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USING IE AND IPL FAILURE RATES TO ESTABLISH MAXIMUM OUT OF SERVICE TIME, AND DEFERRAL TIME LIMITS FOR CRITICAL PROCESS SAFETY FEATURE

William Bridges
Process Improvement Institute, Inc.
Tennessee, USA
wbridges@piii.com

Matias Massello
Process Improvement Institute, Inc.
La Plata, Argentina
mmassello@piii.com

PROCESS IMPROVEMENT INSTITUTE
Risk and reliability specialists

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Main author

William Bridges – President
Process Improvement Institute, Inc. (PII)
e-mail: wbridges@piii.com

Contributing author

Matias Massello – Senior Process Safety Engineer
Process Improvement Institute, Inc. (PII)
e-mail: mmassello@piii.com

Abstract

Since the publication of the textbook on LOPA in 2001 [1] and its subsequent wide acceptance, and the publication of *Guidelines for Initiating Events and Independent Protection Layers* in 2015 [2], a great many companies have begun to maintain the components related to Initiating Events (IEs) and Independent Protection Layers (IPLs) more rigorously. The inspection frequencies have been set from either plant experience or from the industry advice given in the 2015 textbook or other reliability handbooks. The premise is that following this inspection, test, or preventive maintenance (ITPM) approaches the time / interval stated in these sources (or site data) should reasonably ensure the average Initiating Event Frequency (IEF) or Probability of Failure on Demand (PFD) are sustained. But what if an IE or IPL must be out of service for repair, testing, or inspection? Or what if there is a valid need to defer the scheduled ITPM listed for that LOPA factors? Is there industry data or a proven approach to manage the duration and the control the risk during these bypasses or deferrals?

This paper presents a standardized approach for determining the maximum time allowable for bypasses and deferrals, based on when the initiating frequency or the probability of failure on demand changes enough to make a statistically significant change to the stated IEF or PFD of the IE or IPL respectively. Bypasses and deferrals should, of course, be strongly discouraged as a matter of operational discipline and to foster good process safety culture, but the approach in this paper serves to reduce the uncertainty in the risk judgements regarding the maximum time allowable for a bypass or deferral before a statistically significant change in the risk of the scenario occurs. This can in turn reduce the number or time spent on related risk assessments (miniature PHAs) for an associated Management of Change (MOC).

Background: Accidents with MI Issues

On April 2, 2010, the Tesoro Anacortes (WA) refinery experienced a catastrophic rupture of a heat exchanger, fatally injuring seven Tesoro employees working in the immediate vicinity. The Draft Investigation Report (CSB, January 2014) [3] listed many asset integrity failures, especially excessive use of temporary clamps to extend deferrals of equipment replacement.

On August 6, 2012, the Chevron Refinery in Richmond, CA experienced a catastrophic rupture of a process line in the crude unit, resulting in a large fireball that engulfed 15 staff, injuring many of them. The Final Investigation Report (CSB, 2015) [4] noted major deficiencies in the decision making for deferrals of inspections that directly led to the accident. The piping that failed had been recommended for replacement 10 years prior to the accident and enhanced inspections of similar piping had been recommended earlier; neither of these actions were taken.

A follow-on assessment chartered by the Contra Costa County Health Services Hazardous Materials Programs department combined with the City of Richmond, found that the following improvements were needed to the asset integrity programs at Chevron Richmond Refinery [5]:

- Making sure corrosion and other damage mechanisms are thoroughly identified and corrected.
- Make sure that all components related to causes and safeguards listed in the PHAs are properly maintained and inspected, including safety-related instruments.
- Complete the positive identification of the materials of construction in each unit, otherwise the site will not know which components are of the wrong material or grade.

On February 12 and again March 10, 2014, the Tesoro Martinez Refinery (CA) had major releases of sulfuric acid, resulting in serious injuries. A CSB Case Study in 2016 [6] found weaknesses in bypass control systems and other management systems for asset integrity which included:

- Taking inherently safer acid sampling systems out of service
- Reliance on inadequate temporary equipment or other workarounds.

PII has experience on this issue at many companies. All companies we work with require an MOC for temporary bypass of critical equipment (such as an IPL) or for deferral of an inspection period for equipment that make up either an IE or an IPL. Such MOCs in turn require a mini-PHA (risk assessment, HAZOP, What-If, LOPA) of the requested change before allowing the bypass or deferral. At one of our client sites with about 1000 plant staff and 10 production plants, the labor spent on the MOCs overall and the risk assessments of such changes overwhelm the competent resources and delaying such changes as well. So, the clients are concerned that the risk assessment for the MOC for bypasses and deferrals:

- Is many times overly conservative; and also many times overly optimistic – both are bad

- Requires huge resources

But is there a better approach?

Yes. You can use a consistent, statistical approach for determining the maximum bypass time and maximum deferral time. But using this approach must be limited to strong need and used only One time per X Test intervals (X*T)

PII shares this following approach that could be used to shorten the time for a one-time deferral or bypass period that fell within the range that did not change the IEF or PFD of the IE or IPL respectively beyond a statistical limit of 3.16×10^{-Y}, given that the IEF or PFD of the as-is component (IE or IPL) is 1×10^{-Y}. The 3.16 value was chosen because this is a value on log-log plot (e.g., a risk matrix) that equates to a change of 5 times Y, or half of an order of magnitude greater, which is when PII rounds up the failure probability to the next order of magnitude.

Definitions

For purposes of this paper, the following definitions apply:

- **Bypass:** Temporary removal of an IPL from service.
- **Deferral:** A delay from the stated inspection or test or calibration test interval for a safety critical component.
- **Critical Component (or Equipment):** A component, loop, or subsystem that is part of a possible initiating event (IE) or that is part of an independent protection layer (IPL).
- **Mean time to dangerous failure ($MTTF_d$):** Mean time between any failure modes that can lead to failures that may result in hazards to personnel, environment or equipment.
- **Test Interval (T or T_{ITPM}):** The time between inspection, test, calibration, or preventive maintenance tasks (ITPM); will be referred to as T_{ITPM} in this paper from here onward.

Bypass and Deferral Process

At many companies, the test interval (**T**) between reliability activities is chosen based on industry standards or based on site data or based on expert opinion. In those cases, the accepted method to grant a deferral or to allow a temporary bypass is to perform a risk assessment and try to find mitigating measures to control the risk in the interim. One issue with this approach is that (1) it is not quantitative and (2) that it usually relies on expert judgment alone. Further, once one deferral or bypass time is allowed, what's to prevent an extension?

A typical flow chart of the activities and decisions involved during a temporary bypass is shown below in **Figure 1** (on the next page).

Bypasses and deferrals should of course be strongly discouraged as a matter of operational discipline and to foster good process safety culture, but the approach in the sections below serves to reduce the uncertainty in the risk judgements of what is the maximum time allowable for a bypass (MOST) or deferral (MDT) before a statistically significant change in the risk of the scenario occurs. This can in turn reduce the number or time spent on the related risk assessments (mini-PHAs) for an associated Management of Change.

Using these common definitions as the starting point, we introduce the following new useful terms:

- **Maximum Out-of-Service Time (MOST):** The maximum time that an IPL can be out of service, with no alternative path / device available, without changing the IEF/PFD order of magnitude. MOST = max time at risk in days = (3.16-1)*PFD * T (where you have a company decision to make of using 365 days or using T_{ITPM}).
- **Maximum Deferral Time (MDT):** The maximum time that the Test Interval (T_{ITPM}) for an IE/IPL can be extended without changing the IEF/PFD order of magnitude. MDT = T_{max} to reach PFD (or IEF) 3.16×10^{-Y} (per year, if for IEF) minus T_{ITPM} to achieve PFD (or IEF) = 1×10^{-Y} (per year, if for IEF).

LOPA and IE/IPLs values accuracy and tolerance

With the wide acceptance of Layer of Protection Analysis (LOPA) to help ensure there are enough protection layers against severe consequences, T_{ITPM} became widely accepted as a “not-to-exceed” limit and that if that limit was exceeded, the initiating event frequency (IEF) if referring to a cause or the probability of failure on demand (PFD) if referring to an independent protection layer (IPL) would no longer be valid. This is further reinforced in *Guidelines for Initiating Events and Independent Protection Layers*, 2015, CCPS/AIChE [1].

In LOPA, IEFs and PFDs are order-of-magnitude estimates. Ideally these should be supported by site-specific data, but mostly these are supported by other-people’s-data, extracted from the CCPS IE & IPL textbook or similar references. Note that there is no significant digit, just a significant exponent. Therefore, the failure rate data can be expressed as:

$$IEF = 10^{-x} = 1E - X \text{ (per year)} \qquad \text{[Eq. 1]}$$

$$PFD = 10^{-x} = 1E - X \text{ (with } 0 \leq PFD \leq 1\text{)} \qquad \text{[Eq. 2]}$$

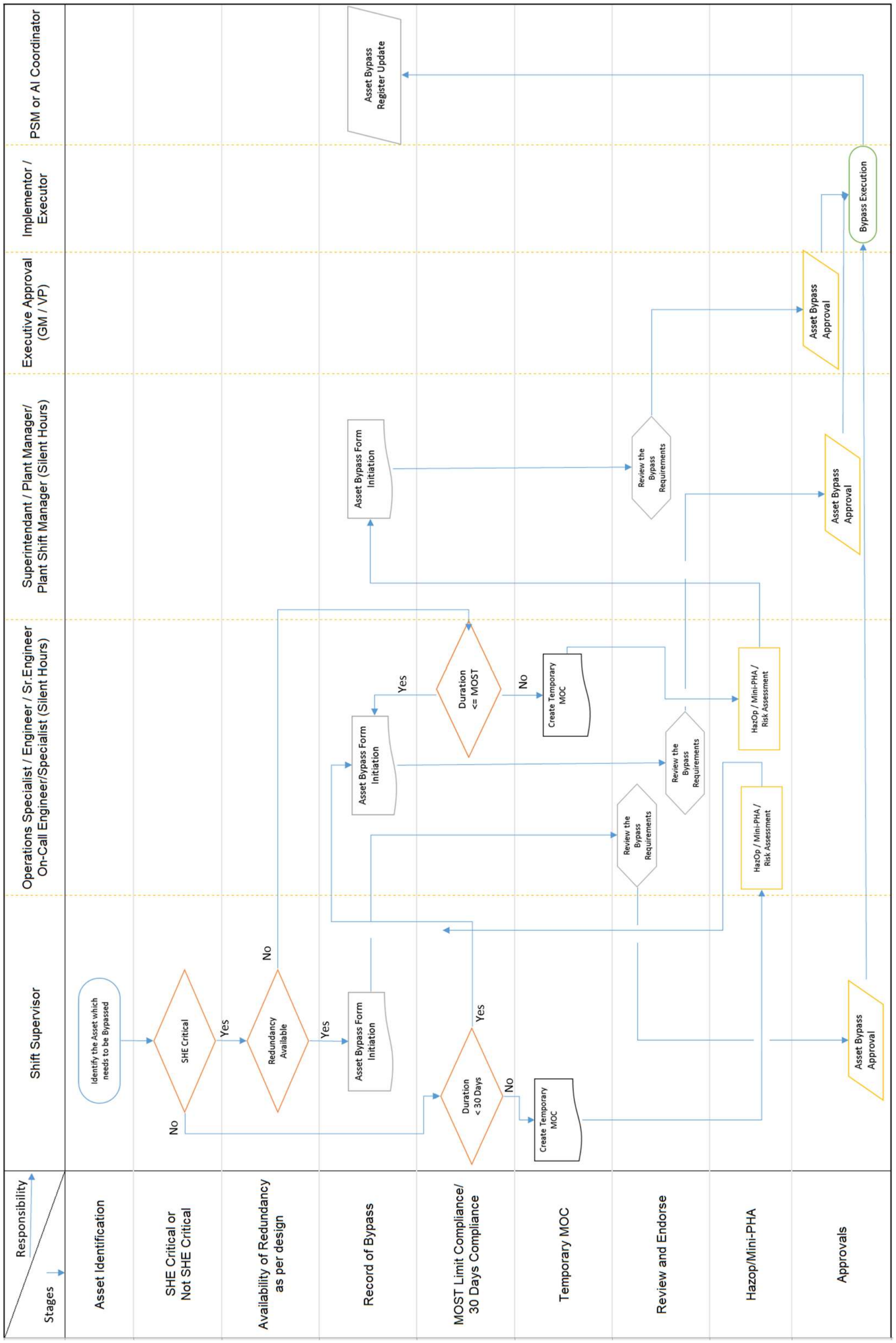

Figure 1. Flowchart for Temporary Bypassing of Systems/Assets

With order-of-magnitude estimates, the failure rate does not increase to the next order of magnitude level until the exponent x is greater than x+0.5. **Table 1** shows the values at which the IEF/PFD should be rounded up or down to the next order of magnitude:

Table 1. Tolerable ranges for IEF/PFD

Nominal IEF/PFD [1E-X]	**IEF/PFD Lower Limit** [1E-(X-0.5)]	**IEF/PFD Upper Limit** [1E-(X+0.5)]
1E-1	3.16E-2	3.16E-1
1E-2	3.16E-3	3.16E-2
1E-3	3.16E-4	3.16E-3

These lower and upper limits will be the basis for the MOST and MDT calculations in the following sections. For the rest of this paper, we will use a value or 3.2 instead or 3.16 for the mid-point factors for half orders of magnitudes (midpoints between decades on log-log paper or risk matrices).

This range also puts under the spotlight a common misconception on the accuracy when using a Risk Matrix (

Figure 2), as discussed in other papers by the originators of LOPA (Art Dowell, III and William Bridges).

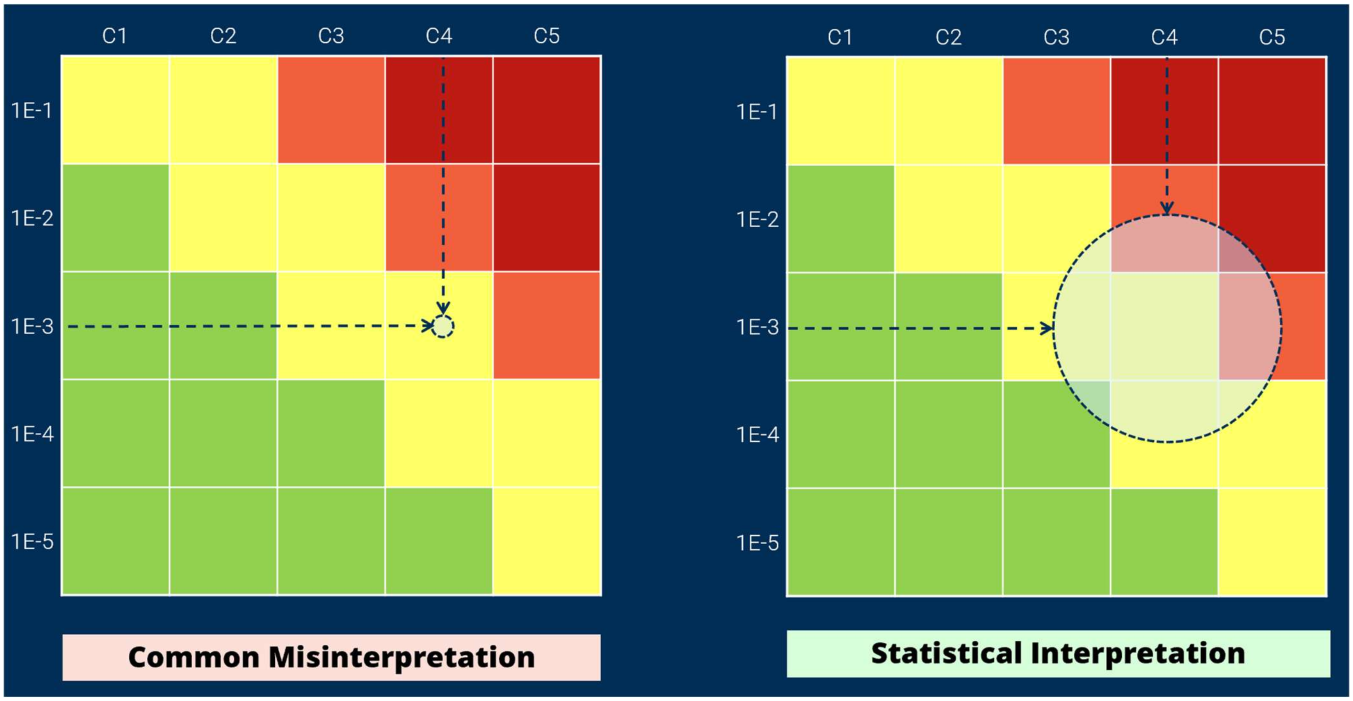

Figure 2. IE/IPL Range Interpretation in a Risk Matrix

Maximum Out-of-Service Time (MOST)

As per the definition above, the MOST is the maximum time that an IPL can be out-of-service, with no alternative path / device available. Therefore, we need to know how long an IPL can be bypassed before its PFD_{IPL}^{avg} is rounded up to the next order of magnitude.

A simplified method for calculating the PFD_{avg} of an IPL is:

$$PFD_{avg} = PFD_{Bypass} \times FTIB + PFD_{ITPM} \times FTIO \qquad \text{[Eq. 3]}$$

Where:

$FTIB$: Fraction of time interval (T) in which the IPL is bypassed

$FTIO$: Fraction of time interval (T) in which the IPL is in operation

PFD_{ITPM}: Nominal value of the PFD at the T specified in the ITPM

Having the IPL bypassed is equivalent to having an IPL that does not work, therefore:

$$PFD_{Bypass} = 1 \qquad \text{[Eq. 4]}$$

Also, since the IPL can be either bypassed or in operation:

$$FTIB + FTIO = 1 \qquad \text{[Eq. 5]}$$

From [Eq. 3], [Eq. 4] and [Eq. 5]:

$$PFD_{avg} = FTIB + PFD_{ITPM}(1 - FTIB) \qquad \text{[Eq. 6]}$$

From the MOST definition, we need to calculate the value of FTIB in which the PFD_{avg} reaches the upper limit before it gets rounded up to the next order of magnitude (see Table 1):

$$FTIB_{Max} + PFD_{ITPM}(1 - FTIB_{Max}) = PFD_{Upper\ Limit} \qquad \text{[Eq. 7]}$$

Isolating $FTIB_{Max}$ from [Eq. 7]:

$$FTIB_{Max} = \frac{PFD_{Upper\ Limit} - PFD_{ITPM}}{1 - PFD_{ITPM}} \qquad \text{[Eq. 8]}$$

Given that the lower the PFD_{ITPM} the closer the term $(1 - PFD_{ITPM})$ gets to 1, the $FTIB_{Max}$ in [Eq. 8] can be estimated as:

$$FTIB_{Max} \cong PFD_{Upper\ Limit} - PFD_{ITPM} \qquad \text{[Eq. 9]}$$

Since the PFD_{ITPM} is a number between 0 and 1, the approximation in [Eq. 9] above would yield results slightly more conservative than [Eq. 8] and with an order the magnitude difference.

To calculate the actual time in which an IPL can be out of service, we need to know the time window in which we are calculating the average combined accident frequency; the company / site must decided on a whether to use a per year basis (T = 1 year) or to use T= T_{ITPM}, which for some IEs or IPLs could be up to 5 years.

$$MOST\ (days) = FTIB_{Max} \times T \qquad \text{[Eq. 10]}$$

Table 2 Shows the MOST calculations for different PFD values.

Table 2. MOST for different PFD values and Test intervals

Nominal PFD (at T_{ITPM}) [1E-X]	PFD Upper Limit [1E-(X+0.5)]	$FTIB_{Max}$ [$PFD_{Upper\ Limit} - PFD_{ITPM}$]	MOST [T_{ITPM} = 1] *(used by PII)*	MOST [T_{ITPM} = 5]
1E-1	3.2E-1	2.2E-1	**80 days**	**400 days**
1E-2	3.2E-2	2.2E-2	**8 days**	**40 days**
1E-3	3.2E-3	2.2E-3	**19 h**	**4 days**

Also important is for the company to set up the rules for when using the set values of MOST allows skipping of the "risk assessment" for the MOC. Examples of such rules are:

- Set T to 1 year and allow one bypass max per year per IPL (easiest rule to implement), or allow one bypass per actual T_{ITPM}
- Set T to T_{ITPM} and allow one bypass max per actual T_{ITPM}
- Allow regardless of whether other IPLs in the same scenario have been bypassed in the same T (easiest rule to implement)
- Limit to one IPL per scenario per T *(difficult to track & implement)*

Regardless, **never bypass more than one IPL per scenario at the same time.**

Maximum Deferral Time

A similar calculation to MOST can be applied to the Maximum Deferral Time (MDT). According to the previously presented definition, the MDT is the maximum time that an IE/IPL Test Interval (T_{ITPM}) can be extended without changing the IEF/PFD order of magnitude ([Eq. 11] and [Eq. 12]). See **Table 1** for the IEF/IPL's upper limits.

$$IEF_{avg}^{@(T+MDT)} = IEF_{Upper\ Limit} \quad \text{[Eq. 11]}$$

$$PFD_{avg}^{@(T+MDT)} = PFD_{Upper\ Limit} \quad \text{[Eq. 12]}$$

In this simplified approach, we will use the IEF_{avg} and PFD_{avg} values from the Guidelines for Initiating Events and Independent Protection Layers in 2015 [2] and Inspection Time (T_{ITPM}) from the same source or from industry best practices.

If you assume that the failure rate is constant (**Figure 3**):

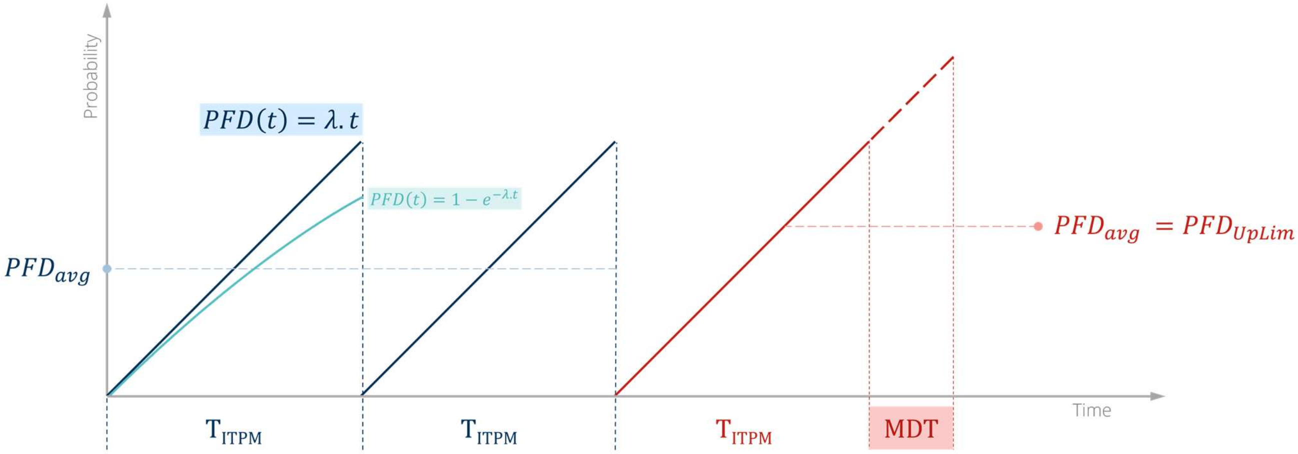

Figure 3. Probability of Failure Approximation

The IEF and PFD can be represented as:

$$IEF(t) = \lambda \times t \quad \text{[Eq. 13]}$$

$$PFD(t) = \lambda \times t \quad \text{[Eq. 14]}$$

Knowing the target IEF_{avg} and PFD_{avg} and the Inspection Time (T), we can do a rough estimation for the Failure Rate (λ^*) from the industry guidance:

$$\lambda^* = 2 \times \left(IEF_{avg}/T\right) \quad \text{[Eq. 15]}$$

$$\lambda^* = 2 \times \left(PFD_{avg}/T\right) \quad \text{[Eq. 16]}$$

Combining all the equations above:

$$T_{max} = IEF_{Upper\ Limit}/\lambda^* \quad \text{[Eq. 17]}$$

$$T_{max} = PFD_{Upper\ Limit}/\lambda^* \quad \text{[Eq. 18]}$$

Where:

$$T_{max} = T + MDT \quad \text{[Eq. 19]}$$

From [Eq. 17], [Eq. 18] and [Eq. 19]the Maximum Deferral Time can be estimated as:

$$MDT = IEF_{Upper\ Limit}/\lambda^* - T \quad \text{[Eq. 20]}$$

$$MDT = PFD_{Upper\ Limit}/\lambda^* - T \quad \text{[Eq. 21]}$$

Table 3 shows the MDT calculations for different combinations of IEF/PFD and T.

DO NOT USE THESE RESULTS IN PRACTICE

These values are being shared to prevent readers from trying this approach.

Table 3. MDT Calculations for Different Combinations of IEF/PFD and T
(Do Not Use these MDTs – Used for Illustration)

Nominal IEF/PFD [1E-X]	**T** (years)	**Example**	**Upper Limit** [1E-(X+0.5)]	**λ*** [$2 \times \left(IEF_{avg}/T\right)$]	**MDT** (years)
1E-1	1	BPCS, SIL1	3.2E-1	2E-1	**0.6**
1E-1	5	Check valve	3.2E-1	4E-2	**2.9**
1E-2	4	PSV	3.2E-2	5E-3	**2.4**
1E-2	5	PSV	3.2E-2	4E-3	**3**
1E-3	10	Pressure vessel	3.2E-3	2E-4	**6**

But the results above for MDT were based on equations that reverse the calculations for approximating risk; the results for MDT are much too long using this approach as the straight-line approximation for failure rate is not valid as the components begin to approach the end of life (wear out). The period is illustrated instead by the wear-out or burn-out curves, as is shown below:

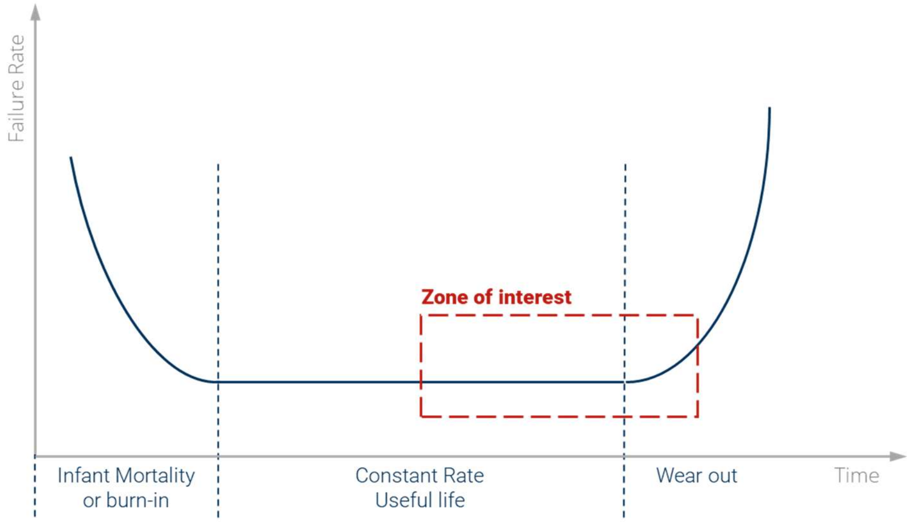

Figure 4. **Typical Bathtub Representation of Failure Rate Highlighting the Zone of Interest for ITPM**

So, it is best to use the actual failure rate curves for the components of interest and determine more accurately where the failure rate (IEF) or the PFD reaches 3.2×10^{-Y}. This is illustrated in the next section.

Calculation with Specific Component Data

As is always the case, using specific data is preferred over the use of generic data or over general rate calculations. However, site-specific data may not be available or there may not be enough data points for statistical significance. If specific data is not available, the $PFD_{Upper\ Limit}$ from **Table 1** can still be used to estimate the MDT.

Figure 5 shows an example of experimental data points that has a polynomial curve fit shown

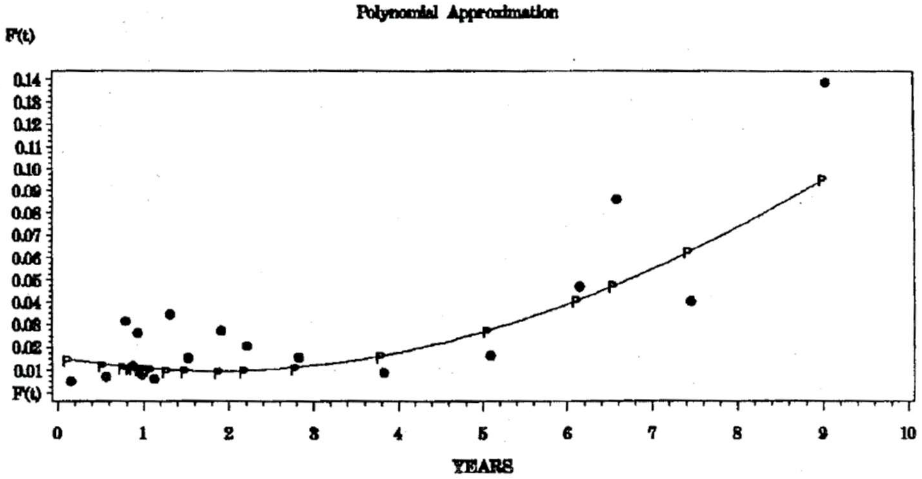

Figure 5. **Actual Test Data for the PFD of Relief Valves with a Polynomial Curve Fit Shown [7]**

Figure 6 shows a further conversion to *Quantal response analysis* of relief valve test data [7].

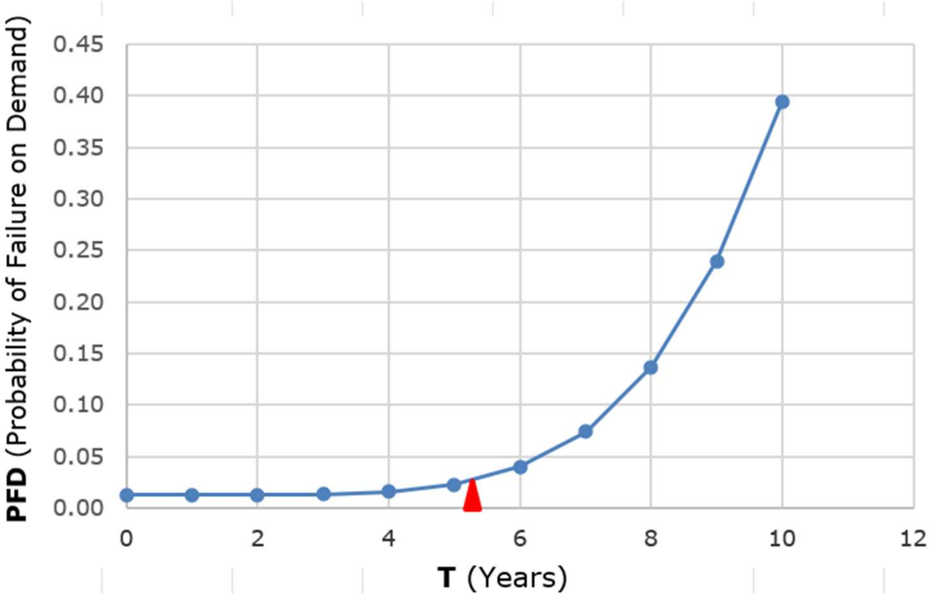

Figure 6. **Quantal Response Analysis of Test Data for the PFD of Relief Valves [7]**

From the chart above, the curve crosses the $PFD_{Upper\ Limit} = 0.032$ at $T_{ITPM} \approx 5.2$. If the Test interval for the relief valve was 4 years, the MDT in that case would be 1.2 and at T = 5, then MDT = 0.2. Typically, we find that 0.5 years is the best value for MDT for relief valves that have a T_{ITPM} of 4 to 5 years. **Note that 0.5 year is 1/5th the MDT shown in Table 3, hence the warning to NOT use the approach leading to Table 3.**

Other examples for relief valves:

- **Raising the test pressure to 150% of design set pressure** (versus testing at 110%, 121%, or 133% of test pressure) drops the initial PFD at time zero to 0.01 (not 0.02 nor 0.03) and extends the test interval a bit as well. One site with about 500 PSVs recorded 20% PFD during testing at 110% of set pressure, but there were NO failures at 150% of set pressure.
- **Test periods can be different from site to site:** One site had a 4% PFD at T=4 years for 665 PSVs. When T was reduced to 3 years ,the PFD dropped to 1% failures for each of the next 3 periods (9 years total and continuing). If they had increased test pressure to 150% instead of 121%, they likely could have remained at 4 years.
- PII helped gather and analyze data in these and other cases. So, from PII experience for PSVs, the best T_{ITPM} for PFD = 0.01 is 4 years when testing at 121% set pressure and likely 5 years for testing at 150% set pressure.

There is less test data on other IPLs and IEs; more data collection and sharing are needed. For check valves, based on limited data, the curve below is available. This shows for a single check valve with a target PFD = 0.1, that the T_{ITPM} = 4 to 5 years with an MDT 1.8 years. More data is needed to validate this MDT, as it appears too large to the authors (PII).

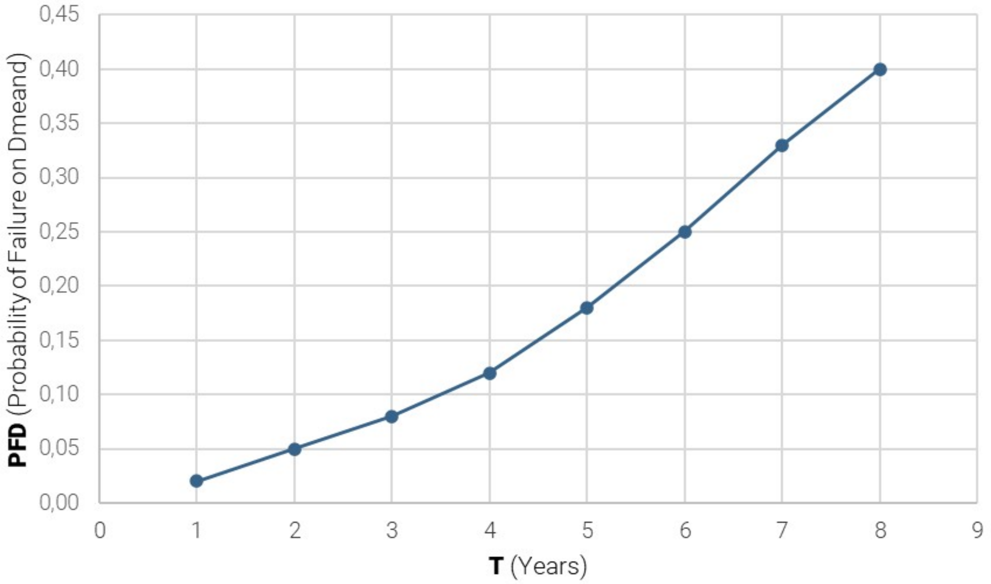

Figure 7. Test Data for the PFD of Single Check Valve in Clean Service; flapper gate type

Based on the observations in the field at many client sites, and informed by the statistical results above, PII compiled tables shown in the **Appendix** for most of the design and human features used as IEs and IPLs in PHA & LOPA (Use with permission and proper citation only). PII believes these values for MOST and MDT are reasonable for allowing **one** deferment of an inspection for the MDT per T_{ITPM} or one bypass for **one** MOST per T_{ITPM}. However, more in service failure rate data compared to inspection time (T_{ITPM}) are needed to determine better values for MDT. Use at your own risk, as PII takes no responsibility for the use of these MOST and MDT values. PII encourages companies to develop values for their site use.

Caution

In some cases, a code or regulation may require a different value for MOST or MDT. For instance, ASME, Section VIII, Appendix M, allows for bypassing a relief valve for up to 24 hours with proper additional precautions, but ASME has not set a performance standard with a target PFD for relief valves until the adoption of UG 140. So far, such prescriptive allowances have not been challenged. The MOST listed in the paper is **8 days** for **one** bypass of a relief device in T_{ITPM} = 4 years.

If your jurisdiction enforces a different MOST or MDT, then you probably should follow that value to prevent potential litigation, but your company management should make such decisions.

Conclusion

MOC is critical for temporary changes to ITPM plans and schedules. But, if MOST and MDT are decided in advance, then your site can:

- Avoid the cost of overusing critical risk review resources
- Avoid uninformed decision-making by a risk review team for a deferral or bypass
- Have a reproduceable, statistical basis for the standardized risk decision

And if such MOST and MDT are agreed to in advance, the site should decide how many deferrals or bypasses per T_{ITPM} period (usually the number is one per period; but some companies start at one per IE/IPL per two periods)

Acronyms

FTIB: Fraction of Time in Bypass
FTIO: Fraction of Time in Operation
IEF: Initiating Event Frequency
IPL: Independent Protection Layer

ITPM: Inspection, Test, Preventative Management
LOPA: Layers Of Protection Analysis
MDT: Maximum Deferral Time
MI: Mechanical Integrity
MOC: Management of Change
MOST: Maximum Out of Service Time
MTTF: Mean Time to Failure
PFD: Probability of Failure on Demand
PM: Preventative Management
PMI: Positive Material Identification
PSM: Process Safety Management
PSV: Relief Valve / Pressure Safety Valve

References

[1] CCPS/AIChE, Layers of Protection Analysis (LOPA), Wiley, 2001.

[2] CCPS/AIChE, Guidelines for Independent Protection Layers and Initiating Events in Layer, Wiley, 2012.

[3] U.S. Chemical Safety and Hazard Investigation Board (CSB), "Report No. 2010-08-I-WA - Investigation report: Catastrophic rupture of heat exchanger (Seven fatalities)," 2015.

[4] U.S. Chemical Safety and Hazard Investigation Board (CSB), "Report No. 2012-03-I-CA - Final investigation report: Chevron Richmond Refinery. Pipe rupture and fire.," 2015.

[5] Contra County Health Services Hazaroud Material Program (CCHMP), "Draft initial report: Safety evaluation of the Chevron Richmond Refinery," 2016.

[6] U.S. Chemical Safety and Hazard Investigation Board (CSB), "Report No. 2014-02-I-CA - Process Safety Case Study: Tesoro Martinez Refinery," 2016.

[7] J. H. Sheesley, H. W. Thomas and C. A. Valenzuela, "Quantal response analysis of relief valves test data," in *49th Annual quality congress*, 1995.

Appendix

The tables shown below are used by PII. Use with permission and proper citation only. **Use at your own risk**, as PII takes no responsibility for the use of these MOST and MDT values. We encourage companies to develop values for their site use.

Table Ap. 1. MOST/MDT for Initiating Events for LOPA Use

#	**INITIATING EVENT** IE Description and Purpose	**IEF** (per yr)	**T_{ITPM}** (year)	**MOST** (days)	**MDT** (days)
	Loss of Containment (for LOPA use)				
1	Pump seal leak - for standard ANSI pumps	1	NA	NA	NA
2	Pump seal leak - for API pumps	0.1	NA	NA	NA
3	Catastrophic pump seal failure (any type)	0.1	NA	NA	NA
4	Hose Failure, Leak	0.1 to 1	1	NA	60
5	Hose Failure, Leak - high vibration	1	1	NA	60
6	Hose Failure, Catastrophic Rupture	0.01	1	NA	60
7	Hose Failure, Catastrophic Rupture - high vibration	0.1	1	NA	60
8	Premature Opening of Spring-Loaded Relief Valve	0.01	4	8	180
	Active System Failure				
9	BPCS control loop failure	0.1	NA	NA	NA
10	Pressure Regulator Failure (Single Stage)	0.1	NA	NA	NA
11	Premature operation of an IPF or SIF. The value must be derived from calculation based on the design of the associated SIF or IPF (typically ranges from 1/yr to 0.1/yr)	0.1	Test interval set by SIL V Calc	80 for SIL 1, 8 for SIL 2	TBD based on 1/2 of T
12	BPCS interlock (state control)	0.1	1	Depends	60
13	Screw conveyor failure (premature stoppage) * CBM = Condition Based Maintenance. Sampling and analysis of oil as often as possible (weekly, even daily) and continuous vibration and temp.	1 to 10	CBM (no PM, no overhaul)	NA *CBM	NA *CBM
14	Screw conveyor over-heating of materials (and overheating caused by screw rubbing on housing/barrel) * CBM = Condition Based Maintenance. Sampling and analysis of oil as often as possible (weekly, even daily) and continuous vibration and temp.	0.1	CBM (no PM, no overhaul)	NA *CBM	NA *CBM
15	Pump, compressor, fan, or blower fails off while operating * CBM = Condition Based Maintenance. Sampling and analysis of oil as often as possible (weekly, even daily) and continuous vibration. and temp.	0.1	CBM (rare PM, rare overhaul)	NA *CBM	NA *CBM
16	Loss of power (localized breaker circuit)	0.01	NA	NA	NA
17	Loss of power (site/unit-wide)	Site-specific	NA	NA	NA
18	Single Check Valve Fails Open (with scenario where the check valve is in high demand mode and for a scenario related to large backflow, not leakage past check valve).	0.1	NA	NA	NA
19	Double Check Valve in series (1oo2) (with scenario where the check valves are in high demand mode and for a scenario related to large backflow, not leakage past check valve)	0.01	NA	NA	NA

	Human Error				
20	Human error for a routine task that is performed once per week or more often, with a checklist as a memory aid	1	1	NA	60
21	Human error for a routine task that is performed between once per month and once per week, with a checklist as a memory aid	0.1	1	NA	60
22	Human error for a non-routine task that is performed less than once per month (perhaps only once per year or two), with a checklist as a memory aid; with the use of a simulator or practice or drills to increase practice frequency	0.01	1	NA	60
23	Human error for a non-routine task that is performed less than once per month (perhaps only once per year or two), with a checklist as a memory aid; without the use of a simulator or practice or drills to increase practice frequency	0.1	1	NA	60

DEFINITIONS and NOTES:

1. *MOST = Maximum Out of Service Time (max bypass time with no alternative path)*
2. *MDT = Maximum Deferral Time, where "maximum deferral time" is the value that change the PFD or IEF from* $1x10^{-Y}$ *to* $3.2x10^{-Y}$ *(theoretically)*

Table Ap. 2. MOST/MDT for Initiating Events for QRA/ITPM Scheduling Use

#	**INITIATING EVENT** NOT for use in LOPA. Use in QRA or for ITPM scheduling. IE Description and Purpose	**IEF** (per yr)	**TITPM** (year)	**MOST** (days)	**MDT** (days)
	Loss of Containment - Not in materials sensitive service (for QRA, not LOPA use)				
1A	Atmospheric tank - catastrophic failure (10 minutes or less for release of contents), where the materials of construction are not critical - *External*	0.00001	5	NA	350
1B	Atmospheric tank - catastrophic failure (10 minutes or less for release of contents), where the materials of construction are not critical - *Internal*	0.00001	10	NA	700
2A	Pressure Vessel Failure (instantaneous or 10-minute release), where the materials of construction are not critical - *External*	0.00001	5	NA	350
2B	Pressure Vessel Failure (instantaneous or 10-minute release), where the materials of construction are not critical - *Internal*	0.00001	10	NA	700
3	Piping failure, full breach (pipe size less than or equal to 150 mm), where the materials of construction are not critical (per meter)	1E-06	5	NA	350
4	Piping failure, full breach (pipe size > 150 mm; includes gasket failure, gasket support ring damage, valve packing blowout, and normal erosion and corrosion), where the materials of construction are not critical (per meter)	1E-07	5	NA	350
5	Piping leak (pipe size less than or equal to 150 mm), where the materials of construction are not critical (per meter)	0.00001	5	NA	350
6	Piping leak (pipe size >150 mm), where the materials of construction are not critical (per meter)	1E-06	5	NA	350
	Loss of Containment - In materials sensitive service (for QRA, not LOPA use)				
7A	Atmospheric tank catastrophic failure (instantaneous or 10-minute release) – material-sensitive service - with 100% PMI - *External*	0.001	5	NA	350
7B	Atmospheric tank catastrophic failure (instantaneous or 10-minute release) – material-sensitive service - with 100% PMI - *Internal*	0.001	10	NA	700
8A	Atmospheric tank catastrophic failure (instantaneous or 10-minute release) – material-sensitive service - without 100% PMI - *External*	0.01	5	NA	350
8B	Atmospheric tank catastrophic failure (instantaneous or 10-minute release) – material-sensitive service - without 100% PMI - *Internal*	0.01	10	NA	700
9	Pressure Vessel Failure (instantaneous or 10-minute release) – material-sensitive service - with 100% PMI	0.001	5	NA	350
10	Pressure Vessel Failure (instantaneous or 10-minute release) – material-sensitive service - without 100% PMI	0.01	5	NA	350
11	Piping failure, full breach (pipe size less than or equal to 150 mm) – material-sensitive service - with 100% PMI (per meter)	0.0001	5	NA	350
12	Piping failure, full breach (pipe size less than or equal to 150 mm) – material-sensitive service - without 100% PMI (per meter)	0.001	5	NA	350
13	Piping failure, full breach (pipe size > 150 mm) – material-sensitive service - with 100% PMI (per meter)	0.0001	5	NA	350
14	Piping failure, full breach (pipe size > 150 mm) – material-sensitive service - without 100% PMI (per meter)	0.001	5	NA	350

DEFINITIONS and NOTES:

1. *MOST = Maximum Out of Service Time (max bypass time with no alternative path)*
2. *MDT = Maximum Deferral Time, where "maximum deferral time" is the value that change the PFD or IEF from* $1x10^{-Y}$ *to* $3.2x10^{-Y}$ *(theoretically)*

Table Ap. 3. MOST/MDT Independent Protection Layers for LOPA Use

#	**INDEPENDENT PROTECTION LAYER** IPL Description and Purpose	**PFD**	**T_{ITPM}** (year)	**MOST** (days)	**MDT** (days)
	Passive IPLs				
1	Unstable (overdriven) Detonation Arrester installed inline between an ignition source (e.g., TOX) and a source of flammable or combustible vapors.	0.01	1 to 4	8	90 to 350
2	Deflagration Flame Arrester or Stable Detonation Arrester installed inline between an ignition source (e.g., TOX) and a source of flammable or combustible vapors.	0.1	1 to 4	80	90 to 350
3	Dike, Berm, or Bund	0.01	5	8	350
4	Drainage to Dikes, Berms, and Bunds with Remote Impoundment	0.01	5	8	350
5	Fire-resistant Insulation and Cladding	0.01	3	8	350
	Relief System IPLs				
6	Spring-Operated Pressure Relief Valve in clean service with no history of blockage or fouling and with no block valve upstream or downstream; and for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less. (With block valves, reduce to 0.1 until external audits prove 0.01 okay.)	0.01	4	8	180
7	Dual Redundant Spring-Operated Pressure Relief Valves in Clean Service, with each relief valve adequately sized for scenario under consideration so that full redundancy is present, the valves are in clean (non-fouling) service and with no block valve upstream or downstream; and for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less. (With block valves, reduce to 0.01 until external audits prove 0.001 okay.)	0.001	4	8 (for one of the PSVs)	180
8	Pilot-Operated Pressure Relief Valve, in clean service with no history of blockage or fouling and with no block valve upstream or downstream; and for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less. (With block valves, reduce to 0.1 until external audits prove 0.01 okay.)	0.01	4	8	180
9	Gas Balance/Adjustable Set Pressure Surge Relief Valve	0.01	3	8	180
10	Buckling pin relief device in clean service with no history of blockage or fouling (such as to ground flares or when used as chlorine relief valves) with no block valve upstream or downstream; for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less.	0.01	4	8	180
11	Buckling pin isolation valve (BPIV), such as for use an emergency shutdown valve	0.1	1 to 8	80	180
12	Rupture Disk, in clean service with no history of blockage or fouling and no block valve upstream or downstream; for failure to open at burst pressure (typically at 100% of MAWP). (With block valves, reduce to 0.1 until external audits prove 0.01 okay.)	0.01	5	8	180
13	Spring Operated Pressure Relief Valve with non-fragmenting type rupture disk on inlet. If process in contact with disk is polymerizing or fouling, an adequate flush is required to keep inlet and disk clean and with no block valve upstream or downstream of relief devices; for failure to open enough at set pressure (100% of rating), if inspection and testing of both PSV and RD meet the criteria and methods used for those individual devices. (With block valves, reduce to 0.1 until external audits prove 0.01 okay.)	0.01	4	8	180
14A	Frangible roofs on flat-bottom tank. Note that in most scenarios involving harm to humans, this cannot be used as an IPL within Basic LOPA. - *External*	0.01	5	8	350
14B	Frangible roofs on flat-bottom tank. Note that in most scenarios involving harm to humans, this cannot be used as an IPL within Basic LOPA. - *Internal*	0.01	15	8	700

#	**INDEPENDENT PROTECTION LAYER** IPL Description and Purpose	**PFD**	T_{ITPM} (year)	**MOST** (days)	**MDT** (days)
15	Explosion isolation valve	0.1	1	80	60
16	Emergency pressure relief valve, spring loaded (also known as a conservation vent) in clean service with no history of blockage or fouling [this entry is for non-ASME code certified devices designed to relieve systems at less than 15 psig]; failure to open at 100% of design pressure (typically at 100% of MAWP).	0.01	0.5 to 5	8	30 to180
17	Conservation vent valve, weight loaded, in clean service with no history of blockage or fouling [this entry is for non-ASME code certified devices designed to relieve systems at less than 15 psig]; failure to open at 100% of design pressure (typically at 100% of MAWP).	0.01	0.5 to 5	8	30 to 180
18A	Explosion panels for internal dust or vapor/gas deflagration explosions. Note that in most scenarios involving harm to humans, this cannot be used an IPL within LOPA. Inspection only. - *External*	0.01	1	8	60
18B	Explosion panels for internal dust or vapor/gas deflagration explosions. Note that in most scenarios involving harm to humans, this cannot be used an IPL within LOPA. Inspection only. - *Internal*	0.01	1	8	60
19A	Vent (explosion) panels for prevention of rupture in low pressure equipment. Note that in most scenarios involving harm to humans, this cannot be used an IPL within LOPA. Inspection only. - *External*	0.01	5	8	350
19B	Vent (explosion) panels for prevention of rupture in low pressure equipment. Note that in most scenarios involving harm to humans, this cannot be used an IPL within LOPA. Inspection only. - *Internal*	0.01	5	8	350
20	Vacuum Breaker (or vacuum relief valve or vacuum safety valve)	0.01	0.5 to 5	8	30 to 180
21	Overflow line from tank/vessel/drum; with no impediments to overflow (no rupture disks, relief valves, or liquid seals). Inspection only	0.001	1	0.8 (20 hr)	15
22	Overflow line from a tank containing a passive fluid, such as mineral oil. Overflow from tank/vessel/drum with additional hardware to form a liquid seal leg. Overflow line with a rupture disk to provide a vapor seal.	0.01	1	8	60
23	Overflow line from a tank containing a non-reactive fluid that is prone to evaporation or freezing, such as water. Overflow from tank/vessel/drum with additional hardware to form a liquid seal leg.	0.1	1	80	80
	Instrumented System IPLs				
24	BPCS control loop (normally operating control loop)	0.1	NA	NA	NA
25	BPCS interlock (state control)	0.1	1	80	80
26	Continuous Pilot; capable of lighting main burner under review.	0.1	NA	NA	NA
27	Pneumatic Control Loop (regulatory control loop, no human intervention required)	0.1	NA	NA	NA
28	SIF SIL 1	0.1	Per SIL V	80	60
29	SIF SIL 2 -- if the SIL Verification did not consider system errors/failures:	0.1	Per SIL V	80 (if 0.1) or 8 (if 0.01)	TBD based on 1/2 of T
	if the SIL Verification addressed and included system errors/failures	0.01			
	Mechanical IPLs				
31	Excess flow valve that will stop or greatly curtail flow from an accidental piping/line failure.	0.01	1	8	60
32	Restrictive Flow Orifice in clean service with scenario related to excess flow rate.	0.01	1	8	60
33	Pipeline Surge Dampening Vessel; for failure to prevent shock due to water hammer	0.01	3	8	180

#	**INDEPENDENT PROTECTION LAYER** IPL Description and Purpose	**PFD**	T_{ITPM} (year)	**MOST** (days)	**MDT** (days)
34	Single Check Valve with scenario related to large backflow, not leakage past check valve. Tested every 36-60 months	0.1	5	80	350
35	Single Check Valve with scenario related to large backflow, not leakage past check valve. Tested every 12 months	0.01	1	8	60
36	Double Check Valve in series with scenario related to large backflow, not leakage past check valve. Tested every 60 months or less	0.01	5	8	180
37	Bubble tight check valve (class 5 or class 6 tightness). For mode of failure to completely close and restrict flow to the appropriate class of tightness	1 to 0.1	0.6	8	60
38	Single Pressure Regulator (in continuous demand)	0.1	NA	NA	NA
39	Continuous ventilation *without* automated performance monitoring capability. Inspection Only.	0.1	1	80	60
40	Continuous ventilation *with* automated performance monitoring capability.	0.01	1	8	60
41	Mechanically Activated Emergency Shutdown/Isolation Devices used to isolate flow paths upon initiation, to limit any release.	0.1	1	80	60
42	Mechanical over-speed trip on a turbine, with a trip/throttle valve	0.1	3 to 5	80	350
43	Mechanical stop that limits travel (non-adjustable, after initial installation). *Checking placement only*	0.01	1	8	60
44	Fire suppression system (water; water and foam; other suppressants) within process equipment; automatic. (See NFPA 25 for details)	0.1	1	80	60
45	Fire suppression system (non-aqueous including dry agent) *for local application*; automatic.	0.1	1	80	60
46	Fire suppression system (non-aqueous including dry agent) *for room*; automatic.	0.01	1	8	60
47	Explosion suppression system for process equipment; automatic	0.1	1	80	60
	Human IPLs				
48	Human response to an annunciation (alarm light and sound) without distractions from other alarms, and the worker can respond to the call for action and complete the required action within the MART, but MART should not be less than 10 minutes, within Basic LOPA.	0.1	1	80 (for alarm only)	60
49	Human responds to an annunciation (alarm light and sound) and he/she has 24 hours to accomplish the required action, but immediate action is required.	0.01	1	8 (for alarm only)	60
50	Human responds to a field reading or sample analysis where the time between samples or field readings is 1/2 of the MART of less	0.1	1	NA	60
51	Movement limiting device (but which is adjustable) such as a strong wire car seal, chain/lock, or an adjustable mechanical stop; intended to prevent operation of a device beyond a limit would then result in an IE of a scenario (not for block valves under relief devices). Only valid if movement limiting device placed or installed by another work group and has been inspected during a routine cycle at least once. - *Inspection Only*	0.1	1	80	30
52	Captive key/lock system intended to ensure position of device whose mis-positioning can be an IE of scenario. - *Inspection Only*	0.01	1	8	60

DEFINITIONS and NOTES:

1. *MOST = Maximum Out of Service Time (max bypass time with no alternative path)*
2. *MDT = Maximum Deferral Time, where "maximum deferral time" is the value that change the PFD or IEF from* $1x10^{-Y}$ *to* $3.2x10^{-Y}$ *(theoretically)*

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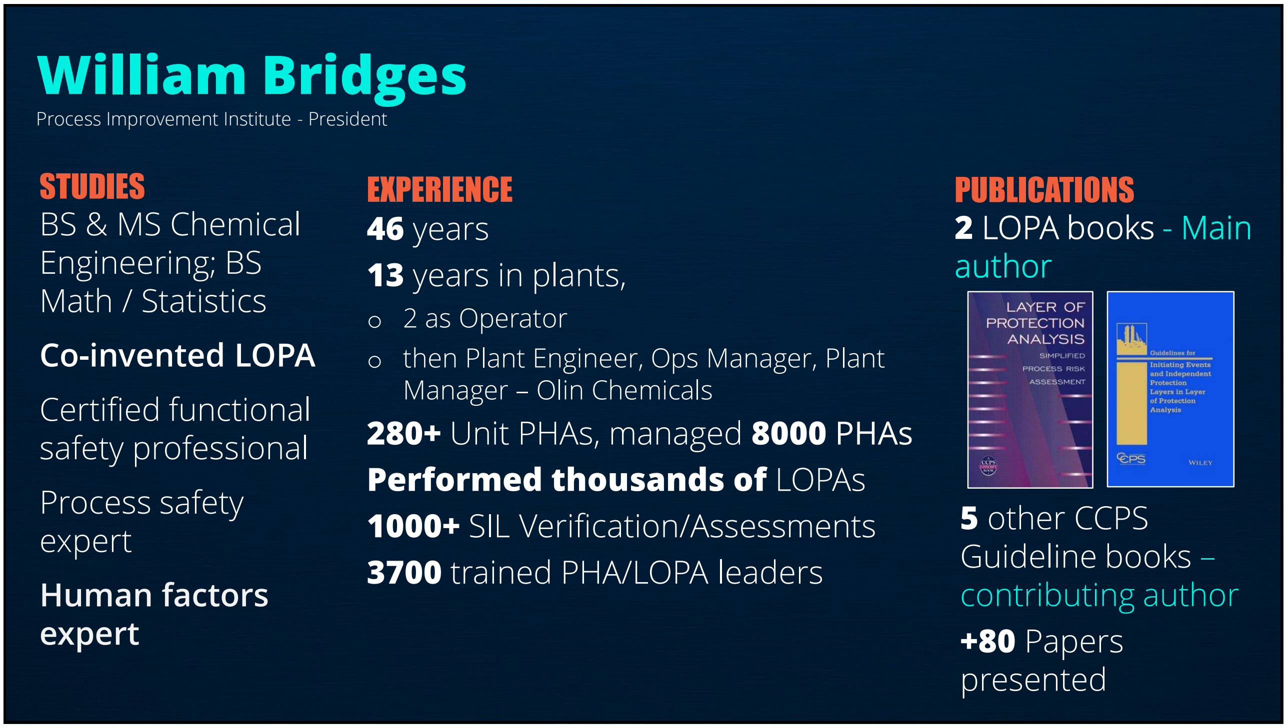
USING IE AND IPL FAILURE RATES TO ESTABLISH MAXIMUM OUT OF SERVICE TIME, AND DEFERRAL TIME LIMITS FOR CRITICAL PROCESS SAFETY FEATURES

William G. Bridges, PII
Matias Massello, PII



William Bridges

Process Improvement Institute - President

STUDIES

BS & MS Chemical Engineering; BS Math / Statistics

Co-invented LOPA

Certified functional safety professional

Process safety expert

Human factors expert

EXPERIENCE

46 years

13 years in plants,

- 2 as Operator
- then Plant Engineer, Ops Manager, Plant Manager – Olin Chemicals

280+ Unit PHAs, managed **8000** PHAs

Performed thousands of LOPAs

1000+ SIL Verification/Assessments

3700 trained PHA/LOPA leaders

PUBLICATIONS

2 LOPA books - Main author

5 other CCPS Guideline books – contributing author

+80 Papers presented

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INTRODUCTION

2012 – Chevron Richmond

Major deficiencies in the decision making for deferrals of inspections that directly led to the accident

CSB Report 2012-03-I-CA

2014 – Tesoro Martinez

Weaknesses in bypass control systems and other management systems for asset integrity

CSB Report 2014-02-I-CA

BYPASS / DEFERRAL PROCESS

PRIMARY CONCERN of CLIENT

The risk assessment for the MOC for bypasses and deferrals:

- **Overly conservative; Overly optimistic – both are bad**
- **Requires huge resources**
- **Is there any better way?**

REPLY to CLIENT

There is a consistent, statistical approach for determining the max bypass time and max deferral time:

- **But must be limited to strong need and only One time use per X Test intervals (X*T)**

DEFINITIONS

Bypass: Temporary removal of an IPL from service

Deferral: A delay from the stated inspection or test or calibration test interval for a safety critical component

Critical Component: A component, loop, or subsystem that part of a possible initiating event or that is part of an independent protection layer

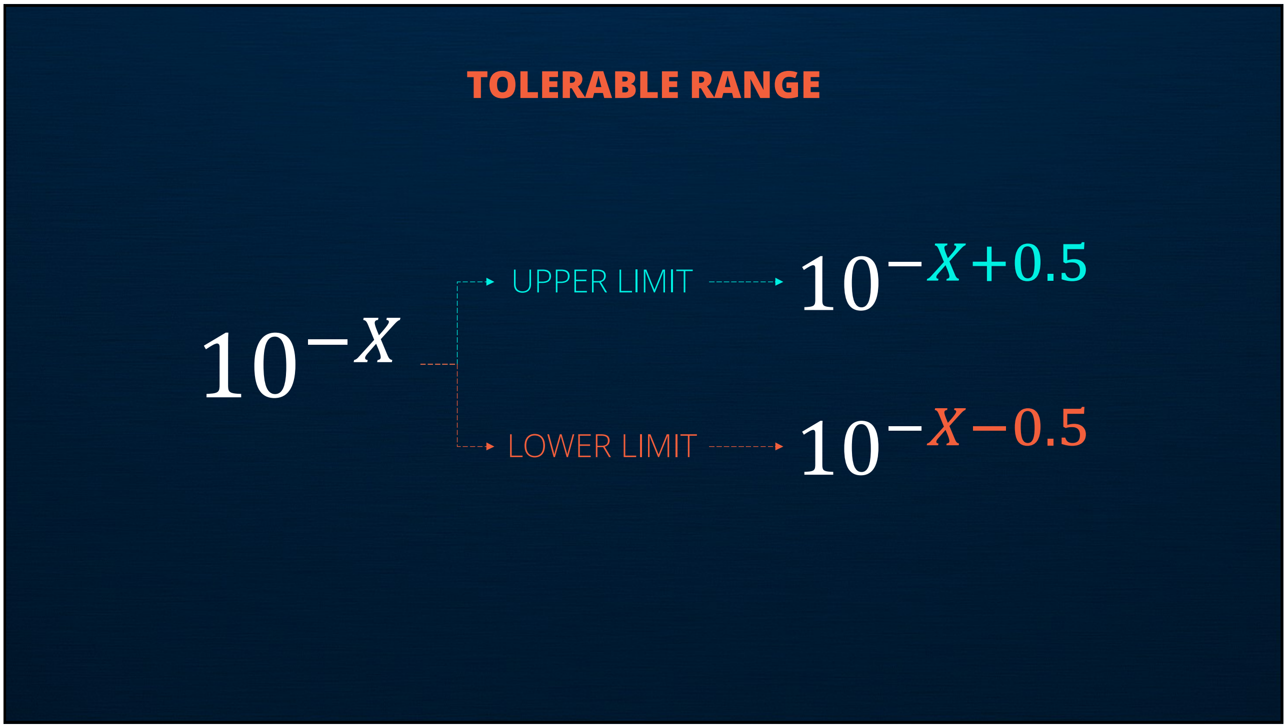
Test Interval: The maximum allowable time between an inspection, test, calibration, or preventive maintenance task

Maximum Out-of-Service Time (MOST): The maximum time that an IPL can be out-of-service with no alternative path/device available, without changing the IEF/PFD order of magnitude

Maximum Deferral Time (MDT): The maximum time that an IE/IPL Test Interval (T) can be extended without changing the IEF/PFD order of magnitude

In LOPA

IEFs and PFDs are Order of Magnitude Estimates

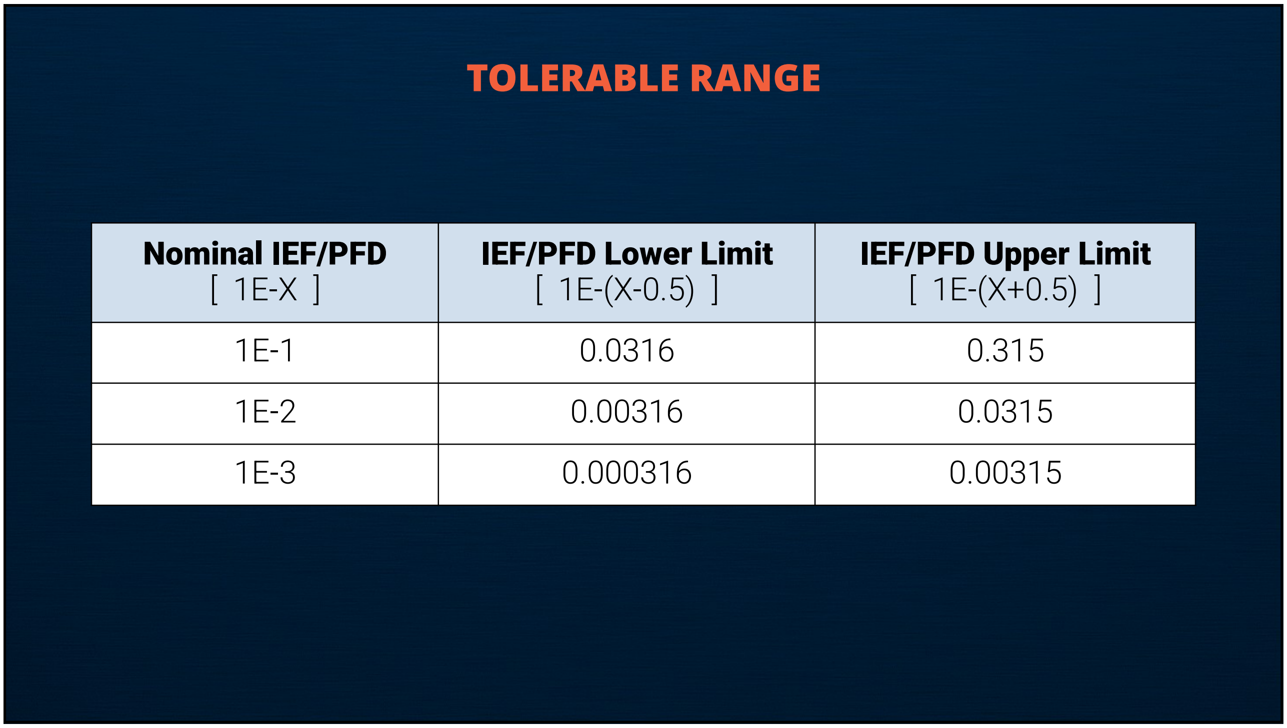


TOLERABLE RANGE

$$10^{-X}$$

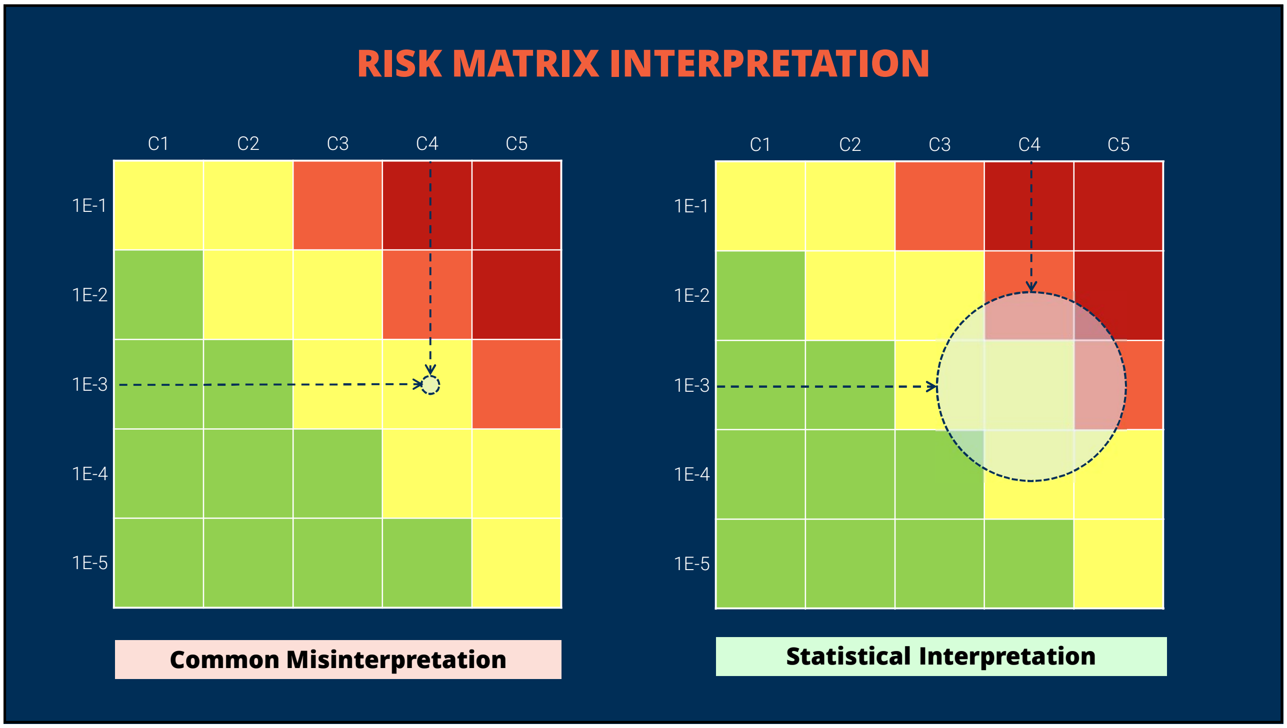
UPPER LIMIT $10^{-X+0.5}$

LOWER LIMIT $10^{-X-0.5}$



TOLERABLE RANGE

Nominal IEF/PFD [1E-X]	**IEF/PFD Lower Limit** [1E-(X-0.5)]	**IEF/PFD Upper Limit** [1E-(X+0.5)]
1E-1	0.0316	0.315
1E-2	0.00316	0.0315
1E-3	0.000316	0.00315



RISK MATRIX INTERPRETATION

Common Misinterpretation

Statistical Interpretation

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MAXIMUM OUT OF SERVICE TIME (MOST)

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Maximum Out-of-Service Time (MOST): The maximum time that an IPL can be out-of-service with no alternative path/device available, without changing the IEF/PFD order of magnitude

PFD AVERAGE ESTIMATION

Fraction of T in Operation

$$PFD_{avg\ (T)} = FTIB + PFD_{Nom} \times FTIO$$

Fraction of T in Bypass
(time at risk)

= 1-FTIB

PFD AVERAGE ESTIMATION

$$PFD_{avg\,(T)} = FTIB_{\text{Max}} + PFD_{Nom} \times FTIO = PFD_{UpLim}$$

Max Fraction of Time Allowed to be at Risk

PFD AVERAGE ESTIMATION

$$MOST = FTIB_{Max} \times T$$ (true for each IPL at a time)

EXAMPLE RULES:

- Set T to 1 year and allow one bypass max per year per IPL (easiest rule to implement), or allow one bypass per actual T_{ITPM}
- Set T to T_{ITPM} and allow one bypass max per actual T_{ITPM}
- Allow regardless of whether other IPLs in the same scenario have been bypassed in the same T (easiest rule to implement)
- Limit to one IPL per scenario per T *(difficult to track & implement)*
- **Never** bypass more than one IPL per scenario at the same time

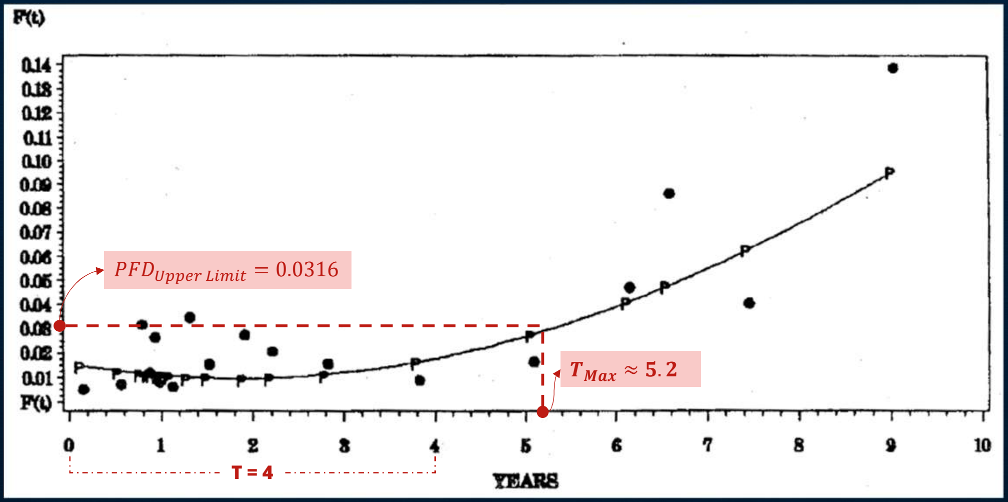
MOST VALUE EXAMPLES

Nominal PFD 1E-X	**PFD Upper Limit** 1E-(X+0.5)	**FTIB$_{Max}$** $PFD_{Upper\ Limit} - PFD_{Nom}$	**MOST** T = 1	**MOST** $T_{ITPM} = 5$
1E-1	3.2E-1	2.2E-1	**80** days	**400** days
1E-2	3.2E-2	2.2E-2	**8** days	**40** days
1E-3	3.2E-3	2.2E-3	**19** hrs	**4** days
1E-4	3.2E-4	2.2E-4	**2** hrs	**8** hrs

PII recommends these values for starters

Maximum Deferral Time

EXPERIMENTAL DATA EXAMPLE, Polynomial Fit



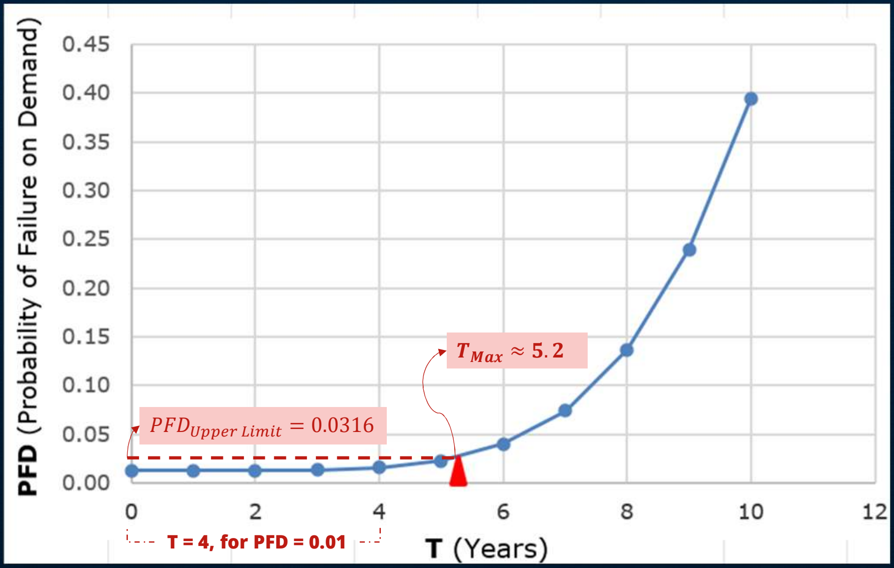
$PFD_{Upper\ Limit} = 0.0316$

$T_{Max} \approx 5.2$

T = 4

Source: J. H. Sheesley, H. W. Thomas and C. A. Valenzuela, "Quantal response analysis of relief valves test data," in 49th Annual quality congress, 1995.

Quantal Response Analysis of PFD Test Data for Relief Valves



$T_{Max} \approx 5.2$

$PFD_{Upper\ Limit} = 0.0316$

T = 4, for PFD = 0.01

Data for other MDT Estimates

- There are limited published failure rate curves/data for most components, though with the CCPS book effort for IEs and IPLs, the committee arrived at consensus of the target IEF or PFD with T_{ITPM} based in part on unpublished site data.
- PII has worked onsite with more than 100 clients and have observed failure rate curves for many types of components from unpublished data.
  - *For starters assume the shape of the IPL curves is similar to those for Relief Valves and Check Valves*
- More published data is needed; perhaps a *Guideline* is needed.

Examples for MOST and MDT

#	**INDEPENDENT PROTECTION LAYER – IPL Description and Purpose:**	**PFD**	**T (year)**	**MOST (days)**	**MDT (days)**
	Relief System IPLs				
6	Spring-Operated Pressure Relief Valve in clean service with no history of blockage or fouling and with **no block valve upstream or downstream;** and for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less. (With block valves, reduce to 0.1 until external audits prove 0.01 okay.)	0.01	4	8	180
7	Dual Redundant Spring-Operated Pressure Relief Valves in Clean Service, with each relief valve adequately sized for scenario under consideration so that full redundancy is present, the valves are in clean (non-fouling) service and with **no block valve upstream or downstream;** and for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less. (With block valves, reduce to 0.01 until external audits prove 0.001 okay.)	0.001	4	8 (for one of the PSVs)	180
8	Pilot-Operated Pressure Relief Valve, in clean service with no history of blockage or fouling and with **no block valve upstream or downstream**; and for failure to open enough at set pressure (100% of rating), if inspected and tested every 4 yrs or less. (With block valves, reduce to 0.1 until external audits prove 0.01 okay.)	0.01	4	8	180

Examples for MOST and MDT

#	INDEPENDENT PROTECTION LAYER – IPL Description and Purpose:	PFD	T (year)	MOST (days)	MDT (days)
	Instrumented System IPLs				
24	BPCS control loop (normally operating control loop)	0.1	NA	NA	NA
25	BPCS interlock (state control)	0.1	1	80	80
26	Continuous Pilot; capable of lighting main burner under review.	0.1	NA	NA	NA
27	Pneumatic Control Loop (regulatory control loop, no human intervention required)	0.1	NA	NA	NA
28	SIF SIL 1	0.1	Per SIL V	80	60
29	SIF SIL 2 -- if the SIL Verification did not consider human errors:	0.1	Per SIL V	80 (if 0.1) or 8 (if 0.01)	TBD based on 1/2 of T
	-- if the SIL Verification included human errors:	0.01			
	Mechanical IPLs				
31	Excess flow valve that will stop or greatly curtail flow from an accidental piping/line failure.	0.01	1	8	60
32	Restrictive Flow Orifice in clean service with scenario related to excess flow rate.	0.01	1	8	60

Regulation/Code limits for MOST and MDT may be different than these values

CLOSING

- MOC is critical for temporary changes to ITPM plans and schedules, but a free-form risk assessment for such MOCs may waste time.
- MOST and MDT can be decided in advance –
  - Avoids the cost of overusing critical risk review resources
  - Avoids uninformed decision-making by a risk review team for a deferral or bypass
  - Has a reproduceable, statistical basis
- If MOST and MDT such as described here are adopted, the site should also establish rules for the number of deferrals or bypasses per T_{ITPM} period.

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THANK YOU

WILLIAM (Bill) BRIDGES
wbridges@piii.com
mmassello@piii.com

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