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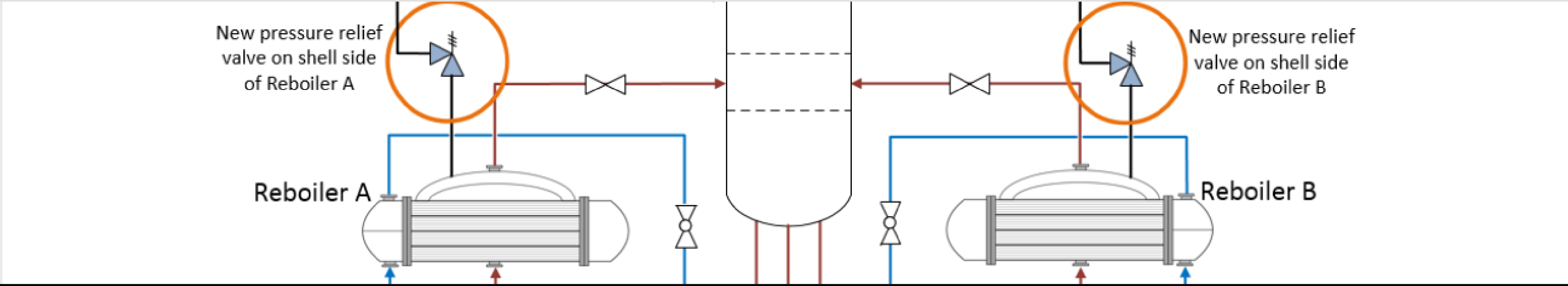
Failure Under Pressure:

Proper Use of Pressure Relief Device Failure Rate Data Based on Device Type and Service



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About the Presenter: Todd Drennen

- Senior Engineer for Baker Engineering and Risk Consultants, Inc. (BakerRisk®)
- B.S. in Chemical Engineering from Drexel University
- Over 16 years of experience doing process safety work, including…
  - Pressure relief system design and analysis
  - Process simulation of complex process upset scenarios
  - Process Hazard Analysis (PHA)
  - Layers of Protection Analysis (LOPA)
  - Fault Tree Analysis (FTA)
  - Safety Integrity Level (SIL) Determination
  - Process Safety Management (PSM) compliance auditing
- Licensed Professional Engineer (Pennsylvania, Illinois, Delaware)

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Introduction, Data Constraints, and Assumptions

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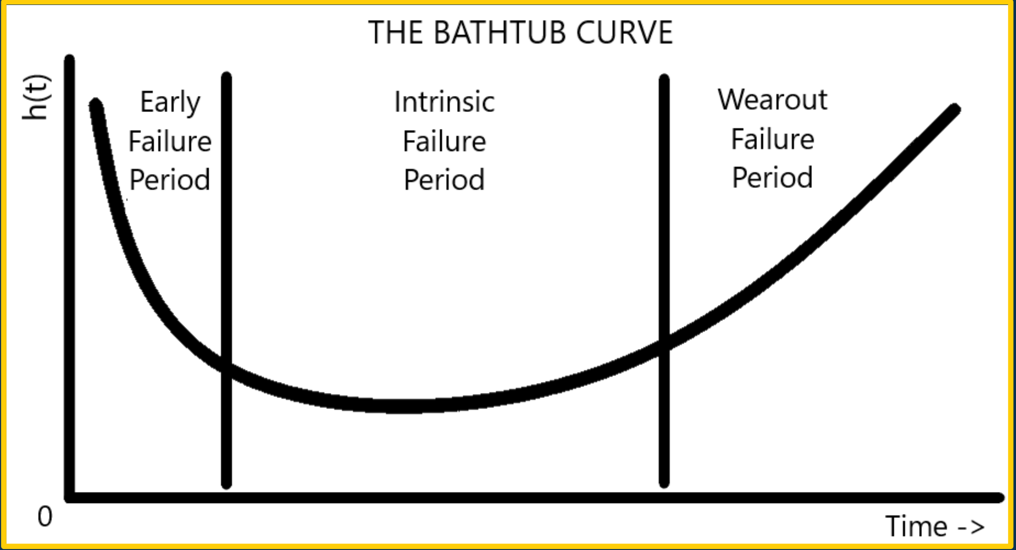
PFD Values for Pressure Relief Devices per CCPS Guidelines

IPL Classification and Description	PFD*
Spring-operated pressure relief valve	1.00E-02
Dual spring-operated pressure relief valves, no isolating valves present	1.00E-03
Dual spring-operated pressure relief valves; single manual valve can isolate one PRV	1.00E-02
Dual spring-operated pressure relief valves; single manual valve can isolate both PRVs simultaneously	1.00E-01
Pilot-operated pressure relief valve	1.00E-02
Buckling pin relief valve	1.00E-02
Rupture Disk	1.00E-02
Spring-operated pressure relief valve with rupture disk (on inlet, assumes non-fragmenting type disk and monitoring for disk burst between disk and PRV)	1.00E-02
Conservation vacuum and/or pressure relief vent	1.00E-02
Conservation vacuum and/or pressure relief vent	1.00E-02
Vacuum breaker	1.00E-02

**Assumes properly sized device and piping for specific scenario, clean service, and correct metallurgy*

Example Component Bathtub Curve

1. “Early Failure” or “Infant Mortality” period in which failure occurs due to manufacturing defects and/or improper installation
2. “Intrinsic Failure Period” characterizes the inherent component failure rate during its useful life
3. “Wear Out” or “Breakdown” failure period in which the curve slopes upward as the component service time extends beyond the useful life



Primary Types of Pressure Relief Device Mechanical Failures

- **Failure to open as designed**
- **Delayed operation**
- **Spurious opening**
- **Leakage**

Failure to open as designed and delayed operation would be considered ‘dangerous failure’ (or ‘failure to operate on demand’), while spurious opening and leakage would not.

Analysis Data Constraints

- Data was only considered for pressure relief valves
    - Significantly more data was available for PRVs than for other types of pressure relief devices, such as rupture disks and low pressure tank vents.
- Failure rate data was only considered if it was documented on a per unit time basis (i.e., per year or per hour), as opposed to a per demand basis, because:
    - Pressure relief valve demand rates might be expected to vary significantly by…
        - Industry
        - Site
        - Service type
    - Relief valve failure mechanisms are more likely to be time-dependent than demand-dependent.

Analysis Assumptions

- All sources of data use the same criteria for defining their failure modes
- The only failure types considered to be failure on demand were…
  - Failure to open as designed (a.k.a., valve stuck closed, valve seizes closed, etc.)
  - Delayed operation (a.k.a., failure to open fully at relief pressure, 10% heavy, etc.).

Analysis Assumptions (Cont'd)

- For data that was categorized both by calendar time and service time, the data sets based on service time were used.
- For data sets for which no test interval was specified, the assumed test intervals were as follows:
  - 12 months for valves located at offshore facilities, based on the requirements established by the U.S. Bureau of Safety and Environmental Enforcement (30CFR 250.880) for pressure relief valves on U.S. offshore facilities
  - 5 years for valves located at onshore facilities, as this was the maximum reported test interval for all data that listed test intervals

Calculating PFDavg

$$\text{PFDavg} \approx \tfrac{1}{2}\,\lambda_{DU}\,T_1$$

Where:

λ_{DU} = Rate of dangerous undetected failure
T_1 = Test interval

Note that in some tables that follow in this presentation, this equation is simplified to "$\lambda t/2$" for readability.

Also note that in the case of a pressure relief valve in continuous service, all dangerous failures (i.e., failures to operate on demand) are assumed to be undetected.

Data Sets Included in the Analysis

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Exida PRV Failure Rate Data

Failure to Open*				
Maximum Rate	1.00E-07	per hour	8.76E-04	per year
Minimum Rate	1.00E-08	per hour	8.76E-05	per year

**All rates assume a "useful life" between proof tests of 4 to 5 years.*

Lees PRV “Fail Dangerous” Probability Data

"Fail Dangerous" Probabilities*	
Maximum probability of dangerous failure	1.00E-07
Minimum probability of dangerous failure	1.00E-08

**All probabilities assume annual testing.*

OREDA 2002 PRV Failure Rate Data

Aggregate Failure Rates	
Aggregate Lower Failure Rate Per Year	2.67E-03
Aggregate Mean Failure Rate Per Year	3.12E-02
Aggregate Upper Failure Rate Per Year	9.28E-02

Failure Rates by Device Type	
Mean Conventional Failure Rate Per Year	2.41E-02
Mean Bellows Failure Rate Per Year	9.77E-02
Mean Pilot Operated Failure Rate Per Year	9.90E-03

OREDA 2009 PRV Failure Rate Data

Aggregate Failure Rates	
Aggregate Lower Failure Rate Per Year	3.81E-04
Aggregate Mean Failure Rate Per Year	3.33E-02
Aggregate Upper Failure Rate Per Year	1.00E-01

Failure Rates by Device Type	
Mean Conventional Failure Rate Per Year	1.45E-02
Mean Pilot Operated Failure Rate Per Year	2.37E-02

OREDA 2015 PRV Failure Rate Data

Aggregate Failure Rates	
Aggregate Lower Failure Rate Per Year	1.22E-04
Aggregate Mean Failure Rate Per Year	2.97E-02
Aggregate Upper Failure Rate Per Year	1.29E-01

Failure Rates by Device Type	
Mean Pilot Operated Failure Rate Per Year	1.12E-02

Parry PRV Failure Rate Data

Aggregate Dangerous Failure Rates Per Year	
All Devices	8.54E-02
Devices in Nitrogen Service	1.60E-02
Devices in Lube/Hydraulic Oil Service	1.42E-01
Devices in Natural Gas Service	4.90E-02
Devices in Ammonia Service	1.10E-01
Devices in Carbon Dioxide Service	1.25E-01

SINTEF PRV “Failure to Open” Rate Data

“Failure to Open” Rate				
Reported Rate	1.00E-06	per hour	8.76E-03	per year

UKAEA PRV Failure Rate Data By Valve Type

Valve Type	# Valves	# Tests	Valve-Years	Effective Test Interval (yrs.)	# Seize Closed	# 10% Heavy	# Dangerous Failures	Failure Rate Per Year	Failure Rate Per Hour
Conventional	3906	7459	12651	1.70	130	340	470	3.72E-02	4.24E-06
Bellows	522	1587	2659	1.68	3	35	38	1.43E-02	1.63E-06
Pilot	77	135	188	1.39	2	0	2	1.07E-02	1.22E-06
All	4505	9181	15498	1.69	135	375	510	3.29E-02	3.76E-06

UKAEA PRV Failure Rate Data By Service

Valve Service	# Valves	# Tests	Valve-Years	Effective Test Interval (yrs.)	# Seize Closed	# 10% Heavy	# Dangerous Failures	Failure Rate Per Year	Failure Rate Per Hour
Air	52	102	166.6	1.63	3	3	6	3.60E-02	4.11E-06
Ammonia	47	93	142.2	1.53	0	2	2	1.41E-02	1.61E-06
Crude Oil	30	59	103.0	1.75	0	6	6	5.82E-02	6.65E-06
Fuel Gas	55	153	239.8	1.57	9	12	21	8.76E-02	1.00E-05
Fuel Oil	52	95	153.8	1.62	1	5	6	3.90E-02	4.45E-06
Hydrogen	40	110	191.5	1.74	0	2	2	1.04E-02	1.19E-06
Light HC	47	106	185.8	1.75	0	1	1	5.38E-03	6.14E-07

UKAEA PRV Failure Rate Data By Service (Cont'd)

Valve Service	# Valves	# Tests	Valve-Years	Effective Test Interval (yrs.)	# Seize Closed	# 10% Heavy	# Dangerous Failures	Failure Rate Per Year	Failure Rate Per Hour
Lube Oil	68	171	314.4	1.84	1	8	9	2.86E-02	3.27E-06
Nitrogen	30	65	119.5	1.84	0	2	2	1.67E-02	1.91E-06
Organic	81	236	381.0	1.61	7	22	29	7.61E-02	8.69E-06
Steam	150	352	610.0	1.73	2	12	14	2.29E-02	2.62E-06
Thermex	23	54	84.2	1.56	1	1	2	2.38E-02	2.71E-06

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Results, Conclusions, and Recommendations

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PRV PFD Data Categorized by Service

Source	PFD	Basis
Parry (Ammonia)	1.65E-01	3-year inspection interval (λt/2)
Parry (Lube/Hydraulic Oil)	2.13E-01	
Parry (Natural Gas/Fuel Gas)	7.29E-02	
Parry (Nitrogen)	2.37E-01	
Parry (Steam)	0.00E+00	
UKAEA (Ammonia)	1.08E-02	Calculated effective test interval = 1.53 years (λt/2)
UKAEA (Lube/Hydraulic Oil)	2.63E-02	Calculated effective test interval = 1.84 years (λt/2)
UKAEA (Natural Gas/Fuel Gas)	6.86E-02	Calculated effective test interval = 1.57 years (λt/2)
UKAEA (Nitrogen)	1.54E-02	Calculated effective test interval = 1.84 years (λt/2)
UKAEA (Steam)	1.99E-02	Calculated effective test interval = 1.73 years (λt/2)
Geometric Mean (All Above Data)*	**5.35E-02**	–

**Probabilities of zero removed from geometric mean calculations.*

PRV PFD Data Categorized by Service (Cont'd)

Source	PFD	Basis
Geometric Mean (Ammonia)	4.22E-02	Note the limited data set.
Geometric Mean (Lube/Hydraulic Oil)	7.48E-02	
Geometric Mean (Natural Gas/Fuel Gas)	7.07E-02	
Geometric Mean (Nitrogen)	6.04E-02	
Geometric Mean (Steam)*	1.99E-02	

**Probabilities of zero removed from geometric mean calculations.*

PRV PFD Data Categorized by Valve Type

Source	PFD	Basis
OREDA 2002 Mean (Conventional)	1.21E-02	Assume annual testing per 30CFR 250.880 (λt/2)
OREDA 2002 Mean (Bellows)	4.88E-02	
OREDA 2002 Mean (Pilot)	4.95E-02	
OREDA 2009 Mean (Conventional)	7.27E-03	
OREDA 2009 Mean (Pilot)	1.18E-02	
OREDA 2015 Mean (Pilot)	5.61E-03	
UKAEA (Conventional)	3.16E-02	Calculated effective test interval = 1.70 years (λt/2)
UKAEA (Bellows)	1.20E-02	Calculated effective test interval = 1.68 years (λt/2)
UKAEA (Pilot)	7.40E-03	Calculated effective test interval = 1.39 years (λt/2)
Geometric Mean (All Above Data)	**1.16E-02**	**–**
Geometric Mean (Conventional)	**1.40E-02**	**Note the limited data set (Offshore and Nuclear Industries Only)**
Geometric Mean (Bellows)	**2.42E-02**	
Geometric Mean (Pilot)	**7.02E-03**	

Overall PRV PFD Data Summary

Source	λ_{DU} (Per Yr.)	PFD	Basis
Exida Min.	8.76E-05	1.75E-04	Min. Test Interval = 4 years (λt/2)
Exida Max.	8.76E-04	2.19E-03	Max. Test Interval = 5 years (λt/2)
Lees Min	8.00E-03	4.00E-03	Defined by Lees as yearly inspection (λt/2)
Lees Max.	2.00E-02	1.00E-02	
OREDA 2002 Lower	2.67E-03	1.34E-03	Assume annual testing per 30CFR 250.880 (λt/2)
OREDA 2002 Mean	3.12E-02	1.56E-02	
OREDA 2002 Upper	9.28E-02	4.64E-02	
OREDA 2009 Lower	3.81E-04	1.91E-04	
OREDA 2009 Mean	3.33E-02	1.66E-02	
OREDA 2009 Upper	1.00E-01	5.00E-02	
OREDA 2015 Lower	1.22E-04	6.08E-05	
OREDA 2015 Mean	2.97E-02	1.48E-02	
OREDA 2015 Upper	1.29E-01	7.40E-03	

Overall PRV PFD Data Summary (Cont'd)

Source	λ_{DU} (Per Yr.)	PFD	Basis
Parry	8.54E-02	1.28E-01	3-year inspection interval (λt/2)
SINTEF	8.76E-03	1.75E-02	4-year inspection interval (λt/2)
UKAEA (Conventional)	3.72E-02	3.16E-02	Calculated effective test interval = 1.70 years (λt/2)
UKAEA (Bellows)	1.43E-02	1.20E-02	Calculated effective test interval = 1.68 years (λt/2)
UKAEA (Pilot)	1.07E-02	7.40E-03	Calculated effective test interval = 1.39 years (λt/2)
Geometric Mean (All)	**9.23E-03**	**6.76E-03**	–

Conclusions

- On the macro level, the data analyzed serves to validate the PFD values for spring operated and pilot operated pressure relief valves presented in the CCPS IPL guidelines.
- No definitive conclusion can be drawn from the PFD data categorized by valve type due to the limited amount of available source data.
- Statistical analysis indicated that relief valve failure rates are likely related to service, but the available data are not broad enough to draw specific conclusions that could be used for predictive purposes.
- In the cases of valve size and set pressure, the amount of available source data was even smaller.

Recommendations

- It is recommended that more failure data be collected for pressure relief valves and that these data be better categorized by valve type, service, size, and set pressure.
- This was a primary goal of the CCPS Process Equipment Reliability Database (PERD) effort, which has generated some relief valve data, but little of this data has been published.
- With more robust and detailed data, further analysis could be conducted to determine whether a statistically significant correlation exists between any of these valve parameters and valve PFDs.

For More Information

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