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Barrier and operational risk analysis of hydrocarbon releases (BORA-Release) Part II: Results from a case study

Snorre Sklet [a,*], Jan Erik Vinnem [b], Terje Aven [b]

[a] *Department of Production and Quality Engineering, The Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*

[b] *University of Stavanger (UiS), NO-4036 Stavanger, Norway*

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Abstract

This paper presents results from a case study carried out on an offshore oil and gas production platform with the purpose to apply and test BORA-Release, a method for barrier and operational risk analysis of hydrocarbon releases. A description of the BORA-Release method is given in Part I of the paper. BORA-Release is applied to express the platform specific hydrocarbon release frequencies for three release scenarios for selected systems and activities on the platform. The case study demonstrated that the BORA-Release method is a useful tool for analysing the effect on the release frequency of safety barriers introduced to prevent hydrocarbon releases, and to study the effect on the barrier performance of platform specific conditions of technical, human, operational, and organisational risk influencing factors (RIFs). BORA-Release may also be used to analyse the effect on the release frequency of risk reducing measures.

Keywords: Risk analysis; Hydrocarbon release; Loss of containment; Safety barrier; Organisational factor

1. Introduction

The Petroleum Safety Authority Norway (PSA) focuses on safety barriers in their regulations relating to management in the petroleum activities [1] and requires that it shall be known what barriers have been established, which function they are intended to fulfil, and what performance requirements have been defined with respect to technical, operational, and organisational elements that are necessary for the individual barrier to be effective.

These requirements and a recognition of the insufficient modelling of human, operational, and organisational factors in existing quantitative risk analyses (QRAs) were the background for the BORA project [2]. The aim of the BORA project is to perform a detailed and quantitative modelling of barrier performance, including barriers to prevent the occurrence of initiating events (like hydrocarbon release) as well as consequence reducing barriers. One of the activities in the BORA project was to develop BORA-Release, a method suitable for qualitative and quantitative analyses of hydrocarbon release scenarios (see Part I of the paper [3] and [4]). The method was tested in a case study on a specific offshore oil and gas producing platform on the Norwegian Continental Shelf. The purpose of the case study was to determine the platform specific hydrocarbon release frequencies for selected systems and activities for selected release scenarios and assess whether or not BORA-Release is suitable for analyzing the effect of risk reduction measures and changes that may increase the release frequency.

The objective of this paper is to present and discuss the results from the case study with emphasis on discussions about whether or not the method is useful for analysing the effect of safety barriers and risk reducing measures. In the case study, BORA-Release was used to analyse the release frequency considering the effect of safety barriers introduced to prevent hydrocarbon release and analyse the effect on the barrier performance of platform specific conditions of technical, human, operational, as well as organisational risk influencing factors (RIFs).

This paper contains four main sections where this first section describes the background and the purpose of the paper.

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* Corresponding author. Tel.: +47 73 59 29 02; fax: +47 73 59 28 96.
E-mail address: snorre.sklet@sintef.no (S. Sklet).

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The next section explains how the case study was carried out, the basis for the case study with respect to selection of release scenarios for detailed analysis, and relevant descriptions of the technical systems, operational activities, and conditions. Section three presents the results from the qualitative and quantitative analyses of the selected scenarios and the overall results. A discussion of the results and experiences from the case study, and some conclusions are presented in section four.

2. Case study description

The BORA-Release method is described in Part I of the paper [3], and the qualitative and quantitative analyses of the risk related to hydrocarbon releases comprise the following main steps:

(1) Development of a basic risk model including hydrocarbon release scenarios and safety barriers.
(2) Modelling the performance of safety barriers.
(3) Assignment of industry average probabilities/frequencies and quantification based on these probabilities/frequencies.
(4) Development of risk influence diagrams.
(5) Scoring of risk influencing factors (RIFs).
(6) Weighting of risk influencing factors.
(7) Adjustment of industry average probabilities/frequencies.
(8) Recalculation of the risk in order to determine the platform specific risk.

The basis for development of the basic risk model in the case study was 20 hydrocarbon release scenarios described in [5]. Three scenarios were selected for detailed analyses:

A. Release due to valve(s) in wrong position after maintenance.
B. Release due to incorrect fitting of flanges or bolts during maintenance.
C. Release due to internal corrosion.

The selection was made after discussions between personnel from the oil company and project team members. The main arguments for selecting these scenarios were: (i) leak statistics showed that these scenarios are important contributors to the total leak frequency and (ii) the scenarios provide a good range of cases to test the method.

The activity flowline inspection was selected as basis for analysis of scenarios A and B. A flowline is a line segment between an automatic flow valve (AFV) in the valve tree and the production or test header. There may be up to 30–40 flanges on each flowline, and between 5 and 15 of them are disassembled during a flowline inspection. Flowline inspections are performed by visual inspections in order to reveal corrosion in the pipes, flanges, and instrument fittings on the flowlines. Each flowline is inspected at least twice a year. The inspector plans the inspection and identifies inspection points. The area technician is responsible for shutdown of the actual well and isolation, depressurization, and draining of the actual flowline. The inspections are carried out while the other wells are producing. The mechanics disassemble and assemble the flowlines zone by zone and install new bolts and gaskets in the flanges after each inspection. The inspector carries out the inspection and decides whether or not some pipe spools need to be changed due to degradation. Findings from the inspection are documented in a specific database. The area technician is responsible for execution of a leak test prior to start-up of normal production, while a central control room (CCR) technician monitors the pressure. Two service point valves (SP1/SP2) are used during the leak test and may be left in wrong position after the inspection. The valves are operated by a single area technician and there is no isolation plan or valve list showing the valve positions for a flowline inspection. No procedure describes the activity since the leak test is a routine operation for the area technicians, but the result from the final (successful) leak test is documented in the platform log book.

A hierarchical task analysis (HTA) was performed for the flowline inspection activity in order to get an understanding of the work process. The top structure of the HTA is shown in Fig. 1. The detailed HTA was reviewed by operational personnel and discussed in a workshop.

In order to develop and make detailed descriptions of the release scenarios, two workshops were arranged. Draft descriptions of the release scenarios based on review of documentation were developed prior to the workshops as basis for discussion. Scenarios A and B were discussed in the first workshop and scenario C was discussed in the second workshop. Operational personnel from the platform and safety specialists from the company attended the first workshop while corrosion specialists from the oil company also attended the second workshop.

The analyses of scenarios A and B were carried out strictly according to the general method description and are described in the following. The analysis of scenario C differed somewhat from the general method description and is described afterwards.

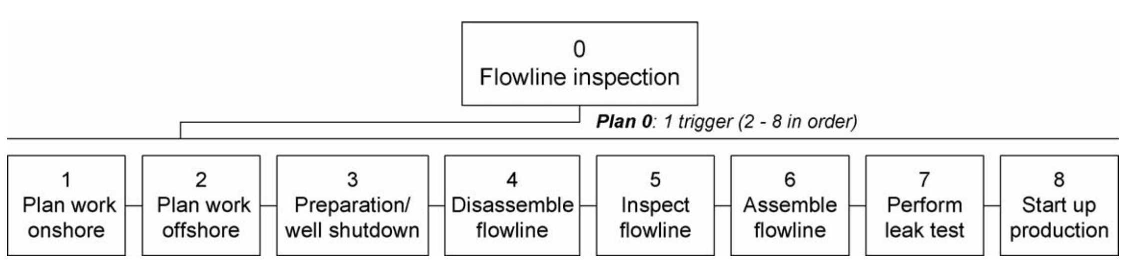

Fig. 1. Hierarchical task analysis (top structure) of a flowline inspection.

Two additional workshops, with operational personnel from the platform and safety specialists from the oil company, were arranged in order to model the performance of the safety barriers, identify RIFs and develop risk influence diagrams, and weight the RIFs for scenarios A and B. The RIF-framework described in Part I of the paper was used as basis for the identification of RIFs. The weights were established by common agreement from discussions in the workshop. Firstly, the most important RIF for each basic event was identified and assigned a relative weight equal to 10. Thereafter, the other RIFs were given weights relative to the most important one on the scale 10–8–6–4–2 (see Part I for more details).

The industry average input data were discussed in the workshops and some input data were established based on discussions during the workshops. The assignment of industry average probabilities for human errors was primarily based on data from THERP [6].

The scoring of the RIFs was based on an analysis of answers on a questionnaire from a survey of the risk level on the Norwegian Continental Shelf (RNNS-project) [7]. Further information about the scoring is given in [8].

Revised input probabilities/frequencies were established by the analysts as described in the method description (Part I) using the formula:

$$P_{\text{rev}}(\text{A}) = P_{\text{ave}}(\text{A})\sum_{i=1}^{n} w_i Q_i \qquad (1)$$

where $P_{\text{ave}}(\text{A})$ is the industry average probability of occurrence of event A, w_i the weight (importance) of RIF no. i for the event, and Q_i is a measure of the status of RIF no. i. The status varies from A (best practice in the industry) to F (worst practice in the industry), where C corresponds to industry average. n is the number of RIFs for each basic event. The calculation of Q_i is described in detail in Part I of the paper. In formula (1),

$$\sum_{i=1}^{n} w_i = 1 \qquad (2)$$

The revised platform specific probabilities/frequencies were used as input in the risk model in order to recalculate the release frequencies for the selected scenarios.

Analysis of scenario C focused on the process segment between the separator and the pipeline. This segment is mainly made of carbon steel and the pipes are not insulated. The pressure is 13–20 bars upstream of the production pump, and 23–35 bars on the downstream side of the pump. The temperature varies from 70 °C in the main flow pipes to 10 °C in the dead legs. The two main differences in the analysis of scenario C were: (1) an overall RIF-analysis was not carried out, but the effects of changes were studied based on sensitivity analyses and (2) fault tree analysis was not used for quantitative analysis of the inspection effectiveness. The performance of the safety barrier inspection was analysed based on a method described by API [9], and assessment of the practice on the platform. Several workshops were arranged to discuss the method used for analysis of the corrosion scenario and the current status of corrosion and inspection on the platform. In addition, results from the last inspection were reviewed in order to predict the corrosion rate within the system.

3. Results from the case study

3.1. Scenario A

The following form contains a description of scenario A.

Scenario name
Release due to valve(s) in wrong position after flowline inspection

General description
Release due to valve(s) set in wrong position after flowline inspection may occur if the area technician forget to close some SP valves prior to start-up of production

Initiating event
Valve(s) in wrong position after flowline inspection

Operational mode when failure is introduced
During maintenance, i.e., while disconnecting hoses after the leak test

Operational mode at time of release
Release may occur during start-up after maintenance.

Barrier functions	*Barrier systems*
The release may be prevented if the following barrier functions are fulfilled: • Detection of valve(s) in wrong position	The release may be prevented if the following barrier systems function: • The system for self control/use of checklist in order to detect possible valve(s) in fail position • The system for third party control of work (actually, no third party control of work is required in this scenario)

Assumptions

- On the flowline system, SP1- and SP2-valves may be in wrong position after the flowline inspection. In addition, the two valves on the closed drain system connected to the hoses may be in wrong position after the inspection.
- The area technician operates these valves (depressurization, draining, and pressurization during the leak test).
- There is no third party control of the work performed by the area technician.
- It is assumed that corrective action is carried out if a valve is revealed in wrong position.
- These valves are used during the leak test where the purpose is to test the tightness of the flanges, and the valves may be left in open position after the leak test.
- A leak due to an open valve on the flowline system will most probably be detected during start-up of normal production, either manually by the area technician, or automatically by gas detectors in the area. The area technician will stay in the wellhead area during start-up of production and may manually close the open SP-valve, or close the choke valve.

The barrier block diagram for scenario A is shown in Fig. 2. The fault trees for the safety barriers "Self control of work" (A1) and "third party control of work" (A2) are illustrated in Figs. 3 and 4. Further, the risk influence diagrams for the basic events A02 (see Table 1), A11, A12, and A13 are shown in Figs. 5–8, respectively.

Table 1 summarizes all input data, weights, scores for all RIFs, and the adjustment factors (MF) for scenario A. $P_{\text{low}}(\text{A})$ denotes the lower limit of $P_{\text{rev}}(\text{A})$ and $P_{\text{high}}(\text{A})$ denotes the upper limit of $P_{\text{rev}}(\text{A})$. s_i denotes the status of the RIF no i. MF denotes

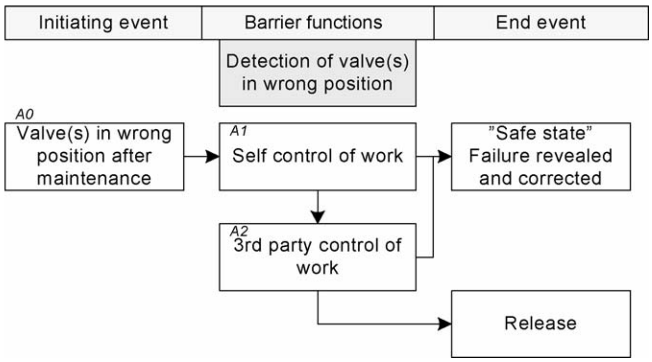

Fig. 2. Barrier block diagram for scenario A.

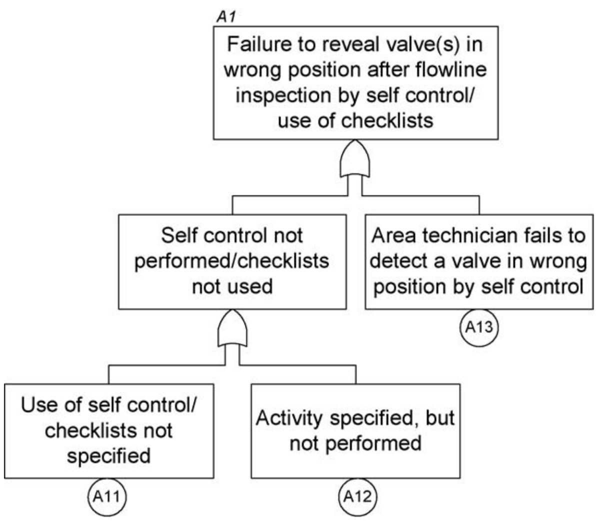

Fig. 3. Fault tree for barrier A1.

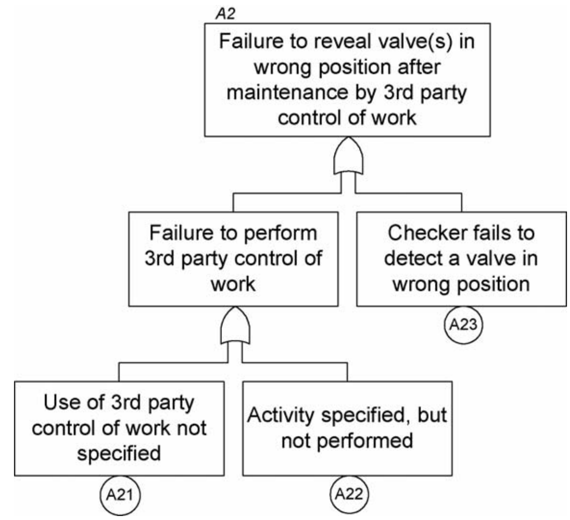

Fig. 4. Fault tree for barrier A2.

the modification factor calculated by use of formula (1) and is calculated as:

$$\mathrm{MF} = \sum_{i=1}^{n} w_i Q_i \qquad (3)$$

The results from the quantitative analysis of the release frequency due to valve(s) in incorrect position after flowline inspection are shown in Table 2 (see, e.g., [10] for information about quantitative fault tree analysis). The release frequency due to valve(s) in wrong position after flowline inspection by use of industry average data is 0.028 per year, while the corresponding frequency by use of adjusted input probabilities allowing for platform specific conditions of the identified RIFs is 0.041 per year. This implies an increase in the release frequency by 46% from scenario A by use of the revised input data. The frequency of the initiating event has increased by 28% (from 0.084 to 0.11 per year), while the probability of failure of barrier A1 (self control) has increased by 14% (from 0.34 to 0.38).

3.2. Scenario B

Scenario B, release due to incorrect fitting of flanges or bolts during flowline inspection, includes leaks due to tightening with too low or too high tension, misalignment of flange faces, damaged bolts, etc. The initiating event is incorrect fitting of flanges or bolts after flowline inspection. The operational mode when failure is introduced is during maintenance, and the release may occur during start-up after maintenance, or later during normal production. The release may be prevented if the following safety functions are fulfilled; detection of incorrect fitting of flanges

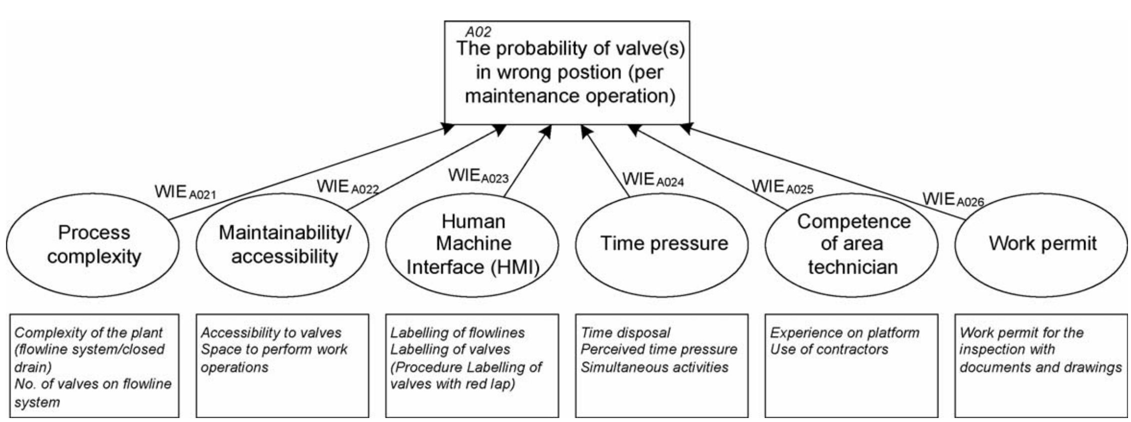

Fig. 5. Risk influence diagram for basic event A02.

Table 1
Scenario A—industry average probabilities/frequencies, weights, scores, and revised probabilities/frequencies

Basic event	P_{ave}	P_{low}	P_{high}	Basic event/RIF	w_i	s_i	MF	P_{rev}
A01	$n_A = 28$			No. of flowline inspections per year				
A02	0.003	0.001	0.009	*P* (valve(s) in wrong position after maintenance)			1.29	0.0039
				A021 Process complexity	2	C		
				A022 Maintainability/accessibility	2	C		
				A023 HumanMachine interface (HMI)	2	D		
				A023 Time pressure	10	D		
				A024 Competence of area technician	10	C		
				A025 Work permit	2	C		
A11	0[a]			*P* (Failure to specify self control)				
				A11 Program for self control				
A12	0.010	0.003	0.030	*P* (Failure to perform self control when specified)			1.51	0.015
				A121 Work practice	10	D		
				A122 Time pressure	10	D		
				A123 Work permit	6	C		
A13	0.33	0.066	0.66	*P* (Failure to detect valve in wrong pos. by self control)			1.13	0.37
				A131 HMI	2	D		
				A132 Maintainability/accessibility	2	C		
				A133 Time pressure	10	D		
				A134 Competence of area technician	10	C		
				A135 Procedures for self control	2	C		
				A136 Work permit	4	C		
A21	1.0[b]			*P* (Failure to specify third party control)				
				A211 Program for third party control				
A22	0.01	0.002	0.05	*P* (Failure to perform third party control of work)			2.03	0.02
				A221 Work practice	10	D		
				A222 Time pressure	10	D		
				A223 Work permit	6	C		
A23	0.1	0.02	0.5	*P* (Checker fails to detect valve in wrong position)			1.53	0.15
				A231 HMI	2	D		
				A232 Maintainability/accessibility	2	C		
				A233 Time pressure	10	D		
				A234 Competence of area technician	10	C		
				A235 Procedures for self control	2	C		
				A236 Work permit	4	C		

[a] Self control is specified in this case as the probability of failure to specify self control is 0.
[b] Third party control of work is not specified as the probability of failure to specify third party control is 1.

or bolts during maintenance, and detection of release prior to normal production. The following barrier systems fulfil these functions:

- A system for self control of work (visual inspection by mechanic) may detect incorrect fitting of flanges or bolts prior to start-up of normal production.

Table 2
Scenario A—results from calculations

Event	Industry average probabilities/frequencies	Revised probabilities/frequencies
f(A0)[a]	0.084	0.11
$P_{Failure}$(A1)[b]	0.34	0.38
$P_{Failure}$(A2)[c]	1.0	1.0
λ_A[d]	0.028	0.041

[a] Frequency of valves in incorrect position after inspection per year.
[b] Probability of failure to reveal failure by self control.
[c] Probability of failure to reveal failure by third party control.
[d] Release frequency from scenario A per year.

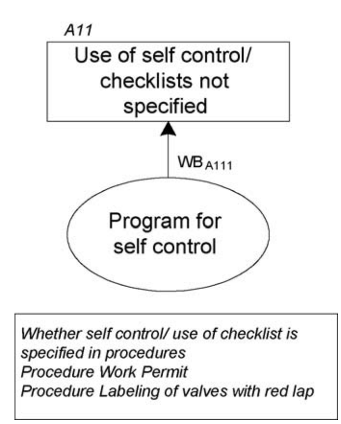

Fig. 6. Risk influence diagram for basic event A11.

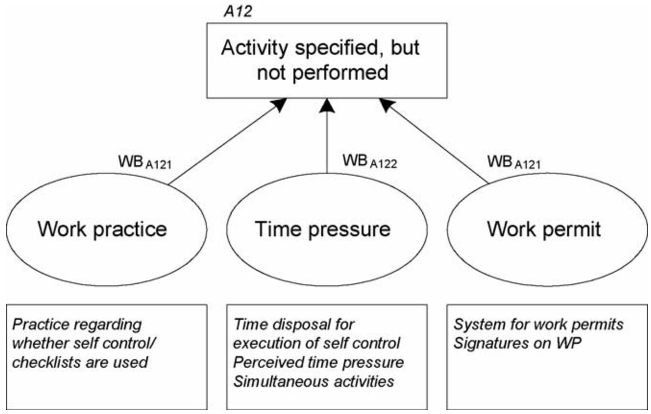

Fig. 7. Risk influence diagram for basic event A12.

- A system for third party control of work (by inspector or area technician) may reveal failures prior to assembling of the system or prior to start-up of production.
- A system for leak testing may reveal potential failures prior to start-up of production. The leak test may be carried out in two ways: (1) by use of glycol/water or (2) by use of pressurized injection water.

The results from scenario B are not described as detailed as the results from scenario A since the principles in the method already is illustrated, but the barrier block diagram for scenario B is shown in Fig. 9. Neither the fault trees of the barriers, nor the risk influence diagrams are shown since the principles are similar as used in scenario A.

Table 3 summarizes all input data, weights, scores for all RIFs, as well as the adjustment factors for scenario B.

The results from the quantitative analysis of scenario B are shown in Table 4. The release frequency due to incorrect fitting of flanges or bolts during flowline inspection is 0.0012 per year by use of industry average data. The corresponding release frequency by use of adjusted input probabilities allowing for platform specific conditions of the RIFs is 0.0038 per year. Consequently, the release frequency due to scenario B has increased by 214%. The frequency of the initiating event (no. of valves in incorrect position after inspection) has increased by 27% from 0.84 to 1.064 per year. The probability of failure to detect release by self control has increased by 10% (from 0.34 to 0.37) and the probability of failure to detect release by third party control has increased by 36% from 0.11 to 0.15. Finally, the probability of failure to detect release by leak test has increased by 66% from 0.040 to 0.066.

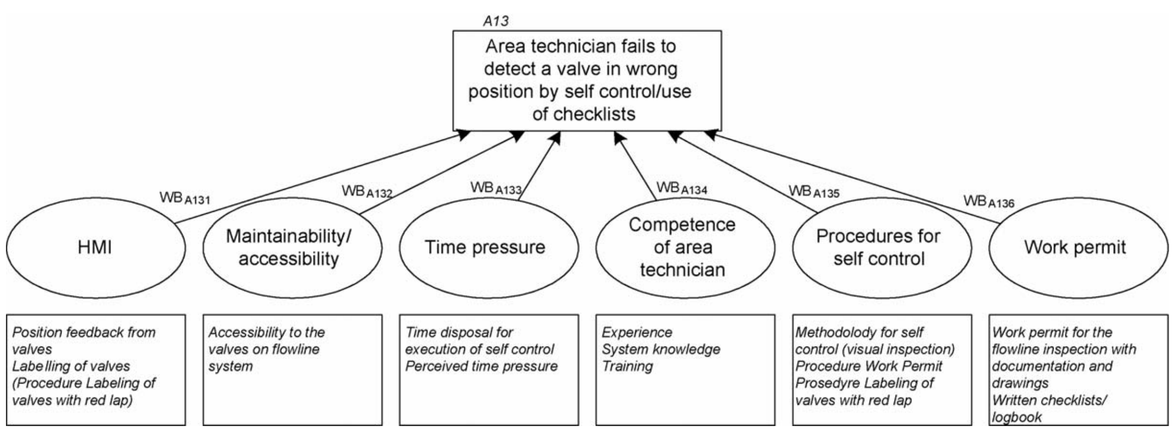

Fig. 8. Risk influence diagram for basic event A13.

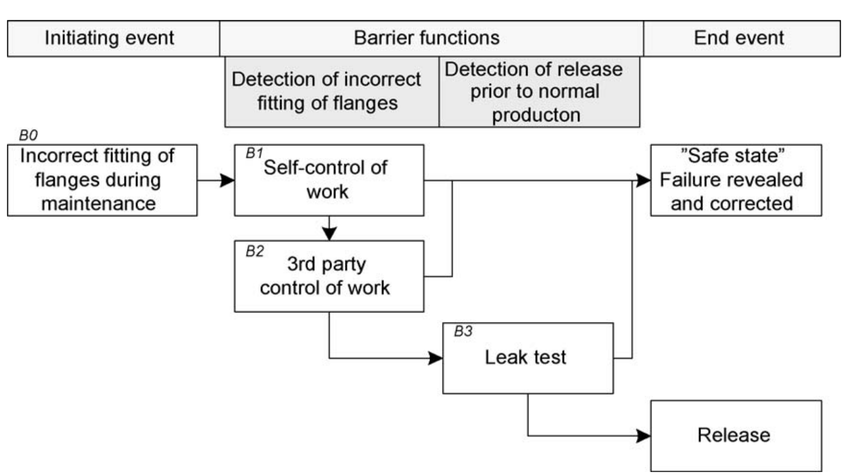

Fig. 9. Barrier block diagram for scenario B.

Table 3
Scenario B—industry average probabilities/frequencies, weights, scores, and revised probabilities/frequencies

Basic event	P_{ave}	P_{low}	P_{high}	Basic event/RIF	w_i	s_i	MF	P_{rev}
B01	$n_B = 28$			No. of flowline inspection per year				
B02	0.03	0.006	0.15	*P* (Incorrect fitting of flange or bolts)			1.27	0.038
				B021 Process complexity	2	C		
				B022 Maintainability/accessibility	2	C		
				B023 Task complexity	10	C		
				B024 Time pressure	6	D		
				B025 Competence of mechanician	10	C		
B11	1.0[a]			*P* (Failure to specify self control)				
				B111 Program for self control				
B12	0.010	0.003	0.030	*P* (Failure to perform self control when specified)			1.51	0.015
				B121 Work practice	10	D		
				B122 Time pressure	10	D		
				B123 Work permit	6	C		
B13	0.33	0.066	0.66	*P* (Failure to reveal incorrect fitting by self control)			1.09	0.36
				B131 HMI	2	D		
				B132 Maintainability/accessibility	2	C		
				B133 Time pressure	6	D		
				B134 Competence of mechanician	10	C		
				B135 Procedures for self control	10	C		
B21	1.0[b]			*P* (Failure to specify third party control of work)				
				B211 Program for third party control				
B22	0.01	0.002	0.05	*P* (Failure to perform third party control of work)			2.03	0.02
				B221 Work practice	10	D		
				B222 Time pressure	10	D		
				B223 Work permit	6	C		
B23	0.1	0.02	0.5	*P* (Checker fails to detect incorrect fitting)			1.31	0.13
				B231 HMI	2	D		
				B232 Maintainability/accessibility	2	C		
				B233 Time pressure	4	D		
				B234 Competence of checker	10	C		
				B235 Procedures for third party control	4	C		
				B236 Work permit	4	C		
B31	1.0[c]			*P* (Failure to specify leak test)				
				B311 Program for leak test				
B32	0.01	0.002	0.05	*P* (Failure to perform leak test when specified)			2.03	0.02
				B321 Work practice	10	D		
				B322 Time pressure	10	D		
				B323 Work permit	6	C		
B33	0.03	0.006	0.15	*P* (Failure to detect incorrect fitting by leak test)			1.56	0.047
				B331 Communication	10	D		
				B332 Methodology	2	C		
				B333 Procedures for leak test	2	C		
				B334 Competence of area technician	10	C		

[a] Self control is specified in this case as the probability of failure to specify self control is 0.
[b] Third party control of work is not specified as the probability of failure to specify third party control is 0.
[c] Leak test is specified in this case, as the probability of failure to specify leak test is 0.

3.3. Scenario C

The general description of scenario C is as follows:

Scenario name
Release due to internal corrosion

General description
Releases caused by internal corrosion. The relevant types of internal corrosion within the actual system on the platform are:
(a) CO_2-corrosion (local and uniform)
(b) Microbial Influenced Corrosion (MIC)
Other types of corrosion like H_2S-corrosion are not considered to be a problem on the platform
Two corrosion groups (CG) are defined within the actual system: (CG1) Main flow pipes and (CG2) Dead legs

Initiating event

The initiating event for this scenario is "Corrosion rate due to internal corrosion beyond critical limit". Quantitatively, the initiating event is defined as "Number of leaks per year due to corrosion if no safety barriers or corrective actions are implemented"

Factors influencing the initiating event

Corrosion resistance of material, corrosion coating, chemical injection/corrosion inhibitor/biocid, internal fluid properties, CO_2-concentration, allowances/safety margins, platform age, etc.

Operational mode when failure is introduced

During normal production

Operational mode at time of release

During normal production or during process disturbances (resulting in, e.g., increased pressure)

Barrier functions	*Barrier systems*
The release may be prevented if the following safety functions are fulfilled:	The release may be prevented if the following safety barriers function:
• Detection of internal corrosion to prevent release	• System for inspection to detect potential corrosion. • System for condition monitoring of equipment to detect potential corrosion.
• Detection of diffuse or minor hydrocarbon release	• System for area based leak search may detect diffuse discharges before they develop into significant leaks. • System for detection of minor hydrocarbon (HC) releases (automatic or manual gas detection) may detect minor releases before they develop into significant leaks.

Assumptions

- Critical limit is defined as damage rate (d) greater than critical damage rate ($d_{critical}$). This damage rate will result in wall thickness (t) less than wall thickness when release is expected ($t_{release}$) before next inspection
- A rate model is applied for both CO_2-corrosion and MIC
- Uniform CO_2-corrosion is not assessed to be a problem at the actual platform
- Corrosion coupons and MIC sample testing are used for condition monitoring. Corrosion coupons are used only in the main flow pipes, while MIC sample testing is performed in both the main flow pipes and the dead legs
- It is assumed that detection of critical corrosion rate by condition monitoring lead to revision of the inspection programme and the assumptions for the analysis of the release frequency due to corrosion. Due to the revisions of the assumptions, a new analysis should be carried out, and this revision of assumption may lead to higher release frequency due to, e.g., higher frequency of the initiating event or lower inspection efficiency
- Two methods are used for inspection, ultrasonic and radiographic inspection. The inspection method depends on the thickness of the pipe and it is assumed that the most suitable method is used in the case study
- Area based leak search is performed in two ways; (1) Daily generic area inspection performed by the area technician, and (2) Daily system specific leak search performed by the area technician. The probability of detection of a leak is assumed to be higher for the second type of leak search
- Minor releases may be detected automatically by gas detectors or manually by people in the area
- It is assumed that corrective actions are implemented when "critical" corrosion is detected. Detection of critical corrosion therefore leads to a "safe state"

Fig. 10 shows a barrier block diagram for the release scenario "Release due to internal corrosion".

Figs. 11–13 show the basic fault tree modelling of the safety barriers inspection (C1), condition monitoring (C2), and area based leak search (C3) illustrated in the barrier block diagram in Fig. 10. The system for detection of hydrocarbons has not been analysed any further in the case study. In principle, the barriers are equal for both corrosion groups, however, the quantitative analysis is different.

The barrier block diagram in Fig. 10 is transformed to an event tree in order to calculate the expected release frequency due to corrosion. The event tree is illustrated in Fig. 14. Safe state in the event tree means that the damage rate is "under control" and corrective actions will be implemented before a release occurs. The frequency of the initiating event (λ_C^0) expresses a prediction of the hydrocarbon release frequency per year due to corrosion if no safety barriers are functioning or no corrective actions are implemented from today. The categorization of releases as diffuse, minor, or significant releases is based on a judgment of the relation between hole sizes caused by the relevant corrosion mechanisms and pressure conditions in the system [11], together with input from personnel from the oil company.

Table 4
Scenario B—results from calculations

	Industry average probabilities/frequencies	Revised probabilities/frequencies
f(B0)[a]	0.84	1.064
$P_{Failure}$(B1)[b]	0.34	0.37
$P_{Failure}$(B2)[c]	0.11	0.15
$P_{Failure}$(B3)[d]	0.040	0.066
λ_B[e]	0.0012	0.0038

[a] Frequency of incorrect fitting of flanges or bolts after inspection per year.
[b] Probability of failure to reveal failure by self control.
[c] Probability of failure to reveal failure by third party control.
[d] Probability of failure to detect release by leak test.
[e] Release frequency from scenario B per year.

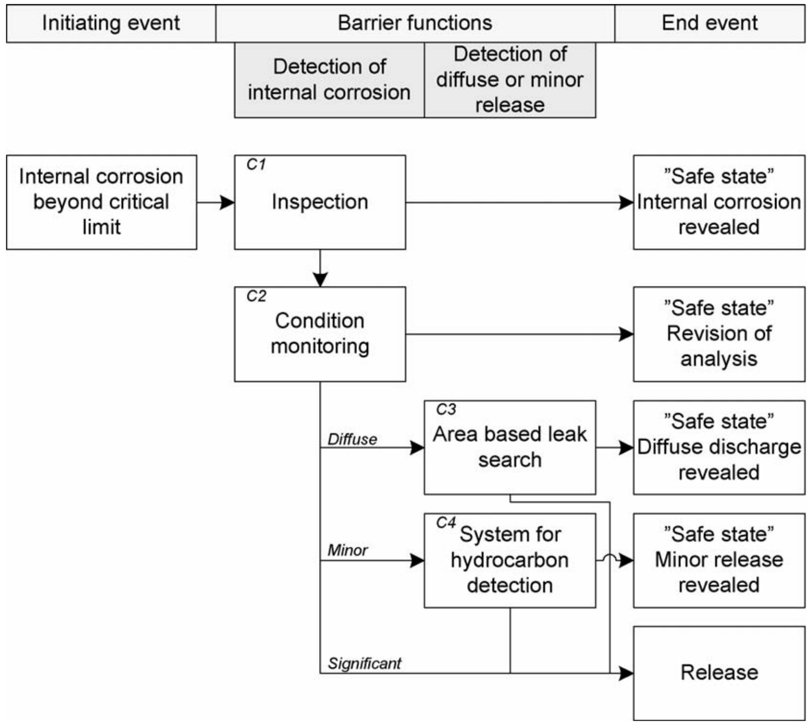

Fig. 10. Barrier block diagram for scenario C.

Success of inspections implies that the predicted damage rate is equal to or less than the actual damage rate, thus no release should occur due to corrosion before the next inspection. Implicit in the definition of success of inspection is an assumption of implementation of corrective actions if the remaining time to release is very short. Further, it is assumed that diffuse discharges and minor releases will escalate into significant releases if not revealed.

Findings from condition monitoring usually imply revision of inspection intervals and the assumptions for the analysis of the release frequency due to corrosion.

The fault trees for the safety barriers (C1, C2 and C3) are shown in Figs. 11–13. Note that the quantitative analysis of the inspection node was not made strictly according to the fault tree in Fig. 11. Quantification of the expected release frequency due to corrosion and the effect of inspection is build on the

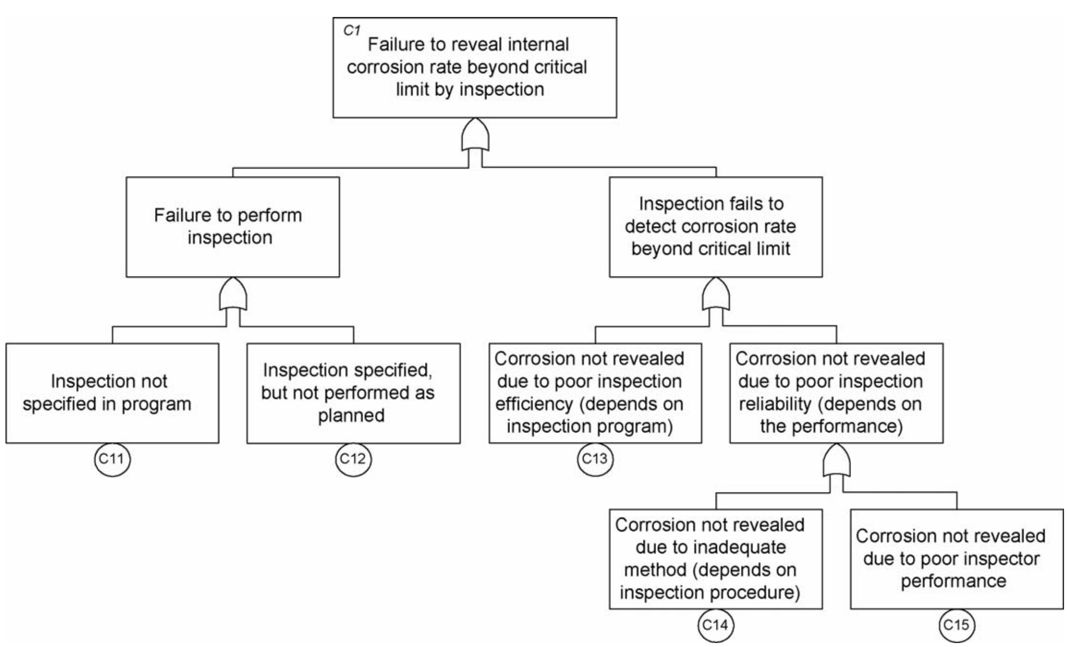

Fig. 11. Fault tree for barrier no. C1, inspection.

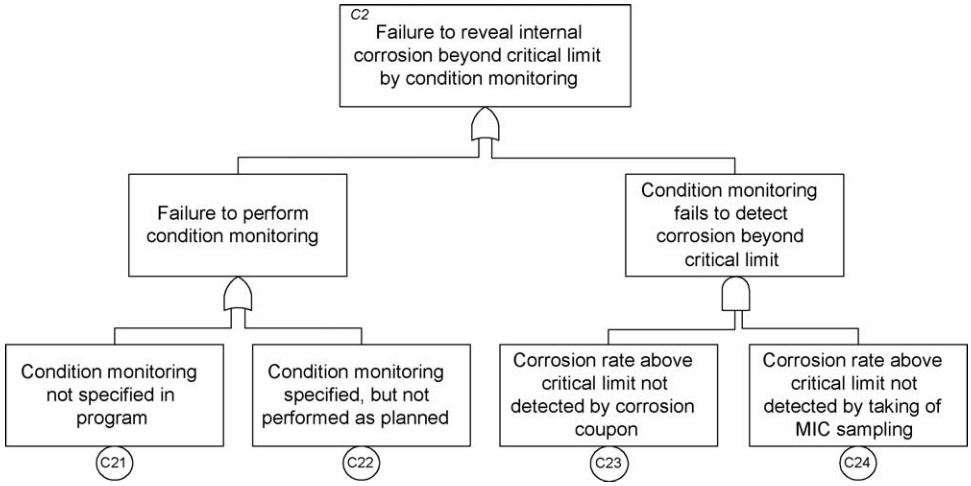

Fig. 12. Fault tree for barrier no. C2, condition monitoring.

principles that corrosion exists in the system with a damage rate d (the damage rate is often denoted as corrosion rate). The damage rate may be modelled as a gamma stochastic process [10]. To simplify, only the mean damage rate d is used in the further calculations. If no preventive maintenance or corrective action is performed, the mean time to hydrocarbon release is t_{release}.

The wall thickness at time t is denoted Q_t. Further, q_0 denotes the wall thickness at time t_0, and q_{release} denotes the wall thickness when release is expected to occur. Then:

$$t_{\text{release}} = \frac{q_0 - q_{\text{release}}}{d} \tag{4}$$

The damage rate d is unknown, but may be predicted, e.g., by using measurements from inspections.

If $\hat{d}$ denotes the predicted damage rate, a prediction of t_{release}, $\hat{t}_{\text{release}}$ may be determined from the following:

$$\hat{t}_{\text{release}} = \frac{q_0 - q_{\text{release}}}{\hat{d}} \tag{5}$$

However, safety barriers are implemented in order to prevent release of hydrocarbons. Inspections are planned to be executed at time t_i approximately equal to $0.5 \times \hat{t}_{\text{release}}$ in order to measure the wall thickness and calculate updated damage rates ($\hat{d}$). When the wall thickness is less than a critical limit, corrective actions are implemented.

Hydrocarbon releases may occur if the damage rate d is greater than d_{critical}, i.e., the damage rate that will result in release prior to execution of next inspection (at planned time (t_i) or delayed). If the inspection t_i is cancelled, the next planned inspection will be carried out at time t_{i+1}.

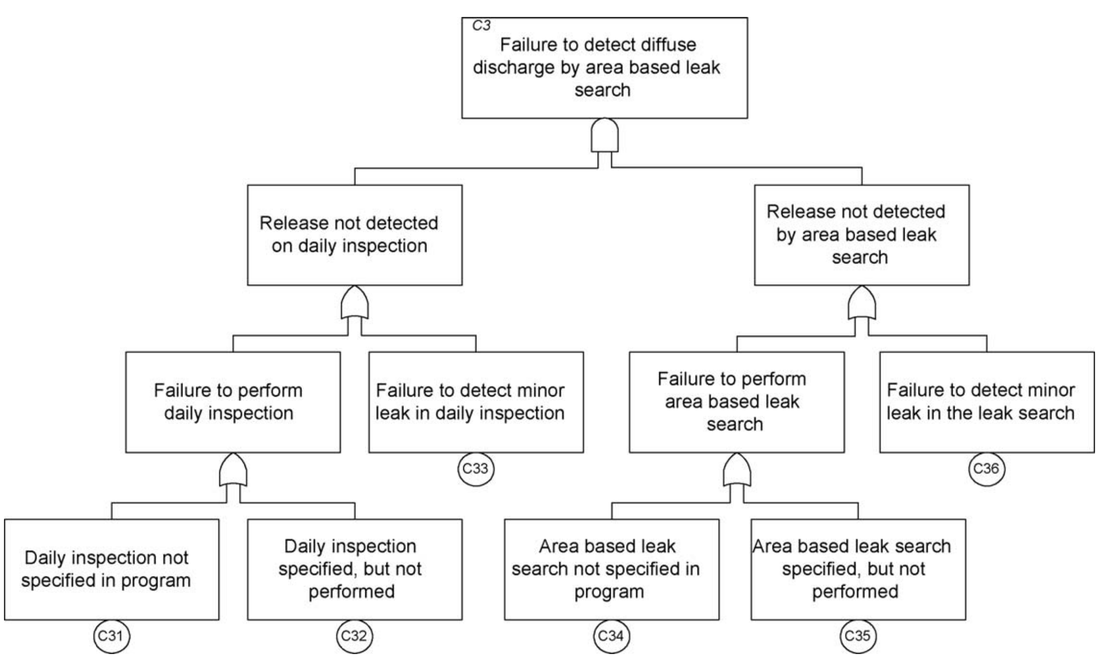

Fig. 13. Fault tree for barrier no. C3, area based leak search.

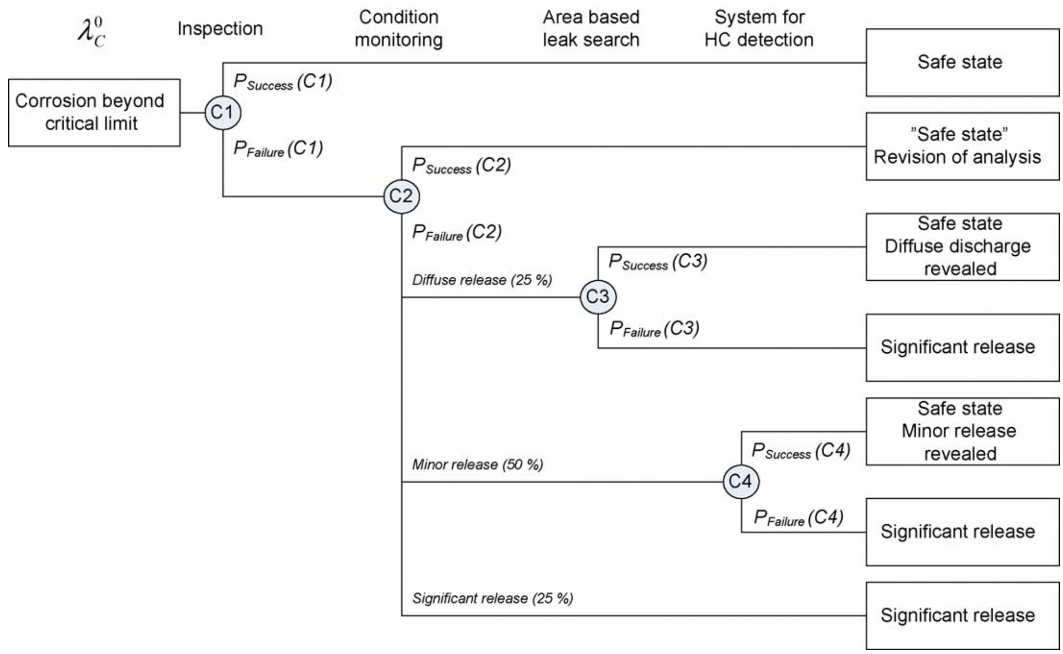

Fig. 14. Event tree used for quantification.

For further quantification, a simplification is made; the corrosion rate is categorized in three damage rate states s_i (according to [9]). The times to leak are here expressed as deterministic quantities, which is a simplification. The times expressed here should be considered as expected values:

s_1 Predicted rate or less, $d=\hat{d}$: In this case we will not have release before $\hat{t}_{\text{release}}$ (because $t_{\text{release}}=\hat{t}_{\text{release}}$). As $t_i \approx 0.5\times\hat{t}_{\text{release}}$, we have $t_{\text{release}} \geq t_{i+1}$. Thus, even if the first inspection (t_i) is cancelled, an inspection (t_{i+1}) will take place before release will occur.

s_2 Predicted rate to two times rate, $d\in(\hat{d}, 2\hat{d})$: In this case $t_{\text{release}} > t_i$, but $t_{i+1} \geq t_{\text{release}}$. A release may occur if an inspection is delayed or cancelled.

s_3 Two to four times predicted rate, $d > 2\hat{d}$: In this case, $t_{\text{release}} < t_i$, and a release will occur prior to the first inspection.

Hence, the probability of failure to reveal that the actual damage rate is greater than the critical damage rate ($d > d_{\text{critical}}$) by inspection may as an approximation be expressed as;

$$P_{\text{Failure}}(\text{C1}) = P(s_3)(1-P(\text{delayed})) + P(s_2)P(\text{delayed}) \tag{6}$$

where P(delayed) expresses the probability that the planned inspection at time t_i is delayed or cancelled. In formula (6), P(delayed) corresponds to the probability of occurrence of basic event C12 in Fig. 11, while $P(s_3)$ denotes the probability of occurrence of basic event C13. The effect of poor inspection reliability (basic event C14 and basic event C15) is not included in the quantification process in this case study. However, this may be included as part of further work.

Our confidence in the predicted damage rate ($\hat{d}$) is important by use of this formula. API [9] describes how to calculate the effect of the inspection program on the confidence level in the damage rate, and presents data for the confidence in predicted damage rates prior to an inspection, the likelihood that the inspection results determine the true damage state, and the confidence in damage rate after inspections.

As mentioned above, the frequency of the initiating event (λ_C^0) in Fig. 14 expresses a prediction of the release frequency per year due to corrosion if no safety barriers are functioning or corrective actions are implemented from today. The frequency λ_C^0 is calculated as the number of segments with $\hat{t}_{\text{release}}$ less than 10 years divided by 10 years. The time limit was set to 10 years since a company requirement states that the maximum permissible inspection interval is 5 years and $t_i \approx 0.5\times\hat{t}_{\text{release}}$. The prediction of λ_C^0 is based on a prediction of the damage rate ($\hat{d}$) established from results from the last inspection on the platform and is calculated to be 2.2 per year. Therefore, a consequence of changes in $\hat{d}$ is that λ_C^0 must be recalculated. We need to calculate λ_C^0 for each of the defined corrosion groups, where λ_{CCG1}^0 relates to corrosion group 1 Main flow pipes, and λ_{CCG2}^0 related to corrosion group 2 Dead legs. Based on a rough calculation, the following numbers were used in this case study:

$$\lambda_{\text{CCG1}}^0 = 0.8\,\text{leaks/year}, \qquad \lambda_{\text{CCG2}}^0 = 1.4\,\text{leaks/year}$$

In order to quantify the expected release frequency per year due to internal corrosion, quantitative numbers should be assigned to the input in formula (1) and all basic events in the fault trees in Figs. 12 and 13. The assigned numbers are presented in Table 5 both for corrosion group 1 and corrosion group 2.

Based on the described models and the data in Table 5, the probabilities of failures of the different barriers and expected release frequencies per year are calculated as shown in Table 6. The annual hydrocarbon release frequency due to internal corrosion in the system is 0.043 releases per year.

Table 5
Corrosion; summary of industry average probabilities/frequencies

Event notation	Event description	Assigned probabilities/ frequencies CG1	Assigned probabilities/ frequencies CG2	Data source
$\lambda^{0}_{CCG1/2}$	"Initial" frequency of release due to corrosion	0.8	1.4	Prediction based on data from inspections
P (B_{C11})	Probability of failure to specify inspection	0[a]	0	Expert judgment
P (B_{C12})/P(delayed)	Probability of failure to perform inspection as planned	0.1	0.1	Rough calculation
P (B_{C13})/P ($d = s_3$)	Probability of damage rate in state 3	0.11[b]	0.047[c]	[9] (Expert judgment)
P (B_{C14})/P ($d = s_2$)	Probability of damage rate in state 2	0.24	0.14	[9] (Expert judgment)
P (B_{C21})	Probability of failure to specify condition monitoring	0[d]	0	Expert judgment
P (B_{C22})	Probability of failure to perform condition monitoring when specified	0.1	0.1	Rough calculation
P (B_{C23})	Probability of failure to detect internal corrosion by corrosion coupons	0.4	1.0[e]	Expert judgment
P (B_{C24})	Probability of failure to detect internal corrosion by MIC sampling	0.6	0.6	Expert judgment
P (B_{C31})	Probability of failure to specify daily area inspection	0[f]	0	Expert judgment
P (B_{C32})	Probability of failure to perform daily area inspection when specified	0.1	0.1	Rough calculation
P (B_{C33})	Probability of failure to detect a diffuse discharge by daily area inspection	0.9	0.9	Expert judgment
P (B_{C34})	Probability of failure to specify area based leak search	0[g]	0	Expert judgment
P (B_{C35})	Probability of failure to perform area based leak search when specified	0.1	0.1	Rough calculation
P (B_{C36})	Probability of failure to detect a diffuse discharge by area based leak search	0.75	0.75	Expert judgment
P (B_{C4})	Probability of failure to detect a minor release by HC detection system	0.2[h]	0.2[h]	Rough calculation

[a] Inspection is specified in this case as P (B_{C11}) = 0.
[b] Basis (prior) is low reliability data and execution of a fairly effective inspection for CG1.
[c] Basis (prior) is low reliability data and execution of a usually effective inspection for CG2.
[d] Condition monitoring is specified in this case as P (B_{C2}) = 0.
[e] No use of corrosion coupons in dead legs today.
[f] Daily area inspection is specified in this case as P (B_{C31}) = 0.
[g] Area based leak search is specified in this case as P (B_{C34}) = 0.
[h] The barrier "System for detection of HC" is not analysed any further in this case study.

Table 6
Scenario C—results from calculations

Event	CG1	CG2
λ_C^0 [a]	0.8	1.4
$P_{Failure}$(C1) [b]	0.12	0.056
$P_{Failure}$(C2) [c]	0.32	0.64
$P_{Failure}$(C3) [d]	0.71	0.71
$P_{Failure}$(C4) [e]	0.2	0.2
λ_C [f]	0.016	0.027

[a] Predicted release frequency with no safety barriers or corrective actions.
[b] Probability of failure to reveal critical corrosion by inspection.
[c] Probability of failure to reveal critical corrosion by condition monitoring.
[d] Probability of failure to detect diffuse discharge.
[e] Probability of failure to detect minor release.
[f] Release frequency due to corrosion (per corrosion group).

The main approach in order to analyse the effect of RIFs (technical conditions, human factors, operational conditions and organisational factors) is use of risk influence diagrams as applied for scenarios A and B. Qualitative analyses by developing risk influence diagrams has been carried out for a sample of basic events in the fault trees for scenario C in order to carry out sensitivity analysis for assessment of the effect of risk reducing measures, but there was not performed a complete quantitative analysis of all the risk influence diagrams. A somewhat different approach was used to analyse the efficiency of inspection programs quantitatively. As previously described, the expected release frequency due to corrosion depends on our confidence in the predicted damage rate. The confidence in the predicted damage rate depends on the inspection efficiency; a highly efficient inspection program will give a higher confidence than a fairly efficient inspection program. The relation between the inspection program and its efficiency for local CO_2-corrosion and MIC are described in the literature [9,11]. The confidence will also depend on the inspection reliability (basic events C14 and C15 in Fig. 11). C14 was not analysed any further in the case study, while C15 was analysed qualitatively by a risk influence diagram (see Fig. 15). Risk influence diagrams for basic event C33 and C36 is shown in Figs. 16 and 17, respectively.

3.4. Sensitivity analyses

One of the purposes of the case study was to analyse the effect of changes and assess whether BORA-Release is suitable to analyse the effect of risk reducing measures and changes that may increase the hydrocarbon release frequency.

The following risk reducing measures was analysed for scenarios A and B in order to calculate the effect on the release frequency:

1. Implementation of an additional barrier, third party control of work (control of closed valves) for scenario A (reduces the leak frequency). The probability of failure to specify third party control is 0.1.

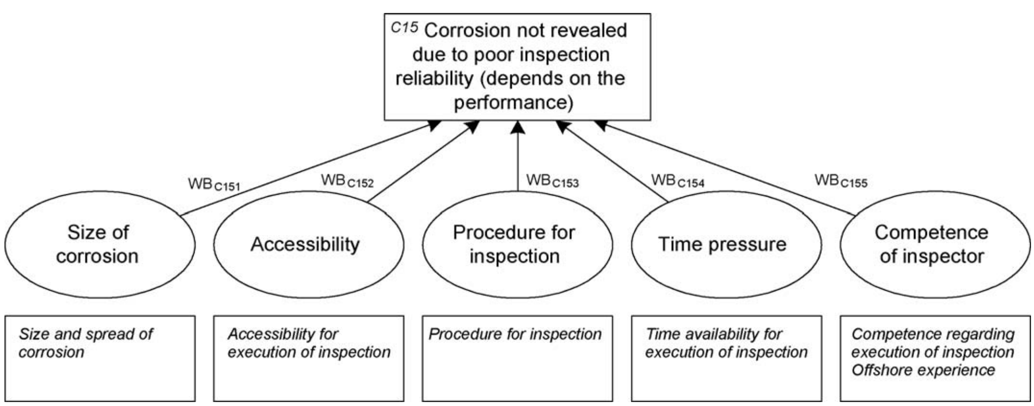

Fig. 15. Risk influence diagram for basic event C15.

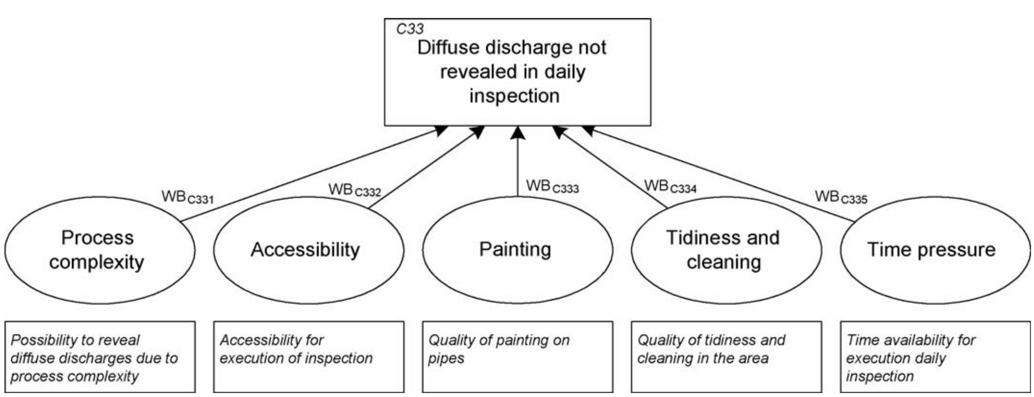

Fig. 16. Risk influence diagram for basic event C33.

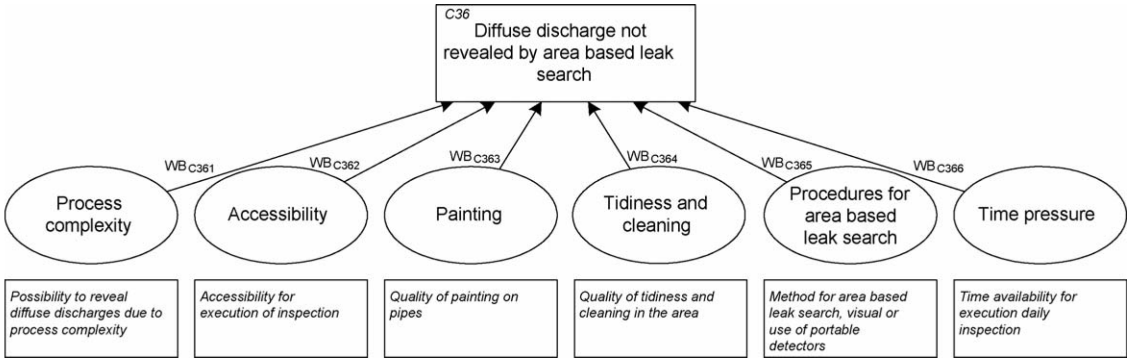

Fig. 17. Risk influence diagram for basic event C36.

2. Improvement of the score of all RIFs by one grade (from D to C, from C to B, etc.) (reduces the leak frequency).
3. Improvement of the score of the RIF Communication (from D to C) (reduces the leak frequency). This RIF influences basic event B33 in scenario B.
4. Improvement of the RIF Time pressure (from D to C) (reduces the leak frequency). This RIF influences several basic event in scenario A as well as scenario B.

The results of the sensitivity analyses for scenarios A and B are shown in Table 7. The sum of the release frequencies for scenarios A and B ($\lambda_A + \lambda_B$ from Tables 2 and 4) was used as base case frequency.

The following sensitivity analyses have been executed for scenario C in order to analyze the effect on the release frequency due to changes in RIFs influencing the corrosion scenario:

5. Use of corrosion coupons in dead legs (reduces the leak frequency). The probability of failure to detect critical internal corrosion by corrosion coupons in dead legs is set to 0.4 (similar to main flow lines).
6. Change of efficiency of inspection programs:
   a. From fairly effective to usually effective for corrosion group 1 (improvement of the effectiveness).
   b. From fairly effective to highly effective for corrosion group 1 (improvement of the effectiveness).
   c. From usually effective to highly effective for corrosion group 2 (improvement of the effectiveness).
   d. From usually effective to fairly effective for corrosion group 2 (reduction of the effectiveness).
7. Change in the status of RIFs:
   a. Worsening of the RIFs Programs (for inspection) and Supervision (increases the leak frequency). The status is changed from C to D. These RIFs influence basic event C21.
   b. Improvement of the RIFs Painting and Tidiness and cleaning (reduces the leak frequency). The status is changed from C to A. These RIFs influence the basic events C33 and C36 (see Figs. 16 and 17).
   c. Improvement of the RIFs influencing the barrier System for detection of hydrocarbon releases (reduces the leak frequency). Since this barrier is not further analysed, the sensitivity analysis is carried out directly by changing the probability of failure to detect minor release by system for HC detection from 0.2 to 0.1.
   d. Changes in RIFs influencing the distribution between diffuse, minor, and significant releases (increase the leak frequency). The sensitivity analysis is carried out directly by changing the distribution to 10% as diffuse, 40% as minor, and 50% as significant.

The results from the recalculation of the release frequencies due to corrosion based on the revised input data are shown in Table 8. The sum of the release frequency due to corrosion ($\lambda^0_{CCG1} + \lambda^0_{CCG2}$ from Table 6) is used as base case frequency for assessment of the change in %.

The main results from the sensitivity analyses are:

Table 7
Results from sensitivity analyses for scenarios A and B

Sensitivity no.	Input data	Base case frequency	Sensitivity frequency	Change (%)
1	Average	0.0295	0.0068	−76.9
	Revised	0.0453	0.0143	−68.3
2	Average	0.0295	0.0295	0.0
	Revised	0.0453	0.0179	−60.5
3	Average	0.0295	0.0295	0.0
	Revised	0.0453	0.0443	−2.1
4	Average	0.0295	0.0295	0.0
	Revised	0.0453	0.0326	−27.9

Table 8
Results from sensitivity analyses for scenario C

Sensitivity no.	Release frequency		Change (%)
	Original	Revised	
5	0.043	0.029	−31.3
6a	0.043	0.034	−20.7
6b	0.043	0.028	−35.3
6c	0.043	0.021	−51.8
6d	0.043	0.074	73.3
7a	0.043	0.050	15.5
7b	0.043	0.037	−13.2
7c	0.043	0.039	−9.5
7d	0.043	0.053	23.6

- Implementation of an additional barrier (third party control of work) in scenario A reduces the release frequency from scenarios A and B with 77% by use of industry average data, and 68% by use of revised data.
- Improvement of the scores of all RIFs by one grade reduces the release frequency from scenarios A and B with 61%.
- Improvement of the score of the RIF Communication (from D to C) reduces the release frequency from scenarios A and B with 2%.
- Improvement of the RIF Time pressure (from D to C) reduces the release frequency from scenarios A and B with 28%.
- Implementation of condition monitoring by use of corrosion coupons in dead legs reduces the expected release frequency due to corrosion by 31%.
- Improvement of the efficiency of the inspection program has a relative high influence on the release frequency due to corrosion (see sensitivity 6a, 6b, and 6c). Changing from fairly effective to usually effective for corrosion group 1 reduces the expected release frequency by 21%. Changing from fairly effective to highly effective for corrosion group 1 reduces the expected release frequency by 35%. Changing from usually effective to highly effective for corrosion group 2 reduces the release frequency by 52%.
- Reduction of the efficiency of the inspection program increases the expected release frequency due to corrosion. Changing from usually effective to fairly effective for corrosion group 2 increases the release frequency by 73%.
- Increased probability of occurrence of basic event C12 (inspection specified, but not performed as planned) from 0.1 to 0.2 (i.e., even more of the planned inspections are delayed or cancelled) leads to an increase in the release frequency due to corrosion by 16%.
- Improvement of the status of the RIFs Painting, and Tidiness and cleaning has positive impact on the expected release frequency due to corrosion (reduction by 13%).
- Changing the probability of failure to detect minor release by system for HC detection from 0.2 to 0.1 reduces the release frequency by 10%.
- Changes in the distribution between diffuse, minor and significant releases to 10% as diffuse, 40% as minor, and 50% as significant, increase the release frequency 24%.

4. Discussion and conclusions

BORA-Release was used to analyse three hydrocarbon release scenarios on an offshore oil and gas production platform on the Norwegian Continental Shelf. Use of BORA-Release in the case study to calculate the platform specific release frequency for scenarios A and B resulted in a higher release frequency than the results obtained by use of industry average data. The reason for this difference is that the status of several of the RIFs measured by the RNNS-data was worse than the industry average standard. If the status of the RIFs had been better than the average standard, the revised release frequency would become lower than the frequency calculated by use of industry average data.

Several sensitivity analyses were carried out in order to evaluate the possibility of using BORA-Release to analyse the effect on the release frequency of safety barriers and risk reducing measures. The sensitivities showed the effect on the release frequency expressed as change in % compared to the base case due to different measures or "changes" (sensitivity 1–7). Several types of changes were assessed, ranging from introduction of a new safety barrier to change in the status of one specific RIF. Thus, the effects on the release frequencies of the sensitivities varied, however, the results and the variation were assessed to be reasonable. The sensitivity analyses illustrated that BORA-Release may be used to analyse the effect on the release frequency of safety barriers and other types of changes.

The qualitative modelling of the release scenarios by use of barrier block diagrams initiated discussions among personnel in the oil company about which type of barriers that most effectively may prevent hydrocarbon release. One example is the discussion of whether or not third party control of work to reveal potential valve(s) in wrong position should be implemented as part of the flowline inspection. Personnel that argued for implementation were supported by the results from the sensitivity analyses indicating that implementation of an additional barrier (third party control of work) in scenario A resulted in a significant reduction of the release frequency. Similarly, the qualitative modelling of barrier performance by use of fault trees and risk influence diagrams raised the consciousness among the personnel in the oil company about which RIFs that influenced the barrier performance.

Application of BORA-Release for analysis of the loss of containment barrier generated and systematized knowledge about factors influencing the release frequency and presented a more detailed risk picture than traditional QRAs since no analyses of causal factors of hydrocarbon releases are carried out in existing QRAs.

A main question with respect to the quantitative results is whether the calculated release frequencies are trustworthy (i.e., whether we have confidence in the frequencies being able to provide good predictions of the actual number of releases) since the analysis is based on a number of assumptions and simplifications. These relate to the basic risk model, the industry average input probabilities/frequencies, the risk influence diagrams, the scoring of RIFs, the weighting of RIFs, or the adjustment of the input probabilities. The quantitative results in the case study for scenarios A and B based on industry average data were assessed to be reasonable compared to release statistics. This view was supported by the answers from the personnel from the actual oil company when they were asked whether or not the results were trustworthy. The confidence in the results based on the revised input probabilities/frequencies was not as good due to use of the RNNS-data for scoring of RIFs. Since the scoring was based on few and generic questions not originally meant to be used as basis for RIF-scoring, the validity (i.e., whether or not it measures what it is supposed to measure [12]) of the scoring was assessed to be low. The main reason for use of RNNS-data to assess the status of RIFs in the case study was the demand for use of existing data in order to minimize the use of resources from the industry representatives in the steering group for the BORA project. Since the revised release frequency to a high degree was influenced by the results from the RNNS-survey, the approach chosen for scoring of RIFs should be discussed in the further work.

Another aspect of the scoring is how specific the assessment of the status of RIFs needs to be. This may be illustrated by an example; is it sufficient to assess the competence in general for all groups of personnel on a platform, or is it necessary to assess the competence for each group in order to reflect differences between the groups? As far as possible, the level of detail should be sufficiently detailed and specific to reflect scenario specific factors, but in practice, it may be necessary to be somewhat more general.

The confidence in the quantitative results from the corrosion scenario by personnel from the actual oil company is lower than for scenarios A and B. The corrosion phenomenon is a complex and dynamic scenario and several assumptions made during the work should be further discussed. The present version is a test model and further research is required to better reflect how more aspects of the corrosion scenario influence the release frequency, e.g., the effect of the inspection reliability (see [13] for a discussion of attributes characterizing barrier performance).

The case study has demonstrated that BORA-Release is a useful tool for analysing the effect on the hydrocarbon release frequency of safety barriers introduced to prevent hydrocarbon releases, and to study the effect on the barrier performance of platform specific conditions of technical, human, operational, and organizational RIFs. In the case study, the sensitivity analyses were used to illustrate this topic, and the results from the sensitivity analyses supported this conclusion. One of the main application areas of BORA-Release may be to study the effect on the release frequency of risk reducing measures or risk increasing changes.

When it comes to further work, BORA-Release should be applied for analysis of the other release scenarios described in [5]. This set of release scenarios is considered to constitute a comprehensive and representative set of hydrocarbon release scenarios where the initiating events cover the most frequent “causes” of hydrocarbon releases. The scenarios include the most important barrier functions and barrier systems introduced to prevent hydrocarbon releases. A detailed analysis of all these scenarios will increase the knowledge about how safety barriers influence the release frequency, and how technical, human, operational, and organisational RIFs influence the barrier performance on a platform.

The main focus on the further development of BORA-Release should be on other methods for assessment of the status of RIFs. Two possible ways are use of results from the TTS project [14], or to develop specific scoring schemes for the different RIFs similar to Behaviourally Anchored Rating Scales (BARS) as described by Jacobs and Haber [15]. Since the main focus of the TTS project is on technical aspects of technical barriers, a combination of these two methods may be a possible approach. However, TTS projects are not carried out on all platforms on the Norwegian Continental Shelf. A more detailed discussion of BORA-Release in general and the different steps is presented in Part I of the paper.

As stated, this case study has focused on analysis of the loss of containment. Further development of BORA-Release should also make an attempt to apply the method on consequence reducing barriers in order to test how suitable the method is for an overall risk analysis. An overall risk model including preventive, controlling, and protective barriers will also make it possible to analyse the effect of potential dependencies (common-cause failures) between different barriers in the event sequence.

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