Risk Based Inspection Methodology and Software Applied to Atmospheric Storage Tanks

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Abstract. A new risk-based inspection (RBI) methodology and software is presented in this paper. The objective of this work is to allow management of the inspections of atmospheric storage tanks in the most efficient way, while, at the same time, accident risks are minimized. The software has been built on the new risk framework architecture, a generic platform facilitating efficient and integrated development of software applications using risk models. The framework includes a library of risk models and the user interface is automatically produced on the basis of editable schemas. This risk-framework-based RBI tool has been applied in the context of RBI for above-ground atmospheric storage tanks (AST) but it has been designed with the objective of being generic enough to allow extension to the process plants in general. This RBI methodology is an evolution of an approach and mathematical models developed for Det Norske Veritas (DNV) and the American Petroleum Institute (API). The methodology assesses damage mechanism potential, degradation rates, probability of failure (PoF), consequence of failure (CoF) in terms of environmental damage and financial loss, risk and inspection intervals and techniques. The scope includes assessment of the tank floor for soil-side external corrosion and product-side internal corrosion and the tank shell courses for atmospheric corrosion and internal thinning. It also includes preliminary assessment for brittle fracture and cracking. The data are structured according to an asset hierarchy including Plant, Production Unit, Process Unit, Tag, Part and Inspection levels and the data are inherited / defaulted seamlessly from a higher hierarchy level to a lower level. The user interface includes synchronized hierarchy tree browsing, dynamic editor and grid-view editing and active reports with drill-in capability.

1. Introduction

Aboveground Storage tanks (ASTs) are significant and common equipment items in the oil, chemical and transportation industry. Figure 1 shows two common types of tanks, one with a fixed roof and another one with a floating roof. ASTs are often used to store very large amounts of inventory, most of the time flammable liquids and sometimes toxic liquids. Their content might be kept under atmospheric temperature and pressure but it can sometimes be refrigerated. The hazards from ASTs can be serious given the large amounts of liquid. On the other hand ASTs can cause serious environmental problems, when the liquid leak reaches surface waters or underground waters. Another

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difficulty with floor leaks is that they can go undetected for a long time and can cause serious contamination of the soil or sub-surface water. Rapid floor failure or catastrophic shell failure are rare events but they do occur and they have very serious consequences. Clean-up of the ground, the groundwater and the surface water are very costly operations and tank owners would obviously like to avoid.

API 653 [13] is standard code for inspection, repair, alteration and reconstruction of ASTs. It should be noted that internal examination of the tank, especially of the floor, is difficult and costly. So it is important for operators to identify the tanks that do not require frequent internal inspection and repair and avoid the wastage of maintenance and inspection resources, while, at the same time, they can use their resources where it matters: when the risk is high and the inspections are useful. This led the tank operators to look for a risk based inspection (RBI) methodology, applicable to aboveground storage tanks. EEMUA 159 [16] is a well-known guidance (particularly in Europe) for inspection, maintenance and repair of ASTs and it fully endorses RBI techniques.

![Fixed Self Supporting Dome Roof Storage Tank](image1)

**Figure 1**: Above ground storage tanks of fixed roof and floating roof respectively.

It is worth summarizing the reasons which motivated the development of the AST RBI methodology:

- Environmental concerns have increased. There are a large number of tanks with leaking floors and the fear exists of the rare but serious event of tank catastrophic rupture. Costs for environmental clean-up and penalties are increasing.
- Internal inspection of the tanks is costly and difficult. Access to floors is difficult and shell inspection requires complex scaffolding and preparation.
- Backlog of tank inspections. Many tanks are overdue for inspection.
- Inconsistency in regulatory requirements. Inspection intervals vary from country to country and they are even different among the various US states (inspection intervals varying from 8 to 20 years).
- Prioritisation of tanks inspections has been largely subjective before the adoption of RBI.

1.1. Risk Based Inspection

The risk based inspection (RBI) approach had already been well established and widely used in the Oil & Gas, Refining, Petrochemical and Chemical Industries. The essential elements of a “quality” Risk Based Inspection analysis have been documented by the American Petroleum Institute (API) in API RP 580 (2009)[1]. API RP 581 (2008) [2] describes a specific RBI methodology with full details: data tables, algorithms, equations, models. The implementation of the RBI methodologies has been facilitated by commercial software tools such as ORBIT Onshore (Topalis, 2007) [3], ORBIT Offshore (Topalis et al, 2011) [4], API RBI (Panzarella et al, 2009) [5], RISKWISE (Ablitt and Speck,
The RBI benefits are well known (API RP 580, 2009) [1] and they can be summarized as follows:

- Risk ranking and prioritization of inspection and maintenance activities
- Optimise spending on maintenance and inspection
- RBI may significantly alter the inspection strategies to become more “efficient”
- RBI may provide substantial cost savings
- RBI may contribute to reducing operational risks or understanding of the current risks
- Improved communication between operations, inspection and maintenance
- RBI study provides database for easy future inspection scheduling, updating and risk control
- RBI improves the mechanical integrity system and provides means to measure the effectiveness of inspection

But it should be said that any RBI methodology relies on the quality of the input data, the assumptions made and so on. Wintle et al (2001) [7] have produced a guideline and best practice for risk based inspection as a part of the plant integrity management.

Orbit AST is DNV’s module for Risk Based Inspection of aboveground storage tanks (ASTs). The origin of the methodology is the AST Risk Assessment Manual RAM (API, 2002) [8] initially created for the AST committee of API and later encouraged by the RBI committee of API. The initial scope was mainly tank floor thinning. The methodology was later extended to include a quantitative method for shell thinning, as well as susceptibility analysis (supplement analysis) for shell brittle fracture and cracking.

Figure 2 shows how risk is calculated for an equipment item in a quantitative RBI analysis, such as the approach in Orbit AST. This is the product of the probability of failure (PoF) and the consequence of failure (CoF). CoF can be expressed in terms of the environmental/safety consequence effects and the economic effects. On the other hand, PoF is the product of the Generic Failure Frequency, statistical frequency of failure for a given type of tank, based on API members’ survey (API, 1994) [9] and other sources, and the damage factor DF.

![Figure 2: Calculation of Risk for an equipment item.](image-url)
Figure 3: Ever-greening: How RBI proposes automatically inspection dates/ effectiveness.

Figure 3 illustrates the process of determining the next inspection date and the inspection effectiveness. A maximum acceptable risk level is set by the user. A future evaluation date is selected by the user (it is typically the date of the 2nd turnaround) and the risk is calculated as a function of time. If the risk at the future evaluation date exceeds the maximum acceptable level, an inspection is suggested. The intersection of the risk curve and the maximum acceptable line sets the next inspection date. The inspection may need to be included in the next turnaround, if it cannot be done on-stream. The inspection effectiveness is selected so that, after inspection, the risk does not exceed the maximum acceptable level at the future evaluation date.

The reader is also referred to the API codes for ASTs (API 650) [10] and inspection codes (API 651, API 652, API 653, API 12D and API RP 575 [11]-[15].

1.2. AST RBI Scenarios, PoF and CoF Models and Inspection Planning

Table 1 shows the scenarios currently implemented in Orbit AST. This includes:
- One floor leak scenario and one floor catastrophic floor rupture (floor to shell region)
- 3 shell leak scenarios and one shell catastrophic rupture

A fixed roof failure scenario is under development and has not been included in the current release.

Figure 4 shows the six modelled scenarios in order of increasing severity:
1. Release inside the dike
2. Release inside the plant fence but outside the dike
3. Release offsite
4. Sub-surface soil contamination
5. Groundwater contamination
6. Surface water contamination
Table 1: Liquid release scenarios analysed in the AST RBI methodology.

| Release Failure Scenarios | Comment |
|---------------------------|---------|
| **Small bottom leak.**    | One hole size is considered: small leak (0.125” diameter hole). |
| Leak may persist for an extended period, depending on local leak monitoring. | This is the main Floor failure scenario that is addressed in the RBI methodology, and is focused on bottom corrosion. The Probability can be influenced by inspection. |

| **Rapid bottom failure.** | One scenario, catastrophic failure |
| Instantaneous release of tank contents from failure at the critical zone (Floor-to-Shell region). | Addressed in the RBI methodology through the corrosion model and compliance with recognized design and inspection / maintenance codes. The Probability is only to a limited degree influenced by inspection. |

| **Small Shell leak.** | Three hole size scenarios: 0.125”, 0.5” and 2” diameter hole. |
| Leak detected visually or by monitoring. | This is the main Shell failure scenario that is addressed in the RBI methodology, and is focused on Shell corrosion. The Probability can be influenced by inspection. |

| **Rapid Shell failure.** | One scenario, catastrophic failure. |
| Instantaneous release of tank contents from brittle fracture or large rupture of the tank Shell. | Addressed in the RBI methodology by screening, and is not influenced by inspection for corrosion. |

AST Consequence Analysis
Overview of scenarios

Figure 4: Environmental and economic scenarios.
Figure 5: Overview of the floor and shell RBI methodology.

Figure 5 shows the overall methodology for calculating corrosion rates, PoF, CoF, Risk and Inspection planning:

- Corrosion rates are estimated first, on the product side, soil side and external corrosion
- Damage factor and PoF are then calculated
- CoF is then calculated depending on the scenarios and this is followed by risk calculation
- The inspection planning is decided based on the planning targets for DF, Risk or PoF

The RBI methodology calculates the total cost CoF as the sum of the environmental clean-up cost and penalties and the other economic cost:

\[ \text{CoF Total Cost} = \text{Environmental Clean-up} + \text{Environmental Penalties} + \text{Lost Business} + \text{Repairs} \]
1.3. Process of Re-Architecturing

DNV’s RBI software packages Orbit AST as well as Orbit Onshore and Orbit Offshore have been widely used around the world since the their first release 10 years ago. However any computer software benefits from re-architecturing, especially after several years of development. Therefore a decision has been taken for a complete re-write of all the RBI software. This started with the offshore/upstream module of the RBI software, which we call Orbit 3 Offshore and the process now continues with Orbit AST. This development brings a number of benefits:

- Opportunity for merging/ integration of the offshore/upstream, onshore/downstream and AST functionalities
- Re-architecturing allows a much more modern and powerful user interface
- The new Risk Framework architecture allows easy maintenance/ addition of new features
- Update to the latest recommended practices.
- Has the possibility to easily interface with external applications e.g. Enterprise Resource Planning (ERP) applications or Computerized Maintenance Management Systems (CMMS)

This paper presents some of the features of the new Orbit AST software. Generally, theory and models from the previous version have been re-used and tested and it is not the authors’ intention to document or justify these models in this paper.

2. New Software Architecture

2.1. Risk Framework Architecture

The RBI application Orbit is one of DNV’s standalone risk applications as it can be seen in Figure 6. Risk applications such as Phast, Neptune and Orbit use similar types of models such as discharge, dispersion, effects, PoF and risk calculation models. Same general design principles apply to all tools but have been implemented independently for historical reasons and typically the risk applications use separate architectures from different implementation technologies:

- Different 3rd party tools
- Different code languages
- There is duplication of effort in development and support
- Investment in common components cannot be shared e.g. risk model updates
- All of the tool environments look and feel different

![Figure 6: Old standalone risk application architecture.](image)

Figure 7 shows the new risk model architecture. Orbit 3 Offshore was the first application in the new architecture. Orbit AST 1.0 is actually the 3rd application in this architecture. The risk framework development has a number of benefits:
One tool that meets all market needs
- Benefits of updates and upgrades are controlled and shared between applications
- Development is more flexible and efficient
- Enhancements and solutions are easier to build
- One common core tool is supported so learning is faster and support is less dependent on tool specific knowledge
- Tools can communicate with each other and user applications
- Quality of tools improves as the framework is the model development environment

Figure 7: New Integrated Risk Model Architecture.

Figure 8: Orbit AST 1.0 Overview.
2.2. **Orbit AST 1.0 Overview**

Figure 8 shows an overview of the Orbit AST user interface, which is typical of a risk framework application interface. This shows the following elements:

- Modern Microsoft-style ribbon at the top with the home tab selected by default.
- Asset tree explorer normally located on the left hand side
- Grid view, normally on the right-hand side
- Output/messages area at the bottom

Navigation/selection are via the assets explorer tree. Any object at any level in the tree can be selected and opened through double-click or the right-click menu on the tree or through the grid.

![Figure 9: Dynamic dialogue for brittle fracture screening.](figure]

![Figure 10: Orbit AST Asset Hierarchy.](figure)
Figure 9 shows the dynamic dialogue resulting from selecting the brittle fracture screening calculation. The Orbit AST asset tree explorer, shown on the left hand side of Figure 8 is used for navigating the main asset hierarchy as well as any additional hierarchies. The main asset hierarchy is shown in Figure 10.

2.3. Dynamic Dialogue
A dynamic dialogue is one method to edit input data or display results for a given object such as installation, system, tag or part. There are 2 types of dynamic dialogues:

1. Dynamic dialogue for object (process unit, tag etc.) general data. This dialogue is normally started by double-clicking on the object or selecting “Properties” in the right-click menu of the object.
2. Specific calculation dynamic dialogue. This is selected from the right-click menu of the object. It shows input and output fields for a given calculation e.g. Brittle fracture dynamic dialogue. Figure 9 shows an example of dynamic dialogue for the brittle fracture screening calculation.

Colour coding is used to mark the status of the object fields:
- **Green** if a default value is inherited from higher in the hierarchy. E.g. if the joint efficiency inherits a default value from a higher level, then it is marked green
- **Red** if a mandatory value has not been set.
- **Black** if the field has been set with a value that has not been defaulted from a higher level.

2.4. Grid
The grid facility is one of the most powerful features of Orbit AST. A grid is a tabular view of the attributes of several objects at the same time. There are numerous grids in Orbit either for editing object general data (production unit general data, tank general data, shell and floor general data) or for specific calculations (shell thinning calculation, tank consequence calculation etc). The grid also facilitates batch import of data from MS Excel, which is a very efficient data entry method. An example of “Tank” grid is shown on the right hand side of ORBIT AST in Figure 8.

Another interesting feature is the hierarchical grid option; displaying data from several object types. An example of hierarchical grid could be the Tank-Shell-Floor Grid, where the Tank grid rows can be expanded to show the underlying Shell & Floor data.

3. Results
Orbit AST produces risk results for a set of tanks (floor & shell risk matrices, executive summaries) but it also produces a detailed risk profile and inspection plan for each tank (equipment summary sheet). This can answer the question what, when and how to inspect (what technique/ effectiveness & coverage). This is shown in Figure 11. The gridviews can also be used to produce custom reports with selected output fields.

If one or more risk targets are set, the inspection time will be determined by the intersection between the risk curve (function of time) and the “target” line. Figure 12 shows a real case study where the RBI suggested date is later than the old regulation inspection date and the date determined by API 653. But this is not always the case and RBI can sometimes suggest an earlier date depending on the tank risk.
Figure 11: Executive Summary and Equipment summary sheet.

Figure 12: Real case with RBI suggested date against the old regulation inspection date and the date determined by API 653.
4. Conclusion
This paper reviews a RBI methodology applied to aboveground storage tanks and implemented into a new generation RBI software. The generic risk framework architecture is a strength of Orbit AST as it will allow easy development and support over the lifecycle of the product. This is also a good base for the further extension of the module to the more general process plant RBI software. Orbit AST has a modern and user-friendly interface with features such as the asset hierarchy tree, the tabular grid view and dynamic dialogues and automatic defaulting mechanism. It is expected that the new methodology can help to address the issues currently affecting ASTs such as leaks, difficulty in conducting internal tank inspections and inconsistent regulations or subjective methods to set inspection intervals.

Nomenclature
API American Petroleum Institute
AST Aboveground Storage Tank
CMMS Computerized Maintenance Management Systems
CR Corrosion Rate
CoF Consequence of failure
DF Damage Factor
DNV Det Norse Veritas
GUI Graphical User Interface
ERP Enterprise Resource Planning
GFF Generic Failure Frequency
FRP Fibre-reinforced plastic
PLL Potential Loss of Life
PoF Probability of Failure
RAM Risk Assessment Manual
RBI Risk Based Inspection
RPB Release Prevention Barrier

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