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Synergetic implementation of LOPA and RBI methodologies for pressure relief device inspection interval optimization.

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This paper presents an optimization analysis methodology for the preventive maintenance interval of a Pressure Relief Device (PRD) that could not be executed at its original planned interval due to the failure of its isolation valve. Initially, deferral analysis for the maintenance of this PRD was performed using Layers of Protection Analysis (LOPA), but the method for updating the initial Risk Reduction Factors for the PRD was not standardized and was qualitatively adjusted by the analysis team. As a result, the risk of deferring the maintenance was initially considered intolerable, and the unit was planning to shut down to execute the preventive maintenance. To address this issue, a second analysis was developed, which consisted of a synergy between risk-based inspection methodologies and LOPA. This resulted in an optimized maintenance interval for this PRD, which allowed the unit to operate safely until the next shutdown window while satisfying operational risk thresholds and financial goals that were initially jeopardized. To ensure reliable adoption of the results of this analysis, it was necessary to thoroughly review both methods to confirm the level of convergence between the results obtained when they were conducted separately. This paper also describes the steps taken to standardize the updating of initial Risk Reduction Factors for PRDs and identifies the equivalent parameter in LOPA and RBI methods that enable the synergy in optimizing maintenance and inspection intervals at the refinery.

Keywords: LOPA, RBI, Pressure Relief Devices, Safety Valves, Inspection Interval, Refinery.

1. Process Safety Risk Analysis and Mechanical Integrity Methodologies Applied in Refineries and Petrochemical Plants

OSHA 29 CFR 1910.119 was issued in 1992 as a response to a series of significant accidents that occurred in the chemical industry within the United States. This regulation played a crucial role in shaping the adoption of the process safety model in the industry by establishing a clear regulatory framework for managing risks in hazardous process facilities.

The standard encompasses 14 management pillars, among which process hazard analysis and mechanical integrity are included. While both pillars are associated with risk management, they have distinct focuses, leading to the implementation of separate methodologies. The process hazard analysis pillar involves the identification, evaluation, and control of hazards, with established methodologies like Hazard and Operability analysis (HAZOP) being commonly utilized. HAZOP is further complemented by Layer of Protection Analysis (LOPA), which aims to determine the safety integrity level (SIL) requirements for safety instrumented systems (SIS).

During the design stage of refinery facilities, HAZOP and LOPA are employed to achieve acceptable levels of risk. These analysis methods enable the allocation of safeguards and risk reduction efforts across various layers of protection, as illustrated in Figure 1. On the other hand, the Mechanical integrity pillar pertains to the effective management of critical equipment to ensure appropriate design, installation, operation, and maintenance. The inspection and maintenance of crucial fixed equipment in refineries are comprehensively addressed by the Risk-Based Inspection (RBI) methodology, developed by the American Petroleum Institute through API 580 and API 581 standards. RBI aims to determine suitable inspection intervals based on the associated risk level for the evaluated degradation mechanisms within a specified time frame.

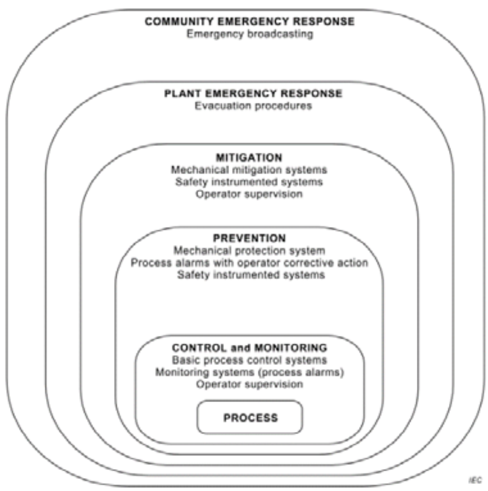

Fig. 1. Layers of Protection Schematic. (IEC 61511-3 2013).

2. Relevance of Pressure Relief Devices and Their Inspection for Process Safety and Mechanical Integrity

Pressure relief devices (PRDs) play a critical role in ensuring process safety, risk management, and the integrity of refinery installations by serving as barriers against the potential loss of hazardous fluid containment. The primary objective of installing and inspecting PRDs is to ensure their ability to protect systems from excessive pressure build-up, which may occur due to operational upsets, external fires, or other hazards. Therefore, it is essential to establish effective inspection and maintenance intervals to maintain the reliability of their safety functions.

The inspection of PRDs is typically performed in a workshop setting, requiring their isolation and removal from operating plants. In refineries, inspection plans for relief devices are established by referring to industry standards such as API 576: Inspection of Pressure-Relieving Devices and API 510: Pressure Vessel Inspection Code.

API 510 sets maximum inspection intervals of 5 and 10 years for PRDs, depending on the service in which they are installed. However, API 510 also allows for the establishment of different intervals based on documented experience and/or assessments conducted through risk-based inspections (RBI). The API 581 standard, which governs RBI assessments, adopts a data-driven approach to evaluate inspection intervals for pressure-relieving devices. By considering both the probability of failure on demand and the potential consequences of failure, this approach generates a risk value that accumulates over time. Consequently, engineers can identify the optimal inspection intervals for each device based on an acceptable level of risk specific to their operation.

2.1 *Use of LOPA for inspection interval validation of a PRD*

Although LOPA is primarily developed during the system design phase, reference standards such as IEC 61511 acknowledge the significance of evaluating the effectiveness of safety barriers during system operation.

In systems where PRDs are considered independent protective layers (IPLs), they contribute to reducing the initial process risk, thus it is crucial to update and adjust the mitigation credits assigned to them in LOPA as their degradation over time can impact their ability to prevent or mitigate hazards. This adjustment of Risk Reduction Factor (RRF) for PRDs is typically carried out in a qualitative or semi-quantitative manner. Consequently, the LOPA team needs to verify the current level of integrity of PRDs to ensure that the overall system's mitigated risk meets the tolerable risk thresholds.

3. Cartagena Refinery Case Study

The PRDs at the Cartagena refinery were initially assigned inspection intervals based on the calculation of probability of failure on demand (POFOD) and probability of internal leakage using API 581. This standard provides Weibull curve shape parameters that vary depending on the severity of service: mild, moderate, or severe. A 2% threshold for the probability of failure was determined based on qualitative expert criteria.

Figure 2 illustrates how the Weibull curves for different types of services intersect at a 2% probability of demand failure, resulting in inspection intervals ranging from 2 to 6 years based on the service category and this threshold.

In the case of the specific relief device examined in this study, PSV 2327, it was assigned a 2-year inspection interval due to its severe service classification. However, upon reaching the end of the inspection interval, the inspection activity could not be carried out on PSV 2327 due to internal leakage in the blocking valve. This condition created a safety risk for personnel attempting to disassemble the valve.

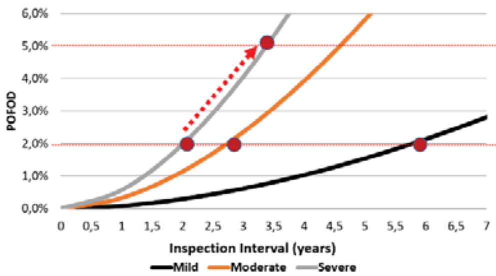

Fig. 2. Weibull Curves Intersection for Probability of Failure on Demand (POFOD) and Identification of Inspection Intervals.

3.1 *Risk analysis for PSV 2327 condition*

To assess the potential loss of function of PSV 2327, a risk analysis was conducted using the LOPA methodology. The selection of this approach was based on the availability of the initial design HAZOP, which had already identified and analysed the 24 overpressure scenarios where PSV 2327 acted as a protective layer. Thus, the analysis team deemed it favourable to update this existing study database, enabling the assessment of the overall risk for these 24 scenarios under the current conditions.

During the LOPA analysis, a qualitative assignment of a risk reduction factor (RRF) of 100 was made for PSV 2327 when maintenance was performed within the specified 2-year interval. With this RRF value, a tolerable mitigated risk was achieved for all the identified overpressure scenarios.

However, in the current situation where PSV 2327 had not undergone maintenance within the specified interval, the analysis team qualitatively assigned an RRF value of 10. This led to an unacceptable level of risk associated with conducting maintenance at intervals longer than 2 years.

Based on this qualitative risk evaluation, the decision was made to shut down the process unit to facilitate the inspection of the PRD.

Considering the significant anticipated loss of production resulting from the unit shutdown, a more quantitative approach was adopted. This involved calculating the probability of failure for PSV 2327 using the API 581 RBI methodology.

3.2 *Results of quantitative approach integrating RBI POFOD into LOPA*

The quantitative calculation of the probability of failure using API 581 enabled the determination that the initial inspection interval of 2 years could be extended to 3.4 years. At this revised interval, the probability of failure reached 5%, corresponding to a Risk Reduction Factor (RRF) of 20. By incorporating the RRF of 20 for PSV 2327 into the overall risk calculation within the LOPA spreadsheet, a tolerable risk level was achieved for each of the 24 overpressure scenarios. Figure 2 illustrates the identification of the 3.4-year interval on the Weibull curve for severe service, precisely where the curve intersects the 5% Probability of Failure on Demand (POFOD).

Based on the outcomes of this new analysis, the inspection interval was adjusted from 2 years to 3.4 years. Consequently, PSV 2327 continued operation for an additional year until the device could be inspected during a planned shutdown, thereby avoiding any unnecessary production losses associated with the inspection. The inspection results for PSV 2327 confirmed the absence of any conditions that could potentially lead to a failure to open on demand at the time of inspection.

4. Conceptual Comparison of LOPA and RBI for Determining PRD Inspection Intervals.

Given the successful implementation of a mixed analysis, incorporating RBI calculations into LOPA, in the case of PSV 2327, the question arises as to whether performing LOPA using RBI POFOD is equivalent to conducting a complete RBI assessment for the PRD.

To establish this parallel, a comprehensive analysis will be conducted for each methodology individually, with a specific focus on the relevant parameters and calculations involved. This detailed examination will allow us to identify the similarities between the methodologies and conclude if they ultimately yield equivalent results.

4.1 *LOPA risk stages: initial, intermediate, and mitigated, and their relationship with probabilities of failure*

4.1.1 *LOPA initial process risk*

For LOPA, the initial process risk of each overpressure scenario R_{pj} is given by the product of the corresponding initiating event frequency IEF_j and the hazardous event consequence severity for the scenario CS_j, such consequences are related to loss of containment due to this overpressure (See Eq. (1)).

$$R_{pj} = IEF_j * CS_j \tag{1}$$

To achieve tolerable risk levels for each overpressure scenario in LOPA, there are two risk mitigation stages: likelihood reduction and consequence severity mitigation.

4.1.2 *LOPA intermediate risk*

In the first risk stage, risk reduction factors of all proactive independent protection layers RRF_{pro} are computed to reduce the frequency of the initiating event. An intermediate event likelihood IEL_j and corresponding intermediate risk value R_{ij} is obtained in this stage:

$$R_{ij} = \frac{R_{pj}}{\prod RRF_{pro}} \tag{2}$$

It is important to emphasize that the intermediate event likelihood IEL_j is the product of the initial event frequency times the probabilities of failure on demand of each proactive IPL PFD_{pro}:

$$IEL_j = \mathrm{IEF}_j * \prod PFD_{pro} \tag{3}$$

This follows from the RRF definition: the initial risk R_0 divided by the mitigated risk R_i. Therefore, the RRF for each proactive IPLs is the inverse of its PFD (See Eq. (4)).

$$RRF = \frac{R_0}{R_i} = \frac{R_0}{R_0\, x\, PFD} = \frac{1}{PFD} \tag{4}$$

Common proactive IPLs considered in overpressure risk analysis are:

- BPCS: Basic process control systems
- SIF: Safety Instrumented Functions
- ALARMS + Operator
- PRD: Pressure relief device
- Design.

4.1.3 *LOPA mitigated risk.*

In the second stage of LOPA, reactive IPLs risk reduction factors RRF_{reac} are applied to intermediate event risk R_{ij} to reduce the consequence severity for the hazardous event, thus obtaining the mitigated risk for the overpressure scenario R_{mj}:

$$R_{mj} = \frac{R_{ij}}{\prod RRF_{reac}} \tag{5}$$

In LOPA, the overall mitigated risk for the system in terms of overpressure $Risk_{op}$ is calculated as the sum of all the mitigated risks for each individual overpressure scenario:

$$Risk_{op} = \sum R_{mj} \tag{6}$$

4.2 *RBI analysis and probabilities of failure calculations*

For Pressure relief device (PRD) the principal failure mode is defined as failure to open during emergency situations, causing an overpressure in the protected equipment resulting in loss of containment.

In the RBI methodology for pressure relief devices, the analysis is conducted in two stages. In the first stage, the probability of failure is calculated for each defined overpressure scenario. In the second stage, the consequences of failure are assessed. The total risk calculation for the scenario is then determined at the end of the analysis.

4.2.1 *Probability of failing to open.*

For each overpressure scenario, the pressure relief device RBI probability of failure POF_{PRDj} is the product of three factors: Demand Rate DR_j, probability of failure on demand of the PRD

$POFOD_J$ and probability of failure of the protected equipment POF_{EQj}:

$$POF_{PRDj} = \mathrm{DR}_j * POFOD_J * POF_{EQj} \quad (7)$$

4.2.1.1 ***RBI overpressure scenario demand rate,*** $\mathbf{DR_j}$

The determination of the RBI demand rate for each overpressure scenario involves multiplying the initiating event frequency IEF_j with the demand rate reduction factors $DRRF_j$ which is a parameter introduced by API 581.

$$DR_j = \mathrm{IEF}_j * \prod DRRF_j \quad (8)$$

From Eq. (7) and Eq. (8), in RBI, the frequency of initiating events IEF_j reduction is achieved through multiplication of DRRF, $POFOD_J$ and POF_{EQj}, this reduction factors are comparable to the PFD (RRF) of proactive independent protection layers in the LOPA methodology.

As the initiating event frequency is reduced by the same factors, the likelihood of intermediate events in LOPA is equivalent to the PRD's probability of failure for each overpressure scenario in RBI:

$$IEL_j = POF_{PRDj} \quad (9)$$

Therefore, the RBI demand rate reduction factors for each overpressure scenario are equal to the product of all proactive IPLs' PFDs, except for the PRD and Design proactive IPLs PFDs:

$$\prod DRRF_j = \frac{\prod PFD_{pro}}{POFOD_J * POF_{EQj}} \quad (10)$$

4.2.1.2 ***Probability of failure on demand of the PRD,*** $\boldsymbol{POFOD_J}$

The second component of the RBI probability is the probability of failure on demand (POFOD) of the relief device. API 581 offers a comprehensive methodology based on Weibull analysis to calculate the POFOD. This RBI POFOD value must be incorporated into LOPA as the probability of failure on demand (PFD) for the relief device.

4.2.1.2 ***Probability of failure of protected equipment,*** $\boldsymbol{POF_{EQj}}$

The third and final component of the probability of failure is the probability that the protected equipment will fail when subjected to overpressure. API 581 provides a complete calculation method for this probability that accounts for the inherent design capabilities, the overpressure level according to the specific initiating event, and the degradation state of the component.

The RBI POF for protected equipment is a suitable quantification for the computation of Design PFD in LOPA. Thus, is important to notice, that the use of RBI POF for protected equipment enables the application of LOPA for analysis of pressure equipment risk, in a similar fashion as it can be applied to PRD inspection interval evaluation.

4.2.1.2 ***RBI Consequence and risk of failure***

API 581 provides a comprehensive methodology for quantitatively assessing the consequences resulting from loss of containment events. Both LOPA and RBI methodologies allow for the quantitative adjustment of consequence levels in the presence of detection and isolation systems.

The risk of failure for the Pressure Relief Device (PRD) to open in each overpressure scenario is determined by multiplying the probability and consequences of failure.

API 581 also offers a quantitative methodology for evaluating the risk associated with secondary failure modes of PRDs, such as internal leakage. If it is necessary to assess this risk, the risk value obtained from API 581 for internal leakage must be added to the risk value derived from the fail to open analysis.

4.3 RBI And LOPA parameters and analysis process parallel

Table 1 provides a summary of the equivalent parameters that foster synergy between RBI and LOPA in the quantitative or semi-quantitative assessment of PRD inspection intervals. The definitions outlined in the table illustrate that both proactive and reactive LOPA IPLs have their corresponding counterparts in the RBI.

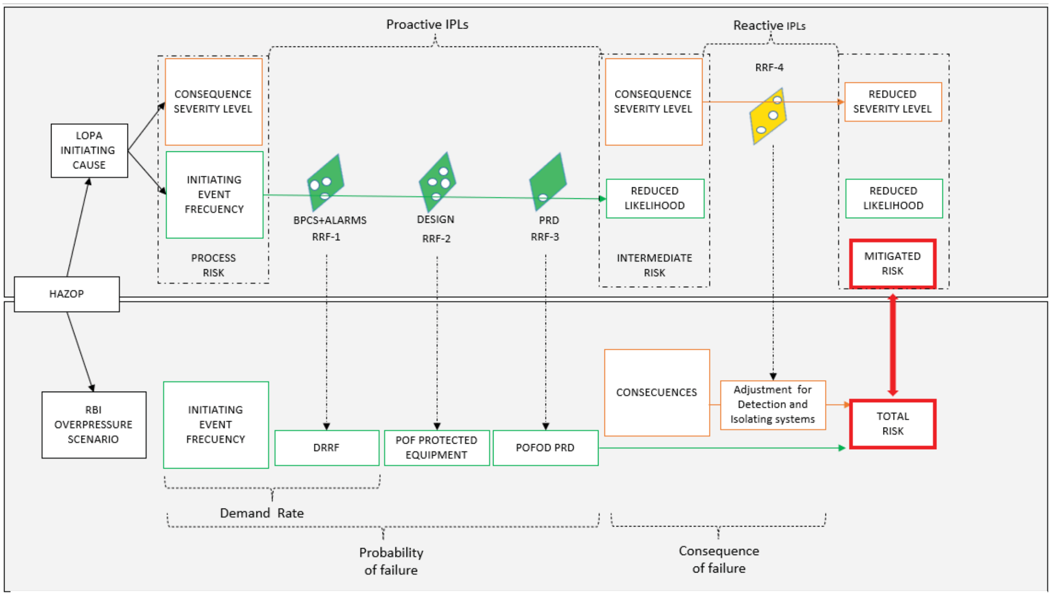

Fig. 3. Schematic representation of equivalent parameters at different calculation stages of each analysis, LOPA, and RBI.

Table 1. Equivalent parameters in LOPA and RBI for PRD analysis

IPL Type	*LOPA*	*RBI*
Proactive (Likelihood reduction)	*BPCS PFD ALARMS PFD Other IPL PFD*	*DRRF*
	Design PFD	POF_{EQ}
	PRD PFD	*POFOD*
Reactive (Consequence Severity reduction)	*Severity Level*	*Consequence Level*
	Mitigation barriers RRF	*Detection and Isolation Systems adjustment factors.*

Specifically, this equivalence becomes evident when conducting a risk assessment for pressure relief devices.

Figure 3 presents a schematic representation of the equivalent parameters and their interaction in both LOPA and RBI analyses. Regarding the flow of each process, it can be observed that the analysis of proactive IPLs in LOPA is equivalent to the assessment of probability of failure in RBI, while the assessment of reactive IPLs in LOPA corresponds to the assessment of consequences in RBI. Both LOPA and RBI methodologies necessitate the assessment of all identified causes of overpressure, typically identified in a hazard identification process like HAZOP, particularly when analyzing pressure relief devices.

In summary, the parallel between LOPA and RBI methodologies lies in their common objective of determining risk levels through the computation of the probability of an undesirable event and its consequence.

4.3.1 *RBI and LOPA Risk and interval selection*

In RBI, the inspection interval is determined based on a risk threshold, and the computed risk evolves over time following a Weibull distribution. The total risk of the PRD failing to open is the sum of the risks for each overpressure scenario. The inspection should be conducted before the device reaches the risk threshold.

In LOPA, the mitigated risk for each overpressure scenario is assessed using different values of RRF for the IPLs. The inspection interval can be validated if the RRF associated with the probability of failure at a specific moment in time results in a tolerable risk level for each overpressure scenario. Typically, this calculation is performed through iteration.

However, this paper demonstrates the synergy between LOPA and RBI, which enables the expression of LOPA PFDs (Probability of Failure on Demand) as RBI probabilities of failure, providing an alternative approach for calculating LOPA mitigated risk.

5. Conclusions

For use cases such as relief devices or assessing pressure vessel failure scenarios LOPA and RBI methodologies are equivalent and can be adopted qualitatively or quantitatively to the same extent. Similarly, the formulation as a function of time is analogous, and the way they relate to obtaining a risk level at a given time or projected in time is the same.

It is important to note that in the case of the study presented in this article, a mechanical integrity methodology, RBI, was used to provide quantitative input to a risk management methodology, LOPA. This allowed for a practical and suitable quantitative level of analysis to be conducted on the inspection interval of a pressure relief device.

As both approaches are equivalent, the synergy between these methodologies does not necessarily result in greater precision, but it does provide a more efficient integration of data that is available in industrial plants and is not considered when each methodology is used separately.

Methods that are available from the design stage, such as HAZOP, prove to be a crucial tool in optimizing safety devices maintenance, such as PRDs, as they allow for the dynamic update and computation of initial assumptions for barriers RRF. The synergy between HAZOP, LOPA and RBI methodologies and interdisciplinary teams allows for rigorous safety analysis and documentation in response to dynamic challenges imposed at operational stages.

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