Methodology for development of risk indicators for offshore platforms

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Abstract

This paper presents a generic methodology for development of risk indicators for petroleum installations and a specific set of risk indicators established for one offshore platform. The risk indicators should be used to control the risk during operation of platforms. The methodology is purely risk-based and the basis for development of risk indicators is the platform specific quantitative risk analysis (QRA). In order to identify high risk contributing factors, platform personnel are asked to assess whether and how much the risk influencing factors will change. A brief comparison of probabilistic safety assessment (PSA) for nuclear power plants and quantitative risk analysis (QRA) for petroleum platforms is also given.

1. Introduction

Over the last few years, the use of risk-based decision-making has increased in the nuclear industry. Probabilistic Safety Assessment (PSA) is used both in design and operation of nuclear power plants (NPP) and in the area of incident and accident mitigation and management. In the petroleum industry Quantitative Risk Assessment (QRA) has been performed as part of the design process since the beginning of the 1980s when the Norwegian Petroleum Directorate (NPD) issued their "Guidelines for safety evaluation of platform conceptual design" (/1/). The QRA has primarily been used as a tool in the design phase. The use of QRA in the operational phase has mainly been limited to assessment of the effect of major modifications.

In 1994, the NPD initiated a pilot project (/2/, /3/ and /4/) with the purpose to develop a tool, a set of indicators, that could be used to measure changes in risk level during operation of petroleum platforms. These indicators should be used in the surveillance of changes in the risk level on the platform. The QRA was chosen as the basis for the development of risk indicators for two reasons. First, the QRA models were presumed to include those factors giving the most significant contribution to the total risk. Second, the QRA expresses the risk for personnel quantitatively and we wanted to develop a quantitative tool. The pilot project was followed up by another project where a set of risk indicators was developed for a specific installation (/5/).

The purpose of this paper is to present the generic risk-based methodology for development of risk indicators developed in these two projects and to present a set of risk indicators established for a specific platform. In addition we will give an overview of some of the differences between PSA for NPP and QRA for petroleum installations. Such a comparison is believed to provide the "PSA-community" with a better understanding of the basis of this "QRA-application".

The methodology for development of risk indicators is generic and can be applied to any petroleum platform and may also be applied in other similar industries. However, the platform (or plant/system) specific QRA must provide the basis for establishment of risk indicators. The risk indicators should be used to control the risk during operation of platforms. The set of risk indicators presented in this paper is thus platform specific.

2. Risk-based decision-making

The usefulness of risk-based decision-making as a complement to the traditional deterministic approach, depends on the quality of the risk analysis, i.e. the coverage or scope of analysis, level of details of the models, input data, etc. There are differences in applications of PSA in the nuclear industry and QRA in the petroleum industry. In this chapter we will compare the applications of PSA and QRA and give a brief description of the differences between PSA and QRA.

2.1 Types of PSA-applications

Areas of applications of PSA in the nuclear industry are shown in Figure 1 (based on /6/). We have also indicated in Figure 1 the type of application presented in this paper, i.e. "safety indicators". Results from QRA are used in risk-based decision-making in a lesser extend than the PSA is used in the nuclear industry. Compared to the applications shown in Figure 1, QRA are mainly used in the design phase in order to:

- Evaluate and compare different platform concepts with regard to total risk
- Verify fulfilment of the risk acceptance criteria (i.e. total risk less than acceptable risk)
- Identify safety critical areas, systems and (to some extent) components
- Evaluate the effect on risk of major modifications.

As indicated in Figure 1, the methodology for development of risk indicators presented later in this paper is comparable to safety indicators in the nuclear industry.

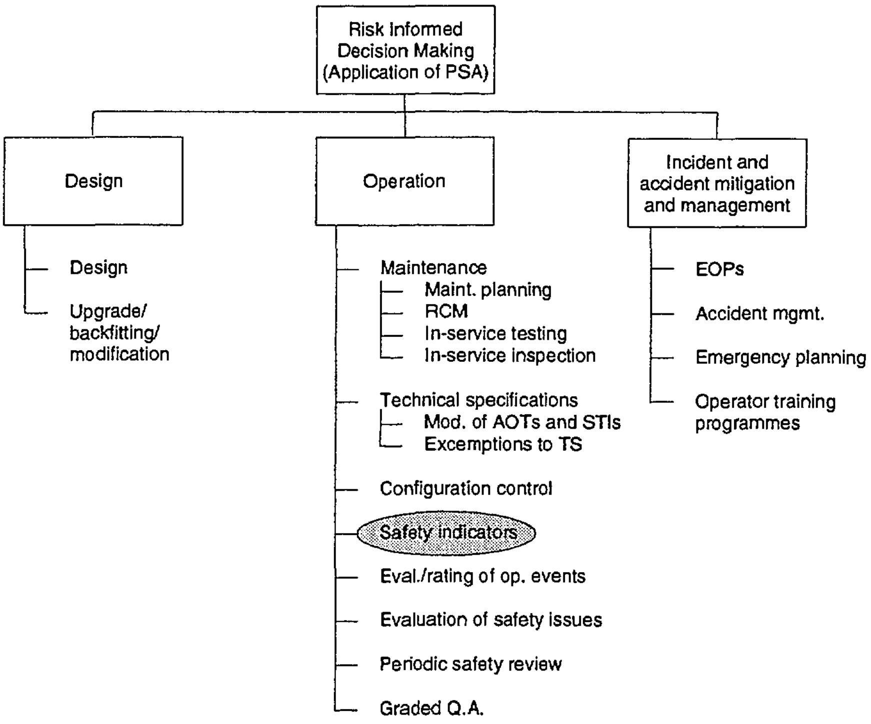

Figure 1. Areas of application for PSA (based on /6/).

2.2 Comparison QRA/PSA

This comparison between the quantitative risk assessments for nuclear power plants and offshore petroleum installations will only cover some aspects, and the main focus is on methodological aspects of interest in order to develop risk indicators[1].

Of course, there are some fundamental differences between risk associated with a nuclear power plant (NPP) and an offshore petroleum platform (OPP). The energies and processes are totally different, and the risk potential and type of consequences are different. The main focus of a PSA is public risk. There is both short-term (early fatalities) and long-term (latent cancer fatalities) consequences. Occupational risk, environmental risk and damage of material assets are normally not included in a PSA. Due to isolation, risk for platform personnel, including occupational risk, is focused in a QRA. Environmental risk (increasing focus) and potential damage of material assets are also covered in a QRA. Except for environmental accidents there is only short-term consequences.

Although the Reactor Safety Study (WASH-1400) (/11/) and some other plant-specific PSA have calculated the public risk (i.e. a level 3 PSA), most of the PSA are of level 1, i.e. calculating the core damage frequencies (CDF). This is somewhat similar as to stop the calculations in a QRA after assessing the risk of loss of the main safety functions (e.g. the integrity of the structure) and not assess the effect on the safety of platform personnel. The QRA can therefore be judged to have broader coverage than the PSA, both with respect to how far out the consequences are followed, and the type of consequences assessed. The depth of the analysis is, however, much larger in a PSA than in a QRA.

The main results from the comparison are shown in Table 1.

Initiating events

In the nuclear power industry there exists both tables of initiating events to be considered (e.g. IAEA lists) and data handbooks (e.g. the Swedish I-book). The latter also gives plant-specific frequencies of the initiating events. A second approach to this predefined list of initiating events is to deduce the initiating events based on what could threaten each safety function (for each core barrier). The root causes are also investigated and presented in a fault tree.

In the QRA, initiating events for process accidents[2] are the leakage of oil and gas themselves. The frequencies are established based on either the amount of leakage points (e.g. valves) times their generic leakage frequencies or plant-specific experienced leakages. The root causes of the leakages are normally not assessed.

Event tree and fault tree analysis

Compared to PSA, the QRA can be said to model the accident sequences by 'small event trees/small fault trees', i.e. the amount of accident sequences and the complexity of system models are much lower than in the PSA. In addition to have a broader spectrum of initiating events in a PSA, all systems including support systems (e.g. power supply) are explicitly modelled (in either the event tree or the fault tree).

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[1] This comparison is based on a review of PSA literature that describes how to perform a PSA (/7/, /8/, /9/ and /10/). However, no actual plant-specific PSA has been reviewed. The review of QRA covers both an actual plant-specific QRA and a general description on how to perform QRAs (/12/).

[2] OPP accidents other than process accidents (i.e. oil and gas release) will be discussed under the topic of external events.

Table 1. Typical features of PSA and QRA.

Topic	PSA	QRA
Initiating events	Root cause analysis of initiating events presented in fault trees. Identification of common cause initiators (CCIs). Predefined lists and handbooks.	No root cause analysis No CCI assessment Predefined categories of leakage Frequencies based on counting leakage point, or platform data.
Fault tree and event tree analysis (system modelling)	Detailed modelling Support systems explicitly modelled. Link between event trees and fault trees. (Time-dependent models for living PSA).	Rough model Support systems not included Only partly use of fault trees No linking of event and fault trees.
Data and parameter estimation	Best estimates and confidence intervals. Classical and Bayesian framework. 'Weighted' plant-specific data	Best estimates Generic data and separate plant-specific data
Human reliability	Thorough analysis of important human actions (e.g. by THERP, SHARP, etc.).	Almost non-existing
Dependencies	Partly inherent in models Separate dependency analysis Regarded as crucial	Partly inherent in models No separate analysis
Uncertainty	Always included, at least qualitatively. Regarded as important	Absent (Some sensitivity analysis)
External events	Covers some external events Linked to the 'internal' event	Covers many external events Separate analysis (Limited modelling effort)
Results	Best estimate and uncertainty in short and long term fatalities. Cumulative distribution functions.	Single best estimate FAR-, and PLL-values

A lot of systems at OPP are only considered implicitly via failure rates or initiating event frequencies. (E.g. power supply to fire water pumps may implicitly be included in the failure rate of the pumps. Trip of a compressor in the process could result in a transient leading to an increased probability of leakage in nearby leakage points. This may be implicitly included in the initiating event frequencies).

Not all the branches in the QRA event tree are modelled and calculated using fault trees. In some cases simple equations are established to describe and calculate the top event of one branch. This means that minimal cut sets will in general not be possible to obtain on a component level, but maybe on a system level. Even if fault trees are used in some of the event tree branches, these are not linked and minimal cut sets on the basic event level cannot be obtained, (i.e. a tool that can combine both event trees and fault trees is not used).

Data and estimation of model parameters

With respect to data estimation two different statistical frameworks could be chosen: Classical or Bayesian framework. In PSA both frameworks are considered since uncertainty analysis normally is included.

In QRA only best estimates are calculated, without any assessment of uncertainties, and the normally used framework for data estimation is the classical approach. If uncertainty in data (and the total analysis) is of no interest, then sparse amount of platform-specific data could be chosen for the estimation of e.g. failure rates, instead of using generic data, even if this implies a large increase in error bands (uncertainty). This is a potential pitfall in QRA.

Human reliability analysis
Human reliability analysis is emphasised in PSA (e.g. due to the large uncertainties associated with human interactions) and methods like THERP and SHARP are used. In QRAs the topic of HRA is almost non-existing. Human errors are often considered to be implicitly covered by the component failure rates and initiating event frequencies.

Dependencies
Analysis of dependent failures is one of the most important and stressed aspects in a PSA. Separate analyses of possible dependencies are carried out. The functional dependencies and shared-equipment (component) dependencies are inherently accounted for in the modelling process (FTA, ETA) both in the PSA and the QRA. Inter-component dependencies, however, requires a specific analysis of the failure causes to search for potential common causes. This seems to be more emphasised in PSA than in QRA. (E.g. in the nuclear power industry they have developed lists of generic and special causes of CCFs).

Uncertainty analysis
The largest methodological difference between a PSA and a QRA is that uncertainty is viewed as a very important topic in the treatment of NPP risk, whereas it is totally absent in a QRA. One very serious consequence of not treating uncertainties at all is that there is less feedback or incentives to include adequate amount of knowledge, information and resources into the analyses. The approximately same best estimates could be obtained whether a rough or a quite thorough analysis is performed. There is little credit gained in carrying out a comprehensive analysis. If uncertainty analysis is carried out, then the efforts (knowledge, information, resources) put into the quantitative risk assessment are reflected in the error bands. The confidence intervals decrease when knowledge about the phenomena analysed increases. The absence of uncertainty analysis can lead to stagnation of further development of the QRAs.

Sensitivity analysis is performed in QRAs as well as in PSAs. Normally, however, this is for QRAs only carried out for risk contributors specified by the operating company (it is not a default task to carry out sensitivity analysis). The development of new modelling tools (e.g. OHRAT) has made it easier to perform sensitivity analysis. To some extent sensitivity analysis covers for the lack of knowledge represented by a risk result without uncertainty bands.

External events
For NPP the external events can be earthquakes, floods, fires, aircraft impact, etc. A part of the external event analysis is to evaluate the fragility and vulnerability of components (e.g. in safety systems). At some point these consequences are included in the 'internal' event analysis. I.e. external events can give rise to initiating event frequencies and/or component failure rates, in addition to the possible direct damage to the plant. Only some of the external events are normally considered thoroughly.

For an offshore petroleum platform other hazards than process accidents could be viewed as 'external events' (i.e. 'external' to the process). These hazards are e.g. helicopter crashes, ship collisions, and dropped objects. Blowout, however, could be viewed as a 'transient' leading to the loss of control of the production process. (This is comparable to the loss of reactivity control in a NPP). It leads to the same consequences as process accidents, i.e. the release of oil and gas, and ultimately fires and explosions (if ignited). Other external events (e.g. earthquakes, winds, etc.) are covered under the heading of environmental impact. In addition to these internal and external events with large accident potential, a QRA also assesses occupational hazards. This is, however, normally just a generic statistical analysis.

The analyses of the different 'external events' are carried out separately and are rarely included in the analysis of process accidents. (However, the impact on, and consequence of damaging process equipment are included in the separate studies).

Presentation of results

The result of a QRA can be compared to a level 3 PSA best estimate result. Normally a single quantitative number is used (e.g. a FAR-value) instead of a cumulative distribution function (e.g. F-N curves). Also the contribution from the different types of hazardous events, and the distribution of risk in the various areas (modules) of the platform are presented.

3. Methodology for development of risk indicators

The methodology for development of risk indicators presented is developed through two pilot projects performed in co-operation with the Norwegian Petroleum Directorate and two oil companies.

3.1 Concepts for development of risk based indicators

Two important concepts used in order to develop risk indicators are:

- *Risk Influencing Factor*, i.e. a factor (condition, attribute) that influences the risk level of a system or activity (here operation and maintenance of a particular offshore installation). Example: Hot work.
- *Risk Indicator*, i.e. a measurable (countable, observable) value used for surveillance of change in a given risk influencing factor. Example: Burning time per period.

The link between these two concepts and the risk level is shown in Figure 2. The effects on risk from changes in the risk indicators can be established through sensitivity analyses. Thereby the relationship between the relative change in the risk indicators and the relative change in risk level can be calculated. By measuring the changes of risk indicators, we are able to follow-up changes in the total risk level on a platform.

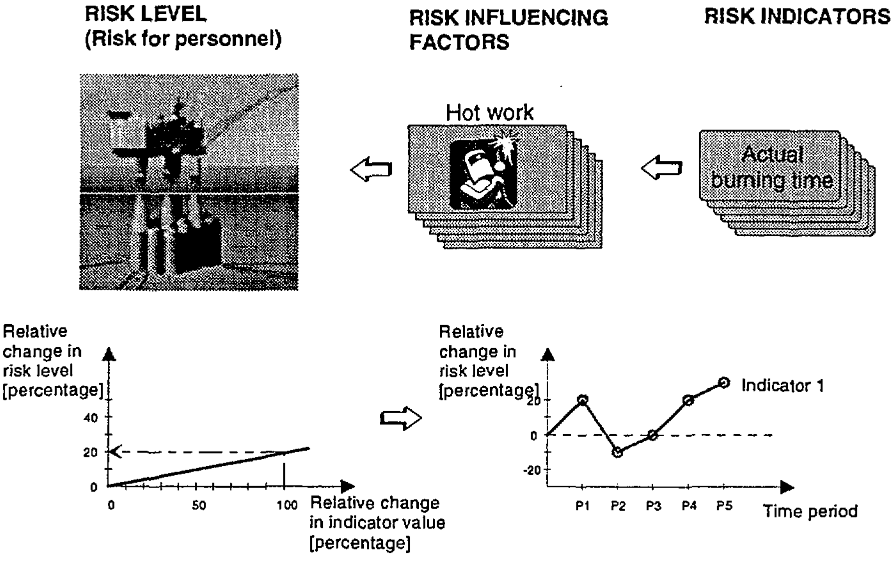

Figure 2. Concepts for development of risk level indicators.

3.2 Methodology for development of technical risk indicators

A brief overview of the methodology for development of risk indicators is shown in Figure 3.

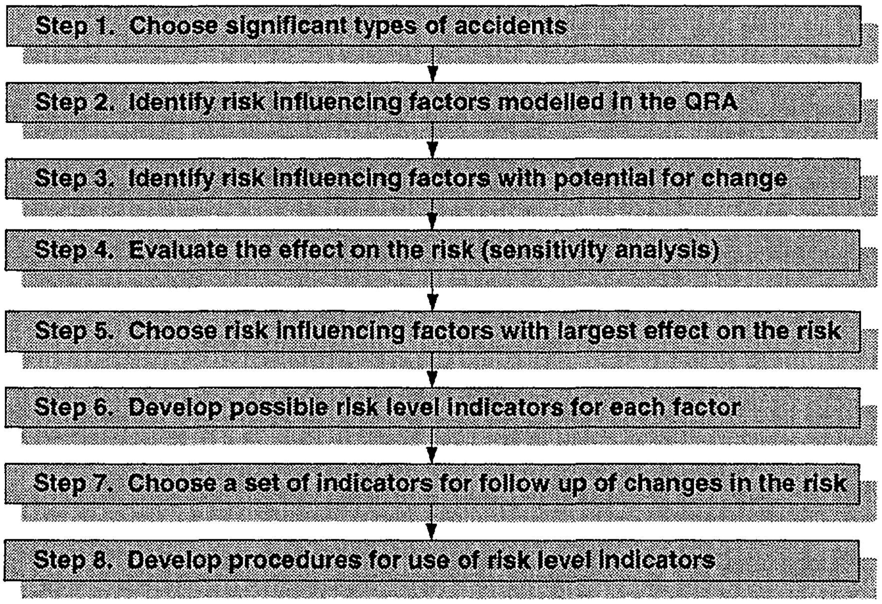

Figure 3. Overview of the generic methodology for development of risk indicators.

In the following description of the methodology we have focused in particular on step 6 and 7.

Step 1 typically include e.g. process accidents (i.e. fires and explosions), riser and pipeline accidents, blowouts and helicopter accidents. In step 2 all factors modelled in the QRA for each accidental event (e.g. process accidents) are identified, listed in tables and illustrated (using e.g. event trees and fault trees). In step 3 the potential change of each single factor or parameter is evaluated by the operating personnel.

In step 4 the effect on risk of change in each factor is assessed using sensitivity analysis. Those factors potentially contributing most to a change in total risk are selected in step 5 using a Pareto diagram and some subjectively chosen cut off criteria.

The pre-establishment and final choice of a set of risk indicators is covered in step 6 and 7. There are several criteria attached to the evaluation of the appropriateness of an indicator. Attaining a relatively high level of control requires frequent registrations (e.g. quarterly). This will affect the amount of data possibly gained by a given indicator, which has to be sufficiently large in order to avoid problems with statistical significance. The indicators should also preferably be based on existing registrations or databases, and not place extra registration burden on the operating company. However, this has to be balanced against the selection of indicators that are sufficiently accurate (i.e. the indicators have to be representative for the risk influencing factors they measure). Need for increased accuracy may result in less simple data collection.

The pre-establishment of (possible) indicators is based on discussions with the operating personnel. However, the final choice also has to be based on testing of the proposed indicators. Such testing also involves personnel responsible for relevant databases (e.g. accident databases, maintenance databases, and different daily reports). The simplicity of registration might turn out to be quite different from what was initially perceived. The willingness to implement new registrations or to modify existing registrations depends on the perceived benefit gained from the use of a specific indicator (and also on the perceived adequacy of the indicator).

The final step, step 8, is the establishment of routines for use of risk level indicators. The relative change in risk should be illustrated showing the total contribution, along a time axis. This illustration will provide a signal or a warning for the need of assessing risk-reducing measures. The results can be documented and discussed in a quarterly report to the management. The report should include proposals for risk reducing measures.

4. Results

In addition to the review of the differences between QRA and PSA presented in chapter 2, there are two major results from our work. First, the generic methodology for development of risk indicators presented in chapter 3. Secondly, the establishment of a set of risk indicators for a specific petroleum installation. This set of risk indicators will be presented in the following.

4.1 Established set of indicators for a specific installation

The generic methodology was utilised to establish a set of risk indicators for a specific petroleum installation. The risk influencing factors assessed likely to change and contributing most to the total risk were identified, and a set of risk indicators was established for the risk influencing factors. The proposed risk indicators for the different risk influencing factors are shown in Table 2.

Table 2. Proposed set of indicators for a specific platform.

No	**Risk influencing factor**	**Risk indicator**	**Effect on risk *%**
1	Process leak frequency	Number of all leaks	46.4
2	Ignition due to failure on electrical equipment	Number of all failures on electrical equipment	18.0
3	Hot work	Number of hot work permits class A and B	5.3
4	Ignition due to pumps and compressors	Number of hours of critical maintenance backlog	2.3
5	Ignition due to driving units (e.g. turbines)	Number of all failures on electrical driving units	7.2
6	Ignition in neighbour module	Number of alarms indicating loss of overpressure	28.0 **
7	Drilling and completion	Number of days with drilling and completion activity	11.0
8	Workover (on wells)	Number of days with workover	10.4
9	Blowout frequency	Number of trips (i.e. withdrawals of the drillpipe)	4.3

* The effect on risk is based on 100% change in the risk indicator values

** This refers to change in ignition probability and not to the proposed risk indicator

The effect on risk stated in the table is based on a potential change in risk indicator values of 100 %, for the reason of comparison. Be aware that this is not the maximum potential change in risk that was the result of the sensitivity analysis.

4.2 Testing of indicators

As we mentioned in section 3.2 (step 6 and 7), it is important to test the proposed risk indicators prior to a final decision on the appropriate set of risk indicators. Only through such testing can it be verified to what extent the different appropriateness criteria are fulfilled for each of the risk indicators. Data for the first and second quarter of 1998 were chosen for the purpose of this test.

It was possible to obtain values for six of the nine proposed risk indicators (indicator no. 1, 3, 4, 5, 7 and 8). However, for one of these (the process leak frequency) the number of leaks reported were much less than anticipated (based on the QRA). The amount of data for this risk indicator is too small for registration (and control) based on periods of three months.

For risk indicator no. 2 and no. 9 we did not obtain data due to the need for manual data retrieval. However, for future use of these risk indicators only minor adjustments in the reporting procedures are foreseen.

The appropriateness of risk indicator no. 6 has not yet been confirmed. However, due to modelling inadequacy in the QRA, this risk indicator has no direct link to the total risk. The effect on risk due to a change in the risk indicator value thus cannot be estimated. It has to be treated separately, looking at the change in risk indicator value from one quarter to the next, without calculating the corresponding change in total risk.

To summarise, we assume that seven of the nine proposed risk indicators will be appropriate for use as a tool for risk control. One has to be further analysed (e.g. looking for root causes and possibly organisational risk influencing factors) and one has to be treated in a "non-risk" manner, or replaced by an alternative risk indicator.

5. Discussions

5.1 Risk-based decision-making in the petroleum industry

Ideally, all decisions should be made on sufficient decision basis. This criterion should also be fulfilled for risk-based decisions in the petroleum industry. Due to limitations in the existing QRA-methodology, the application areas of the QRA for risk-based decision-making today are limited. The limitations arise from e.g. uncertainty associated with input data, modelling assumptions and the completeness of the existing analyses.

Increased use of risk-based decision-making, in order to maintain and improve the existing safety level in the Norwegian petroleum industry, should not exceed the extent supported by the state-of-the-art of QRA-methodology and data. The present situation is such that there is a need for further development of the QRA-methodology in order to expand the possible and suitable applications of QRA (ref. section 2.2).

5.2 General methodology for development of risk indicators

The general methodology for development of risk indicators has been gradually developed through two pilot projects. It is a purely risk-based approach where low risk contributors are screened out. Risk contribution is defined in relative terms, i.e. it is not the absolute risk contribution that is of interest but rather the potential change in risk. This means that e.g. a specific safety system may well be important to the risk level in absolute terms, but if this system most likely remains equally efficient over time (i.e. no change is foreseen), then the relative change in risk due to this system will be negligible. Thus, there will be no justification for the use of resources to control risk through the use of risk indicators. It is important that the operating personnel assess the "realistic" (most likely) foreseen change.

These two distinct features of this methodology, i.e. the purely risk-based approach and the assessment of potential change by the operating personnel, are important when we compare this methodology with other relevant methodologies.

Within the nuclear industry it has been developed a lot of different types of "safety indicators", some of which are described in (/13/). These indicators are ranging from fairly general performance indicators (e.g. the ten WANO[3] indicators) which are only presumed to influence safety, to probabilistic safety indicators which are "known" to have influence on safety. However, even these latter indicators are not developed using the risk analysis (PSA) as a starting point. Instead they are identified from incident databases, and in second hand the effect on risk is determined based on the plant specific PSA. The coverage of these indicators thus remains unknown.

Holmberg et.al. (/14/) describe the development and testing of what they term risk-based PSA indicators. These indicators are used for risk follow-up of events and unavailability of safety related systems. The results are presented as average values for one year of operation. The main aim is to classify the safety significance of events, and not to use the indicators as a tool for "continuous" risk control. In addition, they cover only some selected safety systems. The aim and use of these indicators is therefore quite different from the risk indicators presented in this paper.

5.3 Established set of risk indicators for a specific platform

Of the nine risk indicators proposed, seven are assumed (with minor adjustments in the reporting routines) to be appropriate for use as a tool for risk control, whereas further analyses are required for the last two factors/indicators.

Risk indicator no. 3, 7 and 8 were established as more or less "direct" measures of the corresponding risk influencing factors (i.e. the risk indicator is identical or almost identical to the parameter used in the QRA). For all the other risk influencing factors a direct measure was inappropriate due to low probability (or frequency) of occurrence. These risk indicators are therefore representing a more "indirect" measure of a larger population in which the set of interest is included (e.g. the set of critical failures as part of the number of all failures). Of course, by doing so we make assumptions and introduce uncertainties, but this is the only way to measure changes as frequently as each quarter. These "indirect" measures are still far more direct than organisational risk indicators, which also may be regarded as "indirect" risk indicators.

For the risk influencing factor no. 1 it was not even sufficient to count all leaks (including those being regarded as too small to be reflected in the QRA). For this risk factor we foresee an analysis of possible root causes including organisational factors. It will provide a potential link to organisational aspects, see (/4/).

Provided that an appropriate risk indicator (or set of risk indicators) can be established for the process leak frequency, we believe that the total set of risk indicators provide a reasonable good coverage in relation to the total risk picture (as modelled in the QRA). However, risk indicator no. 9 only covers a part of the corresponding factor. The blowout frequency depends upon failure

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[3] WANO – World Association of Nuclear Operators

in both barriers (hydrostatic pressure and safety valves), whereas the risk indicator (number of trips) only addresses one of the barriers (hydrostatic pressure).

5.4 Limitations of the presented methodology

The set of risk indicators presented is platform specific, but the methodology described is generic and can be applied to any platform. The risk indicators can be used as a tool for risk control during operation of petroleum installations.

The risk indicators express changes in risk in relative terms, it cannot be used to measure the risk level in absolute terms. For this a complete update of the QRA is necessary.

So far, the scope of the work has been limited to focus on risk for loss of personnel and events having major accident potential, but the same methodology can be used to develop risk indicators for environmental and material damage. Some safety systems may turn out to be more important with respect to material damage risk compared to personnel risk (/15/).

The QRA for the chosen installation has been used as a basis for the work, and all assumptions and limitations in the QRA have been adopted. Due to lack of detailed cause analyses in the QRA, the established set of indicators do not cover all risk influencing factors. Additional work has to be done to establish "non-technical" risk indicators, i.e. in order to develop risk indicators for human and organisational factors.

5.5 Application of risk indicators

The practical application of the established set of risk indicators (based on the methodology developed and presented in this paper) is to control risk during operation. Risk control can thus be based on quarterly registrations instead of just an update of the QRA with several years time interval.

5.6 Further development

In order to increase the use of risk-based decision-making in the petroleum industry, there is a general need for further development of the QRA-methodology applied in the petroleum industry.

With regard to further development of the methodology for development of risk indicators, the main research challenge is the modelling of organisational factor's effect on the risk. Focus will be on the most important risk influencing factors identified in the QRA. Our purpose for the further work is to identify organisational risk indicators that complement the QRA-based indicators presented in this paper.

6. Conclusions

Risk-based decision-making based on QRA in the petroleum industry is applied in a lesser extend than PSA is used in the nuclear industry. One explanation is the difference between the state-of-the-art of QRA versus PSA. Some of the differences have been addressed in this paper.

We have described a purely risk-based approach for development of risk indicators for petroleum installations. The basis for the work is the QRA for a specific installation and the determination of risk importance of each risk influencing factor. The risk importance is based on a judgement performed by the operating personnel of "realistic" changes in each factor.

The risk indicators can be used as a tool for risk control during operation of petroleum installation, and should be seen as a supplement to other techniques to keep the risk at an acceptable level.

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