A Wireless, Multi-Parameter Method and Device for Monitoring the Condition of Pipelines and Mechanical Structures

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ABSTRACT

The following paper discusses the results of a 3-year field trial of a multi-parameter method and device for monitoring the condition of pipelines and mechanical structures. The study incorporates testing results for both hardware and software survivability including lessons learned from system elements exposed to off-shore. It is generally accepted that regions of pipelines that experience velocity disturbances and routinely accumulate water and solids, are susceptible to internal corrosion and erosion. Although certain regions of mechanical degradation can be predicted, this is not always the case, and practical and economical methods to improve our assessments and predictions remain an industry objective. One such method is the emergence of a multi-parameter condition monitoring system that provides real-time monitoring of pipelines and pipeline components using an array of ultrasound transducers combined with the capability of measuring product velocity, sediment accumulation and multi-phase fluid flow. Early field trials and laboratory results suggest that, when data are integrated from these multiple sources, a more informed fitness for service decision can be made compared to the use of a conventional single data source. Additionally, real time engineering calculations and lifetime/retirement date projections can be provided to the user. The utility and value of the technology to the industry is further enhanced by integrating the system into a wireless communication network providing real time Internet accessibility.

Key words: Pipeline corrosion monitoring, wireless monitoring, extreme value analysis, pipeline mechanical integrity

INTRODUCTION

This paper discusses recent field trials and laboratory results of a wireless mechanical integrity monitoring system designed for above and belowground pipelines. The purpose of the study was to accumulate field performance information in order to assess its ability to respond to industry and government pipeline integrity monitoring and protection objectives. The system discussed in this paper is a multi-parameter condition monitoring system that provides real-time monitoring of pipelines and pipeline components using an array of ultrasound transducers (for tracking pipe wall thickness) combined with a sensor suite that tracks vibrations, temperature/humidity and local shock events. The system can also be configured to measure product velocity, sediment accumulation and multi-phase fluid flow. Figure 1 provides a photograph of the system configured for solar power and installed on a straight pipe without transitions. Figure 2 is a photograph of a line-powered installation positioned adjacent to a flange.

Performance variables evaluated during field trials included:

- The durability and compliance of a flexible dry couplant used to offset the ultrasonic transducers from the pipe's surface
- Ultrasound (UT) data acquisition accuracy and repeatability
- Corrosion rate measurement accuracy
- Survivability of the electronics under various environmental conditions

The study was conducted over a time period from February 2010 through April 2013 and included data acquired from "baseline" aboveground and belowground installations (it should be noted that the field testing was preceded by laboratory testing beginning in September 2007). Depending on the installation, the number of ultrasound measurements ranged from several hundred to several thousand readings. Installation locations included the northeast, southeast, southwest and south regions of the United States. The dry couplant's survivability and effectiveness was evaluated after exposure on a Gulf of Mexico off shore platform.

The impact of local turbulence and patterns of internal corrosion as well as sediment and fluid characterization and flow patterns of the product were not correlated to the results in this study since they were determined to be random, independent variables. Additionally, these parameters fell outside of the immediate objectives of the current testing. Due to the large quantity of acquired UT data, the results are presented in the form of an extreme value analysis (EVA) with the ultimate goal of determining worst case loss of pipe wall (or highest rate of corrosion) from a very large population of UT readings. In some cases, system users conducted their own independent studies, which in all cases, was shown to be consistent with these field trial results.

Figure 1. Ultrasound array with solar collector integrated into housing.

Figure 2. Installation of original array/cover on a vertical slurry line adjacent to a flange.

EXPERIMENTAL PROCEDURE

Five (5) monitoring installations were the subject of this study. Parameters associated with each installation are summarized in Table 1, below. Two important points: One installation evaluated the compliancy of the couplant only rather than the UT sensors or overall UT performance. This was due to particular operational site constraints. Second, the baseline pipes were not operational and were positioned and instrumented in order to acquire baseline UT and environmental data only.

Table 1. Selected parameters associated with each pipe testing location.

Region	Location	Product	Pipe Diameter (in/mm)	Pipe Schedule	Monitoring Duration (days)	Processed UT Data Points	EVA Data Points
Northeast	Aboveground	Atmosphere	8/203	40	1095	1317	76
Northeast	Belowground	Atmosphere	8/203	40	1095	1715	75
Southeast	Aboveground	Water	12/305	80	912	250	64
Southwest	Aboveground	Gas	12/305	80	912	250	21
South	Aboveground	Refining Process	6/152	160	446	931	125
Gulf - Off-Shore	Off-Shore	Water	4/102	160	1095	N/A	N/A

UT Transducer Installation

Each pipe under evaluation was instrumented with an array with 4 or 8 UT transducers evenly positioned around the pipe (in some instances, the transducers were arranged to monitor specific areas known to experience more aggressive metal loss. These areas occurred at elbows and upstream from weldments). For elbow locations, the array consisted of 8 transducers along the outside radius of the elbow and, in most cases, prior to the elbow's weldment to straight pipe. Both piezoceramic or piezocomposite transducers were used depending on the particular installation requirements. All transducers were 3.5 MHz. Each transducer was mechanically integrated into a mounting assembly that allowed for their repositioning. Contact pressure on the dry, flexible couplant was adjusted to achieve proper transducer orientation and signal quality.

Two pulser-receiver electronic configurations were deployed; the electronics were either located immediately adjacent to the transducer array or located in a remote "gateway" enclosure that also housed the communication electronics. In all cases, array data were transmitted through a wireless gateway to a Cloud server (discussed below). Pulser signals were "long duration" and broadband. Signal processing algorithms were integrated into the firmware or within the Cloud server to improve echo-to-echo peak detection and noise reduction. On-site calibrations prior to installation were conducted to insure that on-site pipe wall thickness readings were consistent with pre-installation manufacturing facility calibration settings. Figure 3 represents a typical B-scan return from a single array UT channel. Multiple high amplitude peaks represent front face reflections that were rejected by the array's signal processing software.

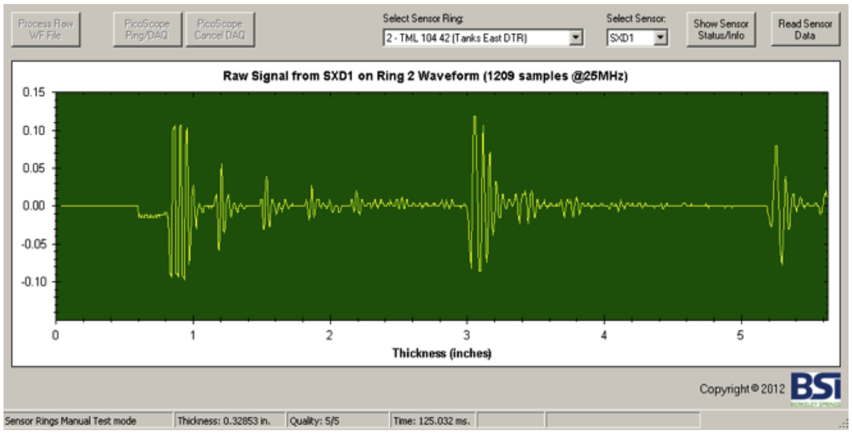

Figure 3. B-scan ultrasound echoes acquired from the pipe's surface and remotely monitored and available to the user on-line.

User Interface

Each field array transmitted either raw or processed data to the array's Cloud server. A user interface was developed that integrated all of the real-time and legacy data into a single display that also incorporated API-570 (1) calculations which were used, in some cases, to make operational decisions regarding the condition of the pipe and the risks associated with its operation. Figure 4 provides a typical example of the user interface with corrosion trending. Figure 5 is an image of the user interface providing results from an 8-UT sensor array.

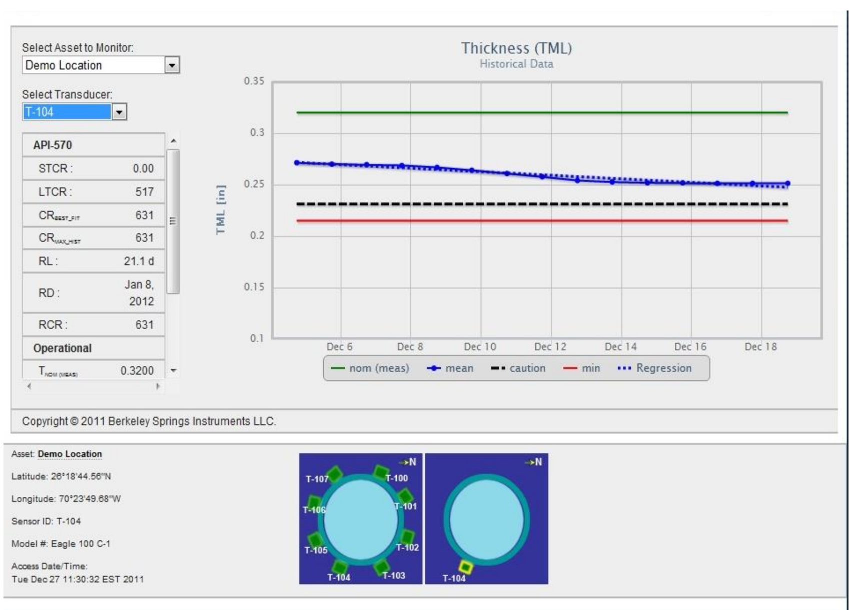

Figure 4. User interface providing real-time mechanical integrity information to the user and updated API-570 calculations regarding remaining useful life and retirement dates. End view of current pipe data under review is shown.

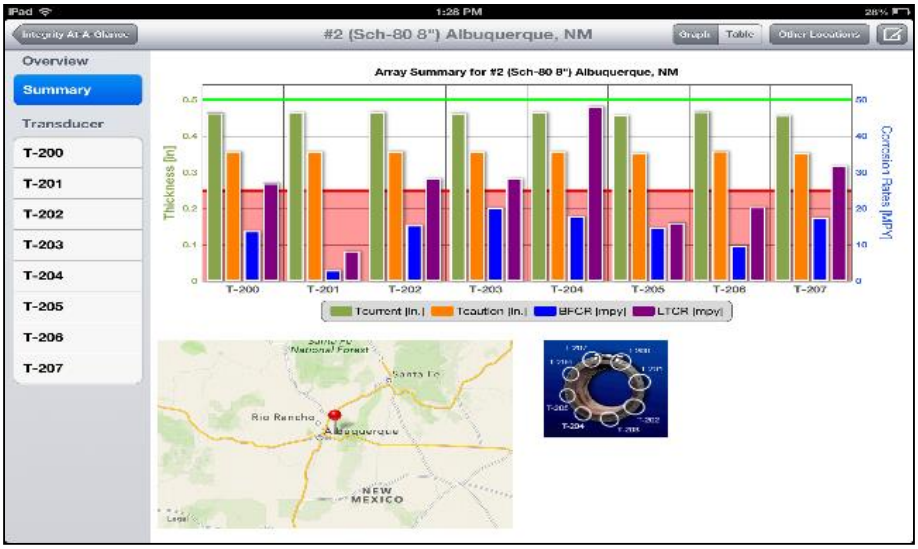

Figure 5. Summary of all arrays located on one pipe segment or pipeline. Pipe location coordinates and geo-location are provided.

Environmental Sensor Installation

Each field trial array incorporated sensors that monitored and stored vibration, temperature and humidity. Sample user interface tools for monitoring and data collection are noted in Figures 6 and 7, below.

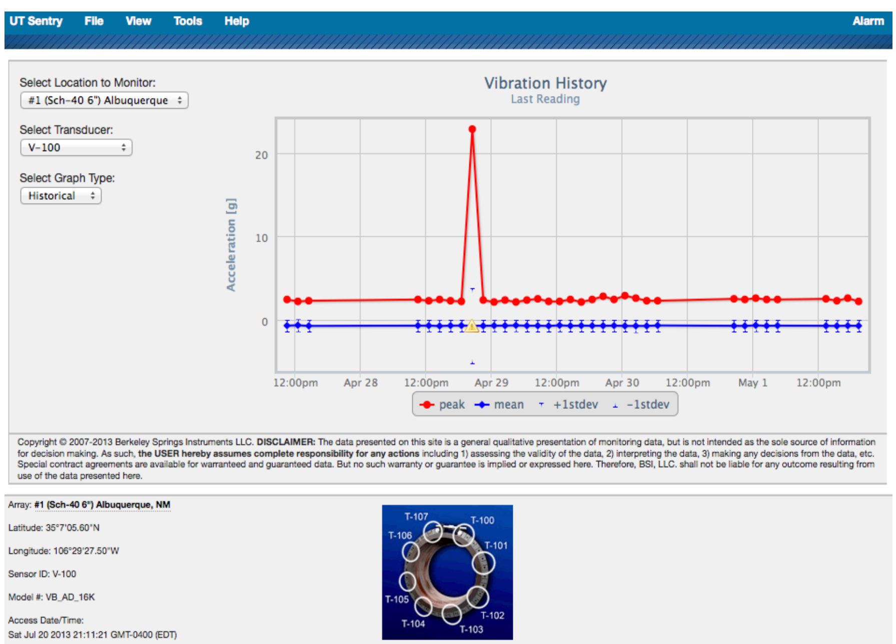

Figure 6. Vibration data monitoring user interface. Vibration information is time-stamped to associate each event with the UT data and corrosion rates.

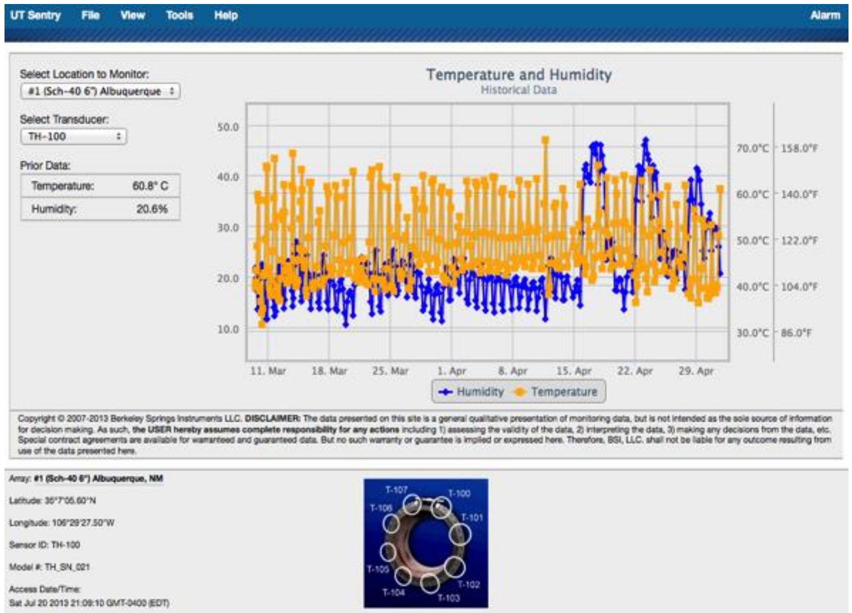

Figure 7. Temperature/humidity data monitoring user interface. Temperature and humidity information are time-stamped to associate each event with the UT data and corrosion rates.

Wireless Network

The network configuration used for all field trial arrays is shown in Figure 8. Communications between the array and the Cloud server occurs through a cellular network or through a direct Ethernet connection to the Internet. Although a mesh network was not incorporated into the field trials (i.e. direct array-to-array linking) this capability was available. UT pulser-receiver scheduling and environmental data acquisition scheduling was accomplished at the Cloud server with commands being received and implemented at each array location.

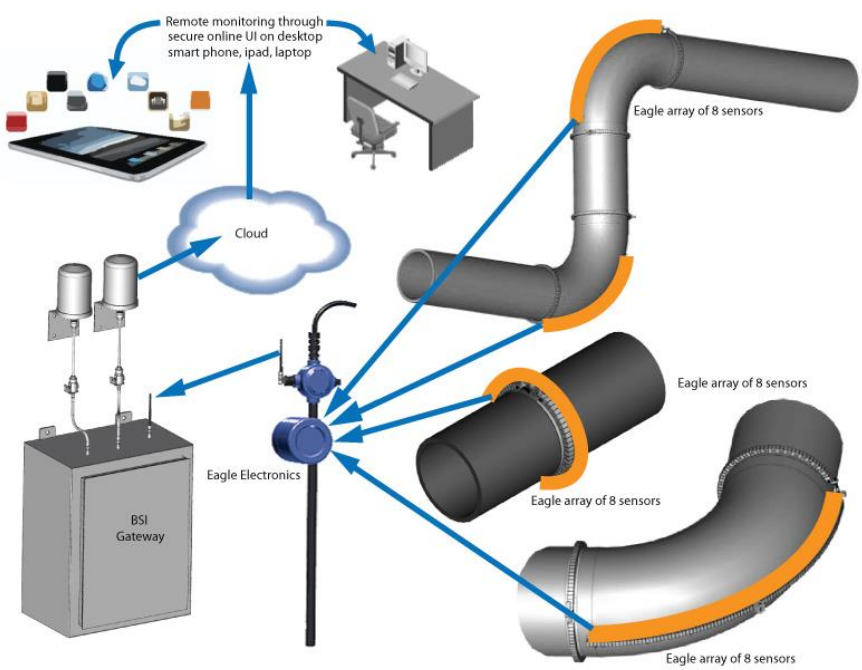

Figure 8. Mechanical integrity monitoring wireless network configuration.

RESULTS

A summary of the basic results of the field trials is presented in Table 2. In general, there was consistency between remotely acquired field measurements and those verified "locally." Additionally, although the environment under which the arrays were installed was not considered extreme, seasonal variations in temperature and humidity did not effect system operation. Higher temperatures noted in the table, under certain conditions, were associated with the pipe's surface temperature. Additionally, local background vibrations or occasional transients (i.e. nearby equipment movement, water hammers, or wildlife movement) did not impact data integrity. A more detailed discussion of the UT data is presented below.

Table 2. Summary of field trial results

Region	Location	Pipe Wall Thickness (in/mm)	Nominal Thickness (in/mm)	Post-Monitor Thickness (in/mm)	EVA Predicted Thickness (in/mm)	On-Site Manual Measurement Value	Monitoring Duration (days)	Low Temperature (F/C)	High Temperature (F/C)
Northeast	Aboveground	Atmosphere	0.250 / 6.35	0.250 / 6.35	N/A	0.250 / 6.35	1095	Ambient	Ambient
Northeast	Belowground	Atmosphere	0.250 / 6.35	0.250 / 6.35	N/A	0.250 / 6.35	1095	Ambient	Ambient
Southeast	Aboveground	Water	0.250 / 6.35	0.238 / 9.37	0.233 / 5.918	0.238 / 9.37	912	63.0 / 17.2	145.6 / 63.1
Southwest	Aboveground	Gas	0.375 / 9.525	0.275 / 10.83	0.229 / 5.817	0.275 / 10.83	912	Ambient	Ambient
South	Aboveground	Refining Process	0.250 / 6.35	0.241 / 9.49	0.241 / 6.121	0.240 / 9.49	446	49.1 / 9.5	134.8 / 57.1
Gulf - Off-Shore	Off-Shore	Water	N/A	N/A	N/A	N/A	1095	Ambient	Ambient

Ultrasound Data Extreme Value Analysis

Conventional techniques of analyzing pipe UT data requires the inspector to evaluate the total population of ultrasonic data (typically with the help of software tools), determine the values of the deepest pits (or thinnest areas), confirm the nominal or design thickness of the pipe and calculate the remaining life of the pipe by using the calculated corrosion rate. One shortcoming with this approach is that unless the inspector is absolutely certain that they have scanned the entire pipe (i.e. using a continuous scan in-line tool) so that any pitting has not gone undetected, the corrosion rate results may not reflect the actual condition of the pipe. This is a common dilemma associated with the use of a low population of Thickness Measurement Locations (TML's). One approach to addressing this issue is with the use of extreme value statistics, a technique that is common to many industry's when the assessment of a greater population is necessary with the use of a limited set of data.

The use of the extreme value methods has been used by a number of petroleum companies for extrapolating pitting corrosion from small inspection patches in an above ground storage tank to the whole tank. One such study (2) has demonstrated how the thickness distributions can be used to estimate the probability of a wall thickness being below a certain level from ultrasonic thickness gauge data for pipelines. Guidelines have also been offered to the oil and gas industry for applying EVA statistics for evaluating the probability of occurrence of pipe wall corrosion that may not be directly measureable (3). A recent paper, however, used extreme value statistics for comparing the results of UT sampling by robotic equipment conducted while a population of tanks remained in-service to the results of out-of-service surveys (4). In all cases the extreme value results matched the results scrutinized from the out-of-service inspections.

In general, extreme value statistics used to evaluate pipe metal loss tends to generate thickness results that are more conservative than if these statistics were not used. That is, the minimum remaining thickness of a pipe circuit determined by a limited data set will be thicker than if the data were subject to an extreme value analysis.

The data in Table 2, above, summarized the general results of the field study that included temperature ranges (pipe surface temperature) and related pipe wall thickness measurements. What the table suggests, as it relates to the UT results, is that simply evaluating the metal loss at monitoring locations may not provide the inspector with a sense of probability of occurrence. When the data are analyzed using extreme value statistics, however, the probability of a particular minimum thickness can be offered. This is shown in Figures 9 and 10 where there is a 1 % probability that there is a Tmin value of less than the value predicted by the analysis. Percent probability is determined from the y-axes. Different predicted Tmins associated with individual arrays can be reported as well as their probability of occurrence.

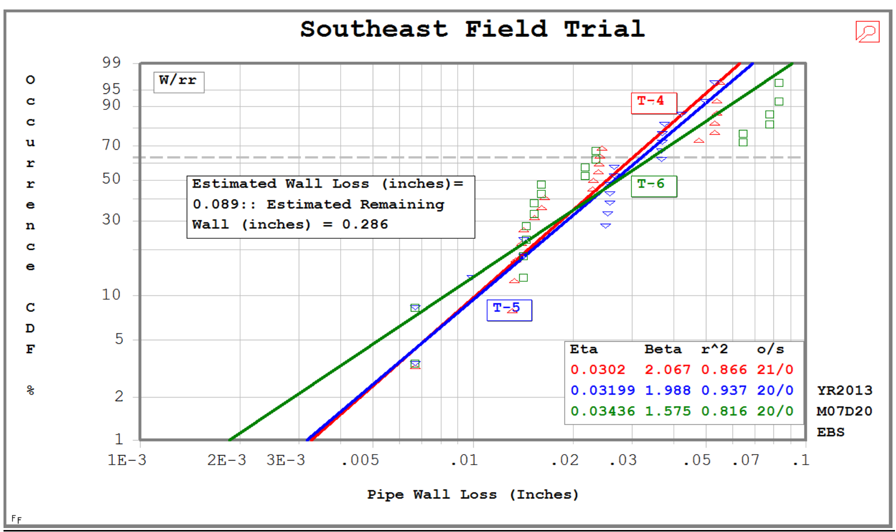

Figure 9. 912 days of data for the Southeast field trial location. Predicted wall loss considering all UT locations is approximately 0.089 inches (2.261mm). Since the best fit reliability coefficient range is between .816 and .937, the predicted wall loss can be used as a general indication of probable areas of greater loss than what is measured. More thickness data from this location gathered over time may result in a higher best fit coefficient, and therefore, a more accurate estimate of wall loss probability, although a best fit coefficient of 0.937 can be used as a reasonable predictor.

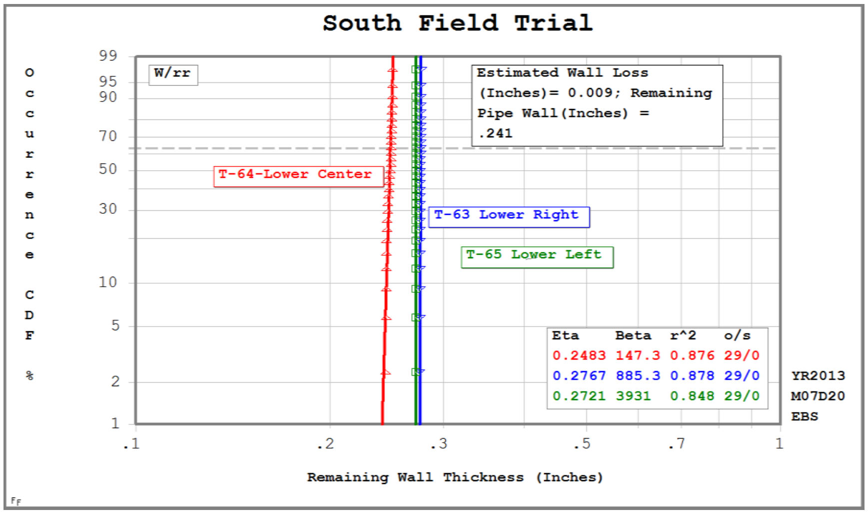

Figure 10. 446 days of data for the Southeast field trial location. Predicted wall loss considering all UT locations is approximately .009 inches (.2286 mm). Since the best fit reliability coefficient range is between .816 and .937, the predicted wall loss can be used as a general indication of probable areas of greater loss than what is measured. More thickness data from this location gathered over time may result in a higher best fit coefficient, and therefore, a more accurate estimate of wall loss probability, although a best fit coefficient of 0.878 can be used as a reasonable predictor.

Transducer Couplant

One of the key components under test was the ability of the dry, flexible couplant to remain compliant during temperature and humidity changes and exposure to vibrations. The flexibility of the couplant was designed to accommodate expansions and contractions of the pipe's surface. Compliance between the transducer face and the surface under evaluation is a challenge associated with epoxy/resin-based adhesives and glues. That is, depending on the circumstances, delamination of the epoxy bond can create signal transmission issues for UT transducers, and in some cases, total loss of signal.

Common drawbacks with flexible couplants (as well as traditional delay lines) include mode conversions, speed of sound variability and signal attenuation effects. In certain circumstances, especially with broadband pulsers, frequency characteristics can be impacted as well. Regardless, all of the couplant was tested prior to and after exposure to their respective elements. Although the results showed some impact of exposure to the environment such as salt atmospheres, high humidity and temperature variance the signal processor's peak detectors were able to identify the proper echos and differentiate them from couplant-induced anomalies. This is a key factor associated with "permanently-mounted" UT transducers since much of the UT signal quality hinges on proper coupling of the transducer's face to the pipe's surface.

CONCLUSIONS

This paper presented the results of a 3-year field trial of a multi-parameter method and device for monitoring the condition of pipelines and mechanical structures. The study incorporated testing results for both hardware and software including lessons learned from system elements exposed to off-shore environments.

Early field trials and laboratory results suggest that, when data are integrated from these multiple sources, a more informed fitness for service decision can be made compared to the use of a conventional single data source. This is especially the case with the use of statistical treatment of data such as an Extreme Value Analysis that was used to describe the results from two field installations. Although extreme temperatures were not experienced (or anticipated) during the present study, no impact on measurement accuracy was encountered. That is, UT A-scan data that was transmitted from a fixed location and processed remotely, yields B-scan values that are equal to those acquired at the fixed location.

Additionally, real time engineering calculations and lifetime/retirement date projections can be provided to the user.

Current applications for remote monitoring locations include monitoring the effectiveness of corrosion control programs, the impact of local turbulence and sediment accumulation at areas of pipe transition, elbows, T’s and injection points. Clear applications can be found for the measurement of erosion and especially flow accelerated erosion/corrosion as well as monitoring anticipated damage mechanisms that increase the likelihood of pipeline failures. Future advances in the technology include the integration of related pipeline performance data for the direct assessment of corrosive conditions, especially conditions associated with internal pipe corrosion.

REFERENCES

1. API Standard 570, Piping Inspection Code, “Inspection, Repair, Alteration and Rerating of In-sevice Piping Systems” (Washington, D.C; API) 2003

2. M. Sparago. “Statistical tools for ultrasonic thickness data analysis, Part 2 – remaining life estimates.” Inspectioneering Journal, 1999 (March/April) 1-4.

3. “Guidelines for the use of statistics for analysis of sample inspection of corrosion.” The Welding Institute Ltd., Cambridge U.K., Research Report 016, 2002.

4. E.B. Silverman, R. Bass, F. Furillo, A. Wolf. “In-Service oil tank cleaning and inspection system: Results of eight (8) independent validations,” ASNT Proceedings, October 2000.