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Minimum requirements to ice management barrier systems

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ABSTRACT

Ice management (IM) is defined as all activities carried out with the objective of mitigating hazardous situations by reducing or avoiding actions from any kind of ice features to a protected unit (e.g. a drilling vessel). The IM activities are risk-reducing barriers. Barriers consist of technical, operational or organisational barrier elements and barrier functions are ranging from ice detection, ice forecasting, ice alerting, physical ice fighting, and disconnection procedures of the protected unit.

Operators in Norwegian Arctic waters must comply with regulatory requirements as stated by the Petroleum Safety Authority Norway (PSA) regarding risk management and with requirements as stated in ISO 35104 "Arctic operations — Ice management". Both ISO 35104 and the PSA regulations require data collection from operations, but information on how to monitor is limited.

This paper describes a part of the PSA minimum requirements to barrier systems and a set of Boolean barrier elements for flexible modelling of a wide range of operational IM barrier systems. The Boolean event model may serve as a modular specification of operative barrier systems to include performance requirements and for defining compensating measures for operators if IM barriers are impaired. Further, the Boolean barrier models may serve as specifications for data collection of standardized system and equipment boundaries, functions and failure modes. The IM barrier system model may be the basis for qualitative and quantitative analyses and for verification of the IM systems.

KEY WORDS: Ice management; Regulatory principles; Risk reducing barriers; Barrier impairment monitoring; Compensating measures

1. INTRODUCTION

Design decisions for safe and efficient ice management (IM) systems can be based on performance models and decision criteria for the overall, or parts of the overall IM system. The Ice Management and Design Philosophy Work Package (WP5) is part of the Centre for research-based innovation, SAMCoT. In the beginning of this project, complete methods for combining all the above types of information in qualitative and/or quantitative decision processes were not available. The WP5 project on barrier management is an attempt to propose a conceptual approach for integrating such information. The starting point in the project was that IM design decisions were proposed to be based on descriptions about the physical environment and performance of risk reducing barriers for the protected unit which e.g. could be a drillship. The study shall provide methods and description models for combining information for:

- A top-down approach of barrier performance descriptions,
- Qualitative and/or quantitative performance models supporting decision processes,
- Handling uncertainties, unknowns, and large variations in data.

In our approach, it is assumed that the PSA requirements (PSA, *Regulatory principles*) for risk reduction is the main and superior source of the requirements hierarchy for operations on the Norwegian Continental Shelf and in the Norwegian Arctic Waters. In addition to the main PSA requirements, ISO standards, guidelines and class rules (e.g. ISO 19906, ISO 35104, ISO 14224, IEC 61508), are also applicable, but in case of conflicting or overlapping requirements, the PSA regulations should take precedence.

The contents of the paper consist of the following sections:

- A selected subset of PSA minimum requirements chosen for establishing a formal qualitative representation of the performance of risk reducing barriers is described.
- A case description that shows how PSA requirements can be modelled quite directly from the regulations in a flexible and modular manner to represent an operational IM barrier system to be presented to IM operators. The presented Boolean operational model may be the basis for qualitative and quantitative analyses of the IM system.
- PSA requires that equipment failure data is collected during the operations and this section presents the methodology and framework for such data collection.
- A measurable space with high-level IM Boolean event variables and Boolean operators in a Sigma algebra.
- A final section comprising a summary, discussions and conclusions of the paper. Possible future work options are briefly presented.

2. SELECTED PSA REQUIREMENTS

2.1 PSA *Defined hazard and accidents conditions (DFUs)*

All offshore oil and gas operations may be hazardous and PSA requires that the responsible operators shall identify possible hazards. PSA has defined the most common hazards, and such hazards are denoted *'defined hazard and accident conditions'* (DFU). Currently PSA has not defined DFUs related to ice hazards, but in this paper the DFUs should also cover ice collision with the protected unit.

> *'A company responsible for pursuing oil and gas activities acceptably must identify the occurrences it needs to guard against – known as "defined hazard and accident conditions" (DFUs)*
> *…Collisions and other structural damage to a facility….*

Figure 1. Quote from PSA *Defined hazard and accidents conditions (DFUs).*

2.2 Framework regulation §11 on Risk reduction principles

In the PSA *Framework regulation §11* it is required that risk reduction shall be based on the established minimum levels of barrier performance requirements according to existing levels, as quoted in Figure 2 below.

> *'Harm or danger of harm to people, the environment or material assets shall be prevented or limited in accordance with the health, safety and environment legislation, including internal requirements and acceptance criteria that are of significance for complying with requirements in this legislation….*
> *….'The requirement in this provision for reducing the risk entails that the* ***established minimum level*** *for health, safety and environment, including acceptance criteria for major accident risk…'…*

Figure 2. Quote from PSA *Framework HSE §11 Risk reduction principles.*

2.3 Management regulation §5 on Barriers

The barrier requirements shall be based on the PSA *Management regulation, §5 Barriers* which are quoted in Figure 3. All §5 requirements are used in the following Boolean models and illustrated in case descriptions in Section 3 of this paper.

> *1. Barriers shall be established that at all times can*
> *a) identify conditions that can lead to failures, hazard and accident situations,*
> *b) reduce the possibility of failures, hazard and accident situations occurring and developing,*
> *c) limit possible harm and inconveniences.*
>
> *2. Where more than one barrier is necessary, there shall be sufficient independence between barriers.*
>
> *3. The operator or the party responsible for operation of an offshore or onshore facility, shall stipulate the strategies and principles that form the basis for design, use and maintenance of barriers, so that the barriers' function is safeguarded throughout the offshore or onshore facility's life.*
>
> *4. Personnel shall be aware of what barriers have been established and which function they are intended to fulfil, as well as what performance requirements have been defined in respect of the concrete technical, operational or organisational barrier elements necessary for the individual barrier to be effective.*
>
> *5. Personnel shall be aware of which barriers and barrier elements are not functioning or have been impaired.*
>
> *6. Necessary measures shall be implemented to remedy or compensate for missing or impaired barriers.*

Figure 3. PSA *Management regulation, §5 Barriers* (numbers 1-6 added).

3. CASE DESCRIPTION

A ship-shaped movable drilling offshore unit is chosen as the protected unit in the IM case. The IM example is covering the following topics:

- Defined hazard and accidental conditions due to collision between ice and the protected unit,
- Four different resulting safe states for the BOP,
- Operational ice observations covering 4 different ice detecting methods related to 4 ice management zones,
- Operator barrier system panel for 4 barrier branches presenting barrier element states,
- Four operational disconnection and move-off procedures and systems for the protected unit.

3.1 DFU and effects on the low ice demand cases on a drilling rig

In this paper we assume Arctic physical environmental conditions which may be found for fields in e.g. the Southern Barents Sea. Under such conditions, the ice collision hazards may probably be found to occur with low frequency meaning that hazardous ice may occur only a few times during the total operational lifetime.

3.2 Safe states for the BOP

In case hazardous ice approaches the drilling rig, the possible safe states for the operation and the blow out preventer (BOP) shall be identified and specified. In this case 4 safe states are given and illustrated in Figure 4. For each safe state, the required time to reach such a state is associated with a circular zone as shown in Figure 5.

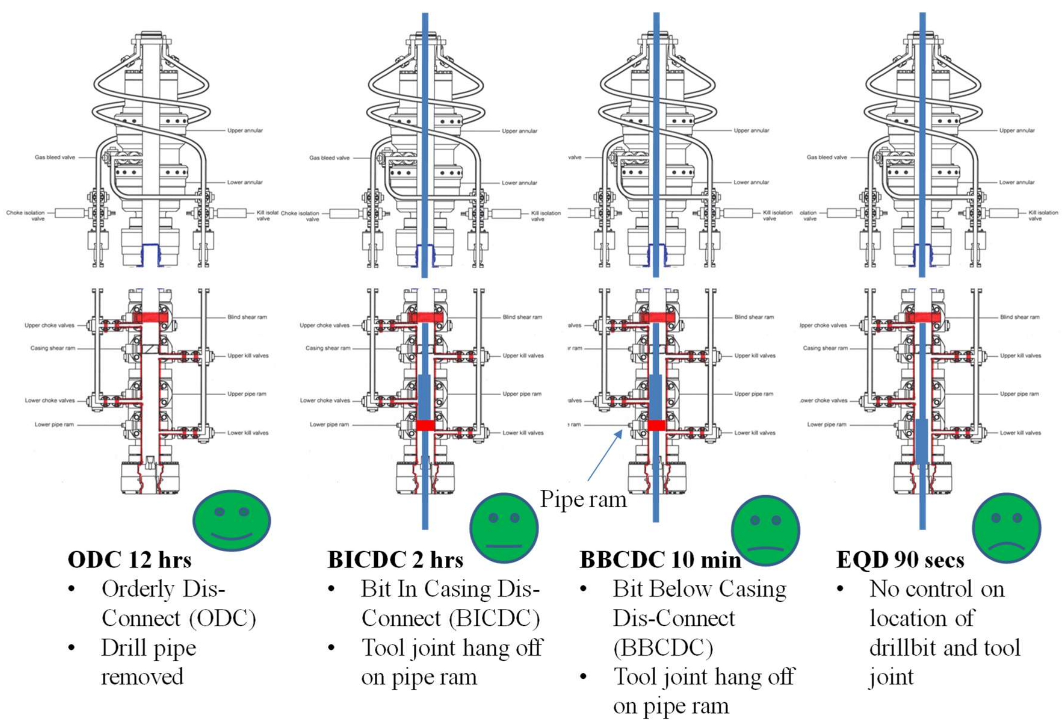

Figure 4. Four safe states (ODC, BICDC, BBCDC, EQD) for the example BOP case (Courtesy DNV GL, DNVGL-OS-E101: 2018).

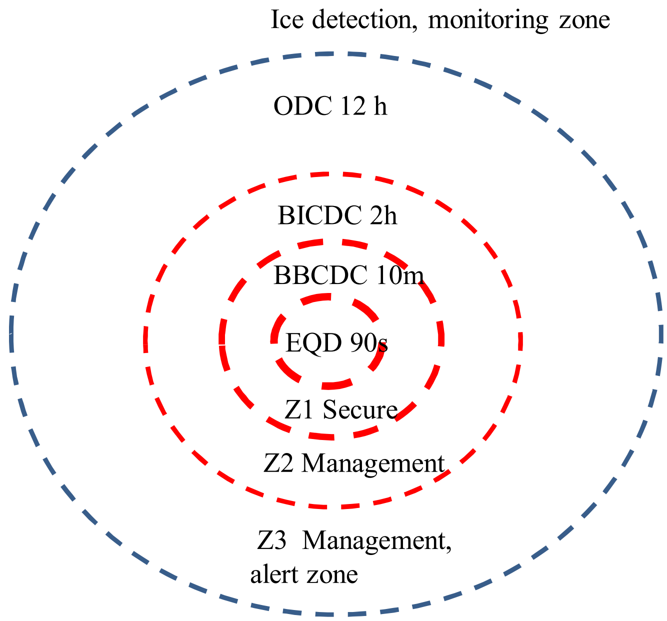

Figure 5. Four IM zone definitions (ISO 35104-2018) for the example Blow Out Preventer (BOP) case indicating required termination time for entering the defined safe states.

3.3 Barrier identification, reduction and limitation for the example case

The proposed IM formal method is based on specification of all events applied in the IM case. Figure 6 presents the main events related to the four barrier branches representing different detection methods and resulting safe states illustrated in an event tree.

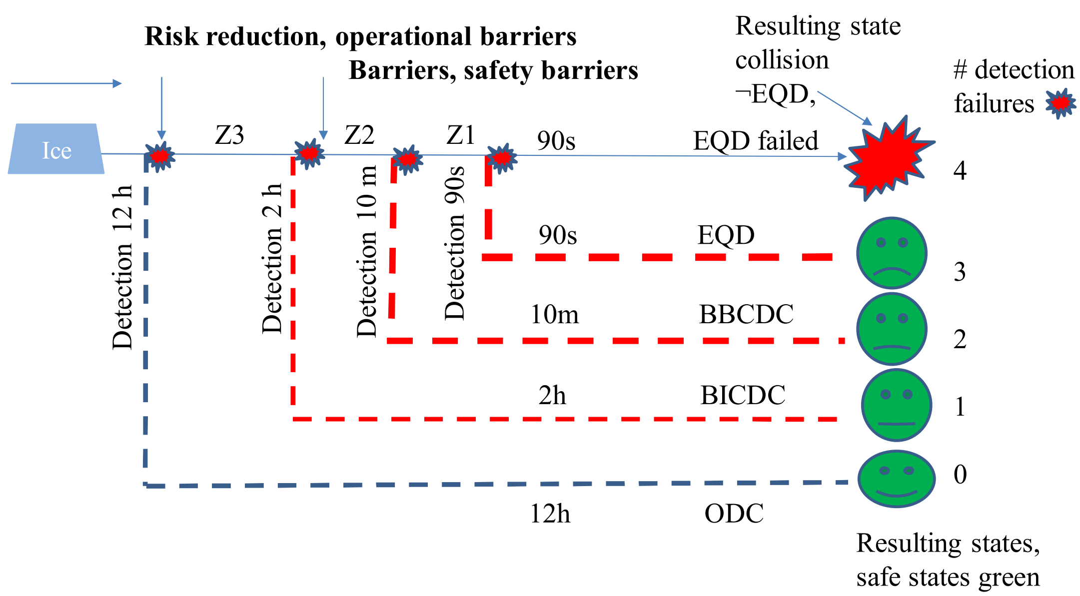

Figure 6. Barrier system event tree model with four simplified detection barrier branches leading to the defined four safe states (ODC, BICDC, BBCDC, EQD) for the BOP. Note that the specific alert actions and associated BOP actions are not included in the figure. The number of detection failures for the different resulting states are indicated in the right column.

Example of IM barrier element events defining the specific ODC barrier branch:

Initial event: ice crossed the borderline (blue) around Zone 3	**Ice12h**
§5,1a) Ice detected crossing borderline (blue) around Zone 3	**Detection12h**
§5,1b) ODC sequence activated successfully	**ODCfunction**
§5,1c) Entered resulting safe state	**ODCsafestate**

The overall Boolean expression for entering the resulting safe state **ODCsafestate** is

$$\textbf{ODCsafestate} = \textbf{Ice12h} \cap \textbf{Detection 12h} \cap \textbf{ODCfunction}$$

The complete IM barrier system will consist of all IM events. The complete barrier system may be established by including similar Boolean events and expressions for all events.

3.4 Sufficient barrier independency

The requirement for barrier independence is stated in Guideline to §5 Barriers

…'The requirement for independence as mentioned in the second subsection, entails that it should not be possible for multiple important barriers to be impaired or malfunction simultaneously, e.g. as a result of a single fault or a single incident'…

The independency requirement implicates that the stated IM events need to be analyzed and it should be verified that no single fault or incident could impair two barriers simultaneously. The single failure criterion is also referred to in the DNVGL-OS-E101: 2018. In SAMCoT a detailed method for single failure analysis is considered (Ruud and Skjetne, 2018)

3.5 Strategies and principles for design, use and maintenance of barriers

Guideline quote
The strategies and principles as mentioned in the third subsection, should be broken down to a convenient level, e.g. area level on the individual offshore or onshore facility, and designed so that they contribute to provide relevant personnel with a common understanding of the basis for the requirements for the individual barriers.

The result of the breakdown of DFU's and the selected level of barrier events indicated above inserted into the designed barrier system tree are assumed to be a convenient level for the operators of the barriers to be operated and maintained during the onsite operations. The operative barrier panel displays are indicated in Section 3.7 below.

3.6 Personnel awareness of performance of barrier functions

Item 4 in §5 Barriers (Figure 3) states requirements for operational personnel to be aware of the intended barrier functions. An IM example could be a vessel-based ice surveillance functional and external variable requirement. The technical performance requirements for successful function F_A of an ice detection barrier element can, e.g. be represented as a Boolean set of requirements:

$$
\begin{aligned}
F_A = \; & (\text{Ice floe size} > 10 \text{ m}) && \cap \\
& (\text{Distance to ice floe} > 2 \text{ km}) && \cap \\
& (\text{Vessel with detector movements} < Z) && \cap \\
& (\text{Stable power supplies and communication})
\end{aligned}
$$

In the case that all the requirements are fulfilled, the Boolean state variable F_A will be 'True', and in the case that one of the requirements are not fulfilled, F_A will be 'False'.

The requirements to the ambient conditions or environment could similarly be stated as

$X_A =$ (Visibility > 2.5 km) $\cap$
(Wave height < 1.5 m)

This is a Boolean type of safety requirement specification (SRS) (IEC 61508-2010, NOG070), representing the functional and external requirements (Ruud and Skjetne, 2018).

3.7 Operational monitoring and presentation of barrier function to operator

The main events for a generic barrier (PSA *Management regulation, §5 Barriers*, Figure 3) are:

- Initiating event
- Detection of initiating event (1a in Figure 3)
- Demand and execution of barrier function (1b in Figure 3)
- Barrier function succeeded event and entering a safe resulting state (1c)
- Barrier function failed event and entering an unsafe resulting state
- Barrier function detected to be impaired and operator to be warned (5)
- Operator should apply compensating measures (6) to handle initiating event

Figure 7 and Figure 8 illustrate the generic principles for monitoring and presentation of barrier status events in addition to main barrier functions (1abc) as required in §5 Barrier (Figure 3).

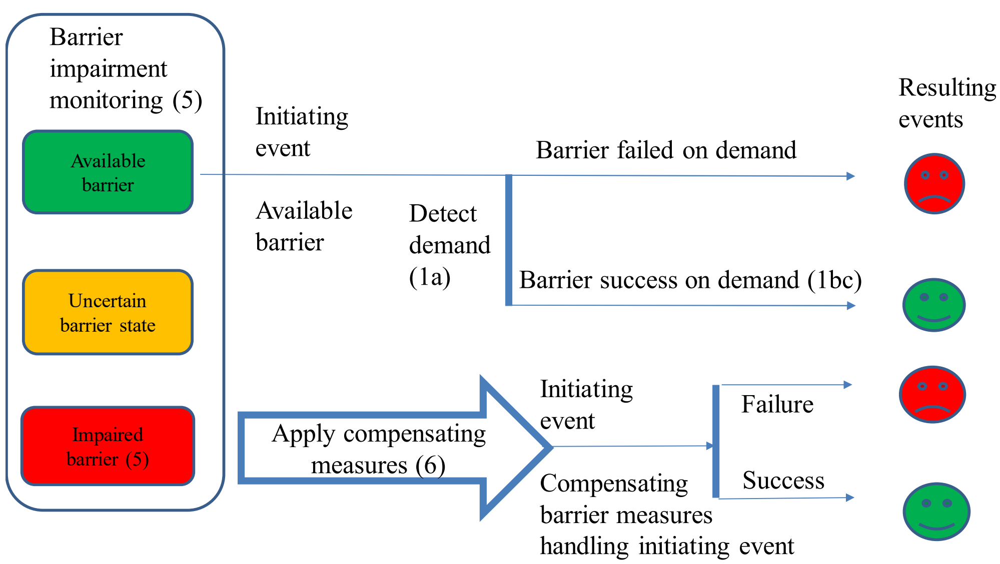

Figure 7. The box to the left indicates operational monitoring barrier states (availability/ impairment). The upper event tree presents the normal barrier events (1abc). The blue arrow and lower event tree represents how the operator may decide to apply predefined compensating measures(6) in case of indicated barrier impairment(5).

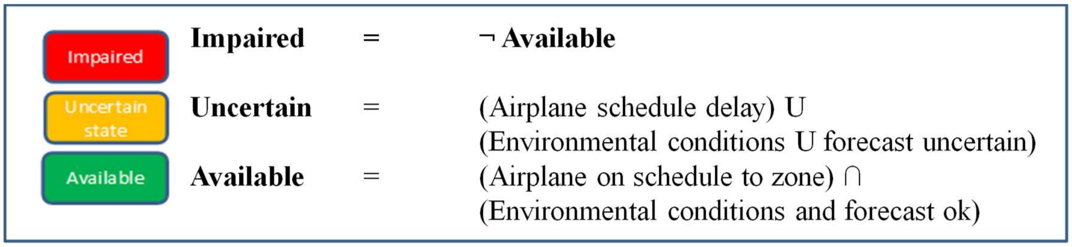

Figure 8. Principle for high-level specification of performance requirements for barrier panel presentation of status and availability color codes of barrier element Aircraft Z3 in Figure 9.

3.8 Compensating measures for missing or impaired barriers.

§5 Barriers, part 6 requires that *Necessary measures shall be implemented to remedy or compensate for missing or impaired barriers.* Figure 9 shows a barrier element panel with all barrier element states. The figure shows the detailed BOP actions available (explained in Figure 10).

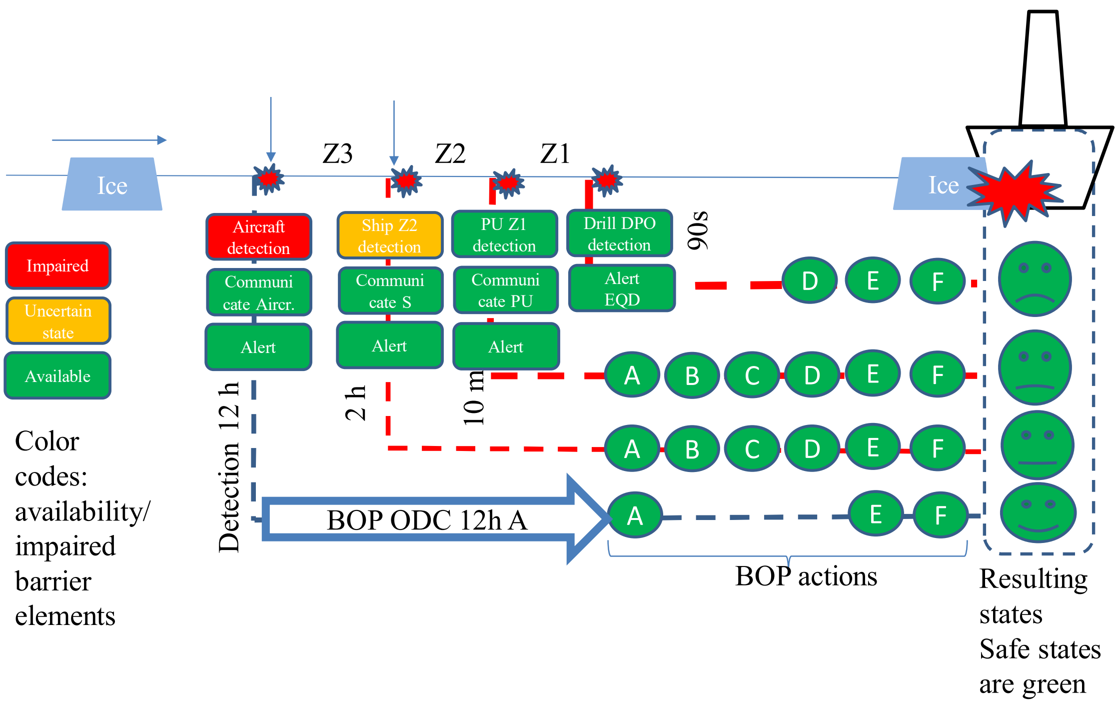

Figure 9. Operator barrier panel presented as an event tree with operating state of 4 barrier branches and color codes for the availability of the specific barrier elements. The impaired barrier elements are shown as Aircraft detection (red) and Ship Z2 detection (yellow). The available compensating measure is shown as a blue arrow for starting BOP action “A” which is to hoist/lift the drill pipe.

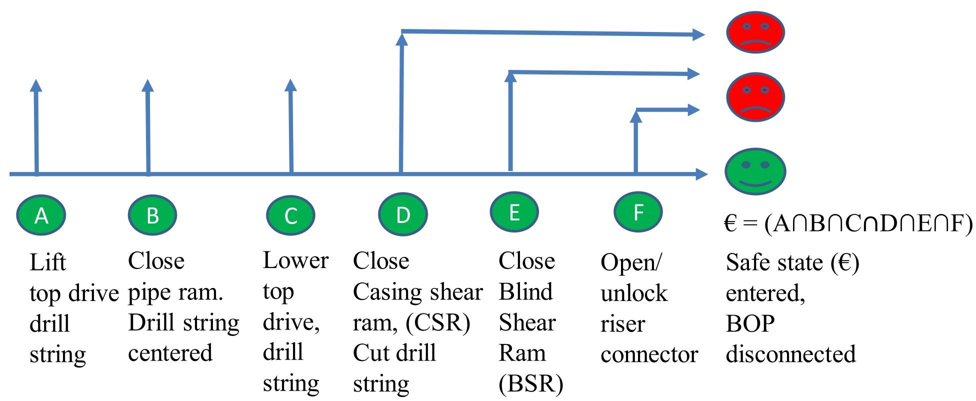

Figure 10. Illustration of detailed BOP actions in an event tree for the operator barrier panel.

Barrier panel display for Aircraft Zone 3 (red) detection and Ship Zone 2 (yellow) detection are unavailable for, e.g., 6 hours. The compensating measure is to start hoisting the drill pipe (BOP action A) and then evaluate the situation before proceeding with BOP actions E and F if ice is detected in Zone 1. In case ice detectors become available again and no ice occurs in the zones, the drilling operation may be resumed.

4. EQUIPMENT FAILURE DATA COLLECTION

Ice management equipment data collection should be based on ISO 14224, as referred in the *Management regulation §19 Collection, processing and use of data*. In order to explain the principles of the standard, the generic system boundary for ice detectors applied in satellites, aircrafts, and ship radars is proposed as shown in Figure 11 below. The set of failure modes shall be defined and used for operational classification and registration of failure events.

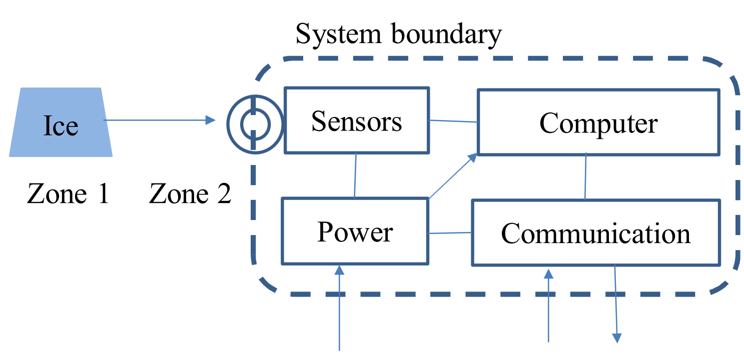

Figure 11. System boundary for an ice detector including subsystems.

5. MEASURABLE SPACE AND SIGMA ALGEBRA REPRESENTATION

The IM event models may be modelled in a measurable space by a set of defined Boolean IM events and the Boolean operators (∩,∪, ¬) as indicated in Figure 12. The modelling techniques like event tree analysis (ETA), reliability block diagrams (RBD), and fault tree analysis (FTA) may form the high level IM barrier system as well as any level of technical details of the IM barrier element technical systems. The state variables of the IM system may be selected to represent the external environment (sea, ice, and atmosphere) and, e.g., the technical systems like detectors, ships, and BOP systems. Requirements to the state variables will establish functional or failure states of selected parameters. The overall model of the barrier system may be used for specification of the complete operational system and the same model may be used for training of the operators and for specification of equipment and barrier data collection. The IM operator barrier panels and the underlying Boolean models are suitable for analysis, testing, documentation, verification, training, drills, and specification of IM operations.

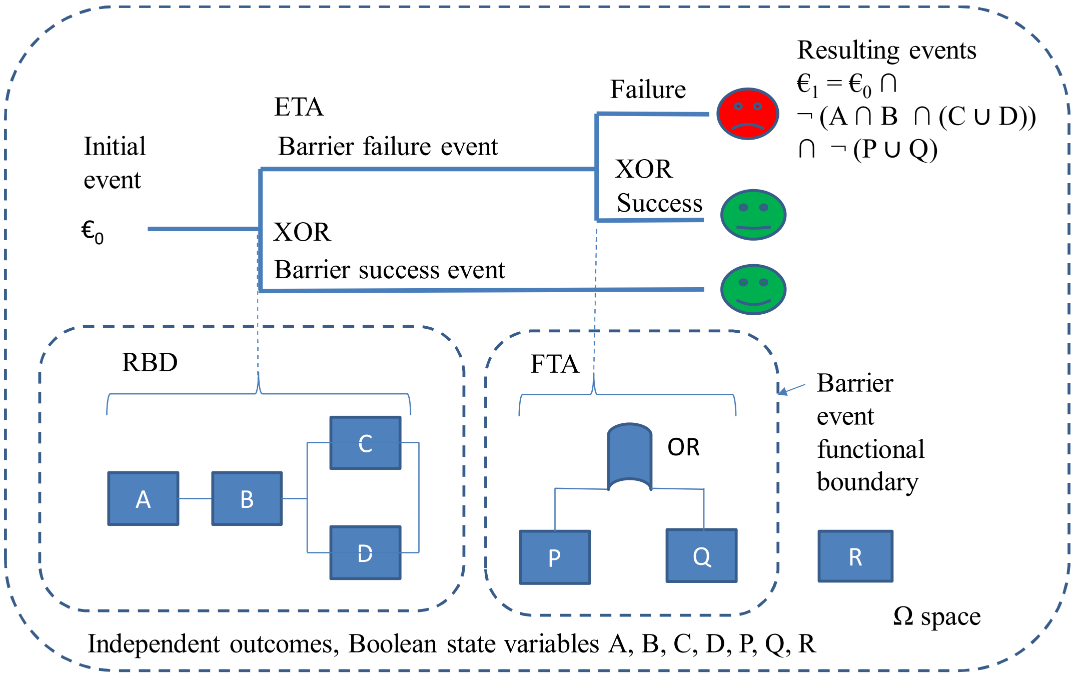

Figure 12. Measurable space with Boolean state variables (outcomes, A,B,C,…) enabling representation of barrier events ($€_0$: Initial event, $€_1$: Resulting event). Event tree (ETA), Reliability Block Diagram (RBD), and Fault Tree (FTA) are Boolean expressions with state variables and Boolean operators ($\cap$,$\cup$, $\neg$) in a Sigma algebra/space.

6. SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 Summary and conclusions

Requirements from PSA on risk reduction and barriers are assumed to take superior precedence in Norwegian Arctic waters and on the Norwegian Continental Shelf. Defined hazard and accident conditions are proposed to include hazards related to impact from sea ice or icebergs. The main objective of an IM barrier system is to ensure that operational decisions lead to predefined safe states in case of approaching ice hazards. The barrier requirements are interpreted as Boolean events and by combination of Boolean operators, a general method for representation of operational barrier systems is presented. The IM operator barrier panels and the underlying Boolean models are suitable for analysis, testing, documentation, verification, training, drills, and specification of IM operations. The terminology and definitions applied are originating from risk reduction barrier methodology, reliability concepts definitions, and ice management standards.

6.2 Future work

Minimum requirements to IM barrier elements

Presently industry good practices to minimum requirements to IM barriers are not established. An effort to establish such requirements should be initiated.

Training and drills

In the PSA *Activities, §23 Training and drills* it is stated that: *'The responsible party shall ensure that necessary training and necessary drills are conducted, so that the personnel are always able to handle operational disturbances and hazard and accident situations in an effective manner….'*. Figure 9 serves as an example on a barrier panel display for an operational situation that IM operators should be trained to operate in covering normal operating situations, or with impaired barrier elements and use of compensating measures.

PSA *Management regulation, §20 Registration, review and investigation of hazard and accident situations*

The barrier system structure is a reference level for how registration and investigation of hazard and accident situations should be organized. The measurable space (see Section 6) should have provisions for data and information structure definitions to accommodate for the future registration of incidents.

ISO 35104 Ice management

Requirements from (ISO 35104:2018, *Arctic operations — Ice management)* like e.g safe learning principle, ice management, and terminology should be included in the further work.

Class requirements

The minimum requirements for drilling facilities may be found e.g. in DNVGL-OS-E101: 2018, and requirements for the dynamic positioning DP system in the DNV GL rules. A method for analysis of redundant barriers and possible common causes should be elaborated and tested.

Framework regulation §11 and the ALARP principle

In the PSA *Framework HSE* §11 it is stated that *'In reducing the risk, the responsible party shall choose the technical, operational or organizational solutions that, according to an individual and overall evaluation of the potential harm and present and future use, offer the best results, provided the costs are not significantly disproportionate to the risk reduction achieved.'* The ALARP cost benefit analysis requires quantification of cost and e.g. probabilities of IM events. The measurable space paves the way for quantification of specific events in, e.g., a probability space (which is an extension of the measurable space).

Demonstration case study

A demonstration case study should be prepared and presented.

Ice management terminology

A set of standardized definitions related to IM, barrier methodology, risk and reliability methodology should be prepared. A key element of this work is to propose a set of definitions of typical IM events.

ACKNOWLEDGEMENTS

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REFERENCES

DNVGL-OS-E101*: 2018, Drilling facilities, Offshore Standards, 2018*

IEC 61508-2010, *Functional safety of electrical/electronic/programmable electronic safety-related systems –*

ISO 14224:2006 -- *Collection and exchange of reliability and maintenance data for equipment Petroleum, petrochemical and natural gas industries*

ISO 35104:2018, *Arctic operations — Ice management*

NOG070 NORWEGIAN OIL AND GAS 2004*, 070 APPLICATION OF IEC 61508 AND IEC 61511 IN THE NORWEGIAN PETROLEUM INDUSTRY, Norwegian Oil and Gas Association*

PSA *Activities, §23 Training and drills, §24 Procedures*
http://www.ptil.no/activities/category399.html

PSA *Defined hazard and accidents conditions (DFUs)*
http://www.ptil.no/news/defined-hazard-and-accident-conditions-dfus-article9296-878.html

PSA *Framework HSE §11 Risk reduction principles,*
http://www.ptil.no/framework-hse/category403.html

PSA *Management regulation, §5 Barriers, §19 Collection, processing and use of data, §20 Registration, review and investigation of hazard and accident situations*
http://www.psa.no/management/category401.html

PSA, *Regulatory principles*
http://www.psa.no/regulatory-principles/category932.html

Ruud, S and Skjetne, R. (2018). *Ice management and design philosophy*, International Marine Design Conference 2018 (IMDC 2018)