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Quantitative Risk Analysis of stability for floating offshore installations

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ABSTRACT: The paper reviews the experience from accidents and incidents involving stability or buoyancy and points out the lessons to be learned from these occurrences. It is pointed out that valve failures are dominating, and that human and organisational factors have been the dominating causes of all severe accidents. An approach to analysis of hazards that may cause loss of stability is proposed, based on fault tree and event tree analysis. The approach should in any case be a tiered approach, by which screening and preliminary assessments are used to ensure that the main attention is focused on the hazards and accident scenarios that may cause significant consequences. These hazards and scenarios should be analysed in detail, using fault trees and event trees. Some comparisons of values from QRA studies and actual experience data are discussed for accidents involving marine systems as well as hydrocarbon leaks.

1 INTRODUCTION

1.1 *Background*

A summary of the work associated with Quantitative Risk Analysis (QRA) for floating production installations and Mobile Drilling Units (MODUs) has been made. It is more than 20 years since serious accidents or incidents occurred in the Norwegian sector associated with loss of buoyancy or stability. But there have been incidents and accidents in other areas, which remind us that this hazard has not been eliminated. The most serious accident ever in this category was the capsize and total loss of semi-submersible drilling unit Ocean Ranger in 1982 off New Found land.

1.2 *Regulatory requirements*

The regulatory requirements discussed here are those applicable to analysis of reliability, vulnerability and risk associated with loss of buoyancy and stability.

There are requirements for the design of ballast systems and for the stability of floating units. The requirements for probabilistic/risk analysis of these systems are somewhat indirect. The survivability of the units is included in the phrase 'main support structure', which in the facilities regulations (PSA, 2002a) §6 is defined as a Main Safety Function. The facilities regulations §10 specifies limits for the frequency of loads that may impair the Main Safety Functions.

The HES management regulations (PSA, 2002b) require that QRA studies are conducted for the Main Safety Functions.

The facilities regulations refer to the detailed requirements of the Norwegian Maritime Directorate (NMD) regulations for ballast systems on mobile units and the regulations for stability and watertight divisions. These again refer to NMD's risk analysis regulations. These regulations do not have explicit requirements for probabilistic/risk analysis of ballast systems, but there are requirements for demonstration of accordance with regulations, which may be satisfied through risk or reliability analysis.

1.3 *Relevant hazards*

Loss of stability may be caused by a single failure or perhaps more likely by a combination of different causes for mobile units and floating production installations. The following list is developed based on experience from accidents and incidents:

- Ballast system failure, including pumps, valves and control systems.
- Operational failure of ballast systems.

- Filling of buoyancy volumes or water filling of volumes on the deck from errors or maloperation of internal water sources, such as fire water or water tanks.
- Filling of buoyancy volumes due water ingress caused by collision impact.
- Filling of buoyancy volumes due to design or construction errors.
- Filling of buoyancy volumes or water filling of volumes on the deck due to fire or explosion, including fire water.
- Filling of pump rooms.
- Displacement of large weights on deck (SS).
- Loss of weights due to anchor line failure or failures in the anchor line brakes (SS).
- Ballast system failure or maloperation during transition of mobile units (JU).
- Loading system failure which leads to abnormal weight condition (FPSO).
- Failure during operation of loading system which leads to abnormal weight condition (FPSO).

The first seven items in the list above are general with applicability for all floating concepts, the last five are special for the following concepts; SS – semi-submersible units; JU – jack-up units; FPSO – floating production, storage and offloading tankers.

1.4 *Previous studies*

The R&D programme Risk Assessment of Buoyancy Loss (RABL) was conducted in the middle 1980s (Vinnem et al., 1987). This programme developed an approach for analysis of ballast system failures, based on event trees and fault trees. It was actually found that in the almost 20 years period after completion of the RABL programme, no other studies had performed similar detailed studies of loss of buoyancy of stability.

The approach normally adopted in QRA studies is discussed in Section 3 below.

An alternative approach to QRA studies has been adopted by Lotsberg et al, (2004). The approach is presented in Figure 1.

The 'stream' on the left side is based on accident statistics, taken from DNV's database WOAD (available from www.dnv.com), whereas the path to the right is the adjustment of values based on accident statistics, in order to reflect field and concept particulars. Please note that the approach has been applied for the Kristin field in the Norwegian Sea, on Haltenbanken.

This approach is an improvement compared to traditional QRA approaches currently being used. One aspect where this approach falls somewhat short, is the lack of ability to identify what could be risk reducing measures and their effects.

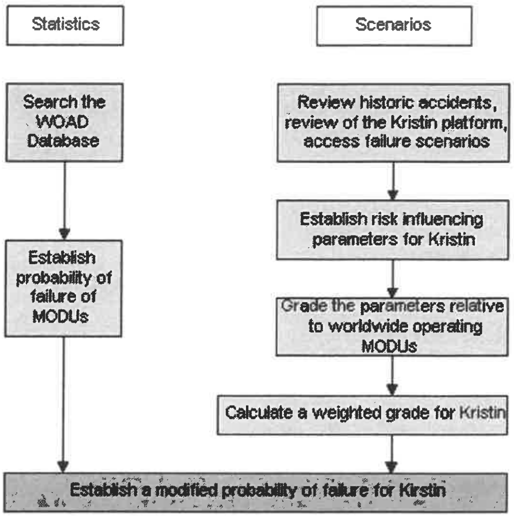

Figure 1. Approach to failure frequency assessment based on gross errors (Lotsberg et al, 2004), for the Kristin field.

2 RECENT INCIDENTS AND ACCIDENTS INVOLVING STABILITY OF OFFSHORE INSTALLATIONS

2.1 *North Sea events*

One total loss has occurred in the North Sea and North Atlantic and Norwegian sea areas during the last 20 years, the water filling and sinking of jack-up West Gamma in 1989. Many minor incidents have been recorded by HSE (2005) and Vinnem et al. (2006), where equipment malfunction or maloperation have been corrected before severe consequences resulted. The most serious occurrences are:

- Loss of 2 anchor lines due to winch failure caused 160 m drift-off and a transient tilting of some 10°.
- Malfunction of the ballast control system caused a 9° list, lasting for 90 minutes before the rig was uprighted.
- 6–8° inclination due to activation of deluge system, caused by loss of main power.
- Unknown inclination due to opening of ballast valves caused by failure of control desk.

2.2 *Worldwide occurrences*

There are some occurrences in the worldwide operations that are well known, and which form an important basis for the evaluations, brief summaries are provided below:

- Ocean Ranger, 15.2.1982.
- West Gamma, 21.8.1989.
- Ocean Developer, 14.8.1995.

- P-36, 15.3.2001.
- P-34, 13.10.2002.
- Thunder Horse, 11.7.2005.

The semi-submersible mobile drilling unit Ocean Ranger capsized on 15.2.82 in Canadian waters. The ballast control room in one of the columns had a window broken by wave impact in a severe storm. Short circuits occurred in the ballast valve control systems, when the seawater entered the room, thereby starting spurious operations of the ballast valves. The crew then reverted to manual control, but were probably not well trained in this, and did actually leave the valves in open position for some time, when it had been assumed that they were in the closed position. Correction of this failure did not occur sufficiently soon to avoid an excessive heel angle. Due to this excessive heel angle, the rig could not be brought back to a safe state, because only one ballast pump room was provided in each pontoon, at one end. The heel angle was such that the suction height soon exceeded the maximum of 10 meters, and water from the lowest tanks could not be removed.

The onshore based SAR helicopters could not assist due to the severe weather conditions involving strong wind and low visibility. The rig therefore capsized and sank before any assistance could be provided.

The personnel (84 men crew) apparently evacuated, probably to two lifeboats, which at least were seaborn, although the exact state is not known, and only one was sighted. One boat collided with the standby vessel during the transfer attempt from the lifeboat onto the deck of the larger vessel. Within a short time the boat started to drift away, and was never seen again. No survivors or bodies were ever found.

Ocean Developer (Vinnem et al., 2006) was under tow between two African ports on 14.8.1995 when it capsized and sunk without loss of life. The investigation report indicates that ballast operation by inexperienced personnel may be one of the causes.

The floating production unit P-36 (Vinnem et al., 2006) capsized and sunk on the Roncador field in Brasil. A ruptured drain tank in a column caused an explosion that destroyed a fire water pipe, killed 11 perons, and caused subsequent water ingress into watertight compartments, pump rooms and thruster rooms.

The FPSO P-34 (Vinnem et al., 2006) developed a serious list due to malfunction of ballast and loading systems, caused by electrical faults. The vessel was close to capsizing before control was reestablished. No fatalities occurred.

Following the passage of Hurricane Dennis in the Gulf of Mexico in 2005, personnel returned to the Thunder Horse facility to find it listing at approximately 20° with the top deck in the water on the port side (MMS, 2005). This incident is under investigation and the exact source/cause of the water influx/listing has not been determined at this time; however, preliminary findings from the investigation indicate that water movement among the access spaces occurred through failed multiple cable transits (MCT's). MCT's are the points in the watertight bulkheads where cables that carry electrical power and instrument signals pass through the watertight bulkheads. Essentially, MCT's are molded blocks of plastic that seal around each cable. Failure occurred in the spaces filled with blank blocks. Specifically, the findings indicate that either the MCT's may not have been installed properly, may have been installed using the wrong procedures, or may not have been properly pressure rated for the configurations being used.

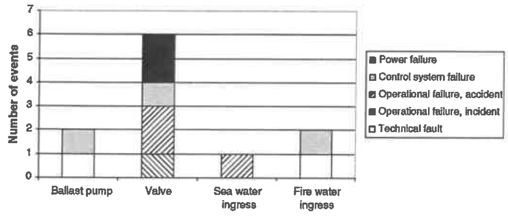

Figure 2. Distribution of causes of stability failures.

2.3 *Observations from incidents and accidents*

Figure 2 presents a summary of causes for stability failures, based on worldwide accidents and incidents discussed in Vinnem et al. (2006). Minor problems are not included.

The diagram pinpoints clearly that valve failures are the main cause category for accidents and incidents. It may further be observed that all the two total loss accidents were caused by operational failures.

It may further by observed that 58% of all accidents, incidents and minor problems are associated with technical problems. This is quite high.

3 EVALUATION OF TYPICAL QRA STUDIES FOR FLOATING OFFSHORE INSTALLATIONS

Current practice in Norwegian QRA studies related to stability of mobile units and floating production units has been surveyed (Nilsen, 2005).

The conclusion is that current practice in QRA studies are not suitable for identification of possible risk reducing measures, nor are they suitable for quantification of the effect of such measures for the risk levels. Deficiencies in a majority of the studies have been demonstrated, including:

- Accident scenarios are not modeled. The possible failure categories are considered on a superficial level, without the possibility to identify how the scenarios could develop.

- Several failure mechanisms are not considered at all, as rupture of fire ring mains, major displacement of heavy loads on deck, operator error during ballasting or loading operations, and water ingress due to collision impact.
- Experience data are not considered. Some data were mention above, and are further documented in Vinnem et al (2006). None of these are usually considered in QRA studies.
- Assumptions, premises and simplifications are not addressed. The PSA regulations require the assumptions and premises to be documented and to be traceable. The studies do not comply with this requirement.
- Presentation of results is without traceability. Some of the studies do not present quantitative results at all, but are limited to conclude that 'the design is considered to be safe'. This is virtually worthless when it comes to transparency, as it fails completely to document how this was reached, and what are the limitations and underlying assumptions.

These observations show that the quality is quite poor in these studies. A proposed approach in order to improve on these weaknesses is presented in Section 4 below.

4 PROPOSED APPROACH TO ANALYZE STABILITY RELATED HAZARDS

4.1 *Life cycle phases*

The main analytical efforts should be made during design and engineering, in order to give good opportunities for implementation of risk reducing measures. Updating of the analysis may be done after completion of construction, and sometimes during the operations.

Detailed studies will be particularly important when untraditional concepts and solutions are adopted, including solutions that are not addressed in the regulations and standards.

The studies should also address special conditions that may occur, such as during displacement of heavy loads, rupture of fire water ring main, as well as special conditions during inspection and maintenance when doors and manholes may be opened, or systems deactivated.

4.2 *Analytical approach*

The proposed analytical approach is presented in Vinnem et al. (2006), adapted from Haugen (2005).

Collection of experience data should be the starting point for the analysis, which should continue with a hazard identification (HAZID), in order to identify those scenarios that may result in critical consequences, particularly with respect to combinations of failure cases and effect of operational error.

A detailed analysis should be performed for the critical scenarios, limited in this context to marine systems or systems that may influence marine systems. If a FMECA and/or task analyses have been carried out, then these may serve as the starting point for the detailed analysis, including fault trees and event trees.

Fault trees and event trees may be used in order to calculate risk values, as well as to identify where the most effective modifications (risk reducing measures) in order to improve the situation. During this part of the analysis, efforts should be made in order to document assumptions and premises, relating to:

- Technical conditions.
- Conditions associated with operations and maintenance.
- Assumptions related to analysis methodology and modeling.

The management regulations (PSA et al., 2002b) have a general requirement for consideration of uncertainty to be addressed for all risk elements, not only marine systems. This is usually most effectively implemented through sensitivity studies, in relation to data and variations in assumptions and premises.

4.3 *Detailed analysis of ballast system failures*

The approach outlined in Figure 3 should be used in order to analyze risk due to failures in ballast system components.

This implies adoption of the same approach as developed in the RABL project. The main elements of this approach are Fault trees and Event trees, see Figures 4 and 5.

The importance of choosing the approach is that it enables a detailed identification of system modifications and operational changes that may be most effective in order to reduce the risk level, and the likely effect of such actions.

This is one of the important requirements in the management regulations (PSA et al., 2002b). Identification of possible risk reducing measures is also an important element in the ALARP demonstration, which is essential in the Norwegian as well as UK regulations.

The following additions to the approach described in the RABL project should be implemented:

- Fault tree analysis should also be performed for the most critical nodes in the event tree, see example in Figure 5.
- Human and organizational errors.
- Common mode failures and dependencies.

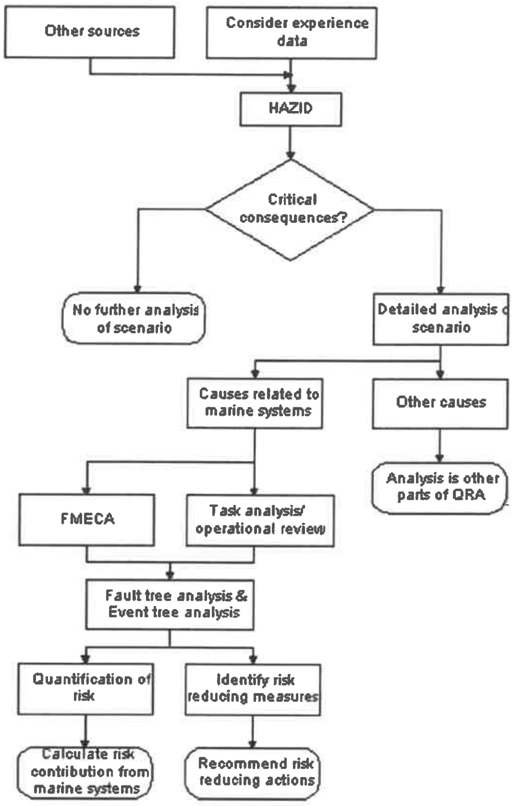

Figure 3. Proposed analytical process for marine systems.

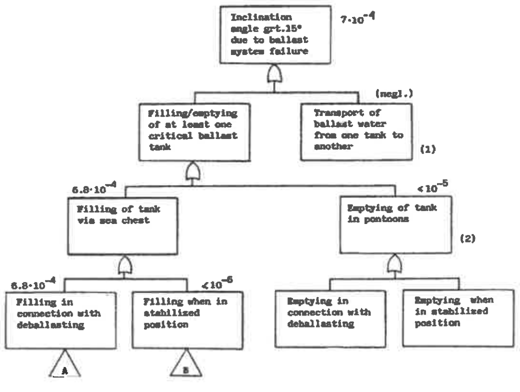

Figure 4. Example of top levels in Fault tree for analysis of ballast systems (Vinnem et al. 1987).

As input to the analysis, a detailed analysis of collision risk may be required, depending on the circumstances. Also fatigue failures may be required as input, in addition to failures during loading of FPSOs.

4.4 *Other failures*

Other failures that according to the approach in Figure 3 are not considered critical may be analyzed using the approach suggested by Lotsberg et.al. (2004), see Figure 1. The disadvantage of this approach is the inability to identify risk reduction proposals. This is due to the inability of this approach to identify what percentage of risk that is attributable to the various potential causes.

4.5 *Analysis of human and organizational aspects*

Human and organizational errors should be included in the fault tree analysis where relevant. The BORA approach (Sklet et al., 2005, Vinnem et al., 2006) may be used.

4.6 *Analysis of dependencies in barriers*

Common mode failures and dependencies should be analyzed as appropriate. Standard approaches in fault tree analysis for both of these aspects exist, normally used in the analysis of failures of nuclear power plants. For offshore installations however, it has not been common practice to include these aspects in the analysis.

4.7 *Analysis of barriers*

In addition to the initiating events, several conditions might contribute to escalation of the events – as improper sectioning of the hull, lack of draining capacity on the deck, lack of or failure in the leak detection systems, lack of pumping capacity, lack of training of personnel in emergency situations or open doors and manholes.

The Norwegian management regulations §15 require that QRAs shall model accident sequences and consequences so that possible dependencies between physical barriers can be revealed, and that the requirements that must be set in respect of the performance of the barriers, can be calculated. A method to analyse barriers related to stability is demonstrated in Ersdal & Friis-Hansen (2004).

4.8 *Discussion of approach*

The capsize of the flotel 'Alexander L. Kielland' in 1980 was the last serious accident involving loss of buoyancy or stability on the Norwegian Continental Shelf. The jack-up 'West Gamma' capsized and sank in 1989 during tow from the Ekofisk field, but the accident occurred in the Danish sector and the platform finally sank in the German sector. No fatalities occurred. This fact could be used to claim that accidents involving loss of buoyancy or stability are very rare. There have on the other hand been near-misses

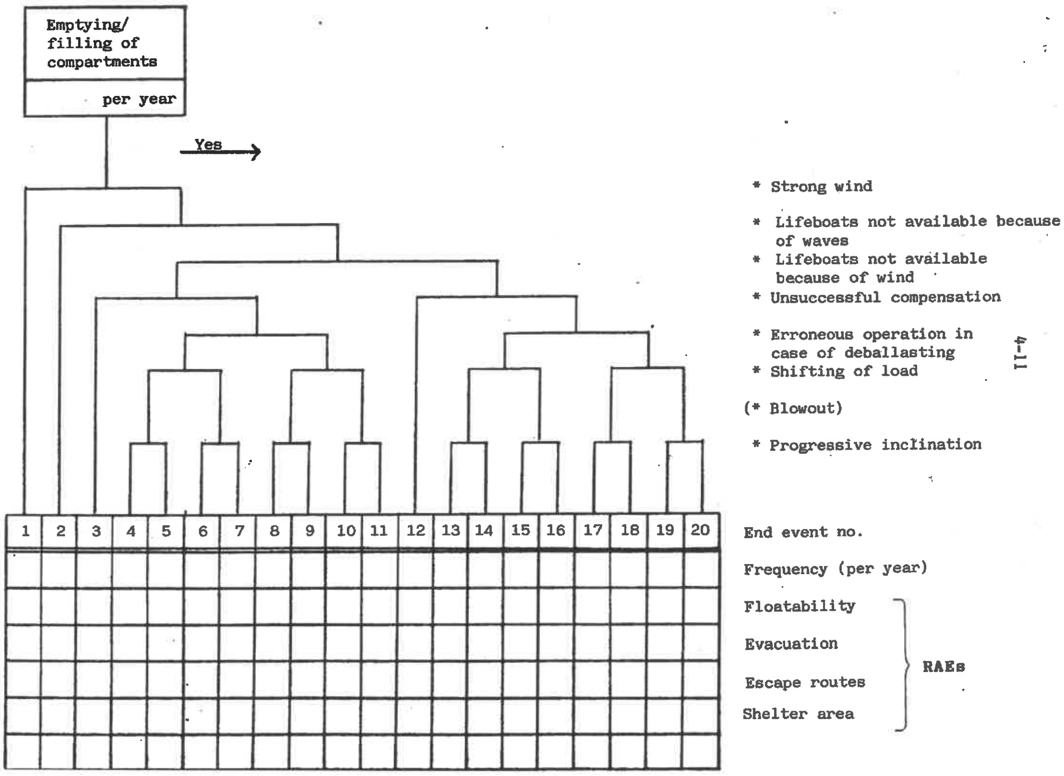

Figure 5. Event tree for analysis of ballast systems (RABL).

also during the last years, which could have developed into serious accidents. It is therefore not reasonable to claim that such accidents are so rare that the hazards may be treated so simplistically as shown in Section 3.

It has been claimed by most experts that gross errors during platform design and construction cannot be analyzed by traditional risk analysis methods. The full analysis of this is outside the scope of this discussion, but it appears that this view has been adopted also for hazards relating to marine systems. This is considered to be a misunderstanding.

There is little similarity between analysis of design and construction defaults and failures of marine systems. Gross errors in design and construction are events that may jeopardize the integrity of the structure, and may prevent the normal redistribution of forces to compensate for local failures. This is difficult to analyze by traditional risk analysis methods. Gross errors may be caused by single failures.

Marine systems like ballast systems are quite different, there is redundancy and possible dependencies, to the extent that it is important to analyze failure event combinations. Traditional risk analysis methods, like fault trees and event tree or similar, may be used in order to analyze such scenarios.

This paper recommends that marine systems are analyzed according to the approach outlined in Figure 3, including HAZID, FMECA and task analysis (or similar), fault trees and event trees.

One alternative could be to employ the approach used by Lotsberg et al. (2004) also for ballast systems and failure of stability scenarios.

A second alternative could be to use event trees for the most critical scenarios, but omit quantification of accident probabilities through fault trees and similar.

The disadvantage of these two approaches is that the basis for identification of possible improvement measures will be significantly weaker. It has already been argued above that identification of possible improvements is one of the main objectives of risk analysis. This is the main reason for why the proposed approach should be selected.

5 COMPARISON OF QRA RESULTS WITH EXPERIENCED EVENTS

5.1 *Stability and marine hazards*

If we restrict the consideration to semi-submersible installations, there is more than 20 years since the last serious Norwegian accident, as noted above. This implies that there is no basis for making a comparison of QRA results with accident statistics.

If we take a 30 year perspective in the Norwegian sector, we have one total loss, the capsize of 'Alexander L. Kielland'. The regulatory requirements were changed in the early 1980s, to the extent that this accident might be unrepresentative for risk levels implied by current standards. The current standards specify weather conditions were failure of one brace should not escalate, if the weather exceeds this level (one year environmental conditions plus safety factors), similar situations might occur. Nevertheless, it may be interesting to consider what the accident statistics implies.

Based on data in the RNNS project (PSA, 2005) the number of mobile installations per year may be calculated. The sum for the period 1990-2005 is 259 unit years. A rough calculation for the period 1976-1989 is 111 unit years. The total value for the 30 years is 370 unit years.

If we assume a Poisson distribution, the expected value is 1/370 per unit years, 2.7×10^{-3}, as the frequency of total loss per unit years. If we consider a prediction interval, the upper 95% limit would be 1.1×10^{-2} per unit years. Assuming a normal manning level during a period, the FAR number exceeds one hundred!

As noted above, it would be expected that the frequency of total loss is lower with today's standards, due to the stricter requirements for damage stability. How much lower it would be, is impossible to know, based on present knowledge. On the other hand, there are no reasons to assume that the frequency would be much more than one order of magnitude lower for modern installations. This implies that it is unlikely that the failure frequency is lower than 1.0×10^{-4} per unit years.

5.2 *Hydrocarbon release hazards*

Risk associated with hydrocarbon releases is another hazard where QRA results may be compared with accident statistics for offshore installations. The comparison is in this case limited to production installations, and is limited to calculation of values of Fatal Accident Rate (FAR), i.e. fatalities per 100 million manhours.

If we limit the consideration to the Norwegian sector, the only fatal accident due to hydrocarbon leaks is the riser rupture on the Ekofisk A platform in 1975, where 3 persons died during evacuation. Again, this is considered to be totally unrepresentative for current standards, but is used in order to indicate what accident statistics will produce.

If we consider the period 1975-2005, the number of manhours on production installations in this period is expected to be around 580 million manhours. The FAR value thus becomes 0.52, as an expected value for this period. The average FAR value for UK and Norwegian sectors would be much higher due to the Piper Alpha accident, if the same period is considered. The average FAR value for UK and Norway during the last 15 years would be between 0.5 and 1, but exact values cannot be calculated due to lack of precise manhour data for the UK sector.

This can be compared against FAR values predicted by QRA studies for current installations. FAR values of four anonymous floating production units were discussed in Aven et al, (2005). The FAR values due to hydrocarbon leaks for these four installations are 0.69 – 1.64 – 1.18 – 1.87, with an average of 1.34.

It may be observed from this exercise that current QRA results has a tendency to over-predict the risk levels, compared to what accident statistics will imply (depending on the area and period included as illustrated above). The representativity of the available accident statistics is questionable as indicated above, but it is the best available source.

5.3 *Appropriateness of comparison*

It may be considered whether it is appropriate to compare results of QRA studies with accident statistics. This is related to the philosophical problem; is there a 'true' value for risk or isn't there such a value?

What we can observe is the occurrence of accidents and possibly fatalities in these accidents. During the last ten years, we have in the Norwegian sector observed almost 300 hydrocarbon releases (>0.1 kg/s), no ignited leaks, and no fatalities in these cases. If we extend the period to 1975-2005, we don't know the number of leaks, there has been a few ignited leaks, and three fatalities in one fatal hydrocarbon accident.

The risk level on the other hand, cannot be observed as such. The FAR values are on the other hand based on occurrence of fatalities.

It is quite common that QRA results over-predict the number of fatalities or fatal accidents when such comparison is possible. This is natural due to the tendency to apply conservative values in case of uncertainties. The difference shown above for hydrocarbon leaks is therefore not alarmingly high.

6 CONCLUSIONS AND RECOMMENDATIONS

The QRA studies normally conducted for floating installations are inappropriate in several ways. It has been implied that when the studies claim that there is an insignificant risk level, there is no basis in available data in order to conclude this way.

What is more disturbing, is that the studies do not give any basis for identification of risk reducing measures, which is one of the main objectives of risk analysis.

An approach based on fault trees and events trees should be implemented for scenarios identified as critical.

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