FUSION OF NDT DATA FROM MODERN INSPECTION METHODS

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ABSTRACT

An increasing demand for cost-effective inspections and maintenance is driving the industry to modern solutions, which will provide the necessary inspection results for the assessment of the condition of static equipment in chemical plants and refineries with minimum disruption to operations and low cost. Results visualization is an important step towards successful interpretation of NDT data. This step is a prerequisite in order to proceed with efficient structural integrity assessment and fitness for service. In addition to that, visual combination of NDT data from different methods is becoming increasingly important as modern NDE techniques produce large amounts of results within short inspection time.

The need to merge, review and manipulate this data together has pushed towards software that is capable of working with data from various techniques. In this paper the necessity for advanced centralized data viewing and integration to asset management databases is discussed. In other words, the real issue of finding a way to integrate traditional NDT data gathered on daily basis with NDT data gathered from modern on-stream techniques, in a user friendly form that will permit data fusion and structure visualization, is discussed and software based solution is presented.

Within this framework, the paper demonstrates the way the NDT data are fused and how this process helps towards evaluation of equipment integrity. Application examples are presented including fusion of in service Acoustics Emission and automated UT testing for corrosion mapping as applied on spheres, pressure vessels and above ground storage tanks. Fusion of Acoustic Emission data with ones from ultrasonic scanning and/or TALRUT[tm] technique is discussed for the screening of the annular ring of Above Ground Storage tanks.

INTRODUCTION

Pressure vessels and atmospheric storage tanks are commonly found in petrochemical and industrial facilities. They represent a major capital investment and are crucial to the operation of the

facility and the economics of the owner. While in service, their structural integrity and operability must be regularly verified because any kind of failure is generally unacceptable from environmental, safety and economical point of view. On the other hand, removal of such components from service for maintenance 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, owners need the appropriate tools to obtain as much information as possible about the structural condition of the equipment, in order to take decisions about whether to remove or not the component from service without wasting money in setting out-of-service components in good condition or risking leaving bad components in-service, as well as to prioritize maintenance.

Evaluation of the structure condition, especially while in service, in an economic and reliable way requires the use of modern and specialized Non Destructive Testing (NDT) techniques. The time and access limitations and the significant cost for detailed assessment prohibit the use of traditional NDT on-line. For Above Ground Storage Tanks the most essential modern on-stream inspection methodologies, not requiring removal from service, are the Acoustic Emission (AE) for the floor (TANKPAC^{TM}), the long-range Ultrasonic (UT) for the annular ring (TALRUT^{TM}) and the use of Advanced Automated Ultrasonic Corrosion Mapping for tank wall and roof (LSI). For Pressure Vessels several techniques could be used such as Acoustic Emission (MONPAC^{TM}), Automated Ultrasonic Corrosion Mapping (LSI) for thickness measurements and specialized UT techniques for Welds (e.g. TOFD). Also in many practical cases combination of the above-mentioned techniques could be used.
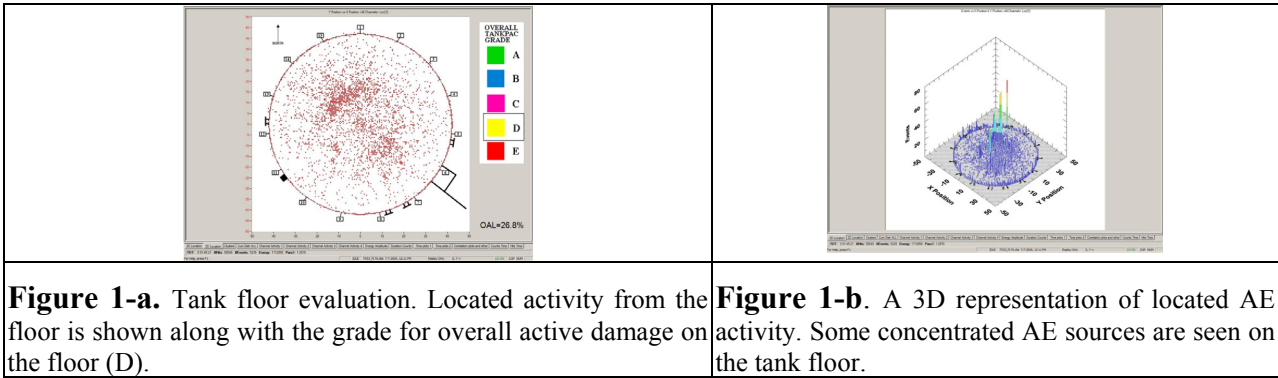
Having in hand all the above information from the different inspection methods, a new need is ensuing: to merge, review and manipulate all the above data. The key element to connect all the data together is the accurate structure visualization and software capable to visualize results from different techniques overlaid with the structure. Furthermore, a representation of the structure and NDT results is offering the opportunity for further examination of the structure health (structural integrity assessment and fitness for Service) by providing the necessary information for analysis using numerical methods such as Finite Elements (FEM). Also, a modern requirement is good management of the corresponding data in accordance with applicable codes as well as state-of-the-art RBI programs. This can now be performed using a combination of Structural Drawing Software, specially designed for the needs of incorporating inspection results, and Plant Condition Monitoring Software. Recommendations for the re-test interval or inspection are based on risk-based inspection (RBI) - like matrix, taking into account individual failure mechanisms of Structural components.

MODERN NDT TECHNIQUES
A. Above Ground Storage Tanks
A1. On-Line Tank Floor Condition Assessment using Acoustic Emission (TANKPAC^{TM})

Acoustic Emission [1], [2] is a global NDT examination technique that can inspect entire structures in one test. For TANKPAC[TM] the AE sensors are placed externally around the perimeter of the tank and detect the generation of corrosion and, potentially, waves generated by the turbulent flow at a leak point [3],[4]. To perform the test the tank remains with its normal product inside and must have been allowed to settle for a maximum of 24h. Data collection can last from one to three or more hours and data analysis is performed using specialized software and an experienced system, based on a data-base of a large number of tank floor tests. Based on the overall received AE activity, the general situation of the tank floor is classified into one of 5 grades, from A (good situation), up to E (bad situation), as depicted in Figure 1-a. Additionally, regions of localized sources with characteristics of severe corrosion are graded separately, from 1 to 5. Considering the above dual grading, a "Composite Grade" is provided and the time of the next inspection is proposed (from "immediate planning for maintenance / retest in 6 months" to "retest in 5 years").

Figure 1-a. Tank floor evaluation. Located activity from the floor is shown along with the grade for overall active damage on the floor (D).

Figure 1-b. A 3D representation of located AE activity. Some concentrated AE sources are seen on the tank floor.

A2. Tank Annular Ring Corrosion Evaluation using Long Range Ultrasonics (TALRUT[TM])

A critical part of any storage tank is the annular ring area; severe damage here over a long distance can lead to major structural failure with the consequential rapid loss of contents. For this area of tank the TALRUT[TM] technique was developed. The method uses a long-range ultrasonic technique to evaluate corrosion damage to the annular ring/floor extension and tank floor within 0.5 meter of the tank wall (Figure 2 – Left). This method is qualitative, and gives indications and their plan position; it does not provide quantitative information. A motorized crawler scanning device runs on the tank wall adjacent to the annular ring. Productivity of more than 40 meters per day has been achieved in the field. The entire test is based on standard procedures and quality plan.
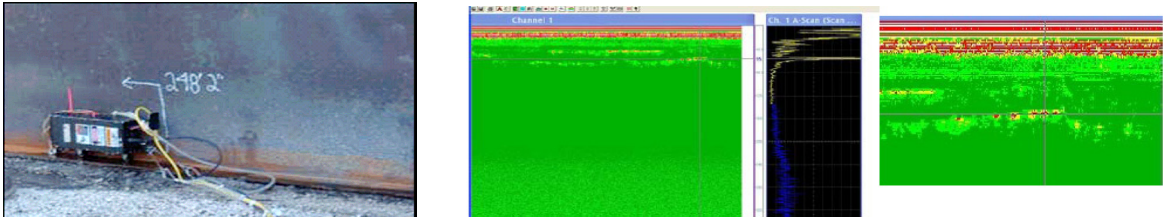

Figure 2. Left: A TALRUT[TM] system. Right: result of severe pitting.

Shown in Figure 2- Right are field results of one 1.5m-long scan and a close-up view indicating

severe corrosion pitting in a local area of this scan adjacent to the wall.

A3. On-Line Tank Shell Corrosion Mapping using Automated Ultrasonics C-Scan (LSI)

Tank shells can be inspected from their outer surface while the tank is in normal service. Several techniques are available ranging from typical ultrasonic thickness gauges to infrared tomography.

Figure 3. Industrial Automated Ultrasonic Crawler (LSI) during scanning of tank wall

Modern Automated UT systems provide a very efficient and fast solution. Using crawlers to mount the ultrasonic thickness probe that have magnetic wheels and can be controlled from a remote station enables them to scan the entire height of the tank without the need for scaffolding or crane (Figure 3). In addition AUT systems can sample the surface at small intervals and produce a very detailed thickness map. The reading step of AUT systems can be below 0.1mm but typically on tank walls the step is set to 10x20mm or higher, for faster scanning depending on the application.

B. Pressure Vessels

B1. On-Line Pressure Vessels Condition Assessment using Acoustic Emission (MONPAC^{TM})

Extensive testing of pressure vessels has led to the development of AE testing procedures, evaluation criteria and international standards [6]-[8]. In addition to that, industry proven procedures such as MONPAC^{TM}[5],[9], extended the codes' evaluation to quantitative evaluation of
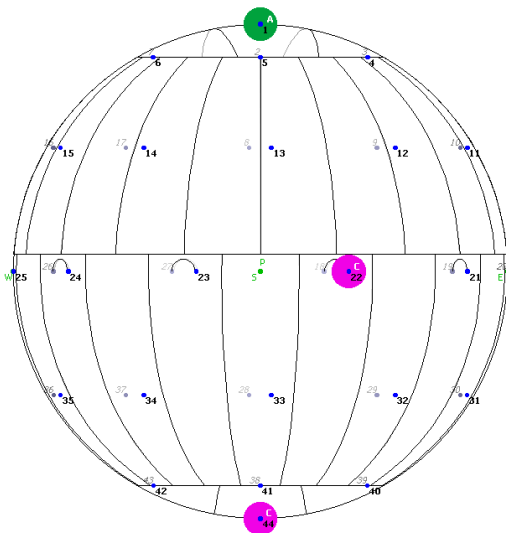

Figure 4: Sensor layout of the AE test of sphere of with MONPAC^{TM} grades.

fault severity and criticality and have provided the industry with a tool for 100% evaluation of the vessel, capable of giving early warning of developing defects, increasing, thus, the operational safety. In the MONPAC^{TM} procedure the results are in the form of a Zone Intensity Plot. This plot provides information of the condition of the whole structure divided in areas in the vicinity of each sensor (rated from A to E). The procedure provides recommendations from "No action" to "Major defects requiring immediate shut-down and follow-up NDE". Example of MONPAC^{TM} results are depicted in Figure 4.

B2. Presssure Vessel Corrosion Mapping using Automated Ultrasonics C-Scan (LSI)

The technique described in the paragraph A3 above is applicable for pressure vessels also.

B2. Localized NDT for Welds (TOFD)

In the recent past, an effort has begun for applying advanced ultrasound inspection on welds.

Figure 4: TOFD results.
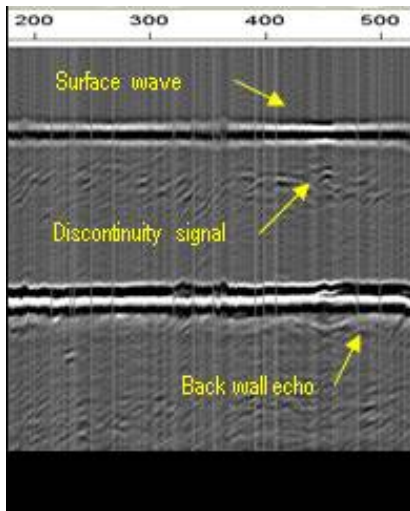
With this context the TOFD technique was developed. The method is a variation of the classic UT weld inspection technique and, according to that, two special longitudinal-wave UT angle probes are used that are placed on either side of the weld and are moved along the weld to scan it. The use of encoders allows digitization of the probes' position for accurate flaw positioning and sizing.

The results of TOFD are displayed in a D-Scan image (see Figure 4) where the limits of the weld are specified by the direct surface wave between transmitter and receiver (upper part of the (lower part of the weld). The signals from the discontinuities are found in-between these two waves.

5. Software for Structure Visualization in NDT Applications

The demand for advanced data analysis of the above-mentioned technologies creates a need for the use of specialized software applications for advanced data processing and superposition of the results with the structure under examination. Such software has been developed primarily for two reasons: a) to aid the preparation for NDT and inspection setup of pressure vessels and storage tanks and b) to provide the tools for effective reporting of results and fusion of the data. Its 3D representation of structures including accurate weld representation, secondary components (like nozzles, pipes, etc.), sensor positioning, Thickness Measurement Locations presentation, coverage calculations are the main tools it provides to the NDT operator.

The software can be used during test preparation to provide an in-depth analysis of the setup and investigate any problematic areas that need to be addressed. During setup and the actual test it provides the operator with a new tool to identify the geometry on-the-spot and assess any activity and any problems during setup, as well as to conveniently re-adjust setup, based on site conditions and in case of unforeseen deviations of the geometry from its drawings. In post-processing it is a very powerful reporting tool capable to depict results from different NDT methods overlaid on the real structure. The scope of the application is not to be a CAD replacement; it is to offer a fast tool for structure visualization with details that affect NDT.

The software supports:

- Typical plants structures (pressure vessels and storage tanks)

- Typical structure components (plates, welds, nozzles, pipes, stairs, etc.)

- NDT components/measurements (AE sensors, UT TML, AE source location, C-scan plots etc.)

- Easy navigation and visualization (Zoom, Rotate, Pan, Standard views)

- Convenient and graphical editing of components (e.g. drag and drop)

- Report facilities (export of images, export of plates/sensor/TML list)

- Export to CAD for further processing (e.g. DXF export)

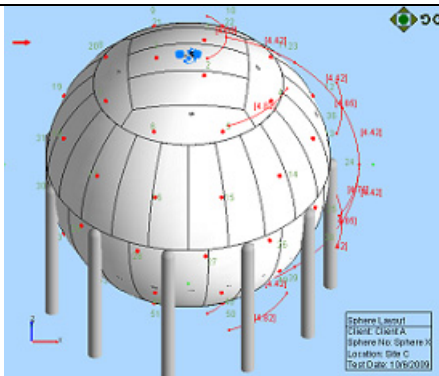Typical output of the application are presented in the following figures

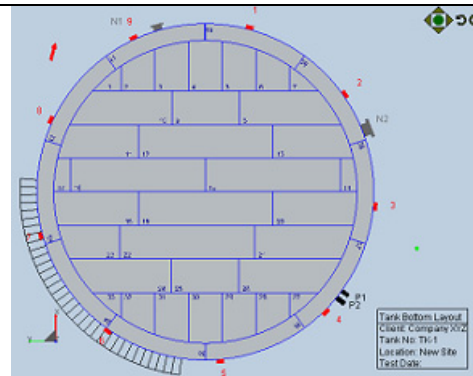**Figure 5:** Spherical Pressure Vessel Example

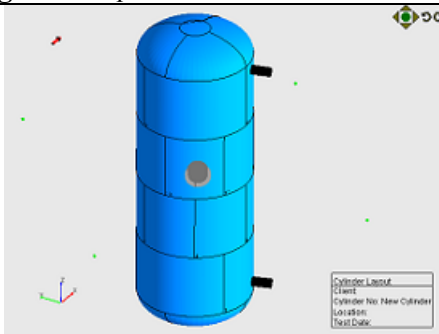**Figure 6:** Tank Bottom Example

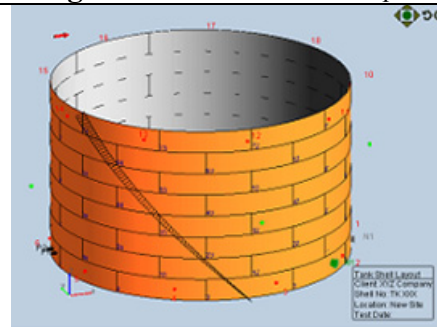**Figure 7:** Vertical Cylindrical Pressure Vessel Example

Figure 8: Atmospheric Storage Tank Example

Example of the software capabilities is the use of this software module together with the advanced Ultrasonic Imaging and Analysis software [10] for detailed analysis of UT measurements. The structural module provides the user with a set of tools for easy and fast input of common structures in refineries such as tanks, spherical and cylindrical pressure vessels. The software allows users to define the structure basic dimensions and all desired structure details and components such as plates, welds, nozzles, pipes. Also the software provides tools for painless stitching of the C-scans onto the real structure. In Figure 9-a the UT measurements are presented on a 3D view of the tank shell, in Figure 9-b the same data are presented in a 2D presentation.
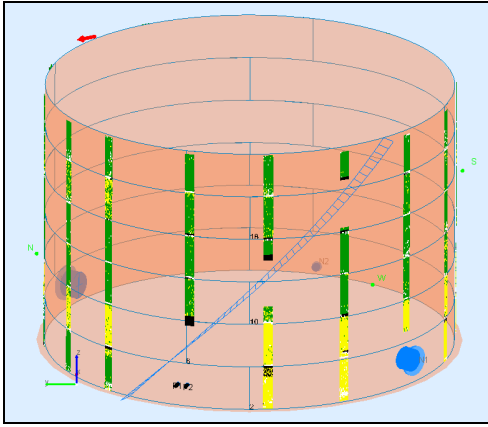
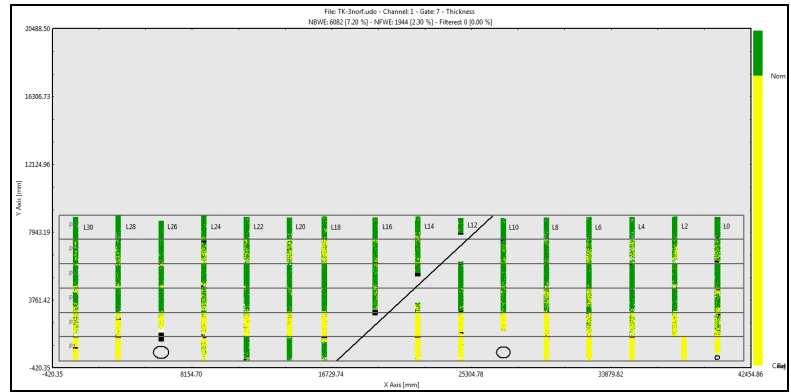**Figure 9-a.** 3D presentation of Tank Shell with UT measurement.

Figure 9-b. 2D presentation of Tank Shell with UT measurement.

The benefits of such accurate presentation of UT measurements with all structure details are many. First of all, it is simple to locate problematic areas with exact location information (e.g. using distances from plate edges or other components such as nozzles). Further, the user may locate general areas of thickness deterioration (for example, in the above pictures the green areas have thickness close to nominal thickness and yellow areas have thickness between the nominal thickness and caution limit).

The approach of using structural information combined with UT measurements offers further tools for examination of the structure status and compliance with regulations. The software provides tools for the definition of constant Thickness Monitoring Location (TML) using simple patterns and taking advantage of the accurate geometry definition (Figure 10). Thus, any kind of measurements (e.g. spot UT readings or AUT readings) can be calculated into the same TML over the time. In that way, the corrosion rate can be calculated and estimate the remaining life of the structure.
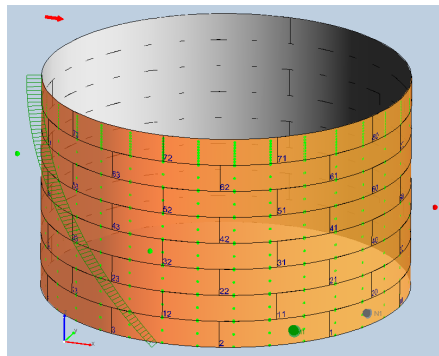
Figure 10. Thickness Monitoring Location in Tank Shell (Green Points).

6. Data Integration and Management

Data from all above techniques should be stored into an asset database for all equipment inspected and, thus, help the safety management program. The PCMS software [11] can perform this action by storing the data and using modules: Corrosion Monitoring and RBI Calculator.

The Corrosion Monitoring module allows plant personnel to track wall thickness on any

equipment. The patented risk technology analyzes reading data to recommend a next inspection date and estimate retirement dates. The thickness data is put through nineteen different tests to determine the next inspection date for each Thickness Monitoring Location (TML). Automatic retiring limit (T-min) calculators are available for use at each TML. ASME Section VIII code is used for pressure vessels, and API 653 standard is used to calculate T-min for storage tanks. A critical step in monitoring corrosion is the establishment of Circuits (zones of like corrosive behavior). For each circuit established, PCMS calculates corrosion rates and inspection due dates as shown in Figure 11.

Figure 11: Calculated Values for Circuit Corrosion

The RBI Calculator module performs the risk assessment. The risk assessment involves two main factors: a) Likelihood of Event Occurrence (usually negative event), b) Consequences associated with the Event c) The equation describing risk calculation that can be expressed as Risk = Likelihood X Consequence.
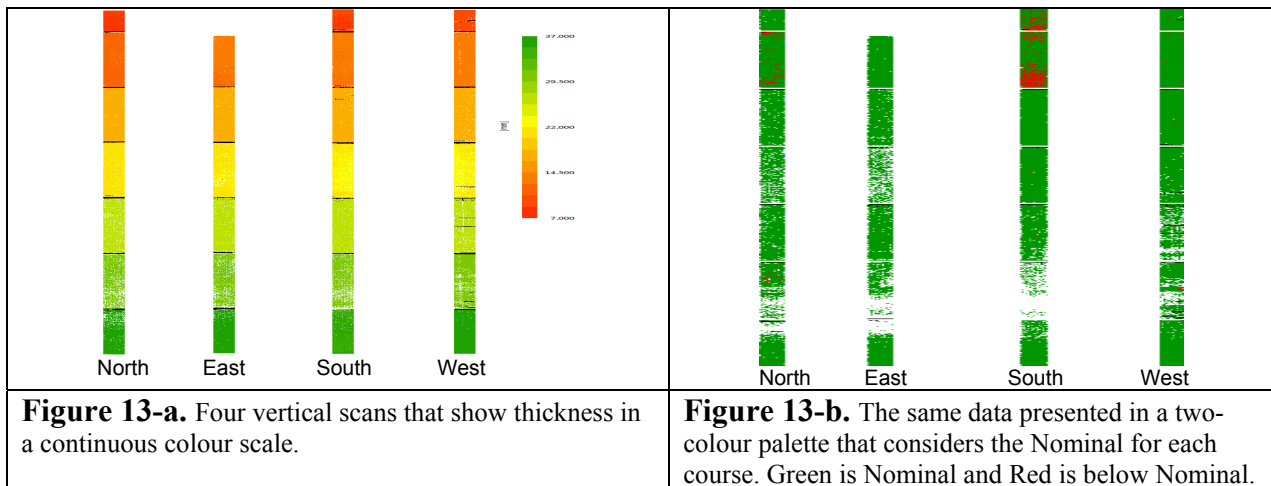
It is evident from risk definition that Likelihood of Event and Consequence of event are equally important and that risk cannot be assessed by ignoring one of the factors. Within this framework, for each circuit in PCMS, the RBI Calculator computes a) Probable damage mechanisms, b) Consequence of failure, c) Risk Rank based on probability & consequence of failure, d) Date the circuit will exceed a risk threshold without inspection and e) Recommended inspection technique for each damage mechanism

Figure 12 shows the results of RBI calculations for each circuit. Overall results as well as specific damage mechanisms could be displayed.

Figure 12: Overall Risk Rank for a given Circuit

Case 1: Advanced Analysis of UT Data

A good example of just how important meaningful data presentation is, is demonstrated in Figure 13, where the processed data from vertical C-Scans from a tank wall are combined to produce the composite C-Scan image shown. The data is presented in two different manners to show how data presentation can affect data interpretation. In Figure 13a (left) the data are shown with a continuous color (thickness) scale where the difference in thickness of adjacent plates is evident. In this case there does not seem to be an area with visible material loss. In Figure 13b (right) the same C-Scan is shown using a color (thickness) scaling that takes into account the nominal caution-reject limits for each plate and thus presents the data in relative color scaling. In this case we can see that a significant area in the 6th and 7th plates of the third scan show thinning below the caution limit.

Figure 13-a. Four vertical scans that show thickness in a continuous colour scale.	**Figure 13-b.** The same data presented in a two-colour palette that considers the Nominal for each course. Green is Nominal and Red is below Nominal.

Case 2: Combination of Techniques

All the above techniques could be combined for achieving the best results. An example of technique combination is presented below.
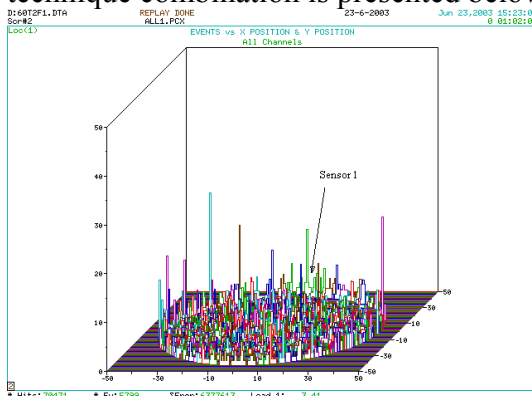
An 85-meter diameter tank with Crude Oil content was tested using the AE TANKPAC™ methodology in June 2003. The AE analysis led to the recommendation for re-inspection in the next 1-2 years. Also, the results indicated significant activity on the annular ring (Most of the AE event locations was at the annular ring, while in the rest of the floor location was generally uniform).

In March 2006, the tank was opened to clean and change product. Based on TankPAC™ test results, manual

Figure 14. Located AE activity. Concentrated AE sources are seen on the annular ring.

UT readings at the annular ring were performed. Indications of low thickness at the annular ring were observed, thus a full AUT test performed for annular plates.

The results of AUT show extensive local corrosion at the annular ring (see Figure 15) caused by water seeping under the tank at certain location around its perimeter. The rest of the floor was near the nominal thickness.

Figure 15. Local corrosion at the annular ring of tank.

Detailed analysis was made using the clustering module of UTIA software and accurate results of the significant thinning at annular ring were extracted.
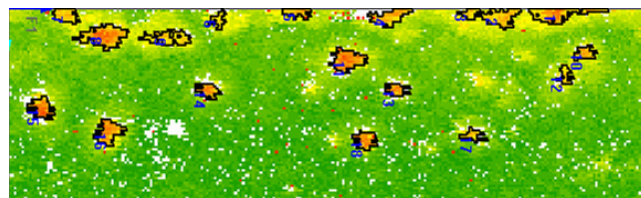
Cluster ID	mm²	Min	Max	Ave
1	348	5.62	8.98	7.71
2	280	6.94	8.97	8.13
3	84	7.28	8.89	8.38
4	280	4.09	8.94	7.79

Figure 16: Details of local corrosion and clustering results

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