>Compressor Cylinder 1 Discharge Piping</td>
<td>Hydrogen, H₂S</td>
<td>5</td>
<td>20,133</td>
<td>4.2</td>
<td>15,000</td>
<td>5,133</td>
</tr>
<tr>
<td>RV-111</td>
<td>Compressor Cylinder 2 Discharge Piping</td>
<td>Hydrogen, H₂S</td>
<td>5</td>
<td>38,100</td>
<td>3.9</td>
<td>14,994</td>
<td>23,107</td>
</tr>
<tr>
<td>RV-112</td>
<td>Compressor Cylinder 3 Discharge Piping</td>
<td>Hydrogen</td>
<td>5</td>
<td>2,230</td>
<td>10.0</td>
<td>6,050</td>
<td>-3,820</td>
</tr>
<tr>
<td>RV-113</td>
<td>Makeup H₂ KO Pot</td>
<td>Hydrogen</td>
<td>5</td>
<td>1,223</td>
<td>10.0</td>
<td>1,893</td>
<td>-670</td>
</tr>
<tr>
<td>RV-114</td>
<td>Sour Water Piping from HP Separator</td>
<td>Sour Water</td>
<td>5</td>
<td>502</td>
<td>10.0</td>
<td>1,318</td>
<td>-816</td>
</tr>
<tr>
<td>RD-116</td>
<td>Condenser - cooling water rupture disc</td>
<td>Cooling Water</td>
<td>5</td>
<td>10,802</td>
<td>6.4</td>
<td>14,999</td>
<td>-4,197</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td></td>
<td></td>
<td><strong>5.0</strong></td>
<td><strong>256,835</strong></td>
<td><strong>AVG 7.4</strong></td>
<td><strong>145,185</strong></td>
<td><strong>111,650</strong></td>
</tr>
</tbody>
</table>
PRD RBI Case Study

![Bar Chart: Risk ($/yr)]

- **RBI Plan**
- **Current Plan**

Risk categories includes RV-106 to RV-001.
PRD RBI Case Study

- **Highest Risk PRD (RV-106)**
  - Accounts for 24% of the total risk for the unit with the current plan
  - Larger of two PRDs located on the Stabilizer Column
  - Protected components include
    - Column Reboiler
    - Overhead Condensers and Accumulator
    - Feed/Bottoms Exchangers
  - Applicable Overpressure Scenarios include
    - Inlet Control Valve Failure
    - Power Failure
    - Loss of Cooling
    - Blocked Discharge
    - External Fire
PRD RBI Case Study

• Highest Risk PRD (Cont.)
  – Main risk drivers for this PRD include
    • Source pressure 5 times the vessel design pressure
    • High H2S concentration in the column overhead
    • The overhead accumulator has a high damage factor related to Wet H2S cracking
  – RBI-Recommended Inspection interval is 2 years yielding a 75% reduction in risk
  – Mitigation strategies beyond reducing inspections intervals could include
    • 100% spare capacity
    • Adding additional Layers of Protection
    • Reducing the equipment damage factor through equipment inspections
Conclusions

- API RBI methodology for Pressure Relief Devices provides a rigorous quantification risk for process unit relief systems
- Probability of Failure of a PRD accounts for previous inspection history, demand rates, and installation details
- The addition of consequences, based on safety and financial impacts, provides a broad overall view of PRDs
- Directly linking fixed equipment and PRD RBI reduces input requirements and helps to establish criticality
- The methodology has been successfully implemented at refineries and petrochemical facilities throughout North American
- Typical implementation results in risk reduction and inspection interval optimization