**Selvik Jon Tømmerås**
*University of Stavanger and IRIS (International Research Institute of Stavanger), Stavanger, Norway*

**Scarf Phil**
*University of Salford, Salford, U.K*

**Aven Terje**
*University of Stavanger, Stavanger, Norway*

# An extended risk based inspection methodology

**Keywords**

maintenance planning, risk based inspection, risk, uncertainty factors.

**Abstract**

Risk based inspection (RBI) is a methodology commonly used in planning of inspections for static mechanical equipment, in particular piping networks. The inspections are prioritized based on risk, expressed as expected values, integrating the likelihood and consequences of failures. In this paper we suggest an extension of the RBI methodology which reflects risk and uncertainties beyond expected values. We argue that such an extension is essential for adequately supporting the inspection planning. A pipeline example from the Norwegian oil and gas industry is presented to illustrate and discuss the suggested approach.

## 1. Introduction

Inspections are widely used in the process industries to reduce risks related to failures on static mechanical equipment, for example on pipelines which accounts for the greatest proportion of equipment damage in petrochemical plants, [37]. Use of inspections is essential if availability and high performance is to be achieved, but preventive maintenance (PM), such as inspections, is expensive and contributes to a relatively large share of the total operational costs. The inspections imply direct costs and also risks for maintenance introduced failures. Maintenance planning is about balancing these concerns.

To aid the decision-makers in their inspection planning, different types of tools are available. One of these tools is addressed in this paper, the risk based inspection (RBI) methodology; a methodology commonly used within the chemical, petrochemical, the oil & gas and the refinery industries. Successful implementation of RBI is demonstrated by many authors, [12]; see e.g. [1], [14], [19], [20], [28], [29], [31], [32] and [39].

The risk based inspection methodology, as indicated by its name, assesses risk to support the inspection planning. Risk is computed for the relevant pressurized equipment and the failure mode loss of containment, caused by either material deterioration or external influence (such as dropped objects). Risk of failure (RoF) is assessed quantitatively following a two-dimensional risk perspective, comprising the probability of failure (PoF) and the consequence of failure (CoF), and is typically expressed as the product of the two; see for example [14].

Based on the risk values calculated, the risk based inspection methodology provides recommendation on what, when, where and how to inspect, and also what should be documented. There exist different versions of the RBI methodology, reflecting variations in preferred approach for modelling of the material degradation and the probabilistic treatment. Some assessors promote an expert-based (subjective) approach, for example [23] who adopts a Bayesian approach for handling errors in equipment wall thickness measurements. Others prefer a more traditional frequency-based probability assessment approach. However, although variations exist, the fundamental pillars are shared; they are defined by technical standards such as [3]-[4] and [16]; see also [22], [24] and [27].

The following mix of qualitative, semi-quantitative and quantitative elements summarise the fundamental pillars of the RBI methodology:

- An inductive analysis of potential failures, for example a failure mode and effects analysis (FMEA), is typically used to screen and assess the consequences of the system, see e.g. [19].
- Calculation of RoF, which is traditionally a part of a quantitative risk assessment (QRA), and includes modelling of the degradation process; see e.g. [14], [15], and [33].
- Application of a qualitative or semi-quantitative risk matrix to express the risk level and relationship between PoF and CoF; see e.g. [31] and [38].
- Use of the ALARP principle for planning of intervals based on the assessed risk; see e.g. [26] and [34].

Our prime concern related to the use of the above elements, is how uncertainties are addressed. The traditional RBI assesses risk as a combination of probabilities and failure events and consequences (or losses), but such a risk perspective fail to bring into account all the relevant uncertainties. The risk assessments are based on background knowledge, and this knowledge may include assumptions that could conceal uncertainties not addressed by the probabilistic assessments. For example, for the assessments of pipeline degradation there are assumptions made on the presence of erosive sources, such as the size and concentration of sand particles in the fluid stream. The probabilities produced to assess the risks are conditioned on these assumptions.

To take such uncertainties as indicated above into account, a broader risk perspective is needed. One way to do this is to apply a risk perspective presented in [7], where probability is replaced with uncertainty in the definition of risk. In this perspective probability is a tool used to describe the uncertainties, and is conditional on the background knowledge. By using such a risk perspective we are able to shift the methodological focus from probabilities and expected values to uncertainties. To highlight this shift, we name this adjusted methodology "extended risk based inspection" or as ERBI for short.

The purpose of the present paper is to motivate for the use of this extended risk based inspection methodology, and to describe its main features.

A pipeline example from the oil and gas industry is used to illustrate the applicability of the suggested ERBI methodology. The aim is to determine the inspection interval for a 15 inch carbon pipeline located in the Norwegian sector of the North Sea. The 9 km pipeline has welding points each 12 meters, and transports a corrosive multiphase well stream from multiple subsea production facilities. The pipe is covered with a protective layer, an inner coating, to avoid damage on the carbon steel from corrosion. Similar cases are discussed by [11], [13] and [37].

The structure of the remaining part of the paper is as follows. The next section presents a brief description of the traditional RBI methodology, demonstrated on the example presented above. Section 3 explains the new extended (ERBI) methodology. The methodology is then discussed in Section 4, where it is compared to the standard RBI. The example presented is used as a basis for the comparison. The last section, Section 5, provides some conclusions.

## 2. Description of the RBI methodology

The risk based inspection methodology comprises the following four phases:

1. Equipment screening
2. Detailed risk assessment
3. Inspection interval assessment
4. Implementation, evaluation and updating

In this section we will give a brief presentation of these phases (see Sections 2.1- 2.4) using the described pipeline example as an illustration. The methodological description of the RBI is based on the available standards [3]-[4] and [16].

Before starting on the RBI assessments, a project team is designed, to ensure that the adequate capacities are included and relevant information is available for the assessments. For the collection and use of data in the oil & gas industry, we refer to [21].

### 2.1. Equipment screening

A screening is performed at the initial phase, for example by use of FMEA or risk matrices, to be avoid unnecessary assessments of equipment of low risk. Equipment assigned low consequences and low probability of failure is excluded from the detailed risk assessments in the next phase.

In order to perform the screening, the equipment is grouped into hierarchal levels. [16] recommends the use of five levels, defined in accordance to [21], but fewer levels may be appropriate, if the number of items is low and no special concerns are present.

The screening is performed for three categories of failure consequences; operational (production availability), environmental and safety consequences. Redundancy, hidden failures and non-operational consequences are not assessed. However, main focus is normally on personnel safety.

### 2.2. Detailed risk assessment

The detailed risk assessment is performed in two steps:

1. Separate probability of failure and consequence of failure assessments
2. Assessment of the risk of failure based on the results from the first step

To describe the steps we refer to the case presented in Section 1. The crude assessments indicate that the pipeline has potential failure consequences that require a more detailed assessment before inspection intervals can be specified. Available historical data show that few similar failure events have occurred, but that those that have occurred have been critical to the production. The detailed assessments will provide a more precise risk picture for the determination of the inspection intervals.

First we assess the probability of failure (PoF), or more specifically, the probability of the occurrence of the failure mode loss of containment. Several databases are available for this assessment, including integrity and reliability databases. This part of the assessment is challenging. An understanding of the failure and degradation mechanisms of the equipment is needed to find a model that produces the expected failure rates. Much of the variation in available literature on RBI is related to alternative ways of improving the modelling of the equipment degradation. [16] for example, has suggested three different models for this purpose; an insignificant rate model, a rate model and a susceptibility model:

- Insignificant rate model: To be used if no degradation is expected. A fixed probability of failure equal to $10^{-5}$ per year is used. It is assumed that time of the assessment is irrelevant for the risk of failure.
- Rate model: To be used if wall thickness is decreasing with time (the most common scenario). The rate modelling includes factors such as wall thickness as a function of time, the material and fluid properties and the operating conditions.
- Susceptibility model: To be used if external events may lead to a suddenly increased probability of failure. Such events could be a dropped object causing pipeline rupture. It is a difficult task to model such events, and knowledge on environmental and operating conditions, and also monitoring capacities and routines are of relevance to the modelled probability of failure.

For schematic illustration of the models described above, see [16]. If none of the above models are applicable further investigations would be required.

For the pipeline example we find the rate model to be applicable as the high sand concentration in the fluid stream cause significant erosion to the pipe walls. The input parameters in the model are determined by a combined use of historical data and engineering judgements, and by summarizing the probabilities for all potential failure events, the annual failure probability for the pipeline is placed in the range $10^{-4}$-$10^{-3}$. For technical details on how to model the degradation (for example fatigue assessments) and determine the PoF, we refer to [16].

Next we assess the consequence of failure (CoF) for the pipeline case, by combining the three categories referred to in Section 2.1. Regardless of the equipment addressed, the failure consequences are to a large extent determined by the operating conditions and system design. For the pipeline, the consequence is dependant on the leakage volume or rate (dispersion), fluid properties, and the ignition potential. For calculation of the expected consequences for the operational, safety and environmental impacts, an event tree is useful to summarize and weight outcomes. Alternatively, [3]-[4] refer to use of consequence relevant factors for the calculations, where CoF is a function of factors for production loss, pressure, explosion damage potential, toxicity, production effect, location, recovery time, non-production effect and safety system effect. In many cases, as another alternative, a qualitative expert judgement is used to assess the consequences, [33]. Often qualitative categories are used, as in our example where five categories were defined: insignificant, minor effect, local effect, major effect and massive effect. In the analysis we assign pipeline failures to have major effect, as a leakage would shut down the entire production.

Based on the assessed RoF and CoF a risk decision matrix may be produced, as shown for the pipeline case in *Figure 1.* It is seen that a two year inspection interval for the pipeline example is recommended.

| | CoF ranking | | | | |
|---|---|---|---|---|---|
| PoF ranking | Insign-ificant | Minor effect | Local effect | Major effect | Massive effect |
| $>10^{-2}$ | 0 | 4 | 2 | 1 | 1 |
| $10^{-3}$- $10^{-2}$ | 0 | 4 | 2 | 1 | 1 |
| $10^{-4}$- $10^{-3}$ | 0 | 0 | 4 | 2 | 2 |
| $10^{-5}$- $10^{-4}$ | 0 | 0 | 8 | 4 | 4 |
| $<10^{-5}$ | 0 | 0 | 8 | 8 | 8 |

*Figure 1.* Example of RBI decision risk matrix [16]: recommended time between inspections (in years)

## 2.3. Inspection interval assessment

The risk decision matrix specifies the inspection intervals as a function of probability and consequences. Equipment assessed to have a low RoF are prescribed corrective maintenance (CM). Equipment assessed to have a high RoF are prescribed to have rather frequent inspections, for example once every year.

In cases where significant variation exists in the failure consequences between the operational, safety and environmental categories, separate matrices are often used. And the minimum inspection interval across the separate matrices is then chosen.
For the use of the results, two different principles are reflected by the referred standards. While [16] point to use of company risk acceptance criteria, the [3, 4] on the other hand, points to use of the ALARP principle. This principle states that the risk should be reduced to a level that is as low as reasonably practicable, meaning that risk-reducing measures should be implemented or chosen unless it can be demonstrated that there is a gross disproportion between costs and benefits. The common tool to verify ALARP is cost-benefit analysis. Indirectly such link is also provided by [16], which refers to the NORSOK standard: Z-008 [30], for planning of maintenance activities in the oil and gas industry. The standard recommends use of cost-benefit assessments to ensure a proper balance between frequency of maintenance and the risks of equipment failures.

## 2.4. Implementation, evaluation and updating

Decision-making and integrating the results into an inspection plan requires additional considerations to be taken into account. These considerations are strongly dependant on the available inspection resources and existing PM programmes. The implementation and evaluation process is typically a part of the company maintenance management systems, [24] and [38], where experience from the inspections will later provide relevant information for updating and evaluating of the inspection programmes. See also [10] and [15].

## 2.5 Potential for methodological improvements: Extended uncertainty assessments

Several studies have showed that uncertainties in assumptions made in the RBI assessments are to limited extent reflected by the final results; see for example [18], [20] and [34]. A main source of these uncertainties is related to the choice of models.
This in its turn has motivated several adjusted RBI methods to cope with this problem. A main category of such methods are based on fuzzy logic; see for example [25] and [27]. It is argued that risk is difficult to assess due to the complexities involved in modelling of the degradation process (e.g. corrosion rate) and failure consequences, and also due to the model input data [35]. A fuzzy approach is believed to express the relevant uncertainties and produce a more precise method by adjusting modelled material degradation with assessed "trust" values [35]. However, we find the values generated by this approach to be "arbitrary" and not justified, and they are not able to properly address uncertainties in the assumptions made.
The adequate tool for quantifying uncertainties is in our view subjective (knowledge-based) probabilities. If the assessor assigns a probability of an event A, given the background knowledge K, equal to 0.1, i.e. $P(A|K) = 0.1$, it means that the assessor regards his/her assessment of uncertainty (likelihood, degree of belief) as comparable to randomly drawing one particular ball out of an urn comprising 10 balls. However, we acknowledge the need for qualitatively assessing uncertainties beyond the probabilities as the K could "hide" uncertainties as was noted in Section 1. We need to capture also the risk contributions from potential "surprises" ("black swans" [36]).
A proper framework for risk assessment according to this perspective is presented by [8]. In this perspective uncertainty and not probability is the main component of risk. Risk is understood as the two-dimensional combination of:

i. Events (A) and the consequences of these events (C); A: leakage due to loss of containment, for example pipe rupture; C: the leakage and maintenance consequence
ii. Uncertainties U about A and C (will A occur and what will the consequences C be?)

Such a risk perspective is referred to as the (A, C, U) perspective [7]. The key to this risk perspective is the broader risk descriptions highlighting uncertainties "hidden" in the assumptions. These uncertainties are referred to as "uncertainty factors".
In the following section we present an extension to the risk based inspection based on this risk perspective. It is referred to as the extended risk based inspection (ERBI) methodology. RBI will still be the methodological platform, but the approach to risk and uncertainties will be more comprehensive.
Our approach is based on similar ideas as supporting the subjective probability approach by [2], but the risk perspective is broader by the incorporation of the uncertainty factors.

## 3. Description of the ERBI methodology

In this section we present the extended risk based inspection (ERBI) methodology as indicated in the previous sections. It is described by eight successive boxes that are placed into a decision framework for determination of the inspection programme, as illustrated by the boxes below:

| |
|---|
| Box 0: Planning, evaluation & information update |
| Box 1: Equipemnt screening |
| Box 2: Detailed risk (or RoF) assessments |
| Box 3: Inspection interval assessments |
| Box 4: Uncertainty analysis |

| |
|---|
| Box 5: Uncertainty evaluation & presentation |
| Box 6: Managerial review and Judgement |
| Box 7: PM programme: Decisions & implementation |

The first four boxes, 0-3, are described by the phases of the RBI methodology as presented in Sections 2.1-2.4, and provide the already existing methodology to the framework. We then introduce some new assessments in boxes 4 and 5. These are separate uncertainty assessments included in the ERBI methodology, and are additional to those performed as integrated parts of assessments in the RBI phases.
In the fourth box we focus on the uncertainty factors mentioned in the previous section. Many of these factors are derived from the assumptions made in the detailed risk assessments. In line with [7], the uncertainty analyses cover the following main tasks:

1. Identification of uncertainty factors
2. Assessment and categorization of the uncertainty factors with respect to degree of uncertainty
3. Assessment and categorization of the uncertainty factors with respect to degree of sensitivity
4. Summarization of the uncertainty factors' importance

Scores, high (H), medium (M) or Low (L), are assigned for the tasks 2-4. Table 1 presents a score system for ranking of the uncertainty, inspired by [17]. The judgement of the sensitivity score is linked to the extent that the factor is able to change the inspection interval, where a medium score is assigned if a relatively large change in the base case values is needed to bring about altered conclusions, a low score is assigned if unrealistically changes are needed, and a high score if relatively small changes are needed. The importance score is interpreted as the average of the score for the tasks 2-3.

*Table 1.* Uncertainty assessment score interpretation

| **Score & interpretation** |
|---|
| **Low:**<br>One or more of the following conditions are met:<br>-The assumptions made are seen as very reasonable<br>-Much reliable data are available<br>-There is broad agreement/consensus among experts.<br>-The phenomena involved are well understood; the degradation models used are known to give predictions with the required accuracy |
| **Medium:**<br>Conditions between those characterizing low and high uncertainty. |
| **High:**<br>One or more of the following conditions are met:<br>-The assumptions made represent strong simplifications<br>-Data are not available, or are unreliable<br>-There is lack of agreement/consensus among experts<br>-The phenomena involved are not well understood; degradation models are non-existent or known/believed to give poor predictions |

The steps 1-4 provide the input to the uncertainty evaluation of the system studied (see box no. 5). Such evaluation is recommended by for example [25], as part of the communication of results to the management function.
A managerial review and judgement feature is also included, as shown in the sixth box in Figure 3, in line with the decision framework presented in [7]. The inputs to management from the various assessments are placed into a broader context, where the boundaries and limitations of the various assessments are taken into account, and also additional aspects and inputs are taken into consideration, e.g. manufacturer recommendations and existing PM programmes. The managerial review and judgement may also request revisions or analytic changes should results appear unreasonable.
Section 3.1 presents the results from the uncertainty assessment for the pipeline example.

### 3.1. Uncertainty assessments in the example

Our focus is on the uncertainty factors that have the potential to change the probabilities (of events and consequences) to such an extent that it may have an effect on the specified inspection intervals. For the pipeline example presented, several critical assumptions made in the detailed RoF calculations were identified. Below we present and list some of the derived uncertainty factors based on these assumptions:

1. The pipeline is properly tested and inspected before and during installation
2. All other items in the assessments are functioning (not only the system considered)
3. Data selection criteria are based on pipe description and fluid type
4. Data are able to describe the pipe material degradation
5. Use of "smart pig" provides accurate sensor readings inside the pipeline
6. External failure events may be ignored
7. Inspection results are representative for the whole pipeline length

These uncertainty factors are briefly described in the following, in the order above.
The first uncertainty factor to be addressed is the assumption that the pipeline, including the welding between the pipes, are adequately tested and inspected prior to production start up. Due to the pipe being produced with a corrosion resistant alloy layer, an inspection challenging type of welding was required to connect the pipes, and thus requiring a new and alternative inspection method instead of

using traditional ultra-sonic inspections. It is assumed that this new method ensures detection of weaknesses in the pipe and welding, but although the methodology was verified during the pipeline qualification process, sparse experience exists on this inspection method and its limitations. As for the assessed risk, this would be considerably higher should the inspection method prove inadequate.

The probability of failure assessments were carried out assuming that only one failure event occurs at the time. It is assumed that all the other items are working perfectly. None of the other items are then in a failure state, are waiting for maintenance or have hidden failures. However, real life may very well be different, and may also have relevance for the assessed consequences.

The risk assessments are, to a large extent, based on data found in company internal databases. However, the selection criterion used may lead to failure probabilities that do not reflect the inner diameter of the pipe and number of welding points, and also the erosive properties of the fluid. It is uncertain to what extent the criterion adopted has included pipelines that are subject to similar conditions.

There are limited amounts of relevant data available to predict the performance of the equipment. The data represent newer pipeline systems, and for these few events have occurred. The relevant items' sizes and material property combinations are not found in older data. Thus, one may question to what extent the data are dominated by the items' "childhood events".

The pipeline is regularly pigged by use of a "smart pig" that monitors pipeline inside parameters, for example the inner diameter and temperature. The reliability and accuracy of this smart pig is not evaluated by the risk assessments. As this smart pig ensures the integrity of the inside protective layer (the inner coating) of the pipeline, the assumption that use of smart pig provides accurate sensor readings, may lead us to ignore potential damage inside the pipe.

It is assumed that the pipeline is located in an area with limited traffic and exposure to dropped objects; however this is an assumption based on the fact that most of the production and maintenance activities are performed close to the production vessel and riser base. But there may be other vessel operating in the vicinity that may cause damage to the pipe. Such events are very difficult to model, and are assumed to have a negligible risk affect, even though such events exist in the company internal reliability data.

It is assumed that inspection results are representative for whole pipeline length, although only parts of the pipeline will be subject to thorough inspections.

Now, having identified a list of uncertainty factors, we next assess and categorize these with respect to degrees of uncertainty and sensitivity, which combined provides a basis for making a judgement of importance. The results are shown in Table 2, based on the score system presented in Table 1.

Table 2 shows that both the uncertainty factors 4 and 7 are classified with high uncertainty. Of these two uncertainty factors, only factor 4 is classified with high importance as the mobilisation times alone do not have a high enough potential to change the assessed interval.

The importance classification points to factors that should, if time and resources allow, be considered and prioritized for further assessments and follow-up.

The uncertainty analysis is qualitatively combined with the results of the prior assessments, including the subjective probability assessments for failure events and consequences in the detailed RoF assessments which are evaluated as a basis for communication to management. The evaluations highlight which uncertainties to give weight to in the presentation of the results.

*Table 2*. Pipeline case uncertainty assessment

| Assumption/ uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|---|---|---|---|
| No. 1 | M | H | M - H |
| No. 2 | M | L | M - L |
| No. 3 | M | M | M |
| No. 4 | H | H | H |
| No. 5 | L | H | M |
| No. 6 | L | M | L – M |
| No. 7 | H | M | H - M |

## 3.2. Managerial review and judgement

The results presented in Table 2 provide additional decision support to that which is included in the standard RBI process. When these results are communicated to management, weight is also given to the limitations in the traditional RBI assessments.

Although management performs review and judgement late in the ERBI process, it does not exclude their involvements in earlier phases, which is often considered a key success factor in project management, so also for the implementation of the ERBI process.

## 4. Discussion – comparison of the RBI and ERBI methodologies

Applying the ERBI methodology will not necessarily result in different decisions compared to the RBI methodology. For the pipeline example, the RBI risk assessments and the first parts of the ERBI methodology led to a two year inspection plan for the steel pipeline. The importance of the factors identified may; however, change this, the conclusion

being that the pipeline should be subject to a different inspection frequency - to prevent failure events.
Consider, for example, a specific segment of the pipeline in the case presented: a 12 meter middle section say, located about 4,500 meters from the riser base. Imagine that during testing this section was somehow neglected and a crack is present in the welding. Consider then the detailed risk assessment performed and assumption 4: 'Data are able to describe the pipe material degradation'. As the type of pipe and welding in uncommon and limited data exist, there is high uncertainty related to this assumption. The sensitivity is also high, meaning that motivating a cautious policy - a more frequent inspection programme could be justified. By giving the assumptions attention, the decision-makers might see the need for further assessments based on alternative or revised assumptions.
In a project development, a number of assumptions are made and these need to be followed up in coming project phases. The ERBI provides a methodology for assessing the importance of the various assumptions and support the decision-making.
The managerial review and judgement allows for quality assurance and second opinions in the ERBI process. Also other risk methodologies, for example reliability centered maintenance (RCM), which is frequently used for assessment of preventive maintenance tasks and intervals for various equipment in the Norwegian oil & gas industry, could be included in the overall considerations in the managerial review and judgement.
Within the ERBI framework, as stated in Section 2.5, we apply subjective probabilities as a quantitative measure of uncertainty. These probabilities are used both in the equipment screening and the detailed risk assessments. In the RBI a relative frequency-based perspective for the probabilities are often used. The way probability and risk are understood strongly influences the presentation and communication of the results.
The additional assessments produce some increase in the time needed to perform the process, as well as the resources required. However, the extra time and costs due to the uncertainty factor assessments should not be very large compared to the overall costs used for RBI. If uncertainty and risk are to be adequately incorporated in the assessments, some extra resources are required.

## 5. Conclusions

RBI is a systematic analysis method for planning inspection intervals of static mechanical equipment used in the process industries. Risk of failures of the relevant system items is assessed in order to identify and determine suitable intervals. Over the years, RBI has gained reputation for being a successful method, but also for having some shortcomings. One of these is traced to the limited assessment of uncertainties.
In this paper we present and discuss the ERBI methodology: a methodology based on the existing RBI, which improves the risk and uncertainty assessments by adding some additional features to the existing RBI. A separate uncertainty assessment is added, to address uncertainties "hidden" in assumptions of the risk assessments. In the ERBI methodology the uncertainties are then communicated to management through an extended uncertainty evaluation, which integrates the results from the detailed risk analyses (and the cost-benefit analyses if such are performed) and the separate uncertainty analysis. An essential feature of the presented methodology and decision framework is the managerial review and judgement, which places the decision process into a broader management context. In this step consideration is given to the boundaries and limitations of the tools used.
An example from the oil & gas industry is presented to demonstrate the applicability of ERBI. The approach is, however, general and could also be used for other types of applications. We believe that by applying the methodology, an improved basis can be established for informing decision makers compared to the traditional RBI method, as the importance of risk and uncertainties is more adequately taken into account.

## References

[1] Ablitt, C. & Speck, J. (2005). Experiences in implementing risk based inspection. Presented at the third (MENDT) Middle East Nondestructive Testing Conference & Exhibition, Manama, Bahrain.
[2] Apeland, S. & Scarf, P.A. (2003). A fully subjective approach to modelling inspection maintenance. *European Journal of Operational Research*, 148, 410-425.
[3] API (2002). RP 580 – Risk Based Inspection. 1st ed. American Petroleum Institute.
[4] API (2008). RP 581 – Risk Based Inspection Technology. 2nd ed. Am. Petroleum Institute.
[5] Aven, T. & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *J. Risk Research*, 12, 1-11.
[6] Aven, T. (2007). A unified framework for risk and vulnerability analysis and management covering both safety and security. *Reliability Engineering and System Safety*, 92, 745-754
[7] Aven, T, (2008). A semi-quantitative approach to risk analysis, an alterative to QRAs. *Reliability Engineering and System Safety*, 93(6), 790-797

[8] Aven, T. (2008). *Risk Analysis: Assessing Uncertainties Beyond Expected Values and Probabilities*, Chichester, UK: John Wiley & Sons, Ltd.

[9] Aven, T, (2010). On how to define, understand and describe risk. *Reliability Engineering and System Safety*, [article in press], Elsevier Science Limited.

[10] Bertolini, M., Bevilacqua, M., Ciarapica, F.E. & Giacchetta, G. (2009). Development of risk-based inspection and maintenance procedures for an oil refinery. *J. of Loss Prevention in the Process Industries*, 22, 244-253.

[11] Bjørnoy, O.H., Marley, M.J. & Jephson, N. (2001). Risk-based inspection principles and their application to corroded pipelines. *Pipes & Pipelines International*, 46 (5), 19-29.

[12] Braggato, P.A., Pittiglio, P. & Ansaldi, S. (2008). The management of mechanical integrity inspections at small-sized "Seveso" facilities. *Reliability Engineering and System Safety*, 94, 412-417

[13] Castanier, B. & Rausand, M. (2006). Maintenance optimization for subsea pipelines. *International J. of Pressure Vessels and Piping*, 83, 236-243.

[14] Chang, M.K., Chang, R.R., Shu, C.M. & Lin, K.N. (2005). Application of risk based inspection in refinery & process piping. *J. of Loss Prevention in the Process Industries*, 18, 397-402.

[15] Chien, C.H., Chen, C.H. & Chao, Y.J. (2009). A strategy for the risk-based inspection of pressure safety valves. *Reliability Engineering and System Safety*, 94, 810-818.

[16] DNV (2009). DNV-RP-G101: Risk Based Inspection of Offshore Topsides Static Mechanical Equipment. Det Norske Veritas.

[17] Flage, R & Aven, T (2009). Expressing and communicating uncertainty in relation to quantitative risk analysis. *Reliability & Risk Analysis: Theory & Application*, 2 (13), 9-18.

[18] Geary, W. (2002). Risk based inspection: A case study evaluation of onshore process plant, <www.hse.gov.uk/research/hsl_pdf/2002/hsl02-20.pdfs>

[19] Hagemeijer, P.M. & Kerkveld, G. (1998). A methodology for risk-based inspection of pressurized systems. *Journal of Process Mechanical Engineering*, 212 (1), 37-47.

[20] Herzog, B.O. & Jackson, P. (2009). The ladder to success: Risk-based inspection reduces costs, *ABB Review* [the corporate technical journal of the ABB group], 1, 30-33.

[21] ISO (2006). 14224: Petroleum, petrochemical and natural gas industries - Collection and exchange of reliability and maintenance data for equipment. 2nd edition. International Organization for Standardization (ISO).

[22] Jovanovic, A. (2003). Risk-based inspection and maintenance in power and process plants in Europe. *Nuclear Engineering and Design*, 226, 165-182.

[23] Kallen, M.J. & van Noortwijk, J.M. (2005). Optimal maintenance decisions under imperfect inspection. *Reliability Engineering and System Safety*, 90, 177-185.

[24] Kallen, M.J. (2002). *Risk based inspection in the process and refining industry*. Thesis for the Master of Science degree at the Technical University of Delft, Delft, The Netherlands.

[25] Khan, F.I. & Haddara, M.M. (2003). Risk-based maintenance (RBM): a quantitative approach for maintenance/ inspection scheduling and planning. *Journal of Loss Prevention in the Process Industries*, 16, 561-573.

[26] Khan, F.I., Haddara, M.M. & Bhattacharya, S.K. (2006). Risk-based integrity and inspection modeling (RBIIM) of process components/ system. *Risk Analysis*, 26 (1), 203-221.

[27] Khan, F.I., Sadiq, R. & Haddara, M.M. (2004). Risk-based inspection and Maintenance (RBIM) multi-attribute decision-making with aggregative risk analysis. *Process Safety and Environmental Protection*, 82 (B6), 398-411.

[28] Landet, E., Lotsberg, I. & Sigurdsson, G. (2000). Risk-based inspection of an FPSO. OTC paper 12146, presented at the 2000 Offshore Technology Conference, Houston, Texas, USA.

[29] Nilsson, F. (2003). Risk based approach to plant life management. *Nuclear Engineering and Design*, 221, 293-300

[30] NORSOK (2001). Z-008: Criticality analysis for maintenance purposes. Rev. 2. Norwegian Technology Centre.

[31] Patel, R.J. (2005). Risk based inspection. Presented at the third MENDT Middle East Nondestructive Testing Conference & Exhibition, Manama, Bahrain.

[32] Poulassichidis, T. (2009). Application of risk based inspection to offshore facilities. SPE paper 124539, presented at the 2009 Annual Technical Conference and Exhibition, New Orleans, Lousiana, USA.

[33] Santosh, G.V., Shrivastava, O.P., Saraf, R.K., Ghosh, A.K. & Kushwaha, H.S. (2006). Reliability analysis of pipelines carrying H2S for risk based inspection of heavy water plants. *Reliability Engineering and System Safety*, 91. 163-170.

[34] Simpson, J. (2007). The application of risk based inspection to pressure vessels and

aboveground storage tanks in petroleum fuel refineries. Presented at the fifth Australasian Congress on Applied Mechanics (ACAM 2007), Brisbane, Australia.

[35] Singh, M. & Markeset, T. (2009). A methodology for risk-based inspection planning of oil and gas pipes based on fuzzy logic framework. *Engineering Failure Analysis*, 16, 2098-2113.

[36] Taleb, N.T. (2007). *Black Swan: The Impact of the Highly Improbable*. 1st. ed. New York: Random House.

[37] Tien, S.W., Hwang, W.T. & Tsai, C.H. (2007). Study of a risk-based piping inspection guideline system. *ISA Transactions*, 46, 119-126.

[38] Truchon, M., Rouhan, A. & Goyet, J. (2007). Risk based inspection approach for topside structural components, OTC paper 18912, presented at the 2007 Offshore Technology Conference, Houston, Texas, USA.

[39] Wintle, J.B., Kenzie, B.W., Amphlett, G.J. & Smalley, S. (2001). Best practice for risk based inspection as part of plant integrity management. HSE book; in www.hse.gov.uk