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Combined Risk Based Inspection and Fault Tree Analysis for Repetitive 3-Phase Line Piping Leakage at West Java Offshore Topside Facility

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Abstract. Hydrocarbon releases might result in serious consequences in various aspects. In addition to the contribution to environmental pollution, repetitive leakages need high repair costs. This study aim is to minimize potential repetitive leakage for other typical 3-phase piping systems. We conducted the risk assessment by adopting Risk Based Inspection (RBI) API 581 to identify risk level, calculating piping lifetime, recommended inspection plan and mitigations. The most relevant root causes can be obtained through quantitative Fault Tree Analysis (FTA). Observation and investigation was taken from eight 3-phase piping systems that experienced repetitive leakages. It has been found that the risk level of some piping systems in yellow and red areas with one pipe in an unfit condition. Next inspection and/or mitigation dates as results of RBI calculation shall be conducted to reduce risk levels and prevent leakage cases. FTA shows the most likely events are the sand problem in fluid, high CO_2 content, material deficiency, and high fluid velocity. If the root causes are known earlier, preventive mitigation can be conducted to prevent hydrocarbon release in the other 3-phase piping systems, such as application of internal coating, injection corrosion inhibitor or inspection/monitoring program.

Keywords*:* 3-phase service; Fault tree analysis; Leakage; Risk assessment; Risk based inspection

1. Introduction

Hydrocarbon releases are one of the main contributors that may lead to major accidents in the oil and gas industries. It can result in severe consequences to personnel, environment, security, business reputation, and assets. Therefore, the prevention of hydrocarbon releases is very crucial. Few studies of safety barriers proposed to prevent hydrocarbon releases have been published. Previous studies of hydrocarbon releases have basically focused on release statistics and causes of releases. The most root cause associated with verification faults, failure to comply with procedural requirements (Jan & Willy 2015). Other paper developing the technical model to describe the major immediate causes of hydrocarbon release and associated with quantitative models for assessing their frequency (Papazoglou et al. 2002). It was found that the safety climate measure was positively correlated with the frequency of hydrocarbon releases, as a result of empirical study (Trond et al. 2011). Other studies have published that 4-year campaigns had succeeded to reduce the annual number of major and significant hydrocarbon releases by 50% to explain/describe the factors that result in a 50% reduction in hydrocarbon release (Neville 2004).

The repair process that was carried out due to repetitive leakage of the piping system caused the fluid flow temporarily stop until repair process was performed. For temporary mitigation, it should be sure that the temporary materials are ready at the platform to make the fluid flow back online. Separately, piping fabrication had conducted to replace the leakage piping and immediately installed it for the critical line. This repair process needs high repair costs for repetitive leakage in the same piping system. This leakage can be caused by several factors, including availability of corrosive medium, high or low velocity, piping component failure, etc.

With that background, risk assessment is vital for safety management. Several studies have been conducted to discuss risk assessment in the pipeline, platform, or equipment that generally has a high operational risk for oil and gas companies. Some of them use qualitative, quantitative, and dynamic risk modelling methods with risk assessment tools such as fishbone diagram, bow tie, Fault Tree Analysis, etc. Varied outputs have resulted from the research; risk-based inspection, failure probability, consequence analysis, etc.

One study established a dynamic risk assessment method that combined risk levels and real-time data to predict leaks in a storage tank (Hartoyo et al. 2022). The fishbone diagram was used as a qualitative analysis method. A combined quantitative risk analysis method of risk levels and FTA was calculated using Boolean Algebra (Favour et al. 2021). Other research related to risk assessment of direct coal liquefaction process involves 885 pipes and 124 vessels. The leakage risk was evaluated with the application of the RBI. The result shows 3 risk levels of the pipes and vessels. To reduce the leakage risk, an inspection plan for equipment to leakage scenarios was proposed based on their risk level (Zhan et al. 2017).

In 2019, one study presented a model to analyze the risk of underground gas storage well integrity failure, taking into account uncertainty treatment. The bow tie model was employed to systematically depict the causal relationships of well integrity failure. To conduct quantitative risk analysis, a Bayesian network was developed to overcome the difficulties of the bow-tie approach in modeling uncertainties and conditional dependency. The occurrence probabilities of the top event and potential consequences are calculated through predictive analysis of the Bayesian network (Long et al. 2019).

There was also studied on pipelines that have potential risk of failure. RBI and FTA methods were used to minimize the possibility of damage (M. Oky et al. 2018). The application of Risk Based Inspection (RBI) is expected to be used as a system for developing efficient and effective strategies in the operation of pipelines to transport natural gas to customers and the root cause of failure is investigated by constructed FTA failure analysis diagram. Risk assessment for oil and gas pipelines laid in one ditch had performed in 2019 based on quantitative method, including risk identification, risk assessment, and risk analysis to ensure the safety of the pipeline and the surrounding environment. It used fuzzy set theory combined with fault tree analysis to calculate the failure probability of each pipeline and bow-tie diagram to realize the risk management and control of the pipeline (Peng et al. 2019).

Other research using a framework for the quantitative risk assessment of LNG-fueled vessels with respect to potential leakage. Event tree analysis (ETA) and computational fluid dynamics (CFD) simulation are integrated for the investigation of the hazard, the analysis of the consequences, and the quantification the risk of the LNG leakage (Shanshan et al. 2016).

In comparison with previous research, the quantitative analysis of RBI and FTA proposed in this paper especially the piping systems in 3-phase fluid with repetitive leakage on the topside offshore area. Eight samples of piping systems are being investigated to demonstrate these two methods. The application of RBI and FTA as risk assessment tools can provide reliability and maintainability to the piping system operations through proper inspection strategies and maintenance procedures that can minimize risks and finally can prevent repetitive leakage in the same piping systems or other piping systems with 3-phase service line.

2. Methods

In this paper, the methodology begins with a detailed study of the substances used and the process. The substances will separate based on their utilities. Some substances will be used for RBI Method and others for Fault Tree Analysis.

2.1. Risk Analysis

Risk can be defined as exposure to the chance of injury/loss or consequence of an event occurring over time (Favour et al. 2021). In mathematical terms, risk is the combination of the probability of some occurring during a period and the consequence associated with the event (see equation 1).

$$\text{Risk}\left\{\frac{\text{Consequence}}{\text{Time}}\right\} = \text{Probability}\left\{\frac{\text{Event}}{\text{Time}}\right\} \times \text{Impact}\left\{\frac{\text{Consequence}}{\text{Event}}\right\} \tag{1}$$

Risk analysis was performed to review the measurement of risk control related to potential hazards, enhance production reliability and reduce work accidents.

A risk matrix was constructed to categorize and prioritize risk events and to decide if certain risks can be accepted based on historic statistical data (Huihui 2010). Probability is plotted along one axis, increasing the magnitude from the origin, while a consequence is plotted along the other axis. Using a 5x5 risk matrix as shown in Table 1, the highest risk components are towards the upper right-hand corner. As shown in Table 1, a scale of risk matrix is divided into 3 risk levels where high risk is highlighted in the orange-red area, medium risk in the yellow area (ALARP/As Low As Reasonable Practicable), and low risk in the green area. There are 3 methods to get the risk level: qualitative, quantitative, and semi-quantitative.

Table 1 5x5 Risk Matrix

Probability Consequence	Almost Impossible (0% < X≤20%)	Very Low (Unlikely) (20% < X≤40%)	Low (Possible) (40% < X≤60%)	Medium (Likely) (60% < X≤80%)	High (Almost Certain) (80% < X<100%)
Catastrophic	5x1	5x2	5x3	5x4	5x5
Major	4x1	4x2	4x3	4x4	4x5
Moderate	3x1	3x2	3x3	3x4	3x5
Minor	2x1	2x2	2x3	2x4	2x5
Slight	1x1	1x2	1x3	1x4	1x5

ORCA software (owned by Pertamina Upstream Regional 2 Zona 5) is a quantitative method tool that was developed based on API RP 581 (2016). This software will be used to estimate the risk level, calculate the estimated life, and propose the next inspection or mitigation plan for related piping systems with repetitive leakage (Operation and Surface Facilities Team 2022). Although this software is built based on API RP 581 (2016), adjustment are expected in damage factors, consequences, and inspection/mitigation algorithms.

The calculation of the risk level involves the determination of probability of failure (PoF) combined with consequence of failure (CoF). The probability of failure is determined as a product of generic failure frequency, *gff*, damage factor $D_f(t)$, and a management system factor F_{MS} (see equation 2).

$$P_f = gff.F_{MS}.D_f(t) \tag{2}$$

where *gff* is intended to be the failure frequency prior to any specific damage occurring from exposure to the operating environment. The damage factor is applied to a component based on a specific damage mechanism while the management system factor is applied equally to all components within a plant. In this paper, the value of F_{MS} was assumed equal to 1.

There are four major consequence categories analyzed for calculating CoF: flammable and explosive consequence CA_{cmd}^{flam} CA_{inj}^{flam}, toxic consequence CA_{inj}^{tox}, non-flammable & non-toxic releases CA_{inj}^{nfnt}, and final consequences area (see equation 3).

$$CA = \max\left[CA_{cmd}, CA_{inj}\right] \tag{3}$$

Beside consequences area, there are several costs associated with any failure of equipment in a process plant: cost of equipment repair or replacement FC_{cmd}, cost of damage to surrounding equipment in affected areas FC_{affa}, costs associated with production losses and business interruption as a result of downtime to repair or replace damaged equipment FC_{prod}, costs due to potential injuries associated with a failure FC_{inj}, and environmental clean-up costs $FC_{environ}$ (see equation 4).

$$FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ} \tag{4}$$

Table 2 indicates the ranges of PoF and CoF which are used to present the categories of the risk matrix. PoF is expressed in terms of the number of failures over time and the CoF is expressed in area or financial terms.

Table 2 Numerical Values Associated with the PoF and Area & Financial-Based CoF Categories

Probability Category		Consequence Category		
Category	Probability Range	Category	Area Range (m²)	Financial Range ($)
1	PoF ≤ 3.06E -05	A	CA ≤ 9.29	FC ≤ 1,000
2	3.06E -05 < PoF ≤ 3.06E -04	B	9.29 < CA ≤ 92.9	1,000 < FC ≤ 10,000
3	3.06E -04 < PoF ≤ 3.06E -03	C	92.9 < CA ≤ 929	10,000 < FC ≤ 100,000
4	3.06E -03 < PoF ≤ 3.06E -02	D	929 < CA ≤ 9290	100,000< FC ≤ 1,000,000
5	PoF > 3.06E -02	E	CA > 9290	FC > 1,000,000

2.2. *Estimated Life*

An Estimated Life (EL) as a function of the difference of the last known thickness (t_{rd}) with a minimum required thickness (t_{req}) and corrosion rate (CR) (see equation 5).

$$EL = \frac{t_{rd} - t_{req}}{CR} \tag{5}$$

where t_{req} is calculated in equation 6 as below.

$$t_{req} = \frac{P\,R}{(SE + 0.4P)} \tag{6}$$

P is defined as 130% MOP (Maximum Operating Pressure); R (Outside radius); S (Maximum allowable stress); E (Joint efficiency) (Surface Facilities Team 2022).

2.3. *Risk Based Inspection*

An important approach in determining the next inspection plan is using the target date. In most cases, probability of failure increases with time as equipment deterioration progresses. ORCA software provides an iteration linear approach for determining the target date considering the risk target as the maximum POF. The value of PoF target is adjustable based on the Company's necessity, as shown in Figure 1.

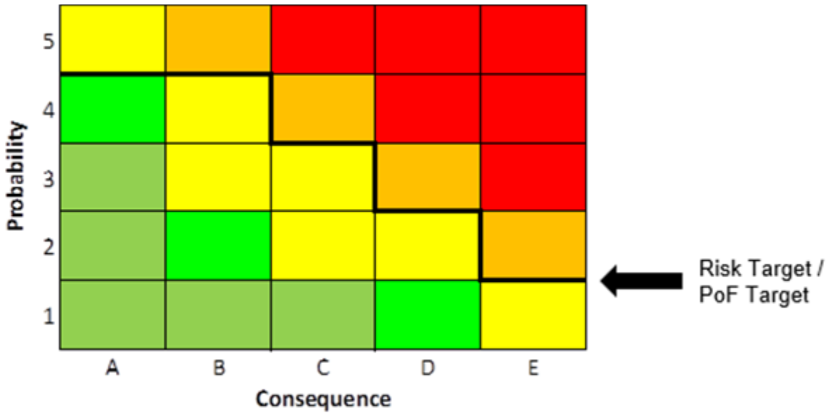


Figure 1 Risk Target/PoF Target in Risk Matrix

When or before the risk target is reached, an inspection of the equipment is recommended based on the component damage mechanisms having the highest calculated damage factor. Inspection planning is based on the fact that at some point in time, the risk will reach a specified risk target.

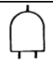
2.4. *Root cause/hazard identification*

In order to construct a Fault Tree Analysis, identification of the root causes or hazards that causes hydrocarbon leakage shall to be performed. Internal corrosion mechanisms are known as causes of repetitive hydrocarbon leakage for all piping systems that are being investigated. Regarding to that, some root causes or hazards such as corrosive medium, material deficiency, and others shall be identified and will be used as basic events in FTA.

2.5. *Fault Tree Analysis*

Fault Tree Analysis (FTA) is a technique to identify and analyze factors that may contribute to an unwanted specified event (Favour et al. 2021; Jose et al. 2017). This tool is a graphical interpretation method that uses special symbols to express the logical relationship between events and causality (Jielin & Lin 2022). FTA is used to analyse the problem where the top of the fault tree (top event) and the end of the event (basic event). A fault tree can be used as a qualitative method to ascertain likely causes and ways in which failure occurs or a quantitative method to estimate the likelihood of the top event from the likelihood of basic events or both (Favour et al. 2021). Fault Tree Analysis uses some events symbols and logic gate symbols as shown on Table 3.

Table 3 Symbols used in fault trees

Symbol	Meaning	Description
	AND gate	The output event happens only if all input events happen
	OR gate	The output event occurs if any of the input events happen
	Top event	An event at the top of the fault tree and prompt an investigation into the system failure
	Intermediate event	An event that is generally caused by one or more events
	Basic event	An event as the root cause of the top event. They sit at the bottom of the fault tree
	Undeveloped event	An event doesn't have enough information and is placed as a subtree.

For the qualitative method, Boolean Algebra is used to simplify difficult logic sequences and resulting minimal cut set. OR gate will be replaced with mark '+' and AND gate with mark 'x'. For quantitative method, the failure frequency or failure rate of basic events can be calculated for each piping system (see equation 7).

$$\lambda = \frac{k}{t} \tag{7}$$

where k is defined as the number of failures and t is the operating time. In order to calculate the top event's failure rate, minimal cut set approach in Boolean Algebra or gate by gate approach can be used.

2.6. *Case Study*

Located on the topside platform offshore northwest Java, 8 piping systems with 3-phase lines (water, oil, and gas) that has been suffered repetitive leakage in the last 3 years are being investigated. Those lines have identification as line 1 until line 8.

3. Results and Discussion

All data are taken from Pertamina Upstream Regional 2 Zona 5. Based on the data obtained, it can use quantitative analysis to perform RBI method using ORCA software. This software allows the user to view the risk level for 3 interval periods (IP1, IP2, and IP3) with 24 months duration. The risk result appears on a 5x5 matrix as shown in Table 4 and plotted on 2 axes: PoF and CoF. Except for line 3, quantitative analysis has not been applied yet because this piping is categorized as a riser. For line 8, due to an inactive line, quantitative analysis has not been applied. ORCA also calculates estimated life, target date, and next inspection or mitigation plan for related piping.

Table 4 Summary of ORCA results for risk level and estimated life

Line No.	IP 1	IP 2	IP 3	Estimated Life (year)
Line 1	1E	1E	2E	0
Line 2	4D	4D	4D	21.24
Line 4	2D	2D	3D	52.78
Line 5	1D	2D	3D	33.92
Line 6	2D	2D	3D	30.38
Line 7	1D	1D	1D	72.46

Three of the lines have initial risk levels in yellow, two lines in green, and one line in red area for IP1. But, for IP2 and IP3, the risk level will go up and stay in the orange-red area for 5 service lines. The increasing risk level due to the projection of active damage mechanisms for that lines.

An inspection or mitigation plan will be performed based on the calculation of estimated life; less than 5 years for the mitigation plan and more than 5 years for the inspection plan. Due to estimated life being 0 years, line 1 shall be performed a mitigation plan and an inspection plan is conducted for the other lines.

Table 5 shows the inspection or mitigation date plan for each piping system. ORCA software will calculate the initial target date. The final target date will be adjusted based on the two criteria; the maximum value is IP3 (72 months) and for mitigation plan is the minimum duration between the initial target date and estimated life.

Table 5 Summary of ORCA results for inspection or mitigation date plan

Line No.	Initial Target Date (month)	Final Target Date (month)	Next Inspection/mitigation Plan
Line 1	39	0	March 1, 2019
Line 2	0	0	June 29, 2020
Line 4	34	34	July 21, 2024
Line 5	34	34	July 21, 2024
Line 6	3	3	December 6, 2021
Line 7	139	72	September 20, 2027

For line 1, due to EL less than 5 years, a mitigation plan shall be performed. Final target date is chosen between minimum initial target date and estimated life; 0 months. For line 7, final target date shall follow the rule of maximum final target date value; IP3 (72 months). Other final target dates shall follow initial target date. Initial target date will be zero if the risk level in IP1 stays above risk target.

The next inspection/mitigation plan date refers to the last inspection/commissioning date. Due to this ORCA assessment being performed in the latest 2022, if there is any next inspection/mitigation plan date has passed, it shall be conducted immediately.

Fault Tree Analysis (FTA) was constructed using gate symbols to describe the relationship between events as shown in Figure 2. FTA was used to determine all the root causes of repetitive hydrocarbon release in 3-phase line as top event. The repetitive leakage can be caused by equipment failure or internal environmental effects. Material deficiency or piping component failure will contribute to equipment failure. Internal environmental effect has two contributors; internal corrosion and inadequate corrosion detection. There are some factors that cause internal corrosion and input them as basic events; high fluid velocity, low fluid velocity turbulent flow, low pH, high internal pressure, high CO2 content, and fluid-containing sand.

Identification of minimal cut sets is one of the most important qualitative analysis of a fault tree. A cut set in a fault tree is a set of basic events whose (simultaneous) occurrence ensures that the top event occurs. A cut set that cannot be reduced without losing its status as a cut set defined as minimal cut set. The calculated minimal cut sets for this FTA structure using Boolean Algebra are; X1, X2, X10*X3, X10*X4, X10*X5, X10*X6, X10*X7, X10*X8, X10*X9.

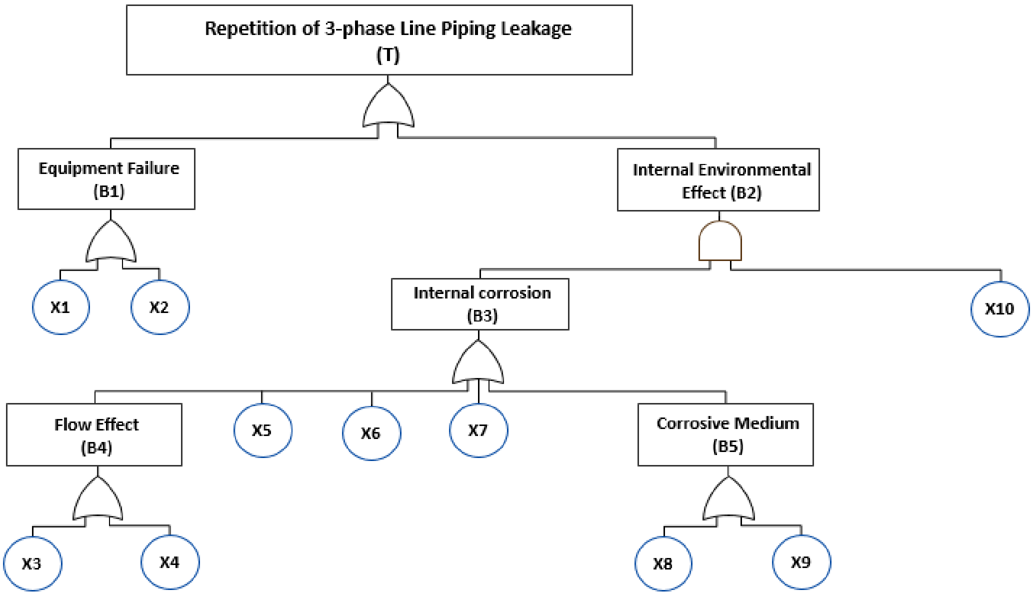


Figure 2 FTA showing repetition of 3-phase line piping leakage

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Based on hydrocarbon leakage data from 2001 -2022, failure frequency of each basic event can be calculated using equation 7. This failure frequency was calculated for each line because they have different operating times. The maximum failure frequency for material deficiency as basic event for X1 from all piping systems is 5/year. It was contributed by line 4. Other failure frequencies for each basic event can be shown in Table 6. High CO_2 content, material deficiency, high fluid velocity, and fluid-containing sand as the primary root causes of piping system leakage due to having the highest score of failure frequency.

Table 6 Failure frequencies of basic events

Index	Description	Max. Failure Frequency ($year^{-1}$)
X1	Material deficiency	5 (line 4)
X2	Component failure	3 (line 7)
X3	High fluid velocity	5 (line 4)
X4	Low fluid velocity	1.8 (line 5)
X5	Turbulent flow	3 (line 7)
X6	Low pH	1.8 (line 5)
X7	High internal pressure	3 (line 7)
X8	High CO_2 content	5 (line 4)
X9	Fluid-containing sand	5 (line 4)
X10	Inadequate corrosion detection	1 (line 4 & line 7)

Table 7 demonstrates failure frequencies of the top event (T) for each line as a result of the FTA quantitative method. With knowing the failure frequency of basic events, the calculation of top event can be performed based on the gates that connect them (gate by gate approach) in FTA structure.

To verify this FTA structure, a calculation of failure frequency based on actual information of hydrocarbon releases was performed. The comparison of top event failure frequencies as FTA structure and failure frequency based on the actual information of hydrocarbon releases is shown in Table 7. The comparison indicates failure frequency results of FTA structure show close to failure frequency based on actual information with maximum discrepancy is 36%.

Table 7 *Failure Frequencies* ($year^{-1}$) of *Top Event*

Line Number	FTA Failure Frequency ($year^{-1}$)	Repetitive Leakage Failure Frequency (k/t) ($year^{-1}$)	Discrepancy (%)
Line 1	0.43	0.375	-14.7
Line 2	0.17	0.125	-36
Line 3	0.52	0.4	-30.0
Line 4	6.5	5.5	-18.2
Line 5	3.52	2.6	-35.4
Line 6	0.12	0.09	-26
Line 7	3.9	3	-30
Line 8	0.09	0.075	-20

This discrepancy might be occurred due to manual calculations of quantitative analysis are incorrectly employed. Regarding fault trees developed based on analysis and experience, it can produce differences in FTA structure. It probably occurred a potential error of calculation if failure paths are omitted. It will impact failure frequency results due to differences in calculation using Boolean Algebra. In general, this FTA structure can be used to explain the relation of top event; repetitive leak occurrence in 3-phase line with the root causes of top event.

4. Conclusions

Risk assessment is vital for safety management. Hydrocarbon release could lead to loss of lives, environmental defects, business reputation, and economic losses, so there is a need for a comprehensive risk evaluation method to identify risk sources before things go wrong.

This paper established a quantitative risk assessment to get the risk level, estimated life, and inspection or mitigation date plan of each related service 3-phase line. By implementation of risk-based inspection, repetitive leakage for that lines can be minimized. The risk level for the first interval period is; three lines in yellow, two lines in green, and one line in red. Based on the calculation of estimated life, 5 lines are in fit condition, and one line is unfit. Using FTA, it has been found that 8 minimal cut sets could be the occurrence of the top event. As a quantitative analysis, the failure frequencies of all basic events were obtained. The most likely event as root causes of hydrocarbon release are sand problems, high CO_2 content, material deficiency, and high fluid velocity. Preventive mitigation shall be prepared after knowing the primary root cause of repetitive leakage to minimize potential repetitive leakage for other typical 3-phase piping systems, such as corrosion inhibitor injection, inspection or monitoring program, material selection study, application of internal coating, etc.

In future work, to get a complete and more accurate analysis and its failure mode and frequencies, relevant historical data for the repetitive leakage is needed. It will complete the FTA structure and get more accurate quantitative analysis results. In addition, in order to get failure probability of basic events as root cause of leakage, Bayesian Network has a flexible framework to describe it better.

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