Journal of Hazardous Materials A137 (2006) 681–691

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Barrier and operational risk analysis of hydrocarbon releases (BORA-Release) Part I. Method description

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

Received 2 December 2005; received in revised form 14 March 2006; accepted 15 March 2006
Available online 3 May 2006

Abstract

Investigations of major accidents show that technical, human, operational, as well as organisational factors influence the accident sequences. In spite of these facts, quantitative risk analyses of offshore oil and gas production platforms have focused on technical safety systems. This paper presents a method (called BORA-Release) for qualitative and quantitative risk analysis of the platform specific hydrocarbon release frequency. By using BORA-Release it is possible to analyse the effect of safety barriers introduced to prevent hydrocarbon releases, and how platform specific conditions of technical, human, operational, and organisational risk influencing factors influence the barrier performance. BORA-Release comprises the following main steps: (1) development of a basic risk model including release scenarios, (2) modelling the performance of safety barriers, (3) assignment of industry average probabilities/frequencies and risk quantification based on these probabilities/frequencies, (4) development of risk influence diagrams, (5) scoring of risk influencing factors, (6) weighting of risk influencing factors, (7) adjustment of industry average probabilities/frequencies, and (8) recalculation of the risk in order to determine the platform specific risk related to hydrocarbon release. The various steps in BORA-Release are presented and discussed. Part II of the paper presents results from a case study where BORA-Release is applied.

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

1. Introduction

In-depth investigations of major accidents, like the process accidents at Longford [1] and Piper Alpha [2], the loss of the space shuttles Challenger [3] and Colombia [4], the high-speed craft Sleiper accident [5], the railway accidents at Ladbroke Grove [6] and Åsta [7], and several major accidents in Norway in the last 20 years [8] show that both technical, human, operational, as well as organisational factors influence the accident sequences. In spite of these findings, the main focus in quantitative risk analyses (QRAs) is on technical safety systems. As regards offshore QRAs, one of the conclusions drawn by Vinnem et al. [9] is that a more detailed analysis of all aspects of safety barriers is required.

Several models and methods for incorporating organisational factors in QRAs or probabilistic risk assessments (PRA) have been proposed. Among these are Manager [10], MACHINE (Model of Accident Causation using Hierarchical Influence Network) [11], ISM (Integrated Safety Method) [12], WPAM (The Work Process Analysis Model) [13,14], I-RISK (Integrated Risk) [15–17], the ω-factor model [18], SAM (System Action Management) [19,20], ORIM (Organisational Risk Influence Model) [21,22], and ARAMIS [23]. These models/methods have been developed and described in the literature in the last 15 years. However, none of them are so far used as an integrated part of offshore QRAs.

The Petroleum Safety Authority Norway (PSA) gives several requirements to risk analysis and safety barriers in their regulations [24] and one is that QRAs shall be carried out to identify contributors to major accident risk and provide a balanced and comprehensive picture of the risk. Nevertheless, existing QRAs of offshore platforms are limited to analysis of consequence

DOI of original article:10.1016/j.jhazmat.2006.03.027.
* Corresponding author. Tel.: +47 73 59 29 02; fax: +47 73 59 28 96.
E-mail address: snorre.sklet@sintef.no (S. Sklet).

0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2006.03.049

reducing barriers with no, or limited analysis of barriers introduced to reduce the probability of hydrocarbon release. Thus, there is need for a method that may be applied to analyse safety barriers introduced to prevent hydrocarbon releases. The method should be applicable for qualitative and quantitative analyses of the effect on the barrier performance, and thus the risk, of plant specific conditions of technical, human, operational, as well as organisational risk influencing factors (RIFs). With this background, the BORA-project (Barrier and Operational Risk Analysis) was initiated [25].

The main objective of this paper is to present and discuss a new method for qualitative and quantitative analyses of the platform specific hydrocarbon release frequency, called BORA-Release. BORA-Release combines use of barrier block diagram/event trees, fault trees, and risk influence diagrams in order to analyse the risk of hydrocarbon release from a set of hydrocarbon release scenarios. BORA-Release makes it possible to analyse the effect on the hydrocarbon release frequency of safety barriers introduced to prevent release, and how platform specific conditions of technical, human, operational, and organisational RIFs influence the barrier performance. The paper is limited to analysis of hydrocarbon release (or loss of containment). However, the principles in BORA-Release are relevant for analysis of the consequence barriers as well.

The paper is organised as follows. Section 2 describes the process for development of the method. Section 3 describes BORA-Release. Section 4 discusses critical issues of the method. The discussion is divided in two parts: a discussion of the different steps in BORA-Release, and a discussion of the extent of fulfilment of a set of criteria. Some conclusions and ideas for further work are presented in Section 5. Part II [26] presents some results from a case study where BORA-Release is applied.

2. Research approach

The research process for development of BORA-Release consists of the following main steps:

(1) Development of a set of criteria the method should fulfil.
(2) Literature review.
(3) Selection of modelling approach.
(4) Development of a preliminary (draft) version of the method.
(5) Application of the method in case studies.
(6) Revision of the method.

Several criteria the BORA-Release should fulfil were developed. The criteria were developed as a result of discussions of the purpose of the analysis method. To what extent BORA-Release fulfils these criteria are discussed in Section 4.2. The aim was to develop a method that:

(1) Facilitates identification and illustration of safety barriers planned to prevent hydrocarbon releases.
(2) Contributes to an understanding of which factors (technical, human, operational, and organisational) that influence the performance of the safety barriers and the risk.
(3) Reflects different causes of hydrocarbon releases.
(4) Is suited for quantification of the frequency of initiating events and the performance of the barriers.
(5) Allows use of available input data as far as possible.
(6) Allows consideration of different activities, phases, and conditions.
(7) Enables identification of common causes and dependencies.
(8) Is practically applicable regarding use of resources.
(9) Provides a basis for "re-use" of the generic model in such a way that installation specific considerations may be performed in a simple and not too time-consuming manner.

A literature review was carried out in order to identify existing methods incorporating the effect of organisational factors in QRAs. Several models and methods for quantification of the influence of organisational factors on the total risk are described in the literature [10–23]. These models and methods were reviewed and compared in view of the criteria (1)–(9) above. The review was partly based on a framework for evaluation of models/methods for this type of risk analyses [27]. None of the models/methods were directly applicable for analysis of platform specific release frequencies including analysis of the effect of safety barriers introduced to prevent release and analysis of how platform specific conditions of RIFs influence the barrier performance. However, the comparison resulted in knowledge about the existing methods used as basis for development of BORA-Release.

An assessment of the suitability of some existing modelling techniques was carried out in order to select an approach for analyses of the release scenarios. The following techniques were assessed: (a) the current practice in QRAs, (b) fault tree analysis, (c) barrier block diagram (corresponds to event tree analysis), and (d) an overall influence diagram. The assessment was based on a discussion of advantages and disadvantages of the different methods and an attempt to "score" the different modelling techniques according to fulfilment of the former described criteria. The assessment is shown in Table 1. A score of 1 indicates "not suitable", and a score of 5 indicates "very suitable".

Based on this suitability assessment and the literature review, it was concluded to apply barrier block diagrams to model the hydrocarbon release scenarios and fault tree analyses and/or risk influence diagrams to model the performance of different barrier functions ("blocks" in the barrier block diagram).

Next, a preliminary version of BORA-Release was developed. This version was discussed in the BORA project group and led to some modifications. Further, the method was reviewed by the BORA steering committee. A case study carried out in order to test BORA-Release in practice is described in Part II of this paper [26]. The experience from the case study led to some adjustments of the method and this paper presents the revised version.

3. Description of BORA-Release

BORA-Release consists of the following main steps:

Table 1
Comparison of various modelling techniques

No.	Criteria	Current QRA	Fault tree	Barrier block diagram	Overall influence diagram
1	Facilitate identification and illustration of safety barriers	1	3	5	2
2	Contribute to an understanding of which factors that influence the performance of the barrier functions	1	3	4	3
3	Reflect different causes of hydrocarbon release	1	4	4	4
4	Be suitable for quantification of the frequency of initiating events and the performance of safety barriers	5	3	3	2
5	Allow use of relevant data	5	3	3	2
6	Allow consideration of different activities, phases, and conditions	2	3	4	2
7	Enable identification of common causes and dependencies	1	4	5	5
8	Be practically applicable regarding use of resources	5	2	3	2
9	Provides “re-use” of the generic model	1	3	5	4
	Total score of modelling approach	22	28	36	26

(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 risk 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.

3.1. Development of a basic risk model

The first step is to develop a basic risk model that covers a representative set of hydrocarbon release scenarios. The purpose is to identify, illustrate, and describe the scenarios that may lead to hydrocarbon release on a platform. The basic risk model forms the basis for the qualitative and quantitative analyses of the risk of hydrocarbon release and the safety barriers introduced to prevent hydrocarbon release. A representative set of 20 hydrocarbon release scenarios has been developed and described [28]. Examples are: (a) release due to mal-operation of valve(s) during manual operations, (b) release due to incorrect fitting of flanges or bolts during maintenance, and (c) release due to internal corrosion.

The basic risk model is illustrated by *barrier block diagrams* (see Fig. 1). A barrier block diagram consists of an initiating event, arrows that show the event sequence, barrier functions realized by barrier systems, and possible outcomes. A horizontal arrow indicates that a barrier system fulfils its function, whereas an arrow downwards indicates failure to fulfil the function. In our case, the undesired event is hydrocarbon release (loss of containment). Hydrocarbon release in this context is defined as gas or oil leaks (including condensate) from the process flow, well flow or flexible risers with a release rate greater than 0.1 kg/s. Smaller leaks are called minor release or diffuse discharges. A barrier block diagram corresponds to an event tree and can be used as a basis for quantitative analysis.

An *initiating event* for a release scenario is the first significant deviation from a normal situation that under given circumstances

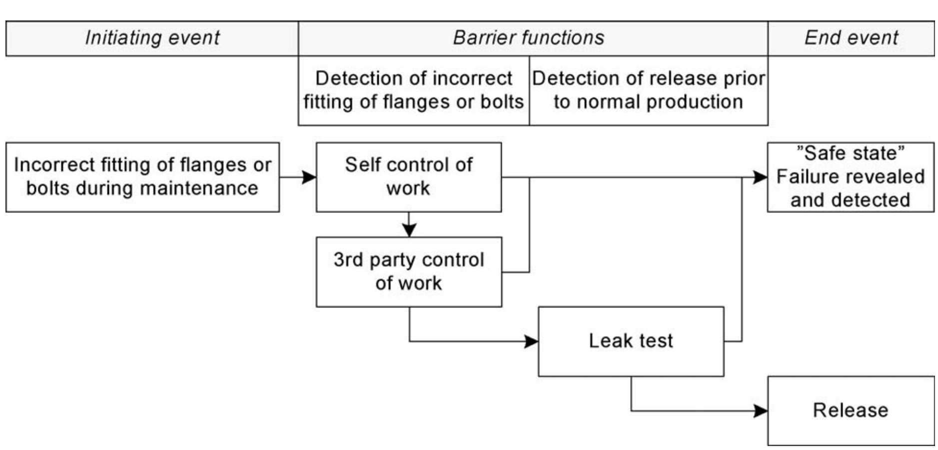

Fig. 1. Barrier block diagram; scenario “Release due to incorrect fitting of flanges or bolts during maintenance”.

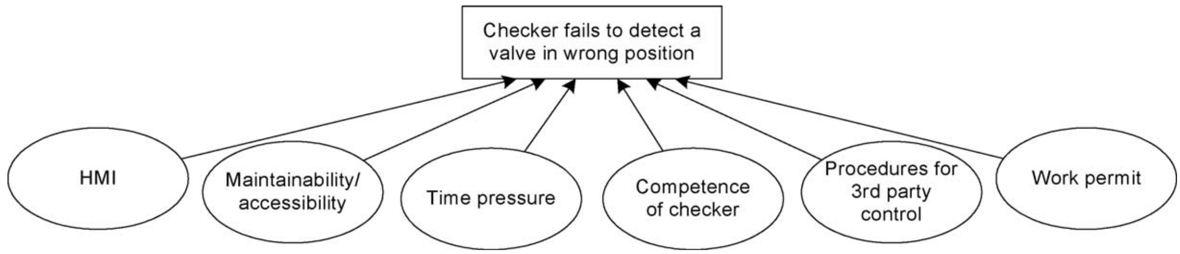

Fig. 2. Risk influence diagram; basic event "Checker fails to reveal a valve in wrong position".

may cause a hydrocarbon release (loss of containment). A "normal situation" is a state where the process functions as normal according to design specifications without significant process upsets or direct interventions into the processing plant. Examples on initiating events are: (a) valve in wrong position after manual operations, (b) incorrect fitting of flanges or bolts during maintenance, and (c) internal corrosion beyond critical limit.

A *barrier function* is defined as a function planned to prevent, control, or mitigate undesired events or accidents [29]. A *barrier system* is a system designed and implemented to perform one or more barrier functions. A barrier system may consist of different types of system elements, for example, technical elements (hardware, software), operational activities executed by humans, or a combination thereof.

3.2. Modelling the performance of safety barriers

The next step is to model the performance of safety barriers in order to analyse the plant specific barrier performance taking platform specific conditions of human, operational, organisational, and technical factors into consideration. The following attributes regarding performance of safety barriers should be allowed for in the analysis [29]: (a) functionality or effectiveness, (b) reliability/availability, (c) response time, (d) robustness, and (e) the triggering event or condition.

Fault tree analysis is used for analysis of barrier performance in BORA-Release. The "generic" top event in the fault trees in BORA-Release is "Failure of a barrier system to perform the specified barrier function". This generic top event needs to be adapted to each specific barrier in the different scenarios (e.g. "Failure to reveal valve in wrong position after maintenance by 3rd party control" and "Failure to detect diffuse discharge of hydrocarbons by area based leak search"). The results from the qualitative fault tree analyses are a list of basic events and an overview of (minimal) cut sets [30].

3.3. Assignment of industry average probabilities/frequencies and risk quantification based on these probabilities

The purpose of step (3) is to assign probabilities/frequencies to the initiating events and the basic events in the fault trees and carry out a quantitative analysis of the risk of hydrocarbon release by use of these probabilities/frequencies (quantitative analysis of the event trees and the fault trees). The results of this calculation may to some degree reflect plant specific conditions since plant specific data should be applied when possible. Plant specific data may be found in, e.g. incident databases, log data, and maintenance databases. In practice, extensive use of industry average data is necessary to be able to carry out the quantitative analysis. Several databases are available presenting industry average data like OREDA [31] for equipment reliability data, and THERP [32] and CORE-DATA [33,34] for human reliability data (see [35] for an overview of data sources). In some cases, neither plant specific data nor generic data may be found, and it may be necessary to use expert judgment to assign probabilities.

3.4. Development of risk influence diagrams

Step (4) is to develop risk influence diagrams. The purpose is to incorporate the effect of the plant specific conditions of human, operational, organisational, and technical RIFs on the occurrences (frequencies) of the initiating events and the barrier performance. Examples on risk influence diagrams for the basic events "Checker fails to reveal valve in wrong positions" and "Failure to detect leak in the leak test" are shown in Figs. 2 and 3. If necessary, we have to develop one risk influence diagram for each basic event.

Due to the complexity and variation in the types of events considered, a combined approach is preferred in order to identify RIFs: (1) a top–down approach where a generic list of RIFs is used as a basis, and (2) a bottom–up approach where the events to be assessed are chosen as a starting point. This implies that specific RIFs are identified for each initiating event and each basic event from the generic list of RIFs. The generic list may be supplemented by new RIFs when necessary.

The framework for identification of RIFs consists of the following main groups of RIFs:

- Characteristics of the personnel performing the tasks.
- Characteristics of the task being performed.
- Characteristics of the technical system.

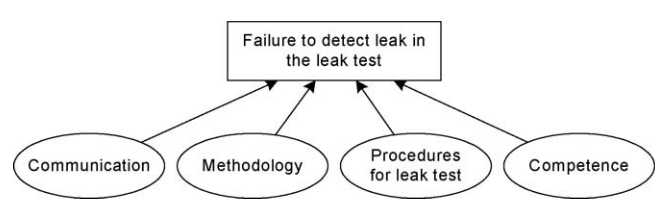

Fig. 3. Risk influence diagram; basic event "Failure to detect leak in the leak test".

Table 2
Descriptions of risk influencing factors

RIF group	RIF	RIF description
Personal characteristics	Competence	Cover aspects related to the competence, experience, system knowledge and training of personnel
	Working load/stress	Cover aspects related to the general working load on persons (the sum of all tasks and activities)
	Fatigue	Cover aspects related to fatigue of the person, e.g. due to night shift and extensive use of overtime
	Work environment	Cover aspects related to the physical working environment like noise, light, vibration, use of chemical substances, etc.
Task characteristics	Methodology	Cover aspects related to the methodology used to carry out a specific task
	Task supervision	Cover aspects related to supervision of specific tasks by a supervisor (e.g. by operations manager or mechanical supervisor)
	Task complexity	Cover aspects related to the complexity of a specific task
	Time pressure	Cover aspects related to the time pressure in the planning, execution and finishing of a specific task
	Tools	Cover aspects related to the availability and operability of necessary tools in order to perform a task
	Spares	Cover aspects related to the availability of the spares needed to perform the task
Characteristics of the technical system	Equipment design	Cover aspects related to the design of equipment and systems such as flange type (ANSI or compact), valve type, etc.
	Material properties	Cover aspects related to properties of the selected material with respect to corrosion, erosion, fatigue, gasket material properties, etc.
	Process complexity	Cover aspects related to the general complexity of the process plant as a whole
	HMI (human machine interface)	Cover aspects related to the human–machine interface such as ergonomic factors, labelling of equipment, position feedback from valves, alarms, etc.
	Maintainability/accessibility	Cover aspects related to the maintainability of equipment and systems like accessibility to valves and flanges, space to use necessary tools, etc.
	System feedback	Cover aspects related to how errors and failures are instantaneously detected, due to alarm, failure to start, etc.
	Technical condition	Cover aspects related to the condition of the technical system
Administrative control	Procedures	Cover aspects related to the quality and availability of permanent procedures and job/task descriptions
	Work permit	Cover aspects related to the system for work permits, like application, review, approval, follow-up, and control
	Disposable work descriptions	Cover aspects related to the quality and availability of disposable work descriptions like safe job analysis (SJA) and isolation plans
Organisational factors/operational philosophy	Programs	Cover aspects related to the extent and quality of programs for preventive maintenance (PM), condition monitoring (CM), inspection, 3rd party control of work, use of self control/checklists, etc. One important aspect is whether PM, CM, etc. is specified
	Work practice	Cover aspects related to common practice during accomplishment of work activities. Factors like whether procedures and checklists are used and followed, whether shortcuts are accepted, focus on time before quality, etc.
	Supervision	Cover aspects related to the supervision on the platform like follow-up of activities, follow-up of plans, deadlines, etc.
	Communication	Cover aspects related to communication between different actors like area platform manager, supervisors, area technicians, maintenance contractors, CCR technicians, etc.
	Acceptance criteria	Cover aspects related to the definitions of specific acceptance criteria related to for instance condition monitoring, inspection, etc.
	Simultaneous activities	Cover aspects related to amount of simultaneous activities, either planned (like maintenances and modifications) and unplanned (like shutdown)
	Management of changes	Cover aspects related to changes and modifications

- Administrative control (procedures and disposable work descriptions).
- Organisational factors/operational philosophy.

The detailed taxonomy of generic RIFs is shown in Table 2. A brief explanation of each RIF is included in the last column. The proposed RIF framework and the taxonomy of generic RIFs are based on a review, comparison, and synthesis of several schemes of classification of human, technical, and organisational (MTO) factors and experience from the case study. The schemes includes classification of: (a) causes in methods for accident investigations (MTO-analysis [36] and TRIPOD [37]), (b) organisational factors in models for analysis of the influence of organisational factors on risk like I-RISK [15] and WPAM [13,38], and (c) performing shaping factors (PSFs) in methods for human reliability analysis (HRA), like THERP [32], CREAM [39], SLIM-MAUD [40], and HRA databases (CORE-DATA [41]).

3.5. Scoring of risk influencing factors

We need to assess the status of the RIFs on the platform. The aim is to assign a score to each identified RIF in the risk influence diagrams. Each RIF is given a score from A to F, where

Table 3
Generic scheme for scoring of RIFs

Score	Explanation
A	Status corresponds to the best standard in industry
B	Status corresponds to a level better than industry average
C	Status corresponds to the industry average
D	Status corresponds to a level slightly worse than industry average
E	Status corresponds to a level considerably worse than industry average
F	Status corresponds to the worst practice in industry

score A corresponds to the best standard in the industry, score C corresponds to industry average, and score F corresponds to worst practice in the industry (see Table 3). The six-point scale is adapted from the TTS (Technical Condition Safety) project [42].

Several methods for assessing organisational factors are described in the literature (e.g. see [38]). Three approaches for assignment of scores of the RIFs are described in this paper: (1) direct assessment of the status of the RIFs, (2) assessment of status by use of results from the TTS projects, and (3) assessment of status by use of results from the RNNS (Risk Level on the Norwegian Continental Shelf) project [43].

Direct assessment of the status of the RIFs in the risk influence diagrams may be carried out in a RIF audit. Usually, a RIF audit is carried out by structured interviews of key personnel on the plant and observations of work performance. Useful aids are behavioural checklists and behaviourally anchored rating scales (BARS) [38]. In addition, surveys may be used as part of the RIF audit as supplement to the other techniques.

The TTS project proposes a review method to map and monitor the technical safety level on offshore platforms and land-based facilities based on the status of safety critical elements, safety barriers, and their intended function in major accidents prevention [42]. The TTS project is based on a review technique using defined performance requirements described in performance standards for 19 areas. The condition of safety barriers is measured against these performance requirements. A number of examination activities are defined and used to check each performance requirement, including document reviews, interviews, visual inspections, and field tests. A six-point scoring scheme is used in the TTS project that may be directly transformed to the scores in Table 3.

Finally, the assessment of the status of the RIFs may be based on results from the RNNS project [43] and accident investigations. The RNNS project includes a broad questionnaire survey, which addresses general health, environmental, and safety (HES) aspects, risk perception, and safety culture. The surveys are conducted once every second year. Data may be provided as average values for the entire industry, as well as on platform specific basis. By selecting relevant questions from the survey, these data may provide input to scoring of the RIFs for different platforms. However, the data should be further analysed to get scores of the RIFs according to the scheme in Table 3 [44]. Results from accident investigations may be used as a supplement to the results from the RNNS project in order to assess the scores of the RIFs.

3.6. Weighting of risk influencing factors

Weighting of the RIFs is an assessment of the effect (or importance) the RIFs has on the frequency of occurrence of the basic events. The weights of the RIFs correspond to the relative difference in the frequency of occurrence of an event if the status of the RIF is changed from A (best standard) to F (worst practice). The weighting of the RIFs is done by expert judgment. In practice, the assessment of the weights is based on a general discussion of the importance with platform personnel and the analysts where the following principles are applied:

(1) Determine the most important RIF based on general discussions.
(2) Give this RIF a relative weight equal to 10.
(3) Compare the importance of the other RIFs with the most important one, and give them relative weights on the scale 10–8–6–4–2.
(4) Evaluate if the results are reasonable.

The weights are normalized as the sum of the weights for the RIFs influencing a basic event should be equal to 1.

3.7. Adjustment of industry average probabilities/frequencies

Further, the industry average probabilities/frequencies used in the quantitative analysis are adjusted. The purpose is to assign platform specific values to the input probabilities/frequencies allowing for platform specific conditions of the RIFs. The industry average probabilities/frequencies are revised based on the risk influence diagrams through an assessment of the weights and the status of the RIFs. The following principles for adjustment are proposed:

Let $P_{\text{rev}}(\text{A})$ be the "installation specific" probability (or frequency) of occurrence of event A. The probability $P_{\text{rev}}(\text{A})$ is determined by the following procedure:

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

where $P_{\text{ave}}(\text{A})$ denotes the industry average probability of occurrence of event A, w_i denotes the weight (importance) of RIF no. i for event A, Q_i is a measure of the status of RIF no. i, and n is the number of RIFs. Here:

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

The challenge is now to determine appropriate values for Q_i and w_i. To determine the Q_i's we need to associate a number to each of the status scores A–F. The proposed way to determine the Q_i's is:

- Determine $P_{\text{low}}(\text{A})$ as the lower limit for $P_{\text{rev}}(\text{A})$ by expert judgment.

- Determine P_{high}(A) as the upper limit for P_{rev}(A) by expert judgment.
- Then put for $i = 1, 2, \ldots n$:

$$Q_i(s) = \begin{cases} P_{low}/P_{ave} & \text{if } s = \text{A} \\ 1 & \text{if } s = \text{C} \\ P_{high}/P_{ave} & \text{if } s = \text{F} \end{cases} \quad (3)$$

where s denotes the score or status of RIF no i.

Hence, if the score s is A, and P_{low}(A) is 10% of P_{ave}(A), then Q_i is equal to 0.1. If the score s is F, and P_{high}(A) is 10 times higher than P_{ave}(A), then Q_i is equal to 10. If the score s is C, then Q_i is equal to 1. Furthermore, if all RIFs have scores equal to C, then $P_{rev}(A) = P_{ave}(A)$, if all RIFs have scores equal to A, then $P_{rev}(A) = P_{low}(A)$, and if all RIFs have scores equal to F, then $P_{rev}(A) = P_{high}(A)$.

To assign values to Q_i for s = B, we assume a linear relationship between Q_i(A) and Q_i(C), and use $s_A = 1$, $s_B = 2$, $s_C = 3$, $s_D = 4$, $s_E = 5$, and $s_F = 6$. Then:

$$Q_i(B) = \frac{P_{low}}{P_{ave}} + \frac{(s_B - s_A)(1 - (P_{low}/P_{ave}))}{s_C - s_A} \quad (4)$$

To assign values to Q_i for s = D and E, we assume a linear relationship between Q_i(C) and Q_i(F). Then:

$$Q_i(D) = 1 + \frac{(s_D - s_C)((P_{high}/P_{ave}) - 1)}{s_F - s_C} \quad (5)$$

Q_i(E) is calculated as Q_i(D) by use of s_E instead of s_D in formula (5). Fig. 4 shows different values of Q_i depending on different values of P_{low} and P_{high}:

Case 1. $P_{low} = P_{ave}/10$, and $P_{high} = 10P_{ave}$.
Case 2. $P_{low} = P_{ave}/5$, and $P_{high} = 5P_{ave}$.
Case 3. $P_{low} = P_{ave}/3$, and $P_{high} = 3P_{ave}$.
Case 4. $P_{low} = P_{ave}/2$, and $P_{high} = 2P_{ave}$.

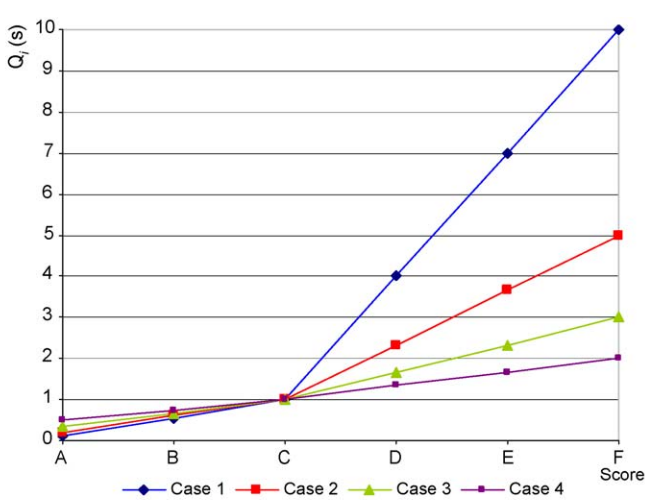

Fig. 4. Values of Q_i depending on different values of P_{low} and P_{high}.

3.8. Recalculation of the risk

The final step of BORA-Release is to determine the platform specific risk of hydrocarbon release by applying the platform specific input probabilities/frequencies (P_{rev}(A)) for all events in the risk model. Use of these revised probabilities results in an updated risk picture including analysis of the effect of the performance of the safety barriers introduced to prevent hydrocarbon release. The revised risk picture takes the platform specific conditions of technical, human, operational, and organisational RIFs into consideration.

4. Discussion

The discussion is divided in two main parts. The different steps in BORA-Release are discussed in part one, while part two contains a discussion to what extent the criteria presented in Section 2 are fulfilled.

4.1. Discussion of the steps in BORA-Release

The basic risk model developed as part of BORA-Release may be seen as an extended QRA-model compared to the current status of offshore QRAs for three reasons:

(1) It facilitates a detailed modelling of loss of containment including initiating events reflecting different causal factors of hydrocarbon release and safety barriers introduced to prevent release.
(2) The risk model incorporates different operational barriers such as use of self control of work/checklists, 3rd party control of work, and inspection to detect corrosion.
(3) Event trees and fault trees are linked together in one common risk model.

Development of a risk model with a set of hydrocarbon release scenarios and RIFs answers the criticism formulated by e.g. Kafka [45] that the existing QRAs are not suitable for analysing the effect of the most effective safety measures to avoid initiating events.

BORA-Release is based on a broad view on safety barriers, which means that the performance of different types of safety barriers like the process shutdown system, 3rd party control of work, and the inspection program need to be analysed. The fault tree analyses applied for analysis of the performance of safety barriers are linked to the event trees in one common risk model. The fault tree analysis will not necessarily cover all attributes relevant for analysis of the barrier performance, and there may be need to carry out other analysis, e.g. human reliability analysis (HRA), analysis of fire and explosion loads, impairment analysis, and qualitative assessments of barrier functionality.

Combination of barrier block diagrams/event trees and fault trees is an attractive modelling technique as barrier block diagrams makes it possible to give a clear and consistent representation and illustration of the different barrier systems that fulfil the defined barrier functions introduced to prevent hydrocarbon release. The approach enables a separate analysis of each barrier at the desired level of detail. The barrier block diagrams may be generic for several platforms, while the detailed analysis of the different safety barriers may be platform specific.

Assignment of industry average probabilities/frequencies implies use of generic databases in addition to extraction of platform specific information regarding operational conditions, experience from surveillance of operational activities, and testing of technical safety systems. Recovery of data from internal databases or surveillance systems may require extensive manual work and often some interpretations of the recorded data may be necessary. Due to the novelty of the modelling of the containment barrier, relevant data are lacking for some barriers. The availability of relevant human reliability data is low, thus there is need for collection of data to support the analyses. Alternatively, some expert judgment sessions may be carried out in order to generate relevant data.

The top–down approach for development of risk influence diagrams ensures that the RIFs are identified and defined in the same manner in different analysis, while the bottom–up approach ensures that unique RIFs for specific plants are identified and assessed. While traditional performance influence factors as reviewed by Kim and Jung [46] focuses on factors influencing human failure events, the RIF framework presented in Section 3.4 also includes factors influencing hardware (system/component) failure events (e.g. material properties and program for preventive maintenance).

Experience from the case study indicates that the main RIF groups in the framework are adequate for identification of RIFs. But the list of generic RIFs in Table 2 may be supplemented by more RIFs to cover all the basic events included in the analyses of barrier performance. This implies that the list of generic RIFs may be a "living" document that may be revised due to more experience by use of the list.

A six-point score scheme is used for assignment of scores to the RIFs and the scores are related to different levels in the industry. The rationale behind is that industry average data reflects the industry average standard as regards status of the RIFs. The argument for the misalignment of the scores (A and B better than average, and D, E, and F worse than average) is that the existing safety level within the industry is so high that the potential for declining in the status is greater than the improvement potential.

Three approaches for giving scores to the RIFs are described. The approaches may be used separately, or combined in order to assign scores. The first approach, direct assessment of the status of the RIFs by a RIF-audit is the most resource demanding approach. However, this approach may ensure a high validity[1] of the assignment of scores since the assessment of the specific RIFs is based on the risk influence diagrams developed for each basic event. There is demand for development of aids for execution of RIF audits, e.g. BARS with description of the reference levels for scoring. Such aids will contribute to better consistence of the assignment of scores.

[1] Validity refers to whether or not it measures what it is supposed to measure [47].

The second approach, assessment of status by use of results from the TTS projects, uses existing data from a project carried out for several platforms on the Norwegian Continental Shelf (NCS) so the use of resources will be limited. The scoring scheme used in the TTS project also consists of a six-point scale, but the scores are related to some performance criteria and not to the industry average level. However, the TTS scores may be transformed to the BORA scores. There are some disadvantages of this approach. The TTS projects are not carried out for all platforms on the NCS. The main focus in the project is the status of technical aspects of the consequence reducing barriers so limited knowledge may be collected about the organisational factors. The TTS assessment may be carried out several years before the actual analysis as the time aspect may cause that the data to be out-of-date. Finally, the relevance of the data may be questionable since the original assessments have been performed for another purpose. Thus, the results should be carefully assessed prior to use.

The third approach, use of results from the RNNS survey and accident investigations has been applied during the case study. The main advantage is the availability of platform specific results form the survey on all platforms on the NCS. However, there are several disadvantages with this approach. The main disadvantage is the low validity since the scores are assigned based on questions from a questionnaire not developed for this purpose where the questions are rather general and not specific for the specific RIFs. As an example, the RIF "time pressure" will be given the same score for all activities on the platform regardless of who, when, or where the activity is carried out. The survey is carried out every second year, and hence the results from the last survey may not be up to date when the data are applied. The last aspect is that the answers in the survey may be influenced by other factors, e.g. general dissatisfaction with the working conditions not relevant for the analysed RIF.

The credibility of the status assessment is one important aspect to consider when selecting approach for scoring of RIFs. As a rule of thumb, we may say that more specific, detailed, and resource demanding the assessment of the RIF status are, the more credible are the results. However, the use of resources should be balanced against the argument from the representatives from the oil companies that it is important to use existing data in order to minimize the use of resources.

A rather simple technique for weighting of RIFs by use of expert judgment is proposed. The weighting process is easy to carry out in practice. The results from the weighting process are unambiguous, and the traceability is good. An important aspect of the identification, scoring, and weighting of RIFs is the involvement of operational personnel working on the platform. Nobody is as competent as the operational personnel to carry out these steps. However, a risk analyst knowing the methodology should guide the operational personnel through the weighting process.

The revised probabilities of occurrences of the basic events are calculated as a sum of products of the scores and the normalized weights of the relevant RIFs for each basic event multiplied with the industry average probabilities. The upper (P_{high}) and lower (P_{low}) values act as anchor values and contribute to credibility of the results. A wide range implies the possibility for major changes in the risk level, while a small range implies minor changes in the risk level. The final results are obviously dependent of these values. The upper and lower limits may be established by expert judgment, preferably supported by experience data. Another approach to be considered as a basis for determining P_{high} and P_{low}, is to use the upper and lower bounds (e.g. generated from failure rates) presented in generic databases like OREDA and THERP.

As illustrated in Fig. 4, a linear relationship is assumed between Q_i(A) and Q_i(C), and Q_i(C) and Q_i(F) respectively. Other relationships may be assumed here. Fig. 4 illustrates another important aspect of the method, that the risk improvement potential is less than the risk worsening potential. This aspect may be explained by the existing low risk level due to high focus on risk reduction measures for several years.

The final step of BORA-Release, recalculation of the risk in order to calculate the platform specific risk by use of revised platform specific probabilities/frequencies, is easy to execute when the other steps have been carried out. The revised hydrocarbon release frequency takes platform specific conditions as regards technical, human, operational, as well as organisational RIFs into consideration. In addition, the effect of the performance of safety barriers introduced to prevent hydrocarbon releases is included in the results.

The recalculated risk picture gives valuable input to decision-makers. The improved knowledge about existing and non-existing safety barriers and better understanding of the influence of RIFs (i.e. the qualitative analysis) are important results in itself, independent of the quantitative results. As in other risk analyses, the quantitative results from use of BORA-Release rely on a set of assumptions. Slight adjustments of the scaling systems or the input to the analysis (e.g. data and expert judgments) influence the final numerical results. Decision-makers using the results from risk analyses using BORA-Release should be aware of these assumptions and not only base their decisions on the numerical results of the analysis. It is necessary to see the results of the analysis in a broader context, where the limitations and constraints of the analysis are taken into account.

4.2. Fulfilment of criteria

Criteria (1)–(4), and (9) presented in Section 2 are fulfilled. Use of barrier block diagrams evidently facilitates identification and illustration of safety barriers (1). A risk model that consists of a combination of barrier block diagrams/event trees, fault trees, and risk influence diagrams allows inclusion of technical, human, operational, as well as organisational elements and the graphical illustrations make them well suited for use in presentations and discussions that will increase the understanding of RIFs (2). BORA-Release allows for analysis of technical failures and human errors as initiating events, as well as analysis of technical, human, and operational barriers (3) (see [28] for more information). Event trees, fault trees, and risk influence diagram are applicable for quantification of the frequency of initiating events and the performance of the safety barriers (4). If a generic risk model is developed, it will be manageable to carry out some installation specific considerations about the status on each platform, and to carry out simple comparisons with other platforms (e.g. practice regarding operational barriers as third party control of work or status of the RIFs) (9).

A problem may arise in respect to the availability of relevant input data (5). To be able to use relevant input data it may be necessary to collect new types of data. Especially within the field of human reliability data it seems to lack relevant data from the offshore field. Some data on a limited set of activities has been collected on the British sector [33,34], but it has been necessary to use data from the nuclear industry in the case study.

With respect to criteria (6), the focus so far has been on failures introduced during normal production, maintenance, shutdown, and start-up within the operational phase of the life-cycle of a platform, and safety barriers introduced to prevent releases due to such failures. Latent failures from the design phase and safety barriers aimed to prevent such failures have not been analysed yet.

Criterion (7) states that the method should enable identification of common causes and dependencies. Events in BORA-Release are considered independent conditional of the RIFs. Independence could be questioned, however, it is likely to be sufficiently accurate from a practical point of view. There may be interaction effects among the RIFs influencing one basic event. Interaction effects mean that a RIF will have a different effect on the basic event, depending on the status of another RIF (positive correlation), e.g. if the competence of personnel is poor, it will be even more serious if the quality of procedures also is poor. A simple approach is suggested for analysis of interaction effects among RIFs in BORA-Release. If two or more RIFs are assumed to interact and the status are worse than average (D, E, or F), the score of one of them is reduced one category (e.g. from D to E), and similarly if the scores of two interacting RIFs are better than average. However, more sophisticated methods should be assessed as part of future research, e.g. use of Bayesian belief networks to more accurately model the interactions between the RIFs (see e.g. [21]). Development of a risk model including safety barriers that may prevent, control, or mitigate accident scenarios with in-depth modelling of barrier performance allows explicit modelling of functional common cause failures (e.g. failures due to functional dependencies on a support system). However, there is need for further research to assess the effect of residual common cause failures that may lead to simultaneous failures of more than one safety barrier (e.g. calibration errors introduced during maintenance that may cause simultaneous failures of gas detectors and fire detectors).

Criterion (8) deals with practical applicability with respect to use of resources. Unfortunately, to carry out a comprehensive analysis of the complex reality in a process plant is resource demanding. If the analysis shall give adequate support during the decision-making process the level of detail of the analysis need to reflect the reality on the platform. However, it may be possible to carry out less comprehensive analysis of specific problem areas on the platform with less use of resources.

One basis for BORA-Release is the assumption that the average standard of RIFs corresponds to industry average (generic) input data and better standard on the RIFs than average lead to a lower probability or frequency of occurrence of the basic events. This assumption seems to be realistic where generic data from the offshore industry exists. However, there are needs for further discussions whether the adjustment of human error probabilities should be based on scores of the RIFs related to the average standard in the North Sea or whether traditional assessment of performance shaping factors applied in human reliability analysis should be applied (adjustment of nominal human error probabilities by assessment of task specific performance shaping factors).

5. Conclusions and further work

This paper presents BORA-Release, a method for qualitative and quantitative analyses of the platform specific hydrocarbon release frequency. The method makes it possible to analyse the effect on the release frequency of safety barriers introduced to prevent hydrocarbon release, and platform specific conditions of technical, human, operational, and organisational RIFs. The method may be used to analyse the plant specific frequency of loss of containment in other types of process plants. However, the main area of application is not the calculation of the release frequency itself, but use of the method to assess the effect of risk reducing measures and risk increasing changes during operations. Sensitivity analysis may be carried out in order to analyse the effect of changes in technical, human, operational, as well as organisational RIFs. Focus on relative changes in the release frequency instead of absolute numbers may increase the credibility to the results. In addition, the effect of introduction of new safety barriers may be analysed.

Application of BORA-Release to analyse the frequency of loss of containment gives a more detailed risk picture than traditional QRAs where no analysis is made of causal factors of loss of containment. The qualitative analysis of the release scenarios generates knowledge about factors influencing the risk of hydrocarbon release within the process plant even though no quantitative analysis is carried out. This knowledge may support decisions of importance for the future performance of the safety barriers.

Only a limited sample of the release scenarios described in [28] have been analysed quantitatively so far. However, further work will be carried out in the BORA-project to analyse more release scenarios. Further work will also be carried out in order to link the model of the hydrocarbon release scenarios to the traditional QRA model that includes analysis of the consequence reducing barriers.

There is still need for further research focusing on some of the steps in BORA-Release. The main challenge is the scoring of the RIFs and further work will be carried out in order to assess whether the results from the TTS project may be used, or if it is necessary to perform specific RIF-audits. In the latter case, it may be necessary to develop behaviourally anchored rating scales (BARS) or similar aids that may be used as basis for the RIF-audits. Another challenge is lack of relevant data, especially for human error probabilities on offshore platforms and there may be need for collecting new types of data that are not available in existing databases. Further work should also be carried out in order to improve the descriptions of RIFs and assess whether the total number of RIFs (see Table 2) may be reduced, e.g. by combining two RIFs into one new RIF.

Acknowledgements

The development of BORA-Release has been carried out as part of the BORA-project financed by the Norwegian Research Council, The Norwegian Oil Industry Association, and Health and Safety Executive in UK. The authors acknowledge personnel from the steering committee that have commented on the preliminary version of BORA-Release.

References

[1] A. Hopkins, Lessons From Longford: The Esso Gas Plant Explosion, CCH Australia Ltd., Sydney, 2000.
[2] W.D. Cullen, The Public Inquiry into the Piper Alpha Disaster, Hmso, London, 1990.
[3] D. Vaughan, The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA, University of Chicago Press, Chicago, 1996.
[4] CAIB, The Colombia Accident Investigation Board Report, vol. 1, 2003, http://www.caib.us/.
[5] NOU-2000:31, Hurtigbåten MS Sleipners forlis 26 november 1999, Justis-og politidepartementet, Oslo, Norge, 2000.
[6] W.D. Cullen, The Ladbroke Grove Rail Inquiry: Report, Part I, HSE Books, United Kingdom, 2001.
[7] NOU-2000:30, Åstaulykken, 4 januar 2000. Justis-og politidepartementet, Oslo, Norge, 2000.
[8] S. Sklet, Storulykker i Norge de siste 20 årene, in: S. Lydersen (Ed.), Fra flis i fingeren til ragnarok, Tapir Akademisk Forlag, Trondheim, 2004.
[9] J.E. Vinnem, T. Aven, H. Hundseid, K.A. Vassmyr, F. Vollen, K. Øien, Risk assessments for offshore installations in the operational phase, in: ESREL 2003, Maastricht, The Netherlands, 2003.
[10] R.M. Pitblado, J.C. Williams, D.H. Slater, Quantitative assessment of process safety programs, Plant/Oper. Prog. 9 (3) (1990).
[11] D.E. Embrey, Incorporating management and organisational factors into probabilistic safety assessment, Reliab. Eng. Syst. Safe. 38 (1–2) (1992) 199–208.
[12] M. Modarres, A. Mosleh, J.A. Wreathall, Framework for assessing influence of organisation on plant safety, Reliab. Eng. Syst. Safe. 38 (1992) 157–171.
[13] K. Davoudian, J.-S. Wu, G.E. Apostolakis, Incorporating organisational factors into risk assessment through the analysis of work processes, Reliab. Eng. Syst. Safe. 45 (1994) 85–105.
[14] K. Davoudian, J.-S. Wu, G.E. Apostolakis, The work process analysis model (WPAM-II), Reliab. Eng. Syst. Safe. 45 (1994) 107–125.
[15] L.J. Bellamy, I.A. Papazoglou, A.R. Hale, O.N. Aneziris, B.J.M. Ale, M.I. Morris, J.I.H. Oh, I-RISK: Development of an Integrated Technical and Management Risk Control and Monitoring Methodology for Managing and Quantifying On-Site and Off-Site Risks. Main Report. Contract no: ENVA-CT96-0243, 1999.
[16] I.A. Papazoglou, O.N. Aneziris, J.G. Post, B.J.M. Ale, Technical modelling in integrated risk assessment of chemical installations, J. Loss Prevent. Proc. Ind. 15 (6) (2002) 545–554.
[17] I.A. Papazoglou, L.J. Bellamy, A.R. Hale, O.N. Aneziris, J.G. Post, J.I.H. Oh, I-Risk: development of an integrated technical and management risk methodology for chemical installations, J. Loss Prevent. Proc. Ind. 16 (2003) 575–591.
[18] A. Mosleh, E.B. Goldfeiz, An Approach for Assessing the Impact of Organisational Factors on Risk, Technical Research Report, CTRS, A. James Clark School of Engineering, University of Maryland at College Park, 1996.
[19] D.M. Murphy, E.M. Paté-Cornell, The SAM framework: modelling the effects of management factors on human behaviour in risk analysis, Risk Anal. 16 (4) (1996).

[20] E.M. Paté-Cornell, D.M. Murphy, Human and management factors in probabilistic risk analysis: the SAM approach and observations from recent applications, Reliab. Eng. Syst. Safe. 53 (1996) 115–126.
[21] K. Øien, A framework for the establishment of organisational risk indicators, Reliab. Eng. Syst. Safe. 74 (2) (2001) 147–167.
[22] K. Øien, S. Sklet, Organisational Risk Indicators Pilot Study Statfjord A (in Norwegian), SINTEF-Report STF38 A00421, SINTEF, Trondheim, Norway, 2000.
[23] H. Andersen, J. Casal, A. Dandrieux, B. Debray, V. De Dianous, N.J. Duijm, C. Delvosalle, C. Fievez, L. Goossens, R.T. Gowland, A.J. Hale, D. Hourtolou, B. Mazzarotta, A. Pipart, E. Planas, F. Prats, O. Salvi, J. Tixier, ARAMIS—User Guide, EC Contract number EVG1-CT-2001-00036, 2004.
[24] PSA, Regulations relating to management in the petroleum activities (The Management Regulations), 3 September 2001, Petroleum Safety Authority Norway, Stavanger, 2001.
[25] J.E. Vinnem, T. Aven, S. Hauge, J. Seljelid, G. Veire, Integrated Barrier Analysis in Operational Risk Assessment in Offshore Petroleum Operations, PSAM7-ESREL'04, Berlin, 2004.
[26] S. Sklet, J.E. Vinnem, T. Aven, Barrier and operational risk analysis of hydrocarbon releases (BORA-Release). Part II. Results from a case study, J. Hazard. Mater. 137 (2006) 692–708.
[27] K. Øien, S. Sklet, A Structure for the Evaluation and Development of Organisational Factor Frameworks, PSAM 5, Osaka, Japan, 2000.
[28] S. Sklet, Hydrocarbon releases on oil and gas production platforms: release scenarios and safety barriers, J. Loss Prevent. Proc. Ind. 19 (2006) 481–493.
[29] S. Sklet, Safety barriers: definition, classification, and performance, J. Loss Prevent. Proc. Ind. 19 (2006) 494–506.
[30] M. Rausand, A. Høyland, System Reliability Theory: Models, Statistical Methods, and Applications, Wiley-Interscience, Hoboken, NJ, 2004.
[31] OREDA, Offshore Reliability Data Handbook (OREDA 2002), 4th ed., SINTEF, Trondheim, Norway, 2002.
[32] A.D. Swain, H.E. Guttmann, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications: Final Report NUREG CR-1278, SAND80-200, Sandia National Laboratories Statistics Computing and Human Factors Division, Albuquerque, 1983.
[33] G. Basra, H. Gibson, B. Kirwan, Collection of Offshore Human Error Probability Data, Phase 2, vol. 1: Offshore Drilling Data, Health & Safety Executive, 1998.
[34] G. Basra, H. Gibson, B. Kirwan, Collection of Offshore Human Error Probability Data, Phase 2, vol. 2: Permit to Work data, Health & Safety Executive, 1998.
[35] ROSS-website, Data Sources for Risk and Reliability Studies, http://www.ntnu.no/ross/info/data.php.
[36] J.-P. Bento, Menneske - Teknologi - Organisasjon Veiledning for gjennomføring av MTO-analyser. Kurskompendium for Oljedirektoratet, Oversatt av Statoil, Oljedirektoratet, Stavanger, Norway, 2001.
[37] J. Groeneweg, Controlling the Controllable: The Management of Safety, DSWO Press, Leiden, The Netherlands, 1998.
[38] R. Jacobs, S. Haber, Organisational processes and nuclear power plant safety, Reliab. Eng. Syst. Safe. 45 (1994) 75–83.
[39] E. Hollnagel, Cognitive Reliability and Error Analysis Method: CREAM, Elsevier, Oxford, 1998.
[40] D.E. Embrey, P. Humphreys, E.A. Rosa, B. Kirwan, K. Rea, SLIM-MAUD: An Approach to Assessing Human Error Probabilities Using Structured Expert Judgment, Department of Energy, USA, 1984.
[41] H. Gibson, G. Basra, B. Kirwan, Development of the CORE-DATA database, Paper dated 23.04.1998, University of Birmingham, Birmingham, United Kingdom, 1998.
[42] O. Thomassen, M. Sørum, Mapping and monitoring the technical safety level, SPE 73923, 2002.
[43] PSA, Trends in Risk Levels—Summary Report Phase 5 (2004), The Petroleum Safety Authority, Stavanger, 2005.
[44] T. Aven, S. Hauge, S. Sklet, J.E. Vinnem, Operational risk analysis. Total analysis of physical and non-physical barriers. H2.1 methodology for analysis of HOF factors, Draft 1, Rev 1, 2005.
[45] P. Kafka, The process of safety management and decision making, ESREL 2005, Tri City, Poland, 2005.
[46] J.W. Kim, W.D. Jung, A taxonomy of performance influencing factors for human reliability analysis of emergency tasks, J. Loss Prevent. Proc. Ind. 16 (6) (2003) 479–495.
[47] Statistics, Britannica Student Encyclopedia, Encyclopædia Britannica Online. 10 November 2005, http://search.eb.com/ebi/article-208648, 2005.