Assessing Probability of Failure for Pressure Equipment: Part 1

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Overview

- Introduction
- Statistics Background
- Pressure Equipment Risk Calculation Process
- Damage Models and Damage Rates
- Probability Of Failure Calculation
- Pressure Equipment Reliability Model
- Examples
- Summary

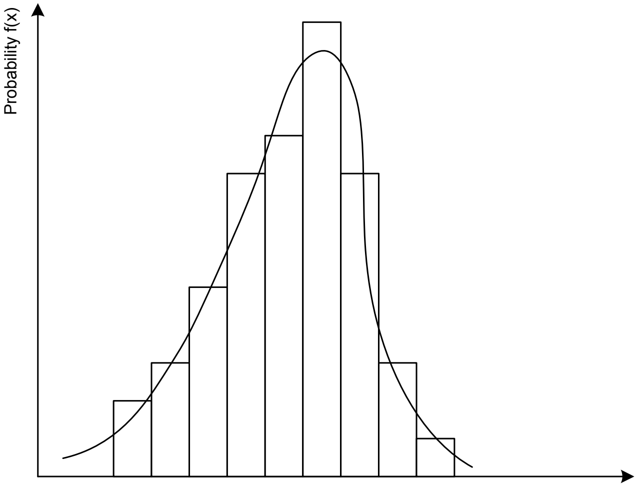
Introduction

- Importance and value of RBI concepts in the safe operation of pressure equipment
- Fundamental physical and mathematical principles are valid irrespective of how the Probability Of Failure (POF) is calculated
- Most RBI methodologies are generally used for screening purposes
- The general risk process as well as the API RBI Probability Of Failure calculation will also be reviewed along with several applications

Statistics Background

- What are the location, shape and scale parameters ?
- How to test for goodness of fit?
- How are the distributions ranked for fit?
- Is the sample representative of the population?

$\Rightarrow$ 4 questions require answers for valid analysis.



Statistics Background

- The calculation of POF can be generally divided into 3 classes:

(1) Non-statistical- Same weight on data points

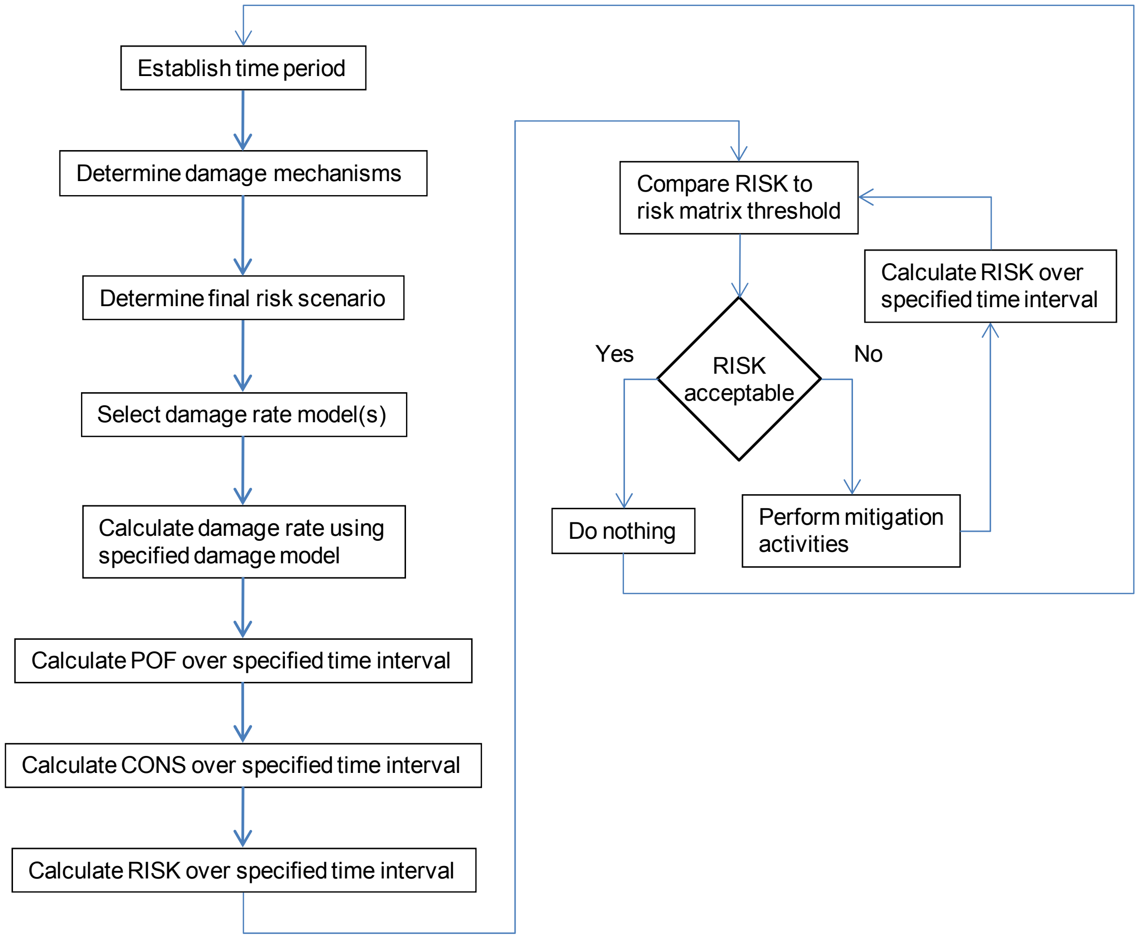
(2) Statistical – can censor data

(3) Hybrid:

- Combination of statistical and non statistical
- Expert judgement

Risk Calculation Process

- General steps in the process:



Risk Calculation Process

Time Period Under Consideration

A time period that is too long (e.g. 15 years) may overestimate POF (e.g. no clear calculation of when to perform mitigating activities. A short time period (e.g. 1 day) will tend to produce a low POF.

The time period under consideration is important for several reasons:

(i) The POF is influenced by time.

(ii) The consequence is influenced by time (but usually less so than the POF time dependence).

(iii) The stream composition may change as a function of time

Risk Calculation Process

Damage Mechanisms

- Stream components and conditions are such that a reaction or susceptibility can exist $\Rightarrow$ damage mechanism exists

- Assumptions made regarding valve position, isolation, operating pressure, temperature and velocity parameters

- Stream Composition
  Components may either be sampled frequently and difficult to test or sampled infrequently and easy to test.

Risk Calculation Process

Determining The Final Risk Scenario (FRS)

Used to determine the probability of the consequence occurring. For example, consider the following:

1. Localized internal corrosion that may require repair."
2. "A corrosion pinhole resulting in a leak to atm."
3. "A corrosion pinhole resulting in leak to atmosphere with exposure and business loss."

FRS	POF	COF	Risk
1	$P_1 \leq PMO$	COF_1	$P_1 * COF_1$
2	$P_2 < PMO$	COF_2	$P_2 * COF_2$
3	$P_3 < P_2$	COF_3	$P_3 * COF_3$

PMO = Probability Of Mechanism Occurring

COF = Consequence Of Failure

P_i = Probability Of failure

Risk Calculation Process

Determining The Final Risk Scenario

The PMO can be used for all three FRS. This conservative approach can lead to the following:

(a) Decreased confidence in pressure equipment integrity program within the organization.

(b) Decrease in funds for inspecting equipment that may really need to be inspected and repaired (e.g. unacceptable risk not being addressed).

(c) Increased effort to conduct multiple equipment reviews, with same data, and arriving at usually different answers.

Risk Calculation Process

Determining The Final Risk Scenario

- An important point to note is that Fitness-For-Service (FFS) can be applied to FRS-1. A FFS analysis could be run to determine limiting flaw sizes prior to inspection (internal or external).

Risk Calculation Process

Damage Models & Distribution of Damage Rates

- Damage mechanisms for different industries are published in API 571, WRC 488, 489 and 490.
- Deliverable from damage models is usually the lowest wall thickness in the system of interest.
- A set of damage rates over the time interval can be generated.
- Determine what statistical distribution fits the data.
- Calculate the probability of a damage rate occurring that would result in a specified thickness (e.g. t_{min}) being present in the system.

Risk Calculation Process

Damage Models & Distribution of Damage Rates

- Conversely, for a given data set of wall thicknesses over the time interval of interest, the user can determine what statistical distribution (if any) will fit the data.

- Using the distribution parameters, the user can calculate the probability of a thickness occurring that would less than a specified thickness (e.g. t_{min}) being present in the system.

Risk Calculation Process

Damage Models & Distribution of Damage Rates

- The data set may come from one or more populations that have different distributions.
- Re-sample from data set based on population characteristics.
- Characteristics such as no flow region, bottom/top of pipe, extrados/intrados of elbow, etc., are all valid ways of producing another sample data set that can be tested against known distributions.
- It is not uncommon to calculate that the data does not come from any known distributions.

Risk Calculation Process

Damage Models & Distribution of Damage Rates

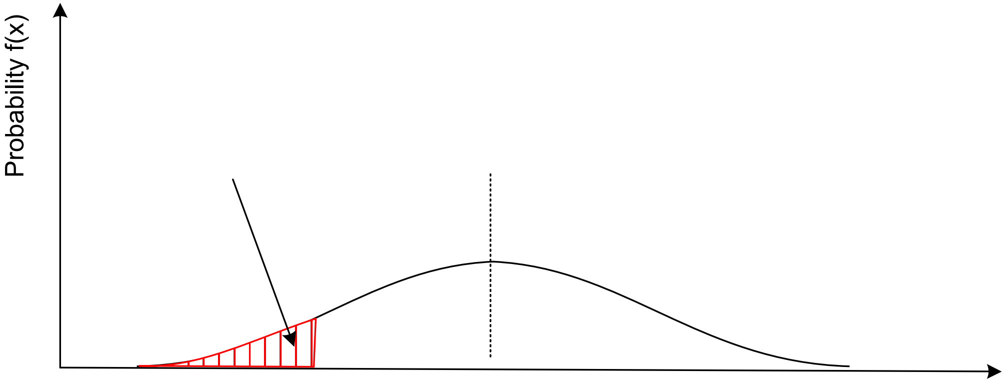
- Distribution can change type over time.
- Re-sample from data set based on population characteristics as well as time (more complicated).
- Changes in damage drivers/operation can aid in re-sampling.

Risk Calculation Process

Calculation of Cumulative Probability Of Failure

- Integrate continuous random variable to get POF:

$$F(x) = \int_{-\infty}^{t} f(t)dt$$



- For a maximum/threshold POF of P_{cr} require:

$$F(x) \leq P_{cr}$$

Risk Calculation Process

Calculation of Cumulative Probability Of Failure

- Maximum Likelihood Estimate (MLE), linear unbiased estimators, method of moments, etc., procedures used to calculate parameters
- The MLE method has the following significant characteristics:

  (a) Can theoretically be used for any continuous distribution and censored data.

  (b) Approximate confidence bounds can be calculated.

  (c) Less suitable for less than 5 (approximately) data points.

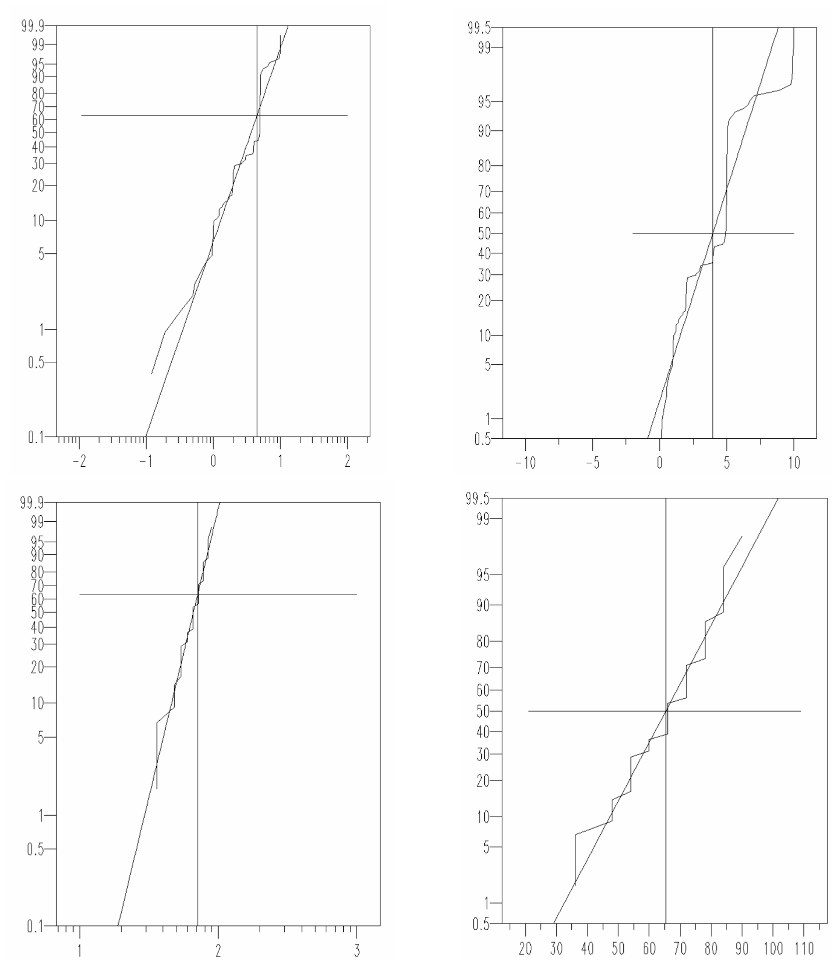
Risk Calculation Process

Calculation of Cumulative Probability Of Failure

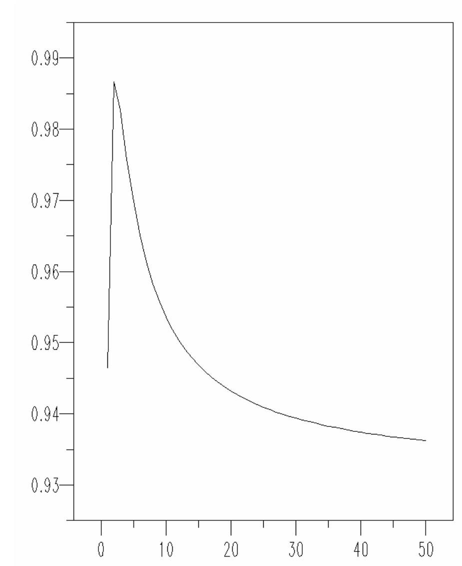
- Parameters must be tested using a test statistic such as Anderson-Darling, Kolmogorov-Smirnov (KS), etc.
- Alternatively, a correlation coefficient (CC) can be used.
- Graphically viewing the probability plots is also used to validate the correlation coefficient and to see if there may be different failure modes present in the data.

Risk Calculation Process

Calculation of Cumulative Probability Of Failure



Correlation Coefficient and Scale Parameter plot



Risk Calculation Process

Limit State Function

- Creates regions of acceptable and unacceptable results

$$G(t) = \text{Resistance}(t) - \text{Load}(t)$$

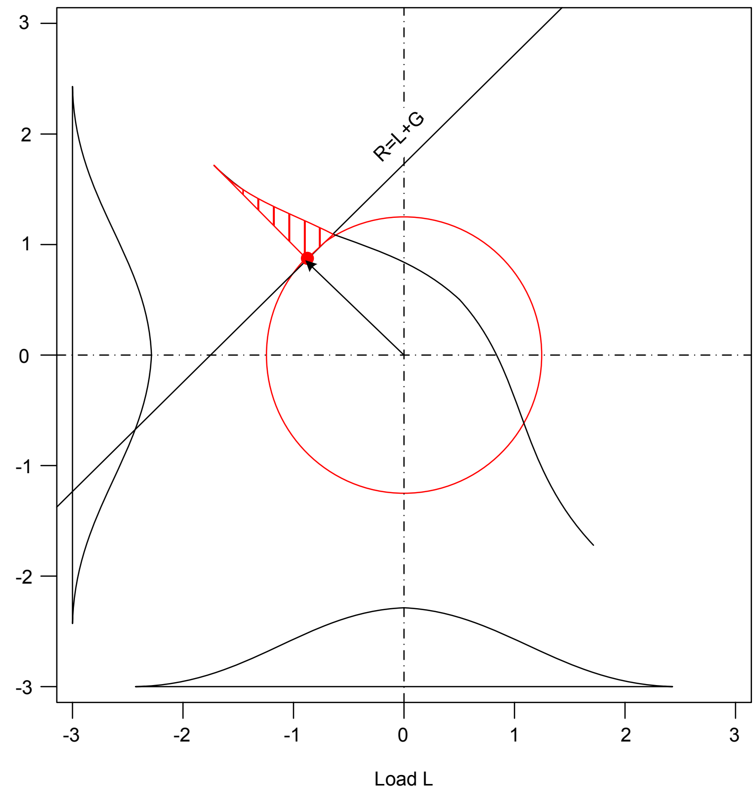
- There are 3 cases to consider:

$G(t) < 0$	Unacceptable (loaded beyond capacity)
$G(t) = 0$	Acceptable
$G(t) > 0$	Acceptable

Risk Calculation Process

Limit State Function

- Use a First Order Reliability Method (FORM) to calculate the POF.
- Most significant error in using a FORM comes from using a linear approximation of G(t).



Risk Calculation Process

Limit State Function

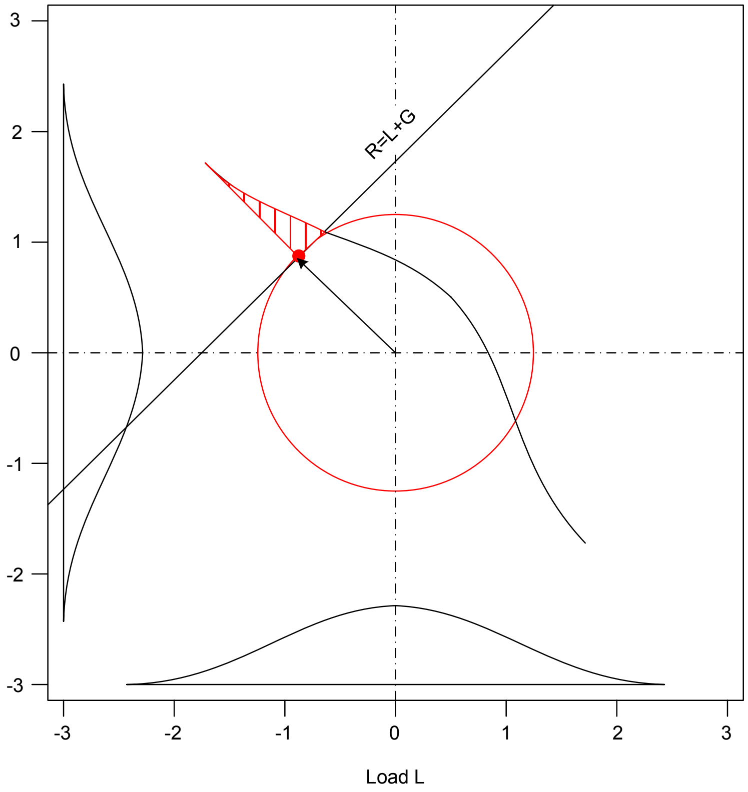
- β is the variable of interest in calculating the POF.

$$\sigma_i = \mu_i * COV_i$$

$$S_G = \sqrt{\sum_{i=1}^{V}\left(S_{v_i}\frac{dG}{dv_i}\right)^2}$$

$$\beta = \frac{G}{S_G}$$

$$POF = \mathrm{NORM}(-\beta)$$



Risk Calculation Process

Limit State Function

- The preceding discussion is the core of the API RBI POF methodology.
- The POF calculation shown here is the seed for the POF to be used in a thinning risk calculation.
- There are other considerations such as a comparison to a Generic Failure Frequency (GFF) for equipment type, etc. These considerations can be modeled numerically and applied to give a final POF result.
- The same techniques can be applied to other vessel failures modes such as cracking.

Pressure Vessel Example

Vessel Data

Vessel:	Atmospheric Overhead Accumulator		
Material:	SA 285 GR C	Corrosion Allowance:	3/16”
Design Pressure:	50 psig	Prior Inspection Data:	None
Diameter:	6’-6”	COV (pressure):	20%
Age:	6 years	COV (CR):	30%
Thickness:	3/8”	COV (σ_{UTS}):	10%

Pressure Vessel Example

Analysis Equations

$$R\left(R_0, t, d_G, n, \sigma_{UTS}\right) = \left[\frac{0.25}{n+0.277}\right]\left[\frac{e}{n}\right]^n \cdot \ln\left[\frac{R_0}{R_0 - t + d_G}\right] \cdot \sigma_{UTS} \cdot RSF$$

$$L\left(P_{applied}\right) = P_{applied}$$

$$d_G = time * CR$$

$$G = \left(\frac{0.25}{n+0.277}\right)\left[\frac{e}{n}\right]^n \cdot \ln\left(\frac{R_o}{R_o - t_{init} + CR * time}\right) \cdot \sigma_{UTS} \cdot RSF - P_{applied}$$

$$\frac{dG}{dCR} = -\left(\frac{0.25}{n+0.277}\right)\left[\frac{e}{n}\right]^n \cdot \sigma_{UTS} \cdot RSF \cdot \left(\frac{time}{R_o - \left(t_{init} - CR * time\right)}\right)$$

$$\frac{dG}{d\sigma_{UTS}} = \left(\frac{0.25}{n+0.277}\right)\left[\frac{e}{n}\right]^n \cdot \ln\left(\frac{R_o}{R_o - \left(t_{init} - CR * time\right)}\right) \cdot RSF$$

$$\frac{dG}{dP_{applied}} = -1$$

Pressure Vessel Example

Analysis Equations

$$S_G = \sqrt{\left(S_{P_{applied}} \frac{dG}{dP_{applied}}\right)^2 + \left(S_{CR} \frac{dG}{dCR}\right)^2 + \left(S_{\sigma_{UTS}} \frac{dG}{d\sigma_{UTS}}\right)^2}$$

$$POF = \text{NORM}(-\beta) = \text{NORM}\left(\frac{G}{S_G}\right)$$

Results

Vessel:	Atmospheric Overhead Accumulator		
Material:	SA 285 GR C	Corrosion Allowance:	3/16”
Design Pressure:	50 psig	Prior Inspection Data:	None
Diameter:	6’-6”	COV (pressure):	20%
Age:	6 years	COV (CR):	30%
Thickness:	3/8”	COV (σ_{UTS}):	10%

Damage State	Corrosion Rate	POF
Corrosion Rate 1:	0.030”/year	1.85388E-07
Corrosion Rate 2:	0.035”/year	1.05330E-05
Corrosion Rate 3:	0.040”/year	2.16402E-04

Pressure Relief Valve Example

PRV Data

- Failure Mode: Failure to Open on Demand (FOD)

Service	Interval (Years)	FOD	
		Pass	Fail
Intermediate Hydrocarbon	36	2	1
Intermediate Hydrocarbon	48	2	1
Intermediate Hydrocarbon	54	4	2
Intermediate Hydrocarbon	60	2	1
Intermediate Hydrocarbon	66	3	3
Intermediate Hydrocarbon	72	3	4
Intermediate Hydrocarbon	78	1	5
Intermediate Hydrocarbon	84	0	4
Intermediate Hydrocarbon	90	-	1

Pressure Relief Valve Example

Analysis Equations

- Use Maximum Likelihood Estimate of parameters

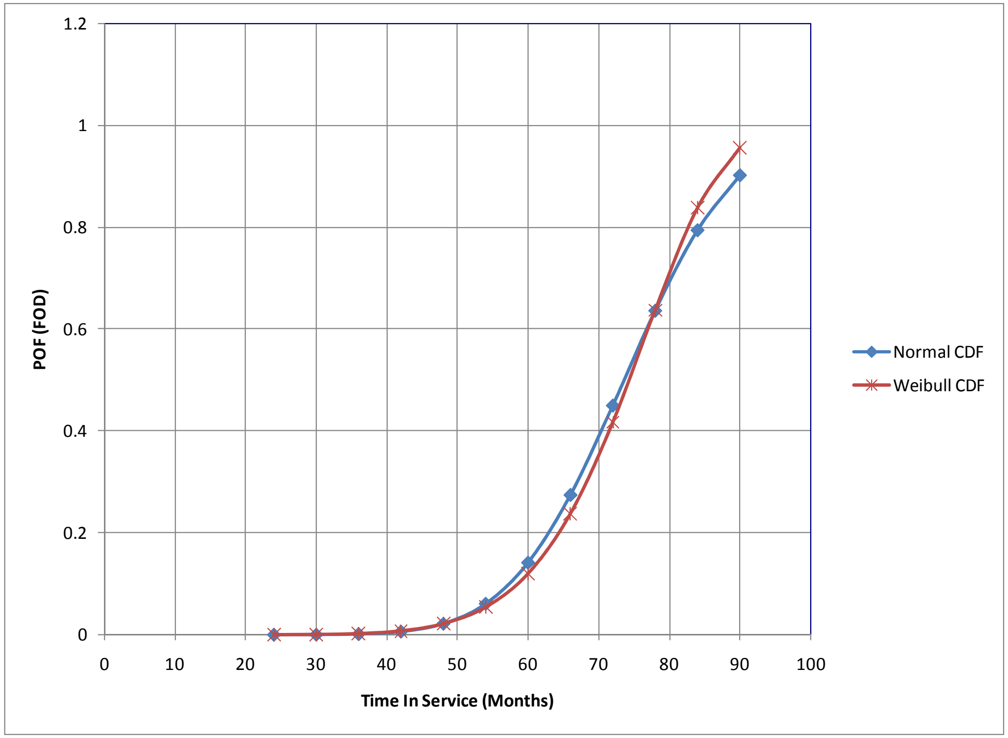
Distribution	Parameters	Type	Random Variable Domain	Probability Density Function	Variable	Maximum Likelihood Estimates For Parameters
Normal	μ = location σ= shape		$-\infty < x < +\infty$	$f(x) = \dfrac{\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]}{\sigma\sqrt{2\pi}}$		$\hat{\mu} = \bar{x} = \frac{1}{N}\sum_{j=1}^{N} x_j$ $\hat{\sigma}^2 = S_x^2 = \frac{1}{N}\sum_{j=1}^{N}\left(x_j - \bar{x}\right)^2$
		Standard	$-\infty < x < +\infty$	$f(x) = \dfrac{\exp\left[-\frac{1}{2}(Z)^2\right]}{\sigma\sqrt{2\pi}}$	$Z = \dfrac{x-\mu}{\sigma}$	
Weibull (2P)	$\mu = 0$ σ= shape α = scale			$f(x) = \frac{\sigma}{\alpha}\left(\frac{x}{\alpha}\right)^{(\sigma-1)} \exp\left[-\left(\frac{x}{\alpha}\right)^{\sigma}\right]$		$\hat{\alpha} = \left(\frac{1}{N}\sum_{j=1}^{N} x_j^{\hat{\sigma}}\right)^{\frac{1}{\hat{\sigma}}}$ $\hat{\sigma} = \left[\sum_{j=1}^{N}\left\{x_j^{\hat{\sigma}}\log\left(x_j\right)\right\}\left\{x_j^{\hat{\sigma}}\right\}^{-1} - \frac{1}{N}\sum_{j=1}^{N} x_j\right]^{-1}$
		Standard		$f(x) = \frac{\sigma}{\alpha}(Z)^{(\sigma-1)} \exp\left[-(Z)^{\sigma}\right]$	$Z = \dfrac{x}{\alpha}$	

Pressure Relief Valve Example

Results

- Normal and Weibull distributions are in good agreement.
- Maximum difference between POF is approximately 15% at 66 months.

	FOD Case	
	NORM	WEIB
Location Parameter	73.58	0
Scale Parameter	12.66	77.85
Shape Parameter	-	7.89
GOF Test	KS	KS
Rank	2	1



Pressure Relief Valve Example

Results

- The PRV POF calculation is the seed for the POF to be used in an API RBI risk calculation for a PRV.
- There are other considerations such as a comparison to a GFF for PRV's, PRV discharge location, chattering. These considerations can be modeled numerically and applied to give a final POF result.
- Same techniques can be applied to other PRV failures modes such as leaking, fail partially open, etc.

Summary

- The API RBI POF general POF calculation method has been demonstrated for thinning damage mechanisms and a PRV.
- The methodology is in the public domain and is defensible from a technical perspective.
- The API RBI methodology can be of significant benefit in obtaining more information from inspection data.
- The methodology generates reproducible and defensible inputs to a risk analysis for pressure equipment.

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