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RESEARCH ARTICLE

COLLECTION AND EVALUATION OF INDONESIA'S ONSHORE PROCESS SAFETY FAILURES AND ACCIDENTS: A BASIS FOR IMPROVING AND VALIDATING QUANTITATIVE RISK ASSESSMENT

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ABSTRACT

Real-world data on onshore process safety failures and accidents offer significant potential as a learning tool for validating and refining Quantitative Risk Assessment (QRA). This paper presents a curated dataset of incidents—sourced from official reports, equipment failure maintenance records, and change management documentation—and a structured methodology for their evaluation. Incidents are classified by industry sector, accident type, and facility age, then analyzed in terms of causes and consequences. By comparing actual events with publictly available failure rate database, the study identifies mismatches and provides evidence-based recommendations for improving hazard recognition and risk estimation. The findings are distilled into case studies designed for use in QRA validation as best practices for embedding incident data into ongoing QRA validation, emphasizing continuous incident database updates as a means to maintain relevance beyond fixed review cycles. The ultimate aim is to support both safer industrial operations and more credible QRA activity.

Keywords: Failure Rate; Quantitative Risk Assessment, Incident Data

1.0 INTRODUCTION

The continuously growing global population requires an affordable and standardized supply of ready-to-eat and ready-to-use products, the majority of which are produced by the process industry (King, 1990). Consequently, the process industry has undergone substantial expansion over the past 70 years (Landau, 1994). In Indonesia, the development of the process industry began following the Industrial Revolution, marked by the establishment of the sugar industry in Java in 1750 (Curry-Machado & Bosma, 2012). The manufacturing industry in Indonesia experienced significant growth during the 1970s, marked by the production of the first stainless steel at the PT Krakatau Steel plant in Cilegon in 1970 (Alijoyo & Shodikin, 2022). This milestone contributed to the rapid expansion of process industries in the Anyer, Merak, and Cilegon regions.

In Indonesia, notable major process accidents include the 2017 explosion at a fireworks factory in Tangerang, which resulted in 51 fatalities (Antara, 2018); the flash fire and subsequent explosion at the perimeter area of the Plumpang Fuel Terminal on 3 March 2023, causing 35 fatalities (Republika, 2023); and the 2023 fire at a nickel refining plant in Morowali, which claimed at least 13 lives (The Strait Times, 2023). The most recent incident was a gas leak in the CO_2 removal unit, which resulted in two severe injuries (Katadata, 2025).

A review of the bibliographic map on process equipment failure rates, as visualized in the Figure 1, indicates that this topic has been substantively addressed in at least five seminal works: Center of Chemical Process Safety, CCPS (1989), Marsh (2018), Gomez-Mares et.al. (2014), Cheng, et.al. (2020), and Pasman (2011). Marsh (2018) has systematically gathered and archived data on major property damage losses in the energy industry, now encompassing over 10,000 incidents from around the world. In parallel, The CCPS (1989) offers guidance on sourcing equipment reliability data essential for quantitative risk analyses, focusing on failure rates expressed as the number of equipment failures per one million operating hours or per one thousand operational demands. Gomez-Mares et.al. (2008) notes that fire accidents represent the most common type of major accident in industrial facilities and during the transportation of hazardous materials. Among these, jet fires occur with a notable frequency; however, their exact occurrence rate cannot be quantified because accident databases often fail to specify the fire type.

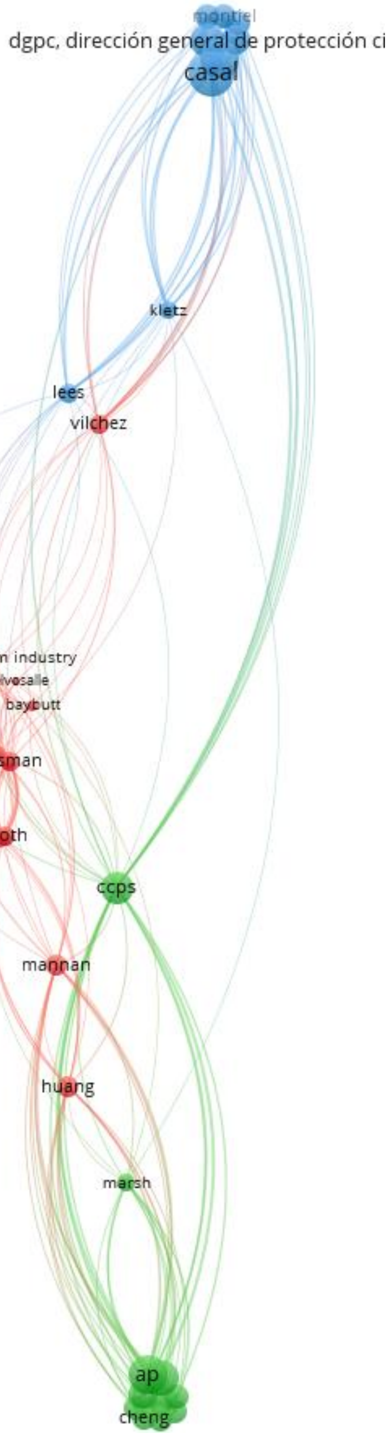

Figure 1 Bibliographic representation of failure rate and accident frequency topic in academic papers

Cheng, et.al. (2020) classifies failure metrics according to four criteria: (1) the degree to which physical failure mechanisms are explicitly incorporated; (2) the form of failure characterization; (3) the type of physical degradation model employed; and (4) the extent to which maintenance considerations are explicitly addressed. Nonetheless, Pasman (2011) outlines a practical approach to data collection, which involves defining the equipment boundary conditions (e.g., stumps, nozzles), categorizing failure modes and leak sizes, assessing external influences and loading history, and evaluating the effects of inspection intensity and maintenance practices. Where applicable, failure rates should be expressed as functions of time to account for aging effects. Data should be reported not only as point estimates but also with confidence intervals, and, where appropriate, empirical observations should be supported by theoretical analysis and enhanced through the application of Bayesian statistics.

To provide representative data for equipment failure rates in onshore process facilities, several technical studies and industry databases—such as International Association of Oil & Gas Producers (IOGP) 434-01, Offshore Technology Report (OTO) 1999-079, The Centre for Marine and Petroleum Technology (CMPT) 1999, Hazardous area classification by (Cox, Ang, and Lee), Collection of Hazard and Reliability Data (CHARAD), and Piping and Vessel Failure Probability (Thomas) 1981—compile and analyze historical accident and reliability records from multiple facilities worldwide.

IOGP 434-01 consolidates reliability and failure frequency data for critical process equipment (e.g., pressure vessels, heat exchangers, pumps, compressors, and storage tanks) based on contributions from multiple international oil and gas operators, representing millions of operating hours and decades of operational history. OTO 1999-079 provides quantified failure rates for offshore hydrocarbon processing systems, derived from United Kingdom Health and Safety Executive (UK HSE) accident investigation records and operator-reported incident databases, with specific emphasis on initiating events such as loss of containment due to corrosion, erosion, vibration, mechanical fatigue, and material degradation. The CMPT (1999) dataset, developed by Det Norske Veritas (DNV), consolidates failure rate and accident frequency data derived from a wide range of quantitative risk assessment (QRA) studies conducted worldwide. It synthesizes frequency and consequence statistics for mechanical and process failures in petrochemical facilities—including rotating machinery breakdowns, overpressure events, and structural failures—based on a large, diverse sample set from multiple sources. The CHARAD guideline, published by TotalEnergies, consolidates equipment failure rate data and accident frequency information from various authoritative sources—including CCPS, The Netherlands Organization of Applied Scientific Research (TNO), and the UK HSE—into a comprehensive reference for hazard identification and reliability assessment in process industry installations. It integrates both generic failure rate data and plant-specific performance records to support credible accident frequency estimation. Thomas (1981) presents one of the earliest systematic compilations of piping failure rate data, with a specific focus on variations by pipe diameter, pipe age, and the distinction between catastrophic ruptures and leaks.

The study adopts both pragmatic and scientifically grounded approaches, combining analyses of industrial incident reports, engineering assessments, and expert judgment, and has since served as a widely referenced baseline in numerous quantitative risk assessment. Together, these sources represent the most relevant and transferable datasets for quantifying failure frequencies in onshore process facilities, particularly where direct regional statistics are unavailable. Indonesia lacks its own generic failure rate data for use in Quantitative Risk Assessment (QRA), therefore international generic data sources are commonly used.

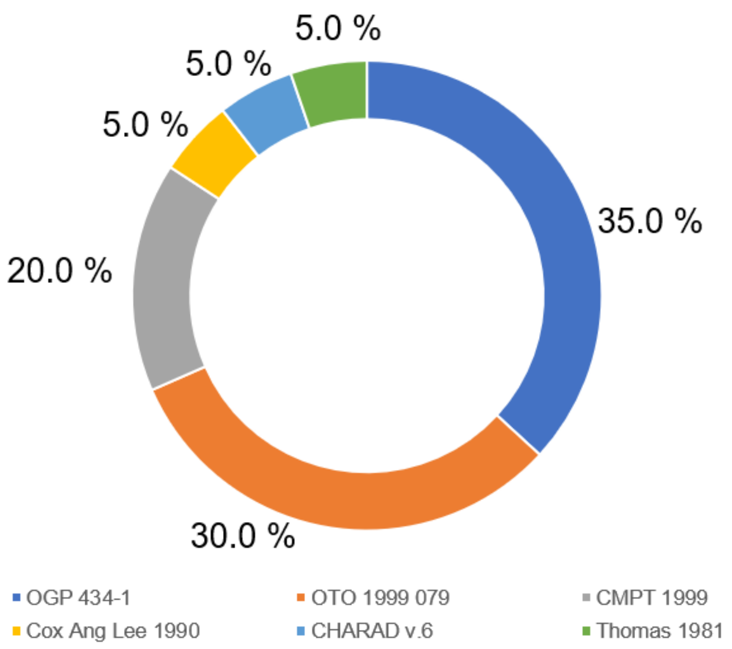

Figure 2 Process Equipment Failure Frequency Model Used In Onshore / Offshore Quantitative Risk Assessment Studies (Gathered by Mukharror from twenty (20) confidential QRA documents)

Figure 2 shows that most QRA studies for process facilities in Indonesia adopt either the IOGP 434-1 or OTO 1999-079 by UK HSE failure frequency models as the primary basis for frequency assessment. A smaller proportion of studies utilize other established references, such as CMPT (1999), Cox, Ang, and Lee (1990), CHARAD v.6, or Thomas (1981). This distribution highlights the reliance on internationally recognized datasets due to the absence of a comprehensive national database for process equipment failures. The present study aims to compile representative failure rate and accident frequency data for Indonesian onshore process facilities to support future QRA applications.

2.0 METHODOLOGY

The dataset encompasses seven process plants representing different segments of hydrocarbon-based industries in Indonesia, including oil and gas processing, gas gathering, oil gathering, and liquefied natural gas production. Although this sample reflects only a fraction of the country's overall industrial base, it captures the predominant types of hydrocarbon-related facilities operating in the region. Besides, the aggregated gas production from these seven plants also contribute to more than 65% of Indonesia gas lifting, which have positioned this sample to represent the onshore facilities with more than half of national production (BPS, 2026).

The cumulative equipment-years indicate that some facilities, such as Process Plant A with 28,895 equipment-years, have been in operation for more than two decades, reflecting mature plants with long operational histories. In contrast, several plants, particularly the gas gathering and Liquefied Natural Gas (LNG) facilities (e.g., Plants C, F, and G), exhibit comparatively lower accumulated operating years, suggesting that the majority of installations remain relatively new.

Table 1 Data Sources and Number of Operating Years.

Plant	Total number of equipment-years	Type of process plant
Process Plant A	28895	Oil and Gas Processing Plant
Process Plant B	9456	Gas Gathering Plant
Process Plant C	6305	Gas Gathering Plant
Process Plant D	5254	Gas Gathering Plant
Process Plant E	2627	Oil Gathering Plant
Process Plant F	7370	Liquefied Natural Gas Plant
Process Plant G	6030	Liquefied Natural Gas Plant

The methodology for analyzing failure rates in process industries in Indonesia – as shown in Figure 3 below – begins with defining the context, objectives, and scope of the failure rate analysis. Two primary data sources are utilized: piping and instrumentation diagrams (P&ID) and incident investigation reports. From the P&ID, a piece of process equipment such as piping, a pressure vessel, or a compressor is selected for evaluation. Once the equipment is identified, the total number of equipment items, or their length where applicable, is counted within the plant under review. The age of the selected equipment is then determined using records from the earliest revision of the P&ID. At this stage, it is essential to verify whether all process equipment listed in the P&ID has been evaluated before proceeding further.

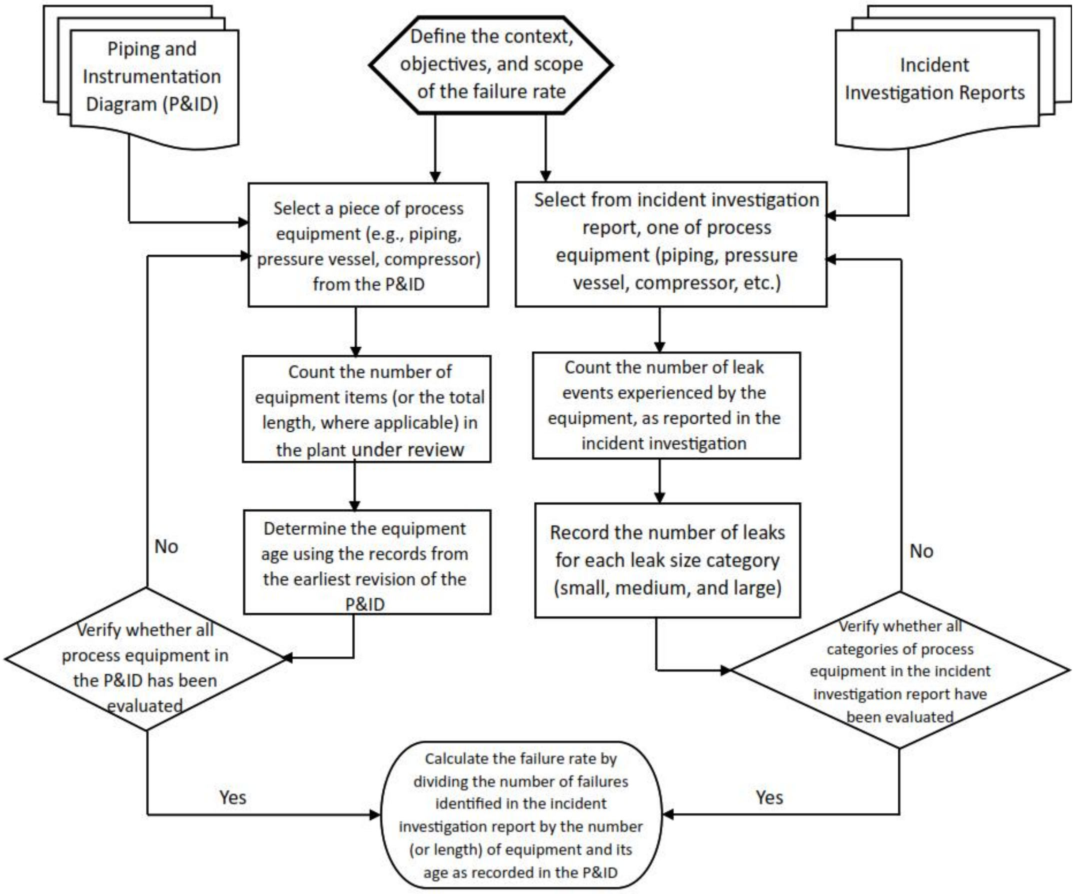

Figure 3 Methodology of Analysis of Failure Rates Of Process Equipment In Process Plants in Indonesia

In parallel, incident investigation reports are used to select a corresponding piece of process equipment for failure analysis. The number of leak events associated with that equipment is counted based on the investigation records. These leaks are then categorized to ensure a more refined understanding of failure consequences by referring to most adopted failure frequency database in Figure 2 (IOGP 434-1 and OTO 1999-079 by UK HSE). Since IOGP 434-1 provide general equation of failure rate as a function of equipment size which offer flexibility for the failure frequency calculation, the leak categories with three grading is proposed based on OTO 1999-079 by UK HSE failure frequency models. Small leak represent leak with diameter up to 10 mm, medium leak for diameter between 10 and 100 mm, and large leak or rupture for diameter more than 100 mm.

A verification step follows, confirming whether all categories of process equipment reported in the incident investigations have been covered in the analysis. Finally, the failure rate is calculated by dividing the total number of failures recorded in the incident investigation reports by associated exposure (both the number or length of equipment and its age as recorded in the P&ID). This integrative approach ensures that the derived failure rates reflect not only the frequency of incident occurrences but also the scale and operational history of the equipment, thereby offering a more reliable basis for quantitative risk analysis in the Indonesian process industry context.

In simple term, the failure rate can be calculated using following equations (Spouge, 1999)

$$Failure\ rate = \frac{Number\ of\ Incident\ recorded}{Associated\ exposure\ (number\ of\ item\ or\ number\ of\ years)} \quad \text{Equation 1}$$

The result of failure rate then compared with IOGP 434-1 and OTO 1999-079 by UK HSE to understand the trend and discrepancy. Even though these two generic datasets are collected from offshore topside facilities and onshore facilities with majority in North Sea, the release frequency between onshore and offshore should not differ significantly. This is because the more severe condition in offshore facilities already compensated in the design, inspection, and maintenance. Moreover, IOGP 434-1 dataset could also be used as appropriate for subsea completions (IOGP, 2019), which reflects the flexibility of data usage across oil and gas facilities in different locations.

Some factors need to be considered when applying generic dateset frequency to specific local conditions. Including physical characteristics of the equipment, the operating conditions, and characteristics of the management system in place. This paper, however, did not address or discuss the specific root cause on how the leak occur as well as the International standard providing generic dataset. The comparison is simply to highlight the trend and discrepancy from actual condition as the basis for validation in the future. The detail influencing factors that contribute to leakage, i.e. ageing, corrosion mechanism, etc, need further detail study.

3.0 RESULTS AND DISCUSSION

The failure rate result then grouping according to type of equipment and its associated leak diameter. All of the equipment has the failure rate unit in failure per year, except for piping, the failure will be calculated per length become failure per-m year.

Table 2 Failure Rate of Process Equipment in Indonesia.

Process Equipment Type	***Small (0 – 10 mm)***	***Medium (10 – 100 mm)***	***Large (Rupture) (> 100 mm)***
Piping (failure per m-year)	0.017	0.00946	0.00126
Vessel (failure per year)	0.004427	0.001207	0.000805
Tank (failure per year)	0.001488	0.004464	0.000496
Pump (failure per year)	0.001426	0.000535	0.000178
Compressor (failure per year)	0.02809	0.008989	0.001124

Actual failure rate then compared with two most referred international standard, which are IOGP 434-1 and OTO 1999-079. The comparison reveals substantial discrepancies for almost every equipment and leak diameter. For vessels, the Indonesian dataset indicates a small-leak failure rate of 0.004427/yr, which is about 77% higher than OTO 1999-079 and over 480% higher than IOGP 434-1 values. The differences become even more pronounced for medium and large leaks: Indonesian values are 1,107% and 1,510% higher than OTO 1999-079 data, and 516% and 4,372% higher than IOGP 434-1 data, respectively.

Table 3 Comparison of Indonesia'a Onshore Failure rate with International Standard

Process Equipment	**Failure rate**	OTO 1999-079		IOGP 434-1	
		Failure rate	Discrepancy	Failure rate	Discrepancy
Vessels, small leaks	0.004427 / yr	2.50E-03	77%	7.6E-04	480%
Compressors, small leaks	0.02809 / yr	1.20E-02	134%	4.90E-03	430%
Pumps, medium leak	0.000535 / yr	5.00E-04	7%	3.34E-04	60%
Pumps, large leak	0.000178 / yr	3.00E-05	493%	4.45E-06	3,900%
Tank, small leak	0.001488 / yr	4.99E-04	198%		
Tank, medium leak	0.004464 / yr	5.00E-05	8,828%		
Tank, large leak	0.000496 / yr	8.00E-06	6,100%		
Piping, small leak	0.017 / m-yr			1.95E-05	87,000%
Piping, medium leak	0.00946 / m-yr			2.13E-06	444,000%
Piping, large leak	0.00126 / m-yr			1.38E-06	91,000%

For compressors, Indonesian data report 0.02809/yr for small leaks, which is more than 134% higher than OTO 1999-079 and about 430% higher than IOGP 434-1. The discrepancy for medium leaks is even greater: 3,229% compared to OTO 1999-079 and 861% compared to IOGP 434-1. For large leaks, the differences are extreme, with Indonesian rates exceeding 38,600% relative to OTO 1999-079 and nearly 1,944% relative to IOGP 434-1.

In the case of pumps, the Indonesian medium leak rate (0.000535/yr) is moderately close to international data, being only 7% above OTO 1999-079 and about 60% above IOGP 434-1. However, large leaks are reported at 0.000178/yr, which is 493% higher than OTO 1999-079 and 3,900% higher than IOGP 434-1, indicating significant divergence in catastrophic event frequencies. For tanks, Indonesia's small leak failure rate (0.001488/yr) is 198% higher than OTO 1999-079, while medium and large leaks are 8,828% and 6,100% above OTO 1999-079, respectively. No comparative IOGP 434-1 data are available for tanks.

The most striking contrast appears in piping, where the Indonesian small-leak rate (0.017 per meter-year) is over 87,000% higher than IOGP's reported value, and the medium and large leak rates are 444,000% and 91,000% higher, respectively. This enormous discrepancy suggests either differences in failure definition and reporting standards or underestimation in global databases compared to empirical Indonesian incident records. Many factors can contribute to the data discrepancy, including physical characteristics of the equipment, the operating conditions, and characteristics of the management system in place. Factors related with physical characteristics of the equipment and the operating conditions could include design code, Operating environment, Process continuity, Material of construction, Cold or hot weather, Stress cycling, Fluid inside equipment, Equipment age, Welds, Operating pressure, Seismic activity, Radiography, Operating temperature, and Integrity status. Management system factor can be found on API 581 to adjust failure frequency using process safety management system approach. (IOGP, 2019)

In general, the failure rate data for process equipment in Indonesia tend to be higher than the international reference values reported by IOGP 434-1 and OTO 1999-079. This observation is consistent with findings on onshore buried hydrocarbon gas pipelines in Indonesia (Mukharror et al., 2023), which also indicated higher failure rates compared to most international datasets. Such elevated failure rates can significantly influence the outcomes of QRA studies conducted in the Indonesian context, underscoring the need for localized reliability data in risk assessment.

4.0 CONCLUSION

The comparison between Indonesian process industry failure rate data and international references (IOGP 434-1 and OTO 1999-079 by UK HSE) highlights substantial discrepancies across all equipment types. Indonesian datasets consistently report higher failure rates, in some cases by several orders of magnitude, particularly for piping, compressors, and tanks. These differences may be attributed to variations in data collection methods, reporting standards, operating conditions, and maintenance practices between Indonesia and the global references. The notably higher values for large leaks and ruptures suggest that local operating environments and inspection regimes could play a significant role in influencing reliability outcomes. While international datasets provide useful benchmarks, the results underscore the importance of developing context-specific reliability data for Indonesian industries. Ultimately, the findings emphasize the need for improved incident reporting and harmonized methodologies to ensure that failure rate analyses accurately reflect both global standards and local realities.

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