Modern Inspection Methodologies for RBI Programs of Atmospheric Storage Tanks

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Abstract
The floor is the most vulnerable to damage part of an atmospheric storage tank. At the same time, it is the most difficult part to inspect. In fact, on-line quantitative inspection and evaluation is not possible for most tanks. On the other hand, removal of such tanks from service is a major hassle for the facility due to the downtime itself and the costs involved in emptying the product, cleaning, and assessing repairs, if any. In this respect, RBI inspection plans provide tank owners the necessary data, as to when will be the right time to remove each tank from service as well as to prioritize maintenance. Acoustic Emission – TankPac™ technology allows qualitative assessment of the floor condition while the tank is in-service and provides valuable input to an RBI program concerning the floor probability of failure due to corrosion. Valves attached on the tank are also evaluated for leakages, as part of the inspection. Once the tank is opened, quantitative damage assessment for maintenance actions is achieved by other advanced NDT technologies such as Magnetic Flux Leakage (MFL) mapping, Automated Ultrasonic corrosion mapping (LSI), and other methods, in accordance with pertinent codes and standards. The present paper discusses the above-mentioned technologies as part of an integrated tank inspection scheme.

Keywords: Atmospheric Storage Tank, floor, RBI, inspection, Acoustic Emission, MFL, Ultrasonic Testing

1. Introduction

In modern times, plant managers/owners, often utilize the option to manage the integrity of their assets based on the estimation of risks of failure, rather than to follow the more traditional time based inspection. The term “Risk Based Inspection (RBI)” is used by the American Petroleum Institute [1] to denote Risk Assessment focusing on Mechanical Integrity of assets in the Petrochemical and Petroleum Industries. RBI focuses risk assessment on maintaining integrity by minimizing the risk of structural/mechanical damage of static equipment such as:

- Pressure Vessels
- Process Piping including safety valves and other piping components
- Atmospheric Storage Tanks
- Pressurized Storage Tanks
- Boilers, Heaters and Furnaces
- Heat Exchangers
- Pump and compressors (mainly casing and mechanical integrity – not functional)

RBI is the use of risk assessment to plan, justify and aid the interpretation of results from inspection, testing and monitoring. Its purpose is to deliver fully developed inspection and monitoring plans that are consistent with the business objectives and regulatory requirements of the end-user.

More specifically, the RBI Inspection Plan must use the risk assessment to determine:

- What to Inspect (Scope)
- When to Inspect (Interval)
- How to Inspect (Method)
- Extend of Inspection (Method coverage)
In addition to the definition of Inspection Plan, Risk Management achieved through implementation of Inspection and Maintenance Planning, results in the following benefits:

- Increase Safety, Availability, Reliability
- Reduce number and duration of plant shutdowns
- Reduce scope of routine activities
- Reduce rate and impact of unexpected failures
- Resources prioritized for greatest effect
- Reduce costs

Specifically for atmospheric tanks, the first step is to define the components that determine the corrosive behaviour; the process chemistry, operating temperature and pressure and of course the condition of the construction material. For various RBI schemes the monitoring of the corrosion process is essential for the calculation of inspection intervals. In this respect, various inspection methods exist, either on-line or off-line that are utilised in order to extract measurements for all parameter needed.

Focus will be given primarily to TankPAC™, as a low cost, reliable and rapid tank floor inspection method and, subsequently, to other follow up inspection methods, as a part of an integrated RBI scheme. TankPAC™ is a modern NDT monitoring procedure of atmospheric storage tank floors, based on Acoustic Emission (AE). A deeper analysis of the TankPAC™ procedure will be given, stating the short and long term benefits that can be resulted, along will complementary statistics in order to provide qualitative results from its usage so far. Within this framework, some follow up inspection methods will be discussed along with their benefits and contributions to various RBI schemes.

2. **TankPAC™ Monitoring Procedure**

TANKPAC™ [2] is a condition monitoring method based on a grading system which provides classification of the tank floors ranging from those that re-inspection is advised after a long time span to those that required immediate actions. TANKPAC™ system is proved to be an essential maintenance planning tool with an intrinsically beneficial character with respect to cost-reduction and resource allocation.

The advantages of TANKPAC technology have been recognized worldwide and are used by the biggest companies of petroleum products and petrochemicals such as Saudi Aramco and Shell [3], [4], [5].

The method is based on the evaluation of Acoustic Emission (AE) activity that is generated from the energy release during the fracture or spalling of corrosion products as the corrosion reaction progresses due to the incipient volume expansion. This results mainly in a fluid-borne wave-like disturbance propagating within the surrounding product and/or metal. The screening of the specific process requires highly sensitive piezoelectric sensors to be mounted to the tank wall as the tank is monitored and subsequently assessed. Due to the increased sensitivity, smooth test conditions and excellent noise recognition are essential.

When the test is performed, acoustic emission sensors are mounted on the tank’s wall around the tank circumference. After the sensitivity verification of the sensors the tank is monitored for 1-2 hours for its AE activity. The AE activity increases with the amount and the rate of corrosion and, based on this, an empirical link is made to the overall condition of the floor. Following data collection and removal of extraneous noise sources, several levels of analysis are carried out:

- All activity from the tank recorded above the system threshold, is graded A-E (least to most) according to developed experience of TANKPAC™ technology.
- Using time of arrival location methods of AE sources hitting three sensors, activity is located and shown on the tank floor plot.
Further analysis is performed to identify PLD (“POTENTIAL LEAK DATA”) which are data found (by experience) to be more characteristic of severe localised corrosion. The PLD data are separately graded as 1 to 5 depending on their AE characteristics and are plotted on PLD location tank plots.

Combining the “Overall Data Grade” and the “PLD Grade”, a “Composite Grade” from I to IV is provided together with a recommendation for inspection planning or re-test (0 to 5 years). Where the tank is considered to be leaking, this must be stated [1].

Advantages of the method include:
- Inspection performed while the tank is in-service.
- Access required only to tank wall
- 100% Tank floor monitoring including the annular ring
- Preliminary results immediately after the test
- The reduction of environmental pollution, due to timely diagnosis of potential leaks.
- The significant reduction in maintenance costs (no money is wasted for opening good tanks).
- The maintenance is prioritized, having the most severely damaged tanks scheduled first.
- It is an ideal tool for application of risk based inspection programs.
- It is a very quick, low-cost inspection with minimal disruptions of operations and tank usage.

Limitations of the method include:
- Does not give quantitative information about the remaining thickness of the tank floor
- The uncertainty of AE source location depends on several parameters, thus the information must be used with care. Accuracy of source location might degrade on large tanks in bad condition
- Small leaks may be located and do not have significant effect on the test result. However small leaks can be masked by a highly active corroding floor.
- Large leaks may be located but may mask other AE activity of the tank floor. In such case, grading might not be possible
- The method is not suitable for assessing active corrosion if the internal condition of the tank changes periodically either by means of product change or mechanical/chemical cleaning of the tank as this resets the internal condition of the tank floor. In this case, underside corrosion detection may still be possible
- Corrosion which does not result in scale formation such as MIC (biological induced) may not be detected.

2.1. TankPAC™ Grading System

Examples and a detail history of the method can be found in [4]. In addition, statistics of the validity and reliability results can be found in [5], [13]. This analysis is an independent analysis of the method from a user group chaired by Peter van De Loo where the test results of the method were compared with follow-up internal inspection results and repairs carried out. Furthermore, the method was also introduced in Japanese industries in 1999 and since them a large AE testing database has also been developed in order to meet the Japanese regulations for tank maintenance [6]. A comparative study, between TANKPAC inspection results with internal inspection results can also be found in [7]. In addition, experimental studies, both in laboratory and in field have been performed that show comparison and estimations of location quality [8] as well as corrosion detection [9] and the ability of AE to discriminate between the onset of corrosion and further stages.
of degradation. The method is continuously refined over the years incorporating the experience that is obtained from the increasing amount of tanks tested (more than 10,000 worldwide) and follow up results shared by various industries which are using the method as the preferred tool for tank maintenance schemes.

The internal condition of the tanks, as revealed by the TankPac technology, is encapsulated in an RBI – like table that separates the classification of the tank floor condition and gives recommendations about the inspection interval or immediate action. Using this grading system, the maintenance and resources are allocated to where they’re most needed. Description of the grading system can be found in the aforementioned sources. In addition, since the grading matrix is directly correlated with the corrosive process (either top side or bottom side of the tank floor), it can be incorporated in various RBI and plant maintenance software such as Mistras Group PCMS (Plant Condition & Management Software) in order to efficiently manage the relevant inspection spans for the specific type of asset [10].

The table below shows the full TANKPAC grading system in a risk matrix format, along with recommendations of future inspection intervals or planning for internal inspection.

### Table 1 – The TANKPAC™ Grading System

<table>
<thead>
<tr>
<th>“PLD GRADE”</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>III</td>
<td>III</td>
<td>IV</td>
<td>IV</td>
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<td>II</td>
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<td>None or</td>
<td>I</td>
<td>II</td>
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<table>
<thead>
<tr>
<th>“OVERALL GRADE”</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<tbody>
<tr>
<td></td>
<td>n/a: Should not occur if standard threshold used</td>
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</table>

1 - No active damage, re-test in 4/5 years.
2 - Minor active damage, re-test in 2 years.
3 - Active damage re-test in max.1 year*.
4 - Very active damage. Re-test in 0.5 year*.
5 - or schedule for internal inspection

2.2. TankPAC™ Usage Statistics of the Mistras Group Hellas Database

Since 1997, a large population of tanks were inspected by Mistras Group Hellas using TANKPAC™ technology. In this section, overall statistics about the usage as well as the grading of the tanks and hence their re-testing interval recommendation will be presented. The pie chart in the Figure 1 bellow shows the percentage of tested tanks as well as their internal products.

**TANKPAC Tests - Light & Heavy Products**

- LIGHT PRODUCTS 38%
- HEAVY PRODUCTS 62%

**TANKPAC Tests per Product**

- Crude Oil 21%
- Gasoline 13%
- Diesel 9%
- Gas Oil 9%
- Fuel Oil 9%
- Naphtha 7%
- Kerosene 4%
- Slops 3%
- Other 25%

Figure 1 – Distribution of products found in above ground storage tanks tested with TANKPAC

The following figure shows the composite grade of all tested tanks, which is mainly used for any prioritization of upcoming inspection or maintenance. Composite grading results show that 80% of all tank floors were graded as “I” or “II”. This corresponds to a suggestion for extension of tank’s usage and postponing of maintenance for at least another 2 years (for “II” graded tanks) or 4/5 years (for “I” graded tank floors), when re-test should occur. One may also observe, based on the figure and the classification given in Table 1, that from all the tanks that were tested, an overall 20% (“III” & “IV”) needs short-term or immediate actions and prioritization.
The similarity of the grading system with common RBI matrices makes it simple to incorporate to any existing RBI schemes and, along with the additional parameters that are included in the calculation of the inspection interval, it assists the owner to decide about resource allocation and planning. Overall, internal inspection time interval is usually defined by the relevant construction codes. To this end, TANKPAC™ testing can be used reliably, as part of a maintenance planning scheme in order to maximize the efficiency of maintenance resources allocation and greatly minimize the economic burden that might accumulate from the blind maintenance prioritization of storage tanks. In other words, if we are to assume that, at any given time, about 20% or so of the assets will be in the worst condition (results shown in Figure 2), then TANKPAC replies to the question: which 20%?

3. Tank Shell and Roof Inspection with Ultrasonic Methods

Additional information about the state of corrosion and the thickness of various components of above ground storage tank such as the shell or the roof or the annular ring of the tank can be obtained using various ultrasonic inspection methods while the tank is still in service. These include, automated, semi automated and manual corrosion mapping on the shell and roof using robotic crawlers.

3.1. Annular ring Corrosion Assessment with Long Range UT (TALRUT™)

The method uses a long-range ultrasonic technique to evaluate corrosion damage to the annular ring/floor extension and tank floor up to 0.5 meter from the tank wall (Figure 3). This method is qualitative, and gives indications and their plan position; it does not provide quantitative
information. Indications are compared with a test plate / calibration block in order to evaluate their severity. The standard test plate has 50% through slots at 100mm, 200mm, and 400mm from the probe, and indications are normalized and graded relative to this (i.e. above/below that amplitude level, and 25-50% of that).

3.2. Large Structure Inspection (LSI) on tank shell and/or roof

Automated Ultrasonic systems can sample the surface at very small intervals using crawlers with magnetic wheels. The UT thickness probe(s) is usually mounted on the crawler and the motion can be controlled from a remote station. They can scan the entire surface of the tank (excluding areas under shell attachment/obstacles) and produce a very detailed thickness map, with a resolution as low as 0.1mm. The result can be hundreds of thousands of thickness measurements providing a detailed mapping of the structure’s thickness.

![Figure 4](a) 3D presentation of Tank Shell with UT measurement (b) Thickness Monitoring Location in Tank Shell (Green Points) (c) Complete Corrosion Mapping

The benefits of this accurate presentation of UT measurements with all structure details allow to easily locate problematic areas (e.g. using distances from plate edges or other components such as nozzles). The approach of using structural information combined with UT measurements makes it easy to incorporate the measurements in RBI calculators to monitor corrosion rates of the structure as well as compliance with regulations.

4. Internal Inspection Follow Up Methods

In the following sections various offline inspection methods are described. These methods are well established in the industry and can provide detailed information about the tank’s current structural status.

4.1. Magnetic Flux Leakage (MFL) tank floor inspection

Magnetic Flux Leakage (MFL) survey is often used to evaluate the condition of carbon steel floor plates of above ground storage tanks. Using floor scanners it is relatively fast and easy to identify (corrosion) loss and guide follow-up ultrasonic and visual tests. The Magnetic Flux Leakage (MFL) and the Low Frequency Electromagnetic Technique (LFET) make use of small changes in (electro)magnetic flux. MFL technique uses a permanent magnet to fully saturate the steel floor plate with magnetic flux. LFET as the name states uses an electromagnet for this. The latter is more lightweight and easy to mobilize, but more sensitive (erroneous noise) for plate surface conditions. Thickness limits of the floor plates are 5 to 20mm; enhanced accuracy is obtained when the thickness is within the range 6-12 mm. Both techniques can be used on relatively rough surfaces and coating layer thickness can be up to 4 to 5mm. Coating must be tightly adherent, if not; this should be removed. The magnetic flux techniques are sensitive to small changes in magnetic flux,
tank floors must therefore be free from water, dirt, corrosion scale and product. The quality of the inspection increases when the floor is fully clean, grit blasted and a higher POD is reached. Dirty floor plates result in false calls which must be confirmed by UT/VT. Pinholes give sharp and distinct indications on the scan equipment. General corrosion is less distinctive due to limited distortion of the field lines; very general, smooth corrosion might not be detected. For determining local remaining plate thickness and/or pit depth and discrimination between corrosion and non-relevant indications like plate laminations and inclusions, follow up inspection is required using UT and/or VT. With the use of MFE / LFET floor scanner, focus is on detection of localized soil side (tank floor under side) corrosion. For detection and quantification of wall loss due to product side corrosion, Visual Testing (VT) is the appropriate technique to be used. Prior to actual scanning of the tank floor, the decision must be made, what scanning method to be used; a. Scanning in “manual” or “stop-on-defect mode”, in which case indications will not be recorded/stored electronically or b. Scanning in “floor mapping” mode, in which case MFL indications (amplitude based MFE signal and X-Y position per scan strake/run) picked up during a scan strake will be stored in the on-board computer.

Traditionally, the floor inspection is carried out with threshold-based stop-on-defect mode. The inspection includes:

- Identification of defects above an operator-adjustable threshold
- Local follow-up for better quantification of the corrosion with manual Ultrasonic testing (automated is also an option)
- Report including areas with maximum degree of corrosion and areas of interest

Using threshold-based stop-on-defect equipment, no indications will be recorded if they fall below the detection threshold. For instance, if threshold is set to 50% metal loss, then no indications will be recorded and reported for 40% or 45% loss. As a result, using stop-on-defect mode one will not be able to project corrosion conditions for the future based on corrosion rate.

![Figure 5 – (a) Corrosion Mapping (b) Max Discontinuity Per Scanned Track](image-url)
4.2. Large Structure Inspection (LSI) on floor plates

The method provides a thickness map of the scanned tank bottom, investigating the results / effect of corrosion on the metallic surfaces. In addition, the existence of possible laminar flaws / defects (parallel to the metal’s surface) can be indicated along with other forms of deterioration (e.g. pitting). The thickness measurements are displayed in the form of a C-Scan representation with appropriate color scaling, with each color representing a certain thickness (also user-defined with accept/reject levels if necessary in Figure 6). The scanning speed depends on the required measurement resolution and the structure geometry (obstructions etc.). Upon completion of the measurements the results can also be displayed in B-Scan (thickness profile for selected sections in Figure 7 and Figure 8) and/or 3D results display. The resolution of the results depends on the density of measurements (scanning step). The minimum thickness that can be measured with standard set-up is 2.5mm. The method is not intended to detect holes or ensure the structure shielding and cannot replace tightness testing.

![Figure 6 – Automated UT colored thickness mapping on a tank floor (Composite C-Scan)](image)

![Figure 7 – Automated UT data analysis on an annular plate showing A, B and C Scans](image)
5. Incorporation to RBI schemes

Having in hand all the above information from the tank, integration requires good management of the corresponding data in accordance with the relevant codes as well as with any RBI schemes. No matter how the software calculator is laid, measurement and inspection interval estimation can be incorporated in order to result in efficient inspection plans.

Most of the aforementioned methods have an intrinsic RBI character, each own, by taking into account the individual failure mechanisms of tank components. The risk management aims to calculate risk due to different failure mechanisms, evaluate risk as acceptable or not acceptable (or as Low-Medium-High) and schedule proper actions for risk reduction.

Having all the aforementioned information, for detailed RBI, the Mistras Group software PCMS [15] (Plant Condition & Management Software) is offered either as a standalone software package or as a service. PCMS captures all operating and design information as it relates to facility tankage. The software is designed to oversee the RBI process per tank circuit, taking into account various parameters, such as, operating information, current corrosion rates and historical inspections. In addition, API 653 Visual Inspections recorded within the software. These software gives various inspection plans with an overall better scheduling flexibility which can be RBI-based, or corrosion-based or can be set to a fixed based interval.

In order to do so, the software defines tank damage mechanisms per mode and automatically screens which damage mechanisms the tank is susceptible to. This results in the calculation of both base and current Probability of Failure (Figure 9).
All user defined Tank circuits are plotted in the RBI Matrix. The plotting takes into consideration the POF and the COF (Probability and Consequence of Failure) whereas the Consequence values are configured per facility. Finally the RBI Matrix is customizable (Figure 10).

For the RBI scheduling, for tank circuits, the software (PCMS) will notify inspector/user what damage mechanisms to inspect for, by the generation of an inspection plan per intrusive/extrusive inspection types, and effective techniques to use to detect potential damage mechanisms. This feature is customizable to the user’s needs. In addition, the user has option to schedule by fixed/corrosion/RBI based intervals (Figure 11).

Especially for API 653 reporting, the user can build customizable inspection templates for field inspection (Figure 12) with the following features:

- All reports stored in PCMS
- Record indications found (customizable)
• RBI schedule plans automatically appended to API 653 checklist
• Record techniques used in the field

Finally the software performs specific calculations for the tanks such as:

• Max Allowable Liquid Level
• Hydrostatic Test Height
• API 653 Thickness Minimum
• Corrosion Allowance Thickness Minimum
• Settlement Calculations (future feature)

6. Conclusions

The service removal of storage tanks for maintenance is an overall major hassle for the facility due to the downtime itself and the costs involved in emptying the product, cleaning, and assessing repairs, if any. In this respect, end users need to take educated decisions as to when is the right time to remove each tank from service without wasting resources human or monetary in emptying tanks in good condition or risking leaving bad tanks in service, as well as to prioritize maintenance. In this respect the information that need to be gathered involves the application of many NDT methods. The most commonly used inspection planning schemes is to use fixed planning interval recommended by most inspection codes. However RBI appears to have an increasing trend in the industry. The combination of the modern NDT techniques as well as the available RBI software schemes provide efficient tools for the inspection planning management and results in the improvement of the overall working efficiency of the industrial plants and units.
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