Acoustic Emission Tank Floor Testing: A Study on the Data-Base of Tests and Follow-Up Inspections

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Abstract. For more than 2 decades now, TANKPAC™ technology has been proven to be a reliable tool to assess tank floor condition without opening or emptying the tank. It is based on the detection of Acoustic Emission (AE) resulting from corrosion of the floor using sensitive sensors mounted on the outside of the tank. Prior to each test, all attached valves are also evaluated for leakages. The technology offers a full evaluation of the tank floor's condition and a recommendation for the re-test interval, making it a cost-effective tool for tank maintenance planning and prioritization.

Major part of the technology is the database containing tanks' structural and historical data, TANKPAC™ test details, test results, and their correlation with internal follow-up inspection information, where available. The database is used to evaluate the acquired AE data, following its separation from the environmental noise by using a range of signal analysis and advanced processing techniques. Database itself is regularly reviewed and results are used to constantly improve the technology through a dynamic fine-tuning, as experience builds up (now accounting to well more than 10,000 tests worldwide).

The present paper reports a review of available bibliography and correlation / evaluation past studies as well as the latest developments in the TANKPAC™ technology, such as new, advanced proprietary software tools which now allow automation of the analysis steps, and enhance results presentation clarity and overall quality. Moreover, Mistras Group Hellas' TANKPAC™ data base of hundreds of tests conducted during the past fifteen years in the Mediterranean / Middle Eastern region is presented, with general statistics referring to type of product of tested tanks. Finally some qualitative validation cases of TANKPAC™ test results with internal inspection results (UT / MFL) are presented.

Introduction

TANKPAC™ is a condition monitoring method based on a grading system which provides classification of the tank floors ranging from those that can be statistically retested after a prolonged 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 from this an empirical link is made to the overall condition of the floor.

Data analysis is performed in two main stages:

- The interpretation stage where the non-relevant data such as environmental, mechanical and electrical noise signals are filtered and discarded.
- The evaluation stage where the resulting/remaining first stage information is graded based on a variety of parameters (e.g. AE activity and its characteristics, various structure metrics). Moreover spatial information about the aforementioned process is extracted by using state-of-the-art trilateration algorithms which may provide indicative areas associated with severe corrosion.

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.

Analysis Tools

Analysis is performed using NOESIS Advanced Acoustic Emission Data Analysis Pattern recognition and Neural Network software [2]. The software is designed to be used in both field or research applications which numerous capabilities, range from advance combination of filters, analysis options, automations to automatic report generation.

The software is made to be intuitive towards the user since all experienced TANKPAC™ analysts are bound to follow specific procedural steps in order to extract active corrosion information. Since the whole procedure is embedded within, the analysis is no longer prone to most small human errors, thus strict conformation to the procedural steps is ensured and consistency and quality are maintained to the highest degree.

The intuitive character of the software towards the user provided great focus on the analysis as minor details such as many various normalisations or other calculations often taken care of automatically resulting in the quickest possible information extraction. Since the user/analyst is free from spending a large amount of time making all the calculations that are usually required for the interpretation stage all the effort can be focused in the combination and fine-tuning of filtering parameters. Very often and were it appears to be a great ambiguity regarding the interpretation data, many alternative filtering combinations or schemes are applied with minimal user actions, thus alternative results or multiple analysis scenarios are available within minutes. Moreover, a complete log of all actions is kept within the software for a Level III review, maintaining this way the highest possible quality and consistency of results. Finally, the software offers complete automated report that can be based on customer templates and export of all test information that can be easily archived in a database for future reference and comparisons. In Figure 1 an example of tank scheduled for inspection is shown.

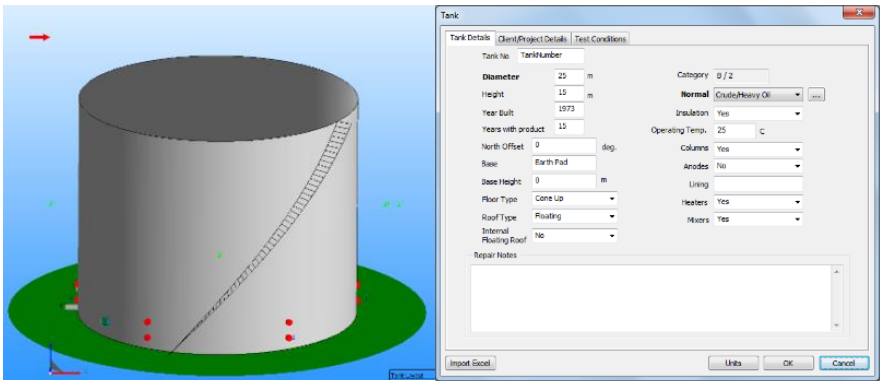

Figure 1 – 3d View of a tank scheduled for inspection. Data overlay using other sources (UT etc.) is also possible.

In Figure 2, the result of the 3d location of unfiltered data is shown. This is a complementary feature, mainly used in fixed roof tanks were some non-relevant data can be acquired due to the condensation inside the tank. Using the information from both mounted sensor rows, AE events that are not generated from the tank floor can be distinguished and discarded from the data set.

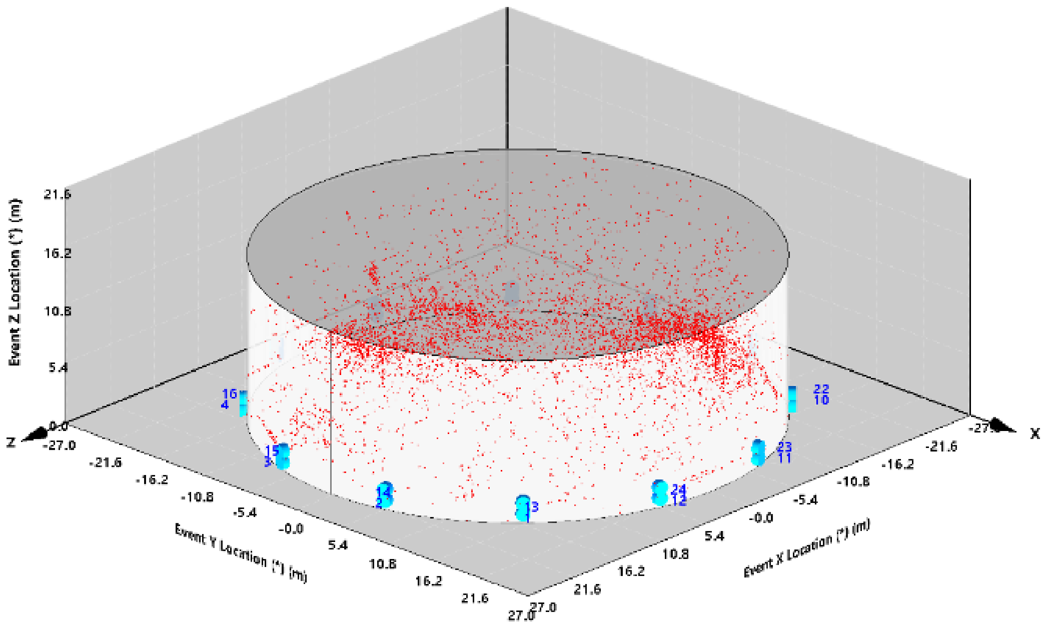

Figure 2 – Three dimensional location of unfiltered AE events using data from two rows for interpretation/filtering

In Figure 3 bellow are some examples of various default (basic) as well as advanced combination of parameter selection which is availiable at any stage of the analysis.

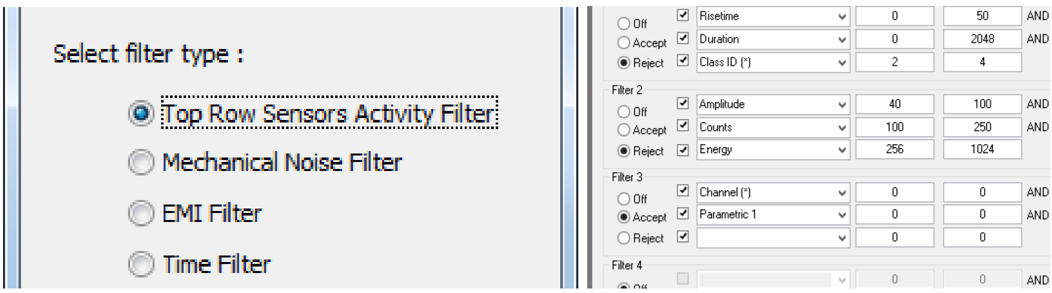

Figure 3 – Examples of default and advance filtering selection

A large selection of pattern recognition modules are included in the software for the advanced classification interpretation and filtering of data, using various unsupervised and supervised methods or neural networks.

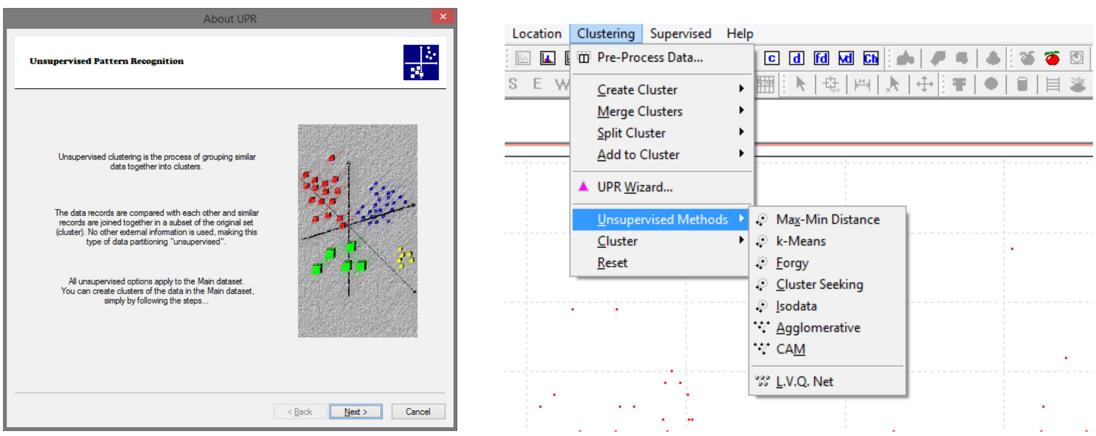

Figure 4 – Examples of unsupervised pattern recognition modules for advance classification interpretation and filtering of data

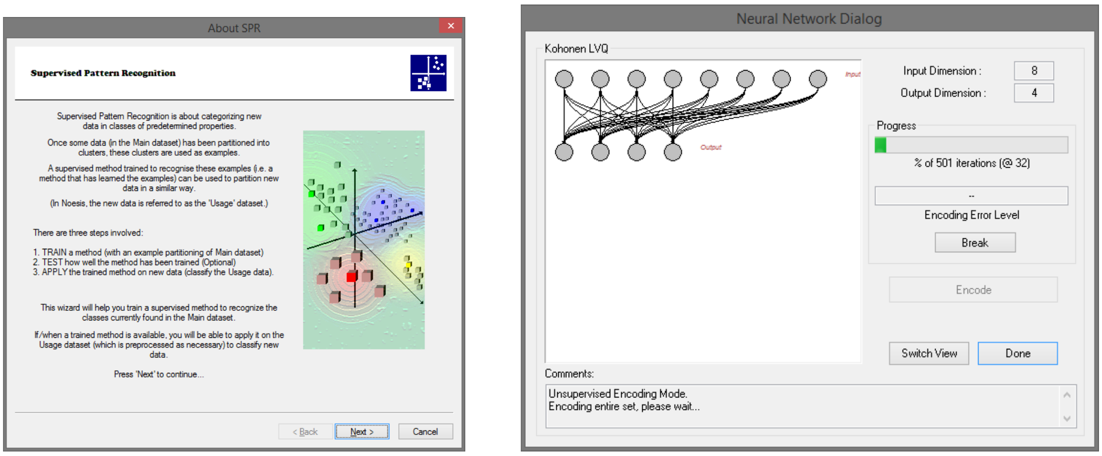

Figure 5 – Examples of supervised pattern recognition modules for advance classification interpretation and filtering of data

A two dimesional location of corrossion sources along with color grading is shown in the figure bellow. The colors are linked with the severity of located corrossion clusters of the tank floor.

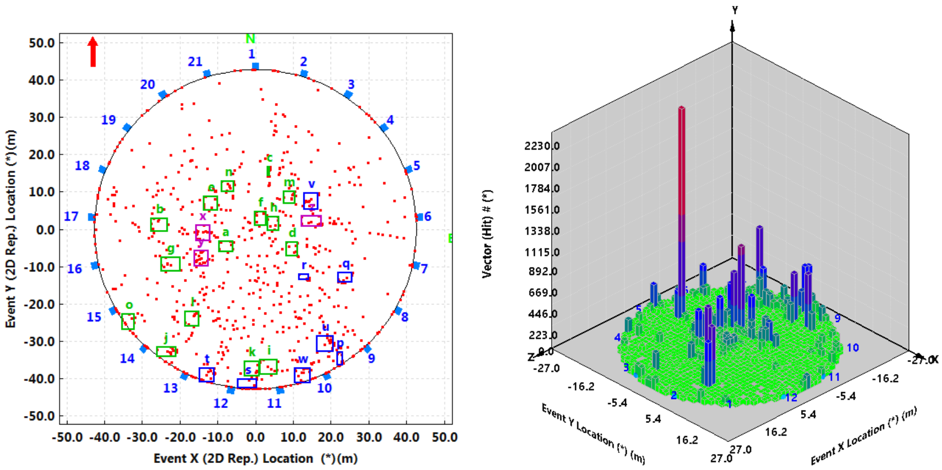

Figure 6 – Example 2d location on a tank floor. Left 2d scatter plot with clustering associated with severity. Right 2d Histogram showing spatial AE activity distribution

All the aforementioned software tools are made to address the most common problem during a TANKPAC™ test. The data contamination with external noise. To this end, excellent noise recognition and control is essential. Three main categories of noise sources are common during testing:

The first category includes the environmental sources due to weather conditions including but not limited to wind gusts, rain or temperature gradients that cause condensation droplets to be formed and impact upon the product's free surface. The second category includes all mechanical sources that can be present during testing, such as operation of neighbouring equipment (e.g. operation of mixers, pipes in contact with the tank, active pumps etc.). The third category, easier to control and isolate compared with the previous two categories, includes all those signals that can be produced and subsequently acquired due to electrical, electronic or RF interference.

The effect of non-relevant noise sources that fall in the first category is the least controlled by the operator while testing and in some cases can be so extreme that may prohibit or inhibit the testing procedure. However, post processing software tool can minimise their impact on the data evaluation as long as the temporal location of sources is well documented.

The second and third categories can be controlled efficiently by the operator/analyst before and while testing, as well as in the post processing stage by using the aforementioned specialised software tools for advance data processing.

Past Studies & Tank Grading

AE as a method can be tailored to monitor various processes. Especially for the assessment of the internal condition of tank floor a two-fold question is greatly emphasised and needs to be addressed. How the tanks can be prioritised for maintenance and in order to save the overwhelming amount of resulting annual costs [3] and environmental issues from the handling of toxic waste.

Since the development of the method and its initial application in the late 80's, several studies have be conducted in order to verify the methods validity and the reliability of results. The method started as a leak detection method in 80s, however, it was soon evident that it could be expanded greatly in order to be used to prevent leakages rather than just detecting them [11].

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],[12]. 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 been also developed in order to meet the Japanese regulations for tank maintenance [6]. A comparative study, between TANKPAC inspection results with internal inspection results can be also found in [7]. In addition, experimental studies, both in laboratory or in field have been performed that show comparison and estimations of location quality [8] as well as corrosion detection [9] and discrimination 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 increasingly amount of tanks tested (more than 10,000 wordwide) 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, resulted from the large population of conducted tests, is encapsulated in an RBI – like table that separates the classification of the tank floor condition and gives recommendations about the inspection interval. Using this grading system, the maintenance and resources are allocated to where they're most needed. The analysis of the grading system can be found in the aforementioned sources. The table below shows the TANKPAC grading in a risk matrix format.

"PLD GRADE"	5	III	III	IV	IV	IV	**I - No active damage, re-test in 4/5 years.**
	4	II	III	III	IV	IV	**II - Minor active damage, re-test in 2 years.**
	3	II	II	III	III	III	**III - Active damage re-test in max.1 year*.**
	2	I	I	II	II	n/a	**IV - Very active damage. Re-test in 0.5 year*.**
None or	1	I	I	II	n/a	n/a	***or schedule for internal inspection**
"OVERALL GRADE"	----	A	B	C	D	E	***n/a: Should not occur if standard threshold used***

Table 1 – The TANKPAC™ Grading System

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].

Statistics of Mistras Group Hellas Database

Since 1997, a large population of tanks were tested by Mistras Group Hellas using TANKPAC™ technology. In this section, various statistics about the usage as well as the grading of the tank will be presented and discussed. The pie chart in the Figure 7 bellow shows a representative percentage of the products that are handled. The classification of the tanks based on the product that is stored, will be given considering whether the product is "light" (processed / final product) or "heavy" (crude, "thick" products etc.).

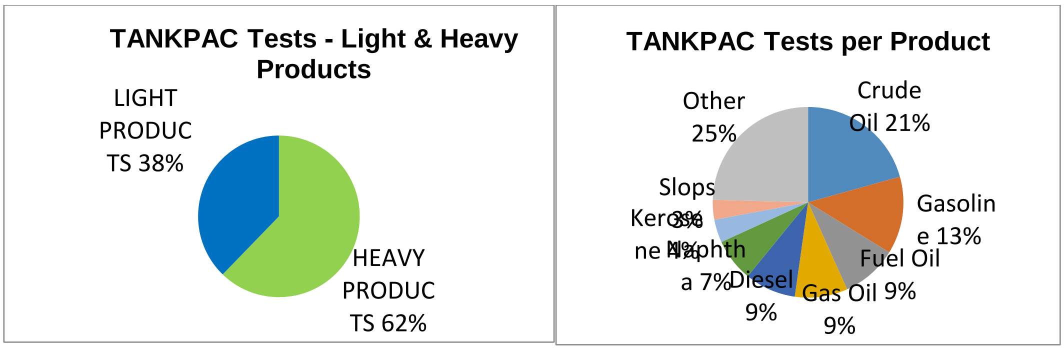

Figure 7 – Distribution of products found in above ground storage tanks tested with TANKPAC

The figure bellow shows the distribution of five grades of the tank floor condition of heavy product tanks based on the tanks AE activity. More than 70% of the tested tanks were found to have minor to intermediate AE activities ("A", "B", "C" categories) usually indicating the onset and/or the development of active corrosion either localized or general. This is found to be typical in most heavy product tank since corrosive environment can be developed due to the water or high sulphur content that can be present together with the product inside.

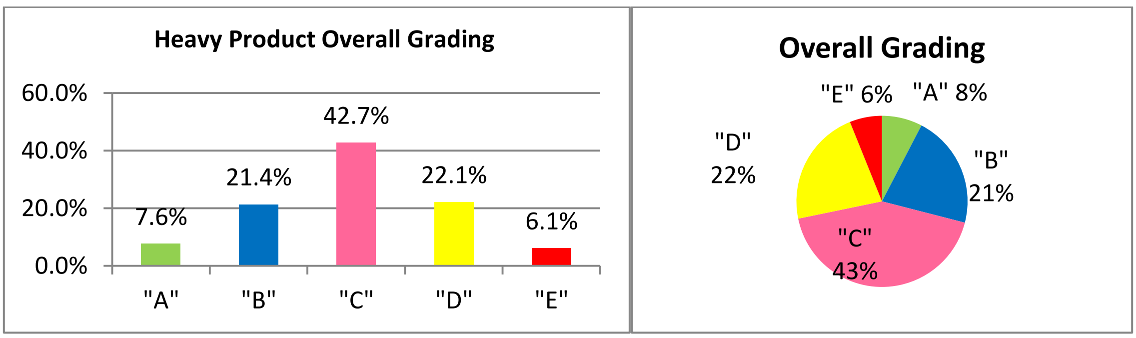

Figure 8 – Overall Grading of above ground storage tanks containing heavy products

In the following figure the distribution of PLD grading results are shown from the tested heavy product tanks. The PLD grading is associated with localised clusters of located AE events associated with severe active corrosion. From the figure it is easily seen that nearly in nearly 60% (“1”, “2”) have very sparse or none, localised clusters. The 26% of the cases requires further investigation on the locations found, while in the rest 20% (“4”, “5”) percent of the cases strong localised AE activity appears which needs to be taken under special considerations, while post processing the data, in order to exanimate thoroughly the activity and to provide meaningful, useful and reliable results.

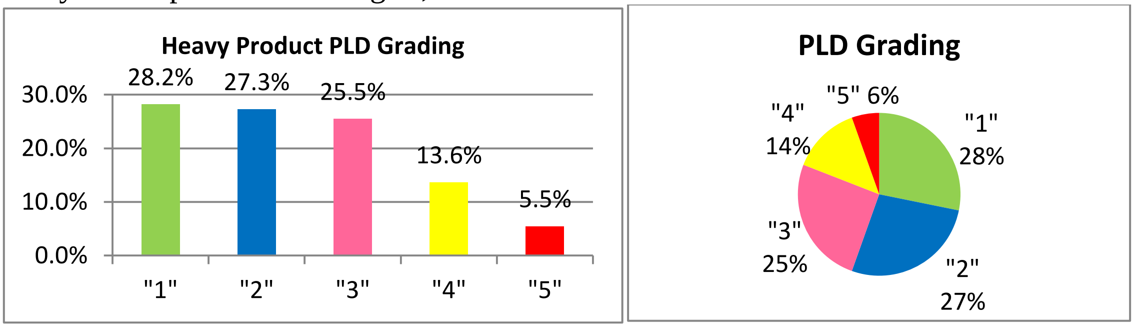

Figure 9 – PLD Grading of above ground storage tanks containing heavy products

The Figure 10 presents the distribution of the composite grades that was presented in Table 1, which were resulted from the TANKPAC analysis in heavy product tanks. From this distribution one can deduce with confidence that at least 60% (“I”, “II”) of the tested tanks could be retested in later time in order to estimate again the differences in their internal condition, while a large percentage of nearly 25% (“III”) should be retested within a smaller time interval or be prioritised for maintenance. A small percentage of 14% (only category “IV”) of heavy product tanks, as expected, appear to be in the worst category and therefore immediate actions, from inspection prioritisation to full maintenance, should be taken.

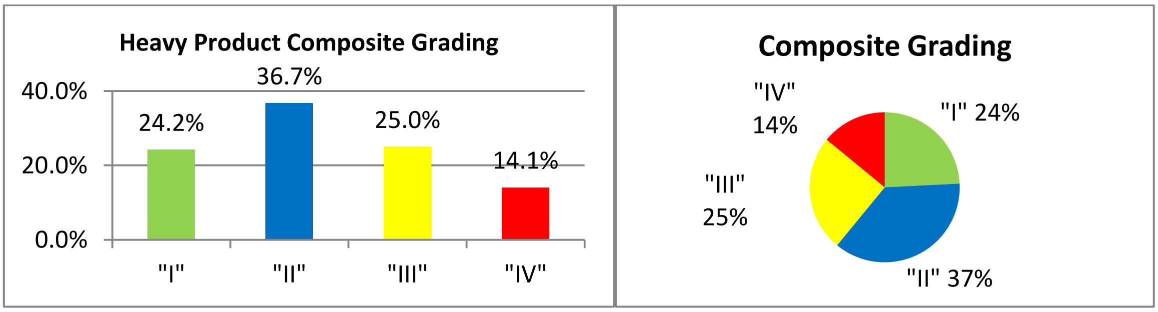

Figure 10 – Composite Grading of above ground storage tanks containing heavy products

The tested storage tanks that containing light products, appear to have minor to intermediate classification, based on their activity. This is reflected in the following figure as nearly 90% of the tested tanks appear to have minor to intermediate AE. One of the main reasons behind this, could be that generally speaking, lighter products as cleaner and more homogeneous, whose chemical composition and pureness is kept within strict offsets.

Therefore, it is less possible, for other corrosive agents or contaminates to be present inside the storage in such quantities that would create a corrosive environment, such as water. Of course, failure of lining as well as many other causes are factors contributing to active corrosion, but, in general, minor to intermediate AE is usually observed.

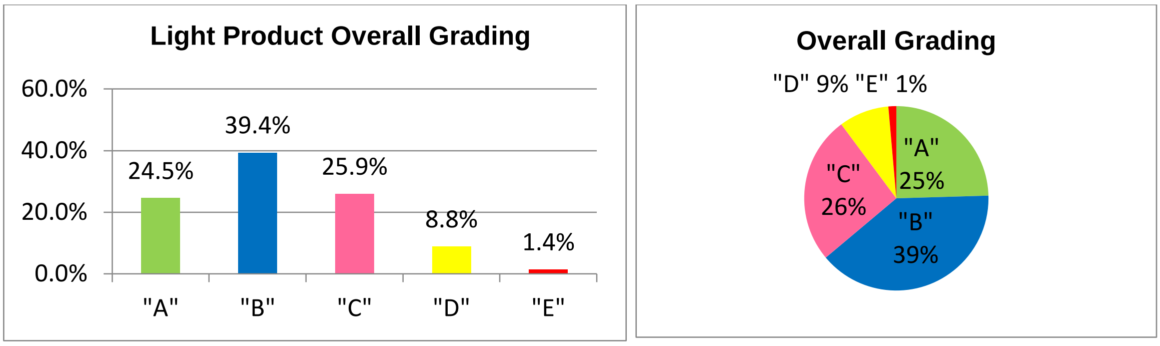

Figure 11 – Overall Grading of above ground storage tanks containing light products

The PLD grading for light products does not appear to show any significant trends apart from the fact that minor localisations can appear. This is shown in the Figure 12 were 82% ("1", "2") of the tanks appear to have none to sparse local clustering of AE. In addition the other almost 16% ("III") again as in the previous cases of heavy products requires further investigation of the located clusters. However there is a small by significant presentage of almost 10% with strong localised AE activity. The same reasoning of the aforementioned controlled environment and quality of the product can be also applied here in order to give an explanation of the resulting statistics.

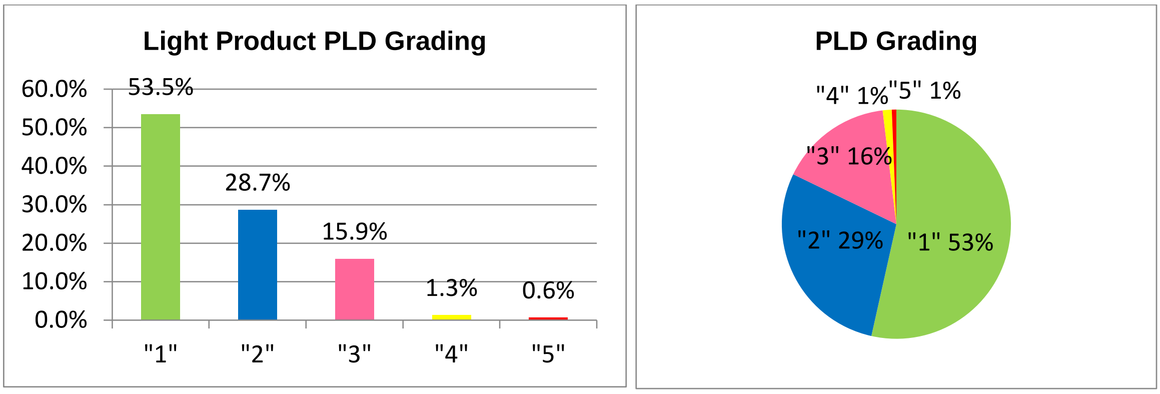

Figure 12 – PLD Grading of above ground storage tanks containing light products

Finally, based on the composite grade distribution in Figure 13, most of the tested light product tanks (around 90% categories "I" & "II") appear to be in a good condition so that they can be retested within a prolonged time span in order to re-assess their condition. However, a small but significant percentage of 10% requires immediate prioritisation for inspection and/or maintenance.

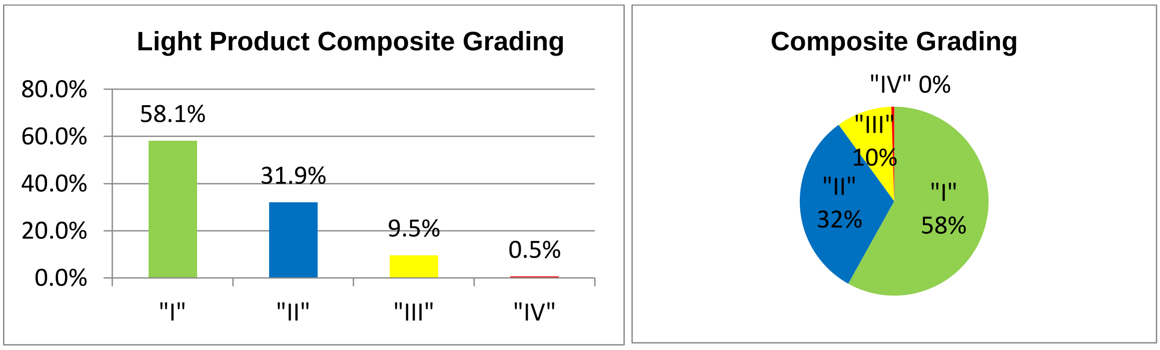

Figure 13 – Composite Grading of above ground storage tanks containing light products

From the statistics of the two representative cases discussed above, the difference between the estimated condition of light product storage tanks and heavy product storage tanks is apparent. In addition, one can extrapolate and generalise that there is a big difference in storage environment of light and heavy products and this is clearly incorporated in the method in order to have normalised and comparable results.

Figure 14 bellow shows the distribution of overall grades in all tested tanks in our database. From this, it is apparent that 87% (“A” to “C”)of the tested tanks independent of product appear to have minor to intermediate activity which is very good considering all inspection and maintenance that has took place over the years. However 17% (“D” & “E”) of the tanks appear to be highly active with respect to AE activity.

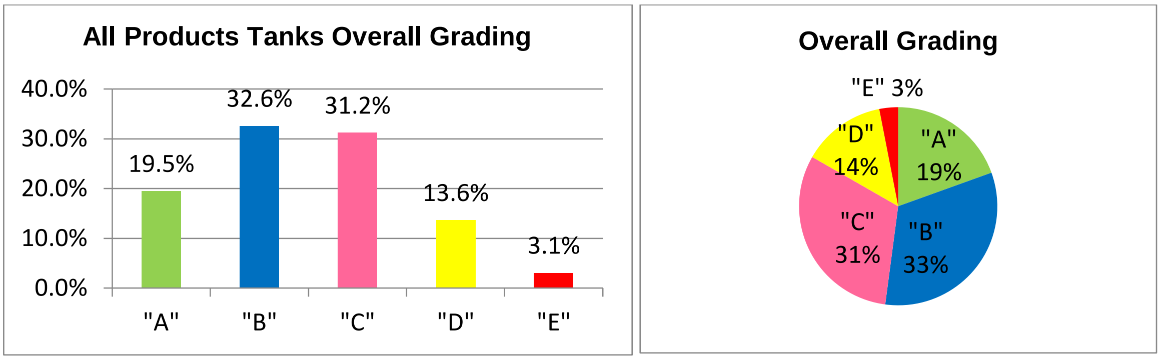

Figure 14 – Overall Grading for all above ground storage tanks tested

The PLD AE activity appears to be descending in a linear manner, however the highly active localised clusters (“4” & “5”) are mostly caused by additional reasons that are not so transparent and straight forward such as partial failure of lining, damaged areas not identified during internal inspection, constructions flaws and generally root causes that either way, are rare to happen but nevertheless exist.

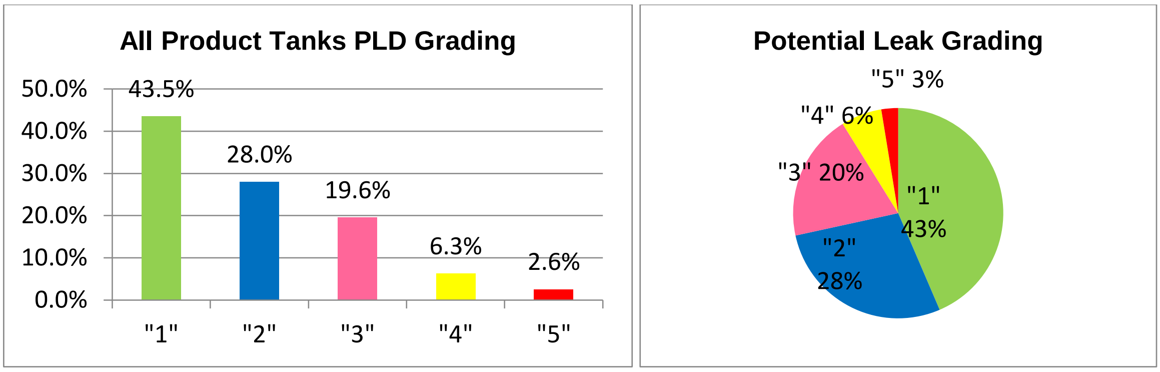

Figure 15 – PLD Grading for all above ground storage tanks tested

The following figure shows the composite grade of all tested tanks, which is of major importance due to the fact that this is mainly used for any prioritisation 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 delay in 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 immediate actions and prioritisation.

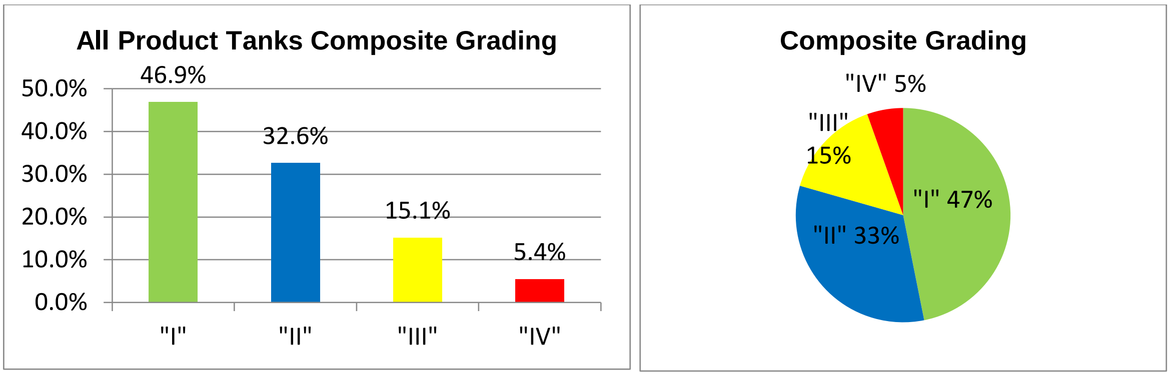

Figure 16 – Composite Grading for all above ground storage tanks tested

An example of the consistency of results as well as the time variations of the grading is given in the following table. table shows examples of test results of various tanks that were tested more than two times without intermediate internal inspection. This means that the internal condition of each tank was not effected or reset by any means of chemical or mechanical actions. As expected, grading has a slightly increasing trend with time, meaning that the tank floors conditions with have advancing corrosion state or it will be stabilised.

Other factors that are to be consider are the overall age of the tank, inspection intervals, its roof type and of course the settlement type of the tank, but these are outside of the scope of this paper.

Tank	Year	Dia.	Product	Roof Type	Year Build	Overall	PLD	Composite	Recommendation
1	2004	36.5	Fuel Oil	Fixed	1971	C	2	II	2 years
	2007					C	2	II	2 years
	2009					C	3	III	1 year
2	2004	56	Gasoline	Floating	1981	C	1	II	2 years
	2010					C	1	II	2 years
	2012					C	2	II	2 years
3	2007	56	Gasoline	Floating	1981	B	3	II	2 years
	2011					C	2	III	1 year
	2012					C	3	III	1 year
	2013					C	3	III	1 year
4	2004	14.7	Gas Oil	Fixed	1990	A	1	I	4-5 years
	2009					A	1	I	4-5 years
	2012					A	2	I	4-5 years
5	2006	53.7	Gasoline	Fixed	1972	C	3	III	1 year
	2008					D	3	III	1 year
	2009					D	3	III	1 year
6	2009	84.1	Crude Oil	Floating	1973	D	3	III	1 year
	2010					E	3	III	1 year
	2011					E	4	IV	0.5 years
7	2009	85.4	Crude Oil	Floating	1972	C	3	III	1 year
	2010					D	3	III	1 year
	2012					D	3	III	1 year

Table 2 – TANKPAC™ grading variation over time

Qualitative Validation of TANKPAC™ Results

TANKPAC™ technology package is continuously developed, based on inspectors' experience and the investigation of results of internal inspections performed at later stages, after each AE test. A common internal inspection method used is the scanning of the tank floor plates with Magnetic Flux Leakage (MFL). This method provides qualitative inspection and information about the percentage of thickness loss. Investigation of subsequent internal inspection results provides an opportunity to reconsider and re-analyze the acoustic emission data, aiming to improve the filtering procedures in light of the new results.

Unfortunately, the available internal inspections were performed many months or years after the AE test, therefore a direct qualitative comparison for both methods is not available due to the time difference of the two tests. Still, however, indirect comparison of results shows that TANKPAC™ method gives evidence of possible active damage in the early stages. The test cases that are presented below are major examples of significant costs that could have been saved if a proper inspection plan had been used based on the recommendation of the TANKPAC™ procedure. In both cases no actions were made from the tank owners according to the procedure and this resulted in the need for major repairs (i.e. additional accumulated costs) several years later.

1st CASE – HEAVY FUEL OIL 46m DIAMETER FIX ROOF TANK

The following case described the testing of the tank as inspected in 2009 using TANKPAC™. The tank has a diameter of 46m and is used to store heavy fuel oil. The TANKPAC testing lasted for a full day and based on a scale from "A" (minor activity) to "E" (highly active), tank was graded as "C", along with indications of very persistent localized AE activity. Based on the results, customer was advised to re-test the tank after two years (on 2011), but no action was made.

The specific tank was opened for maintenance and inspected internally with MFL five years after the AE test, on 2014. MFL scan was performed and holes were found on most of the areas where TANKPAC™ had revealed high AE activity five years ago. In addition, it appears that the corrosion areas increased within the five years' time between the two different inspections.

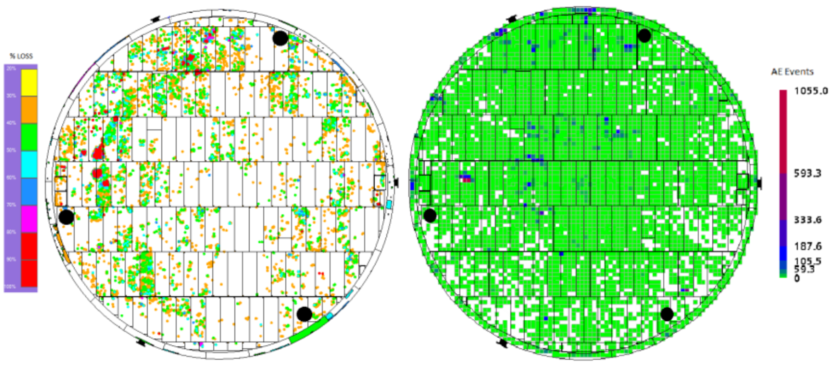

Figure 17 – MFL Inspection Results (left - Thickness Loss >30% on 2013) VS TANKPAC™ Results (right on 2008) five year before internal inspection

There are additional things to be considered when reviewing this specific case. MFL results are reported for more than 30% plate thickness loss while in TANKPAC separating this information is not possible. The MFL testing lasted for nearly 10 days and of course the resolution and detail is order of magnitude higher. However when reviewing TANKPAC results it appears that a general corrosion state already existed in the whole tank floor. In addition, apart from the generalized state of corrosion indicated by the "C" grade, the presence of localised areas with high AE activity, should have signified the importance to re-test in accordance with the recommendation (i.e. 2 years), however no actions were made. The result, was that the whole tank floor was replaced after the internal inspection. It is clear that earlier prioritisation might have resulted in significant maintenance cost reduction due to the fewer repairs that would have been needed and downtime of the tank.

2nd CASE – CRUDE OIL 85m DIAMETER FLOATING ROOF TANK

The specific tank was inspected with TANKPAC™ in 2009. This was a routine inspection that lasted for no more than 8 hours. The results showed a highly active tank with most of the AE activity to take place around the annular ring of the tank. The tank grade was given as D, with a re-test recommendation in maximum 1 year or to be scheduled for internal inspection. However, as in the previous case, no actions were taken. The tank was opened in 2012 for scheduled internal inspection and maintenance and an MFL survey was performed. The MFL testing lasted for nearly 3 weeks.

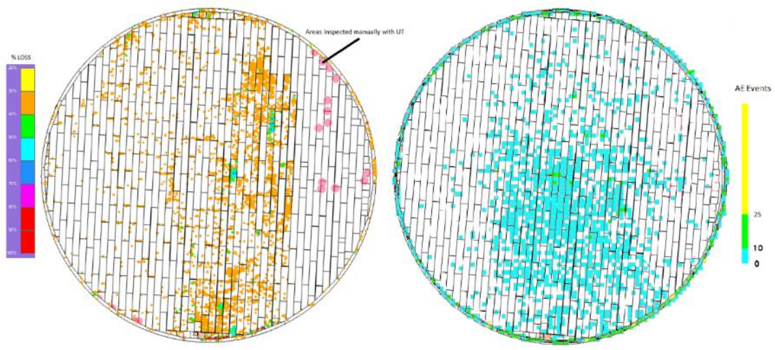

Figure 18 – MFL Inspection Results (left - Thickness Loss >30% on 2012) VS TANKPAC™ Results (right on 2009) three years before internal inspection. Note annular ring activity

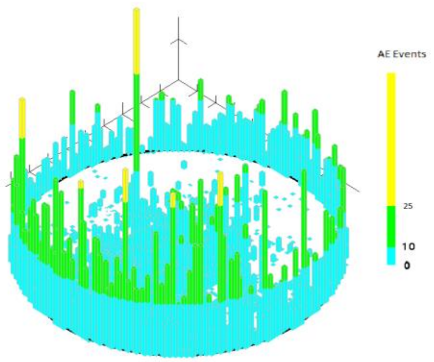

Figure 19 – TANKPAC™ Results of spatial distribution of located AE activity. Note annular ring activity

The TANKPAC™ inspection revealed that most of the AE activity was emitted from the annular ring area of the tank. However, the MFL equipment coverage was up to 100mm from the annular ring area. The area that could not be covered with MFL was inspected with ultrasound. In this case, it was found that the annular ring was suffering from a bottom side corrosion and high thickness losses. This is apparent in the left graph of Figure 18. It is also demonstrated in Figure 19 that shows a three dimensional view of the spatial distribution of located AE events.

In this case, the tank floor was found to have both top and bottom side general corrosion as it is shown in both MFL and TANKPAC™ results. However TANKPAC™ yielded evidence about the ongoing activity under the annular ring, as well. Overall, extensive repairs were performed in this tank. In addition, the cost of having it out of service, was the most important fact in this case, since this large capacity tank had remained out of service for nearly a year.

Conclusions

As the technology progresses the demand of cost effective and reliable NDT methods is increasing. As such, more and more effort is given to the development of new methods and ideas. TANKPAC™ is a relatively new method when compared with the classical NDT methods. However the benefits from its application are enormous.

- Non-intrusive. No service interrupts.
- Quick and reliable results within hours with low cost inspection and consistency
- If used as a part of a tank management maintenance program can result in enormous cost savings.
- RBI compatible

Comparison of TANKPAC™ AE testing results with follow-up off-line floor inspection clearly demonstrates the ability of the method to identify the overall state of floor corrosion and early stage damage, as well as to pin-point areas on the early stage of damage development, with reasonable accuracy considering that no access is available to the internal side of the tank. Overall, internal inspection time interval is usually defined by the relevant construction codes. To this end, TANKPAC™ testing can be used reliably, as a 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, in any given time, about 20% or so of the assets will be in the worst condition (see also the results shown in Figure 16), then TANKPAC replies to the question: which 20%?

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