Analysis of barriers in operational risk assessment – a case study

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ABSTRACT: The BORA methodology consists of barrier block diagrams, fault trees, event trees and risk influencing diagrams for quantification of the influence on barrier performance from human and organizational factors. Two case studies have been performed, once of which is presented in the paper, including two leak scenarios and some selected consequence barriers. Examples of barrier block diagrams, fault trees and event trees are shown. Four alternative sources for quantification of the status of the risk influencing factors are introduced, and the differences in results are shown for each. It is also shown how the methodology may be used for sensitivity studies in order to identify how risk reduction may be achieved.

1 INTRODUCTION

1.1 *About BORA project*

The offshore petroleum industry has for a long time invested considerable resources in engineering defences, or barriers, against fire and explosion hazards on the installations. The performance of barriers is to some extent followed up through performance standards and Key Performance Indicators, though often not extensively. Safety systems are usually addressed on a one-by-one basis, not allowing dependencies and common mode/cause failures to be identified.

Half of the leaks from hydrocarbon containing equipment occur in connection with manual activities in hazardous areas, during which engineered defences often are partially inhibited or passivated, in order not to cause disruption of stable production. The occurrence of leaks is a clear indication that system and human defences relating to containment of leaks are not functioning sufficiently well during these operations. There is an obvious need to understand better the performance of barriers, particularly non-technical, during execution of manual activities.

In a paper presented at ESREL 2003 (Vinnem et.al. 2003a), operational risk assessments were discussed. A clear need for improvement of the analysis of barriers was concluded. These aspects form the outset for an extensive research activity called the BORA (Barrier and Operational Risk Analysis) project (Vinnem et.al. 2003b). A PSAM7-ESREL2004 paper (Vinnem et.al. 2004) gave some preliminary observations and introduced a proposed approach.

Two case studies covering modelling and analysis of physical and non-physical barriers on offshore production installations have been carried out. Barriers intended to prevent the incident occurring along with those intended to eliminate/reduce consequences are included, and particular emphasis is placed on barriers during execution of operational activities. The results from the studies should enable both industry and authorities to improve safety through:

- Knowledge about overall performance of barriers and improvement potentials
- Identification of the need to reinforce the total set of barriers, especially during operational activities
- Identification of efficient risk reduction measures for barriers, together with effective modifications and configuration changes.

The analysis has been quantitative as far as was possible. Barriers are in general characterized by reliability/availability, functionality and robustness. All of these performance measures are addressed. The Norwegian regulations require that dependencies between barriers shall be known. The analysis is therefore performed such that, where relevant, common cause or mode failures and dependencies between barrier elements are accounted for.

1.2 *Objectives of the BORA project*

The objectives of the BORA project is to establish a methodology for analysis of operational barriers and to carry out a demo project in order to illustrate the analytical approach. The purpose with the analysis is to facilitate:

- Identification of risk contributions and control possibilities
- Effect of modifications etc.
- Effect on barriers when operational activities are carried out

1.3 *Methodology development*

The BORA project has proposed a methodology in order to analyze failure of operational barriers, as outlined in Aven et.al. (2006), and presented in detail in Sklet et.al. (2006). Figure 1 presents the BORA methodology as well as the sources for scoring of Risk Influencing Factors (RIFs). The methodology has three main processes:

- Qualitative analysis of scenarios, basic causes and RIFs
- Quantification of average frequencies/probabilities
- Quantification of installation specific frequencies/probabilities

1.4 *Case studies*

Case studies were planned and conducted in order to explore how effectively the approach could be applied, the availability of sources for assessment of the status of the RIFs, and the type of results that may be achieved through these studies. Two case studies have been conducted:

- Case study 1: Four scenarios
- Case study 2: Two scenarios

The case studies were conducted for stand alone production installations in the Norwegian sector, the Case study 1 for an old installation, with steel jacket support structure, and Case study 2 for a relatively new floating production installation. The following scenarios were analyzed in detail:

- Case study 1:
  - Scenario A: Release due to valve(s) in wrong position after maintenance
  - Scenario B: Release due to incorrect fitting of flanges or bolts during maintenance
  - Scenario C: Release due to internal corrosion
  - Scenario D: Release due to external corrosion (qualitatively)
- Case study 2:
  - Scenario A: Release due to valve(s) in wrong position after maintenance
  - Scenario B: Release due failure prior to or during disassembling of HC-system

Case study 1 is not discussed explicitly in the paper, but the experience is utilized when drawing conclusions. Case study 1 is presented in Sklet et.al. (2006). Case study 1 was limited to containment barriers, whereas Case study 2 also considered a selection of consequence barriers, i.e. barrier functions intended to limit the consequences of a hydrocarbon leak, if it occurs.

1.5 *Objectives of presentation*

The purpose of the paper is to present results from a case study where the BORA approach was used. The case study also included several approaches for the assessment of the status of RIFs. These sources are discussed.

The paper also illustrates how the approach may be used in sensitivity studies in order to explore different possibilities for risk reduction.

2 INFORMATION SOURCES IN THE BORA METHODOLOGY

The sources for the installation specific quantification of frequencies and probabilities are presented in Figure 1. The following sources are available:

- TTS/TST verifications
- MTO (Man, Technology and Organisation) investigations
- RNNS (Risk Level Project) questionnaire surveys
- RNNS barrier performance data
- Detailed assessments (Expert input)
- General background studies

The TTS/TST verifications (Thomassen & Sørum, 2002) are focused on technical and documentation aspects of barriers. These verifications were developed by Statoil, and the approach has been adopted by several Norwegian offshore operating companies in Norway. MTO investigations (Tinmansvik et.al. 2005) are investigations with special emphasis on human and organizational aspects that have been conducted for many accidents and incidents in the past few years, mainly by or on behalf of the Petroleum Safety Authority (PSA) in Norway. RNNS is a project conducted annually by PSA for the entire Norwegian Continental Shelf (PSA, 2005), which for the purpose of the BORA methodology has two applicable activities:

- Biannual questionnaire survey
- Annual collection of barrier performance data

The questionnaire survey has extensive questions relating working environment factors as well as a number of aspects relating to perceived risk and safety culture. The barrier performance data, see PSA (2005), is concerned with a selection of barrier elements, most of which are technical barriers.

3 CASE STUDY – OPERATIONS IN PROCESS AREA ON FLOATING OFFSHORE INSTALLATION

3.1 *Scope of study*

The case study has been worked out in close cooperation with operational personnel, both on land and offshore, as a result of a visit offshore and several meetings at the onshore operations office. Relevant cases have been introduced based on their activity and experience with the operation of the installation.

– The first scenario being considered is based on the shutdown that was performed in 2005, when one of the tasks was cleaning and minor modifications to the separators. This involved isolating the separators, opening them and doing internal cleaning. The release scenario considered is related to the possibility that one (or more) valves are left in the wrong position after the work is completed such that a release occurs when the production is started. (Scenario 2b: Release due to valve(s) in wrong position after maintenance)

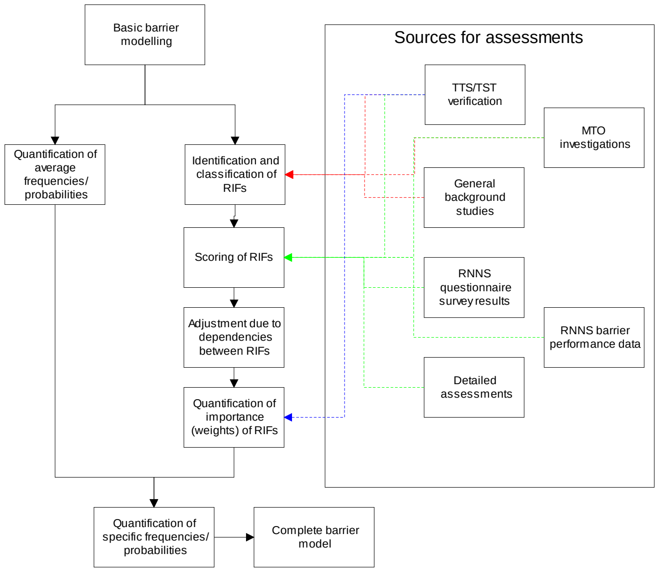

Figure 1 Summary of main combination of barrier failure causes

– The second scenario is also identified from a situation that occurred prior to the 2005 shutdown. A problem was then identified in relation to the pipeline compressors and it was concluded that it was necessary to perform maintenance. The specific scenario is however not seen in relation to the shutdown.
– Scenario 1a: Release due to failure prior to or during disassembling of HC-system

The scope of work includes definition of possible deviations and abnormalities which may develop into leaks, based on written documentation and interviews. The following consequence barriers functions are addressed:

– Prevent Ignition
– Reduce Release

3.2 *Qualitative analysis*

The modelling started with barrier block diagrams for the two scenarios, see Figure 2 and Figure 3.

Thereafter, Fault trees were developed in order to structure the possible causes of operational failures. An example is shown in Figure 4.

3.3 *Risk influencing factors*

The framework for RIFs is described in Sklet et.al. (2006), and consists of the following groups:

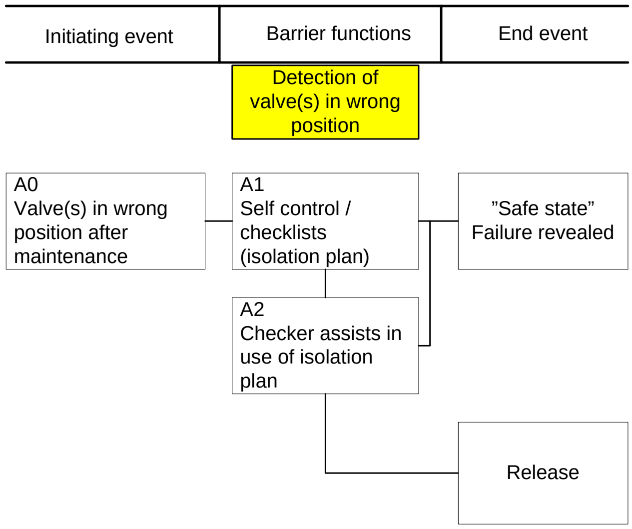

Figure 2 Barrier block diagram - Scenario A

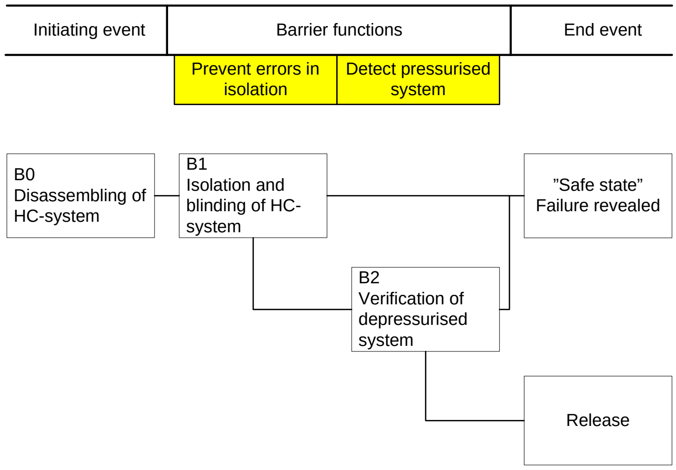

Figure 3 Barrier block diagram for Scenario B

– Characteristics of the personnel performing the tasks (internal, psychological stressors, and physiological stressors)
– Characteristics of the task being performed
– Characteristics of the technical system
– Administrative control (procedures and disposable work descriptions)
– Organizational factors / operational philosophy

The weights of the RIFs for the individual Basic Events were obtained through work meetings, involving operating personnel and BORA project personnel. In practice, this was done as follows:

– A set of tables was prepared, showing a general list of RIFs and a 6-point scale going from "High Importance" to "Not Applicable". One table was established for each Basic Event.
– The meeting participants were asked to rate the importance (weight) of each RIF on the scale provided. This was done by each participant in the meeting on their own.
– The resulting weights were then compared and discussed until an agreement was reached on the weight that each RIF should have.

– This process was repeated for all Basic Events.

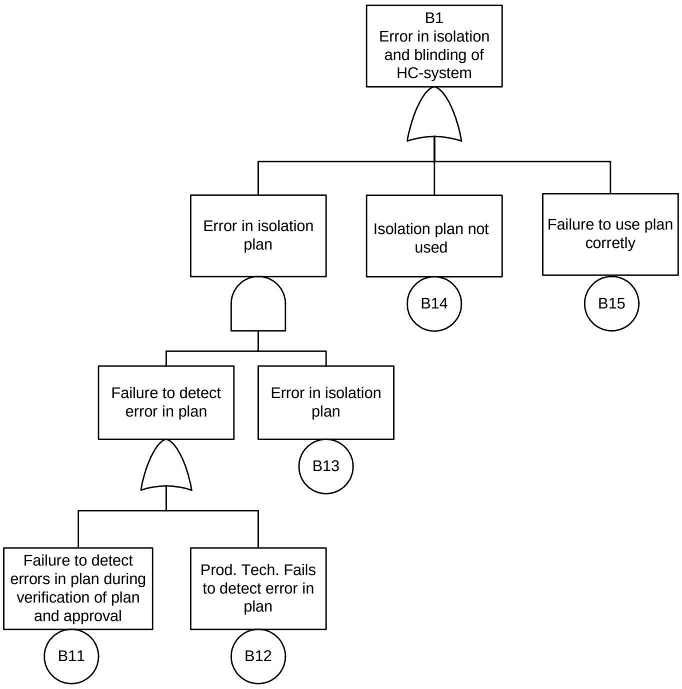

Figure 4 Fault tree for the top event ”Error in isolation and blinding of HC-system”

In this way, all RIFs were given a weight for each Basic Event. The scale from “High” to “Not Applicable” is converted to a scale from 5 to 0. A brief illustration of one RIF and its weights in relation to four failure events is shown in Table 1.

Table 1 Illustrations of RIF weights for basic events

RIF:	Process complexity
Description:	System complexity, no of valves, complex routing of plant, etc.
Valve left in wrong position after maintenance, A_0	4
Operator fails to detect a valve in wrong position due to error in isolation plan, B_{A11}	4
Operator fails to detect valve in wrong position because self control/ isolation plan is not used, B_{A12}	4
Operator fails to detect a valve in wrong position by self control/ use of isolation plan, B_{A13}	4

3.4 *Input to RIF scoring*

The BORA Methodology report (Aven et.al. 2003) discusses two principally different approaches to RIF scoring and quantification:

- Specific studies tailored to the needs of the BORA methodology
- Use of existing studies where applicable, supplemented with additional studies where needed

The feedback from the industry on the Methodology report has been virtually unanimous, that existing studies should be used as the primary source, as far as possible. The following are discussed in the Methodology report as possible existing studies:

- RNNS questionnaire survey data
- RNNS test data for barrier elements
- Data from TTS/TST
- Experience from MTO investigations

In this case study, it was decided to look at four different approaches for obtaining platform specific values, applying the following methods:

- Use of RNNS questionnaire data.
- Use of TTS data – TTS has been performed for the installation and these reports are utilized in the analysis.
- Expert judgement – A group of experts has been consulted to provide a scoring of the status of the RIFs for the specific cases being considered.
- Use of results from MTO investigations.

Rather than combining these, quantification was performed using these four approaches individually, producing four different results. This provides useful information in several respects:

- The suitability of each source is investigated, with respect to overall suitability and whether a source has particularly strong and weak areas.

Results based on different sources can be compared, to see if there are large differences or not. Since only two cases are considered, it is difficult to draw wide-ranging conclusions, but this is an interesting comparison. Two examples of the scoring based on TTS and expert judgement are outline in the following.

TTS (Technical Condition Safety) is a system for reviewing/auditing the technical safety condition of Statoils offshore installations. The review is performed on a predefined set of Performance Standards (PS), all of which are listed in the Table 2.

For each PS, a set of Performance Requirements (PR) has been established and these are again split in sub-requirements. The condition of the systems is measured against these requirements and the condition is rated as shown in Table 3. In practice, this has been used as follows in the quantification:

- The TTS reports are reviewed with the purpose of identifying all statements in the reports which are of relevance for the Basic Events.
- The degree of relevance of each statement is evaluated in relation to each Basic Event, on a three-point scale (High/Medium/Low). The relevance rating is converted to numbers according to the following scale: High=9, Medium=4 and Low=1.
- After all statements have been evaluated, their total “coverage” of the Basic Event is evaluated and determined as a % value. This is evaluated subjectively, by the analyst. The “residual relevance” identified in this way is assumed to always have an average score.

Table 2 Performance standards (PS)

PS no	Description
1	Containment Function
2	Natural Ventilation and HVAC
3	Gas Detection System
4	Emergency Shut Down (ESD) System
5	Open Drain System
6	Ignition Source Control
7	Fire Detection System
8	Blowdown and Flare/Vent System
9	Active Fire Fighting
10	Passive Fire Protection
11	Emergency Power and Lighting
12	Process Safety (PSD/PSV etc.)
13	PA, Alarm and Emergency Communication
14	Escape and Evacuation
15	Explosion Barriers
16	Offshore Cranes
17	Drilling and well barriers
18	Ballasting and positioning
19	Collision barriers
20	Structural integrity

Table 3 Rating - TTS

Rating	Description of condition
A	Condition is significantly better than the reference level (PR)
B	Condition is in accordance with the reference level (PR)
C	Conditions satisfactory, but does not fully comply with the reference level (PR)
D	Condition is acceptable and within the statutory regulations' minimum intended safety level, but deviates significantly from the reference level (PR)
E	Condition with significant deficiencies as compared with "D"
F	Condition is unacceptable

- The score is determined from the TTS report directly or based on the judgement of the project team where the TTS report does not give a score directly. The TTS grades from A to F are used.
- The TTS scores are then converted to adjustment factors for each RIF.

The calculation of the adjustment factor for each RIF is done in accordance with the methodology proposed in the method statement report, Aven et.al. (2003). Adjustment factors are assigned as follows (ref Table 3):

A 0.1
B 0.55
C 1.0
D 2.5
E 5.5
F 10

This conversion presupposes that the probability value is less than 0.10. A probability of 1.0 is specified for rating F, if the basic probability is in excess of 0.10. When the score is calculated, the ratings are multiplied with these scores to arrive at a total score for the RIF:

$$Q_i = \frac{\sum_k RR_k \cdot s_k}{\sum_k RR_k}$$

RR is rating of a requirement, s is the score of that requirement, and Q is the total score.

There will be some instances when several statements are identified as being relevant for one Basic Event, but where the statements essentially cover the same issue. One statement could e.g. be that "P&IDs are not up to date" (relevance rating 4), another statement "Documentation is generally not always updated" (relevance rating 1) and a third could be "Contractor is frequently behind schedule with document updates" (relevance rating 1). The first is specific, while the second and third are more general. If this is the case, only the statement with the highest relevance rating is included, i.e. a rating of a total of 4 is applied to cover all three of these statements.

Table 4 Guidelines for evaluation of relevance of statements from TTS

Relevance Rating	Description of relevance
High	Directly relevant for the basic event being considered. Example: "Routines for testing of ESDVs" will have a High relevance for the probability of failure of ESDVs.
Medium	Relevant for similar operations/equipment or partly relevant for the basic event being considered. Example: "F&G system shall be independent" has a Medium relevance for the probability of failure of the F&G Node.
Low	General comments that may be relevant. Example: "Deviations and non-conformances are reported in several systems rather than just one" is a comment that will have a Low relevance for several technical basic events since this may be an indication that it is difficult to keep track of e.g. problems with equipment

Guidelines for how the relevance rating is used have also been prepared. These are provided in Table 4.

In order to illustrate the approach, consider the following example.

Let us assume that the TTS reports have been reviewed and the following information has been found to be relevant for one specific Basic Event:

TTS1 – Medium relevance (Relevance rating 4) – Rating C (Adjustment factor 1.0)
TTS2 – Medium relevance (Relevance rating 4) – Rating D (Adjustment factor 2.5)
TTS3 – Low relevance (Relevance rating 1) – Rating E (Adjustment factor 5.5)

The first step now is to add the ratings:

$$RR_{PR} = RR_{TTS1} + RR_{TTS2} + RR_{TTS3} = 4 + 4 + 1 = 9$$

Further, it is assumed that the total "relevance coverage" of this information is 60%, i.e. 40% is "residual relevance. The % relevance of each TTS statement can then be calculated:

TTS1: $4/9 \cdot 0.60 = 27\%$
TTS2: $4/9 \cdot 0.60 = 27\%$
TTS3: $1/9 \cdot 0.60 = 7\%$
Residual: $0.40 = 40\%$

The total adjustment factor for the Basic Event can now be calculated:

$$\text{Adj factor} = 1.0 \cdot 0.27 + 2.5 \cdot 0.27 + 5.5 \cdot 0.07 + 1.0 \cdot 0.40 = 1.7$$

RIF scores can also be determined through the use of expert judgement. For this purpose, a scale ranging from A to F is applied, where A is the best score and F is the poorest score, in line with the TTS rating system.

The following definitions are the guidelines that were used in the work meetings as a basis for to how to rate the individual RIFs.

Table 5 Rating – expert judgement

Score	Description of interpretation of score
A	Condition is significantly better than what may be considered "best practice".
B	Condition in accordance with "best practice".
C	Conditions are satisfactory, but are not in full compliance with "best practice" ("reference level"). "Average" North Sea conditions would be scored with a C.
F	Condition has significant deficiencies compared to minimum regulatory requirements and is not acceptable.

D and E were not defined, but these were stated to be intermediate levels between the definitions provided above.

The scores must be converted to adjustment factors before application, and this is done using the scale shown above.

3.5 *Quantitative analysis*

To be able to quantify the leak frequencies by use of the BORA methodology the probability of initiating events and all the basic events in the fault trees need to be quantified. The following data sources have been used:

- Generic databases:
  - HEPs from THERP, Swain & Guttmann (1983). THERP is used as a simple and coarse assessment, recognising that more advanced techniques are certainly available.
  - "A guide to Practical Human Reliability Assessment", Kirwan (1994)
  - "Managing the Risks of Organizational Accidents", Reason (1997)
  - "Reliability Data for Safety Instrumented Systems", SINTEF (2004)
- Data from vulnerability and reliability analysis of safety systems, Safetec (2005)
- Data from expert judgment (personnel from Statoil)

From the generic assigned probabilities, for example the HEPs from THERP, plant specific probabilities and frequencies are established using the adjustment system described in Section 3.4.

3.6 *Results from quantitative analysis*

The event tree below illustrates how the resulting risk numbers have been established for Scenario A. The probability of release is calculated for the branch where the two first (containment) barrier functions have failed while the two other probabilities are calculated for the two end events which have been named in the event tree.

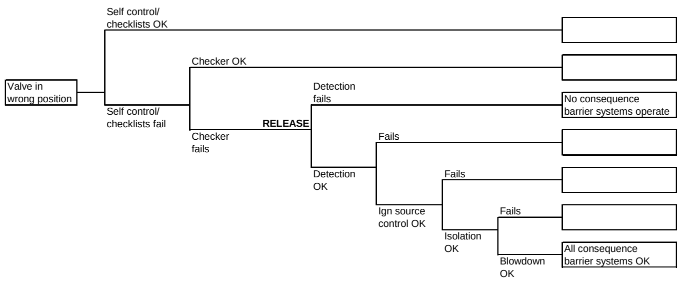

Figure 5 Event Tree for Scenario A

The tables below present the risk numbers for the four alternative scoring methods that have been applied in this case study. The numbers shown are the probabilities given the alternative sets of input data.

The release frequency is 0.0027 if RNNS data is used as basis, 0.0043 if TTS data is used as basis, 0.0022 if expert judgement is used as basis, and 0.0019 if data from MTO investigations is used as basis. The values are then related to the lowest value (in this case 0.0019 based on data from MTO investigations).

Under "RNNS" and for "Release", a value of 0.0027 is shown, which is 140% of the lowest value, 0.0019. This means that the probability of release calculated using RNNS results is 1.4 times the smallest release probability calculated (in this case for MTO).

For the release probability, the highest value (0.0043, based on TTS) is 2.3 times as high as the lowest value (based on MTO). When the consequence barriers are taken into account, the differences increase further, with a factor of 3.6 between the highest and lowest probability.

Table 6 Results – Scenario A, for 3 different parameters

Risk parameter	RNNS	TTS	Expert Judgment	MTO
Release	0.0027	0.0043	0.0022	0.0019
Prob. of release and all consequence related systems functioning	0.0022	0.0035	0.0019	0.0016
Prob. of release and no consequence related systems operating	$2.5 \cdot 10^{-4}$	$3.5 \cdot 10^{-4}$	$9.8 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$

Similar results are also found for Scenario B, with somewhat lower variations.

Table 7 Results – Scenario B, for 3 different parameters

Risk parameter	RNNS	TTS	Expert Judgment	MTO
Release	0.0495	0.0820	0.0531	0.0504
Prob. of release and all consequence related systems functioning	0.0411	0.0655	0.0466	0.0420
Prob. of release and no consequence related systems operating	$4.7 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	$4.6 \cdot 10^{-3}$

4 DISCUSSION AND EVALUATION

4.1 *Qualitative analysis*

The qualitative analysis consists of construction of event trees, barrier block diagrams, fault trees and identification of RIFs and their weights. The present case study has included the containment barrier function (prevention of leaks) as well as some consequence barrier functions.

The identification of RIFs and assessment of weights was done in expert input sessions, which proved to be an efficient way to perform these tasks.

Involving expert groups in these tasks also has the advantage of preparing the participants for possible subsequent RIF scoring sessions.

The last aspect is the awareness aspect, implying that when operational personnel and installation management are involved in such sessions, their awareness of what are important aspects in order to avoid leaks due to operational reasons may increase.

4.2 *Input to RIF scoring*

The table below presents the maximum and minimum adjustment factors for the overall leak scenario probability that have been calculated using the different approaches.

Table 8 Comparison of magnitude of scenarios probability adjustment factors (Scenario A and B)

	RNNS	TTS	Expert Judgment	MTO
Maximum adjustment factor	1.06	2.27	1.05	3.00
Minimum adjustment factor	0.97	0.78	0.45	0.50

The results show variations in the adjustment factors for scenario probability when making a comparison between the different approaches for scoring. RNNS has very low variation range, while the largest variation is seen for MTO investigations. However, this is also the method associated with lowest confidence and it is recommended that these results not are used as a single data source. The data basis should have been larger for this to be a reasonable single basis for determining adjustment factors.

For TTS and Expert Judgment, the variation in adjustment factors is larger than for RNNS, although they do not match very well. One reason for this is that the Expert Judgment scores only are established for the operational basic events while the TTS results clearly have their strength in relation to technical failures.

In general, it is noted that the variation range in adjustment factors is relatively limited. When considering that the maximum variation range that is allowed is one order of magnitude up or down from the average (adjustment 0.1 to 10), the variation ranges are small.

One reason for this may be that there will be a certain tendency that there are effects pulling in both directions, i.e. some effects indicate that the installation is better than average while others indicate that they are below average. This tends to reduce the differences. It is noted that this of course also may represent an adequate representation of the situation. Most platforms probably have their strong and weak areas!

Another aspect is that the model has been set up in such a way that when we do not have information about the scoring of a RIF, the score is assumed to be equal to North Sea average. If the information is limited, this means that the adjustment factors tend to get closer to 1.0, with small variation range. There are also alternatives to starting out with this "average" assumption:

– One approach would be to start from scratch, i.e. we make no a priori assumption about the status

of the RIFs but use whatever (limited) information we have as the only evidence. If this information indicates that the deviation from average is large, this should be taken as an indication of the total status of the RIFs rather than using this to update an initial “average” assumption.
– Another approach would be to use high level information about the platform, e.g. a comparison of leak statistics for the installation versus average leak statistics for the North Sea. If this information indicates a higher or lower leak frequency than the average, this can be used as a priori information about the status of the RIFs.

These are fundamentally different approaches which also will give different results and it is difficult to conclude on what is the best approach.

If we look at individual Basic Events and the adjustment factors calculated using the different methods, we find that the biggest difference is adjustment factors of 0.93 vs 2.27. In general, it is however difficult to find a consistent pattern or trend in the differences.

4.3 *Sensitivity studies*

One of the advantages of the BORA is approach is that sensitivity studies are easy to carry out, in order to evaluate the effect of potential actions in order to reduce risk.

As an illustration of how this is performed, consider Table 9 which summarizes some results from sensitivity studies.

Table 9 Illustration of results from sensitivity study – effect of reducing probabilities with factor of 10

Parameter	**Scenario A**	**Scenario B**
Probability that a checker fails to detect valve in wrong position when isolation plan is not used	0.20	
Probability that a checker will fail to detect valve in wrong position after maintenance if control of work is performed	0.11	
Probability of failure to use plan correctly		0.12
Probability of failure to detect pressurized system		0.10

The value for Scenario A, 0.20, implies that if the probability that a checker will fail to detect valve in wrong position when isolation plan is not used can be reduced by a factor of 10, then the probability of leak due to Scenario A will be reduced by a factor of 5 (or down to 20 % of original value), when no other changes to probabilities are made.

The values shown in Table 9 are those that have the most extensive effects, for the two scenarios considered in the case study.

5 CONCLUSIONS AND RECOMMENDATIONS

Two cases studies performed with the proposed approach have demonstrated the potential of the methodology and how it can be used. It may be characterized in the following way:
– It is practical and not difficult to understand
– It has been shown that the best practical implementation may be achieved if several input sources are combined, one of which should be expert judgement where operational personnel are involved.
– The methodology is useful for identification of actions to reduce risk through use of sensitivity studies.

A generalized methodology description is being prepared for wider application.

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