DEFECT ASSESSMENT USING CONFORMABLE ARRAY DATA

FINAL REPORT
October 1, 2002–September 30, 2003

Prepared by

Alfred E. Crouch
Todd H. Goyen
Southwest Research Institute®
San Antonio, Texas

December 2003

DOE Contract No. DE-FC26-02NT41644
SwRI® Project 14.06239

Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
Morgantown, West Virginia 26507-0880

SOUTHWEST RESEARCH INSTITUTE

SAN ANTONIO
DETROIT

HOUSTON
WASHINGTON, DC

DEFECT ASSESSMENT USING CONFORMABLE ARRAY DATA

FINAL REPORT
October 1, 2002–September 30, 2003

Prepared by

Alfred E. Crouch
Todd H. Goyen
Southwest Research Institute
San Antonio, Texas

December 2003

DOE Contract No. DE-FC26-02NT41644
SwRI Project 14.06239

Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
Morgantown, West Virginia 26507-0880

Written by	*Approved by*
Alfred E. Crouch Staff Engineer *and* Todd H. Goyen Scientist	*Signature on File* Glenn M. Light, Ph.D. Director

DISCLAIMER

This Final Report was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-02NT41644. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the DOE.

ABSTRACT

This report covers the design and fabrication of a conformable eddy current array useful for the mapping and measurement of external corrosion on a transmission pipeline. The feasibility of the basic measuring approach was demonstrated and the general guidelines for sensor design were disclosed in a previous project. This project was concerned with design of a practical array, development of interface electronics, and design of the operation and analysis software. A prototype system was constructed, checked out, and demonstrated on natural corrosion in a field environment.

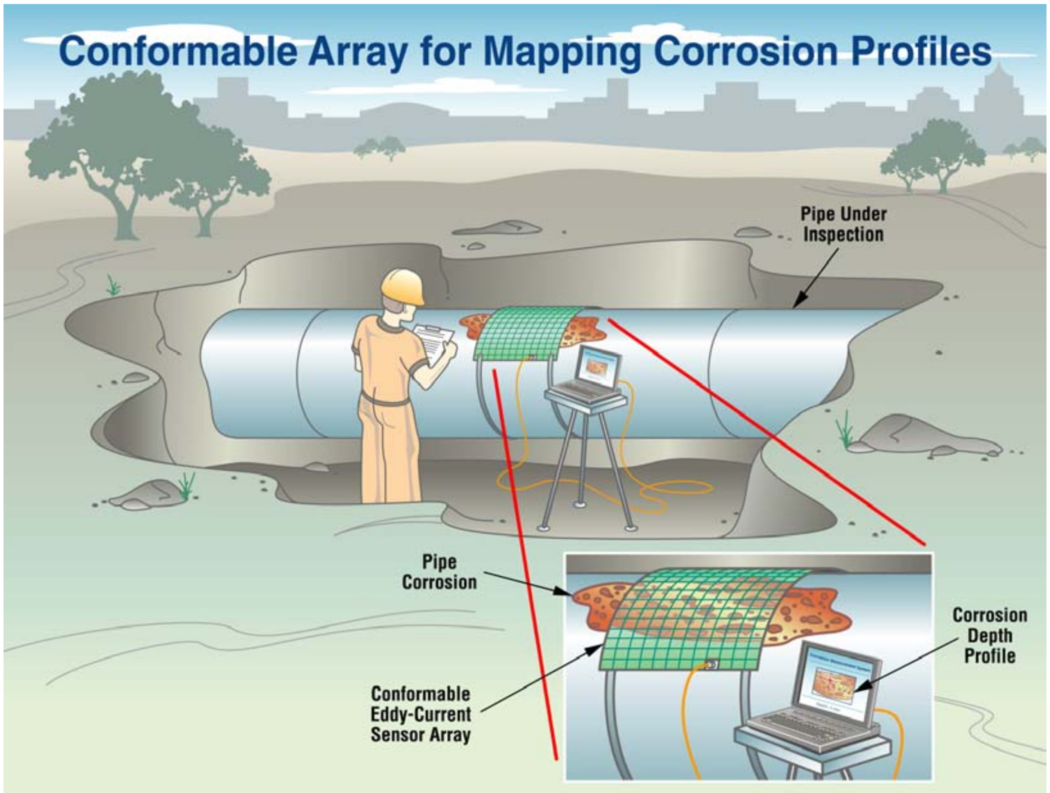
TABLE OF CONTENTS

Page

LIST OF GRAPHICAL MATERIALS

LIST OF GRAPHICAL MATERIALS

1. INTRODUCTION



This project focused on the reliability and safety of the transmission infrastructure. Corrosion in gas transmission pipelines occurs primarily (but not exclusively) on the external surface of the pipe. When such corrosion has been detected by in-line inspection, the common procedure, if significant corrosion depths are suspected, is to unearth the pipe and examine the corroded area to determine its depth and other dimensions. Assessment algorithms such as RSTRENG and B31.G require corrosion dimensions, including primarily the maximum depth and length of the corrosion patch. A common way to acquire those data is to lay out a grid on the pipe surface and make physical measurements of the corrosion depth at nodes of the grid. This is a time-consuming process. Further, it requires that the pipe be clean. And, finally, it is subject to human errors of mismeasurement and misrecording of data.

Southwest Research Institute (SwRI) has an extensive background in application of eddy current test methods to detect cracks and other defects. In one successful project, SwRI was involved with a single-coil eddy current device to measure depth of graphitic corrosion in cast-iron gas pipes. The experience gained in this project suggested that the same approach could be used in an array to quickly map a corroded area on a transmission pipe. With the support of NETL and the cooperation of industrial partner, Clock Spring Company L.P. (Clock Spring), SwRI has been able to establish the viability of the approach and bring the new technology to a commercial reality.

1. The completed work relates to Gas Infrastructure Reliability

The stated objective of the NETL Gas Infrastructure Reliability program is to develop technology that will place the necessary tools into the hands of those who maintain and enhance the integrity and operational reliability of the nation's gas transmission and distribution network. This project has produced just such a tool. The conformable array is intended for hands-on use by the field technicians who have the responsibility for assessment of pipeline corrosion.

2. Data to support the technology claims

The previous related project demonstrated that eddy current coils could be used for measuring the depth of corrosion pits. Figure 1 shows the response of an eddy current coil pair to the depth of pits whose diameters vary from 12 to 24 mm. The relatively smooth curve and the substantial independence from diameter effects supported the proposal to carry the project to this phase, i.e. to design and fabricate a field deployment of the system.

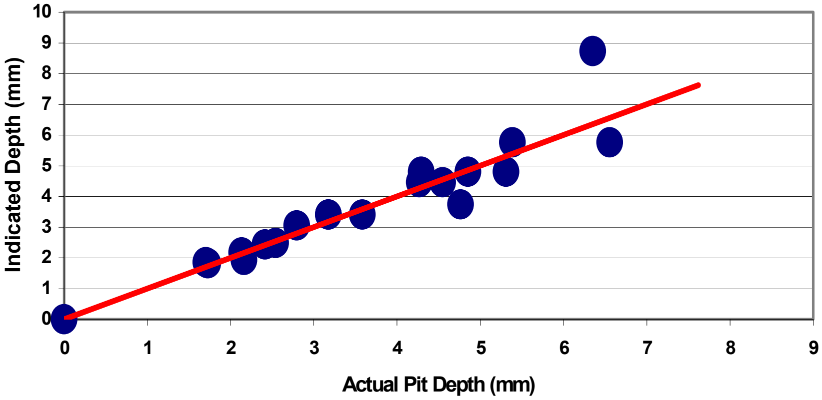


Figure 1. Response of an eddy current coil pair to the depth of pits whose diameters vary from 12 to 24 mm

3. Improvements over existing technologies

Existing technologies for measuring external pipe corrosion are time-consuming and require a high degree of cleaning of the pipe surface. The developed technology promises to be quick, inexpensive, and immune to the presence of dirt or residual coating material in the corrosion. It will be usable with a minimum of training.

4. Benefits of completed work

Prior to this development, there was no inexpensive, automated method to make detailed corrosion measurements on the outside of excavated pipelines. Such measurements had to be made manually or with expensive, complex laser or ultrasonic machines. This project produced an affordable, rugged system that field personnel can be trained to use in the typical, dirty field environment.

2. EXECUTIVE SUMMARY

Corrosion in gas transmission pipelines occurs primarily (though not exclusively) on the external surface of the pipe. When such corrosion has been detected by an in-line inspection (ILI), the common procedure, if significant corrosion depths are suspected, is to unearth the pipe and examine the corroded area to determine its depth and other dimensions. Assessment algorithms such as B31.G and RSTRENG require corrosion dimensions, including primarily the maximum depth and length of the corrosion patch. A common way to acquire those data is to construct a measurement grid on the pipe surface and make physical measurements of the corrosion depth at nodes of the grid. This is a time-consuming process. Further, it requires that the pipe be quite clean. And, finally, it is subject to human errors of mismeasurement and misrecording of data.

The stated objective of this project was to develop a new, affordable technology for making measurements of external corrosion in the field environment. The project produced just such a tool. The conformable array is intended for hands-on use by the field technicians who have the responsibility for assessment of pipeline corrosion. Before this work, there was no inexpensive, automated method to make detailed corrosion measurements on the outside of excavated pipelines. Such measurements had to be made manually or with expensive, complex laser or ultrasonic machines. This project produced an affordable, rugged system that field personnel could be trained to use in the typical, dirty field environment.

This project included five tasks as follows.

2.1 Design and Fabricate Field Array

In the previous (2002) Conformable Array project, a small array was designed and built. It was only 75 mm square with 64 coil pairs, but it proved the principle of using an eddy current array to map corrosion pitting. For practical field use, a much larger array was considered necessary. The new array, 150 mm square with 256 coil pairs, was built on a flexible substrate just flexible enough to wrap around a corrosion patch on a pipe, but stiff enough to hold its curvature and not sink into the corrosion pits. Stiff boards at the edges of the array carry the interface circuitry.

2.2 Design and Fabricate Interface Circuits

The density of the array was 9.5 mm per coil, yielding a total array size of 16 by 16 coils, or 256 total channels. This put severe spatial requirements on interconnections and on the choice of circuitry to be able to drive the coils and receive signals from them. State-of-the-art printed circuit techniques were used to make the multilayer flexible board with sufficient interconnects while avoiding crosstalk and sneak current paths.

2.3 Develop Data Analysis Algorithms

The primary data display is a color map of corrosion depth. This task acquired and used those data for input to B31.G or RSTRENG-type assessments. National Instruments LabView software was used to implement the data collection and analysis algorithms. All software functions were reviewed and refined with input from our industrial partner, Clock Spring.

2.4 Field Test Prototype

Once the array and interface electronics were checked out in the laboratory, they were taken for evaluation on actual corrosion. The purpose of field-testing was twofold. First, it was necessary to validate the performance of the array approach on natural corrosion. Second, it was necessary to evaluate the procedure for use of the array to verify that it was consistent with the field environment and useful for field technical personnel.

2.5 Documentation for Technology Transfer

Once the conformable array system was fabricated and field-tested, SwRI transmitted all the design specifications to Clock Spring, to aid them in developing a commercial design. Although the project produced a working design, it still had to go through the production design process. Clock Spring may privately contract for that design and for the production fabrication of arrays and electronics.

3. EXPERIMENTAL

The predecessor project to this one showed that pairs of circular eddy current coils could be used to measure pit depth. This project produced a prototype system that embodies that concept. This section describes the basic approach and the testing that validated the concept on natural corrosion.

3.1 Theory of Operation

A coil of wire carrying an alternating current will generate a magnetic field, as seen in Figure 2. If the coil is brought close to a conducting surface, it will induce eddy currents to flow as to oppose the magnetic field, as seen in Figure 3. The magnitude and phase of these "secondary coils" are influenced by the geometry of the arrangement (which includes the spacing between coil and conductive material) and the conductivity and permeability of the material. Some eddy current systems use coil pairs, with one serving as an exciter and the other as a receiver, much like a two-winding transformer. The coupling between the two coils is affected by the way in which the probe is coupled to the test piece; a strong factor in this coupling is the spacing between the coil and test piece surface, as seen in Figure 4. When the coil is close to the test piece, the coupling is strong; as the coil is moved farther away, the coupling is reduced. Thus, there is a significant effect of this spacing (or probe liftoff) on the probe impedance and the ECT response. When ECT is used for applications such as the detection of small cracks, this effect is usually undesirable because it creates "noise" as the probe liftoff varies. In other cases, the liftoff response is advantageous because it allows ECT to measure the distance between the probe and test piece. ECT probes operating in this mode are the basis for displacement sensors used in many applications.

For corrosion depth measurement, it is this liftoff or displacement mode that is of interest. Because the corrosion areas to be measured are generally large compared to the probe size, the corrosion pits appear more as a change in liftoff rather than a localized change in conductivity. The corrosion measurement approach is to use ECT probes as liftoff sensors to measure the pit depth by measuring the "displacement" between the probe and bottom of the pit, as shown in Figure 5. Similar approaches have been investigated by scanning a single coil to map the surface or find the maximum depth.

The conformable array was designed to mitigate this need to scan. It contains 256 coils in a 16 by 16 matrix, which is 157 mm on a side, thereby allowing large areas to be covered without moving the array. It can be seen in Figure 6. Closeups of the coil spacing and an individual coil are shown in Figures 7 and 8, respectively. Other factors were designed into the array to lower the effect of conductivity and permeability variations inherent in pipe steel. This included increasing the operating frequency and the circuit modifications required by such a change.

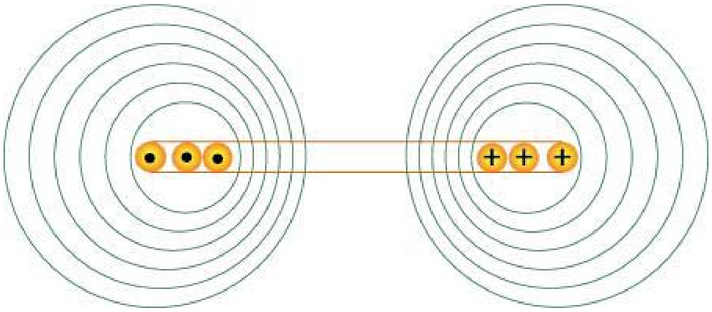


Figure 2. Basic eddy current coil

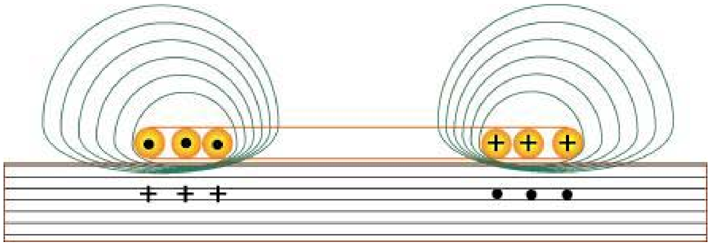


Figure 3. Interaction between coil field and test specimen

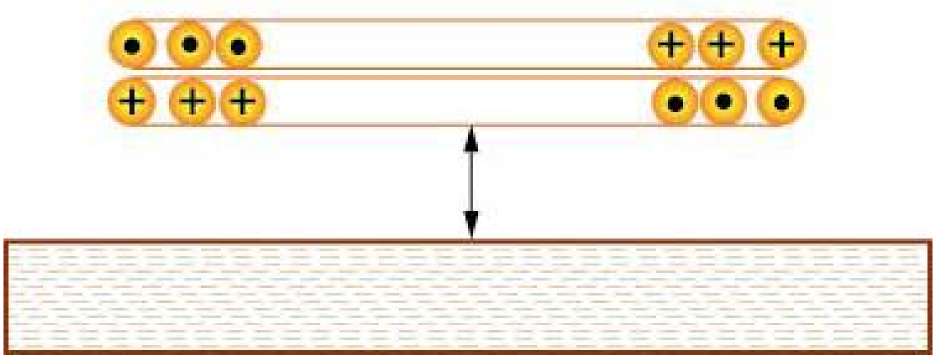


Figure 4. Definition of liftoff for eddy current coil pair

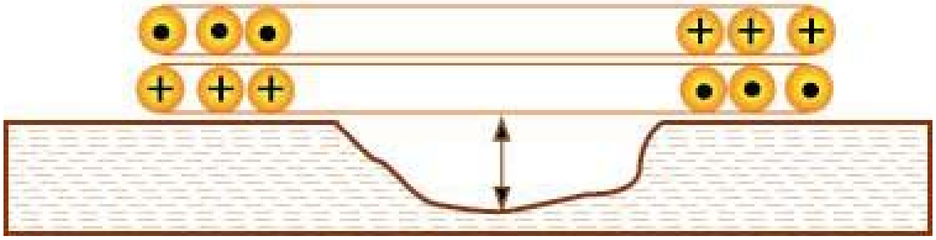


Figure 5. Liftoff of pit depth

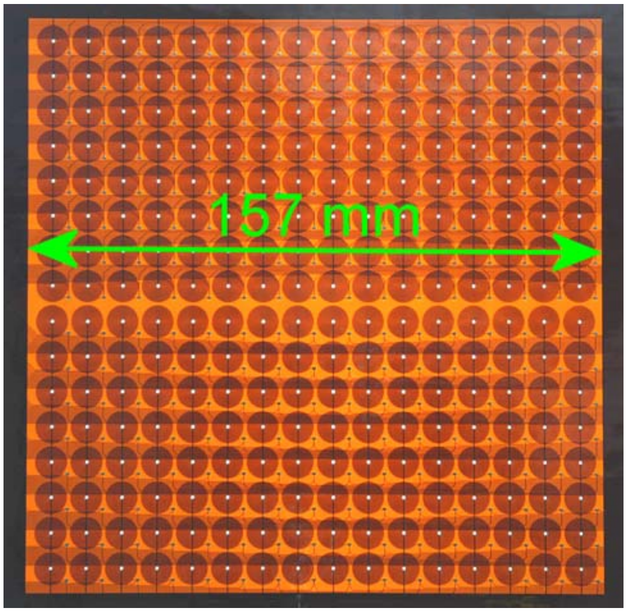


Figure 6. A 256-coil array

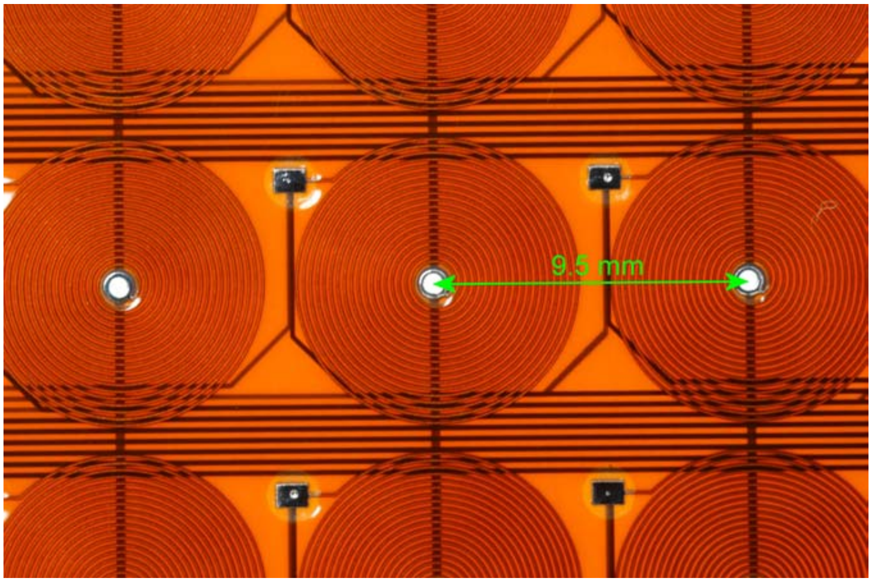


Figure 7. Mid-view of coil array

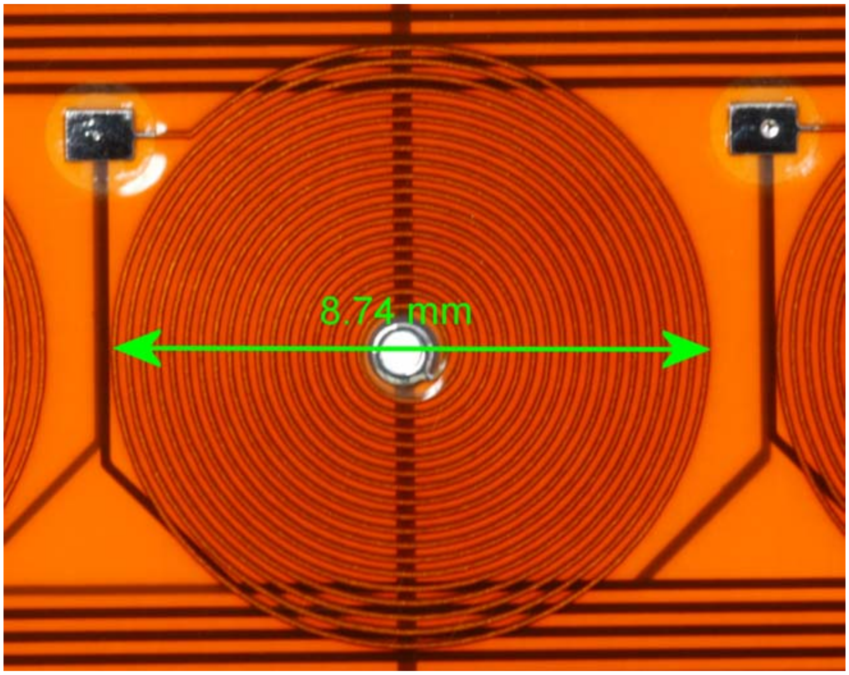


Figure 8. Single-coil pair superimposed

3.2 Prototyping and Hardware Design

The original conformable array project determined 100 kHz to be the ideal operating frequency. This frequency provided a strong coupling between the driver and receiver coils. However, there are two major drawbacks, the severer of these being the fact that the reactance of the coils at this frequency is on the order of one Ohm. This necessitates the use of 256 separate buffers to drive the large currents and greatly increases the board size. At this frequency, there are also large variations seen as the coil is scanned across an uncorroded pipe surface. These variations are caused by inconsistencies in the pipe steel and are a direct effect of the high penetration depth of 100-kHz eddy currents. Both of these problems lead to the conclusion that increasing the operating frequency would be very beneficial.

Early attempts at increasing the frequency found that the coil coupling significantly decreased until the circuit was operated in a regime where stray capacitance causes a ringing effect. By adding additional capacitance in series with the receiver coil, it is possible to control this ringing and set a resonance frequency for the circuit. The resonance circuit involves tuning the oscillator to make a coil resonate in air. Then, as the coil is moved towards a pipe, its inductance changes and the circuit detunes. This detuning results in large voltage drops, which can be measured and from which an accurate measurement can be extracted. This resonance operation is shown in Figure 9. A resonant frequency of 4.7 MHz was chosen for the final array design. The benefits of this were threefold. The higher frequency increased the reactance to nearly 50 Ohms, meaning that only one amplifier is needed. Its output is switched between coils by a set of tree'd multiplexers. As expected the single amplifier chip also lowers power requirements and board size. The higher operating frequency also reduced the surface variations because of the decreased penetration depth of only 6 microns. The lower surface noise also results in an enhanced resolution for the array system.

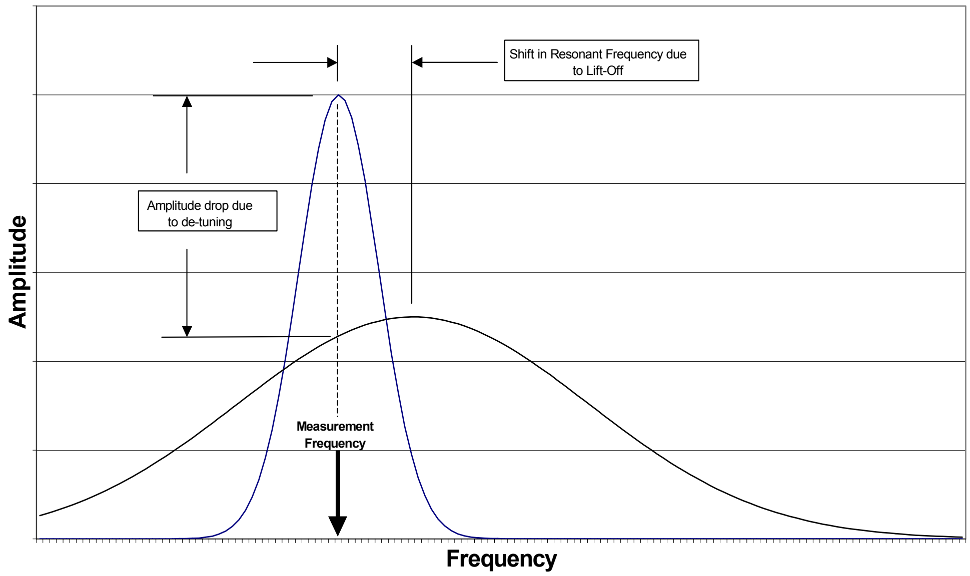


Figure 9. Resonant frequencies

The final circuit design can be seen in Figure 10. The receiver side of the board is fed from a oscillator tuned to the resonant frequency. The output of this oscillator is sent into a high-current buffer amp whose output is mutliplexed by the computer into a single coil. The receiver side of the board starts at the complementary coil, whose signal is fed through the multiplexers and into a peak detector. The capacitor controlling the resonance is attached at the peak detector's input. After being fed through the peak detector, the signal is further amplified and then sent to the computer for A/D conversion. The completed array is shown in Figure 11.

The array system also requires an interface box containing the power supply and acquisition hardware, as well as the necessary cabling. The system also requires a computer with an available USB connection.

A National Instruments E-series data acquisition device (DAQ) was purchased for the acquisition hardware. It provides 100-kS/s analog channel sampling as well as eight digital I/O lines. Four digital output lines will be used (three for channel selection and one to enable the device) and one analog input line (to sample coil voltage). The channel selection signals will switch the multiplexer output to the detection stage for transmission to the computer, so that only one channel of the 256 discrete sensor coil channels in the conformable array is active at a given instant.

3.3 Software

The conformable array software was written in LabView and performs data acquisition and analysis in real time. A screen shot of the software is shown in Figure 12.

Data are acquired through the DAQ and read into LabView as a matrix. Each pixel of the matrix represents a 4,096-point sample acquired at 50 kHz and averaged to form a single data point. A typical surface scan can be seen in Figure 13. Notice these large variations in the data.

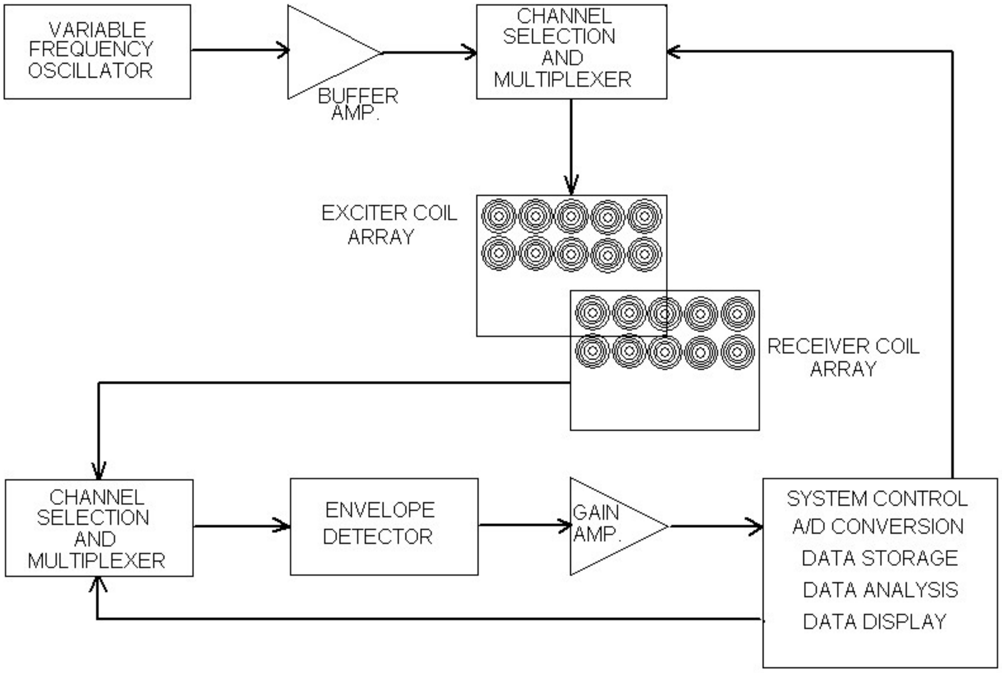


Figure 10. Data acquisition hardware schematic

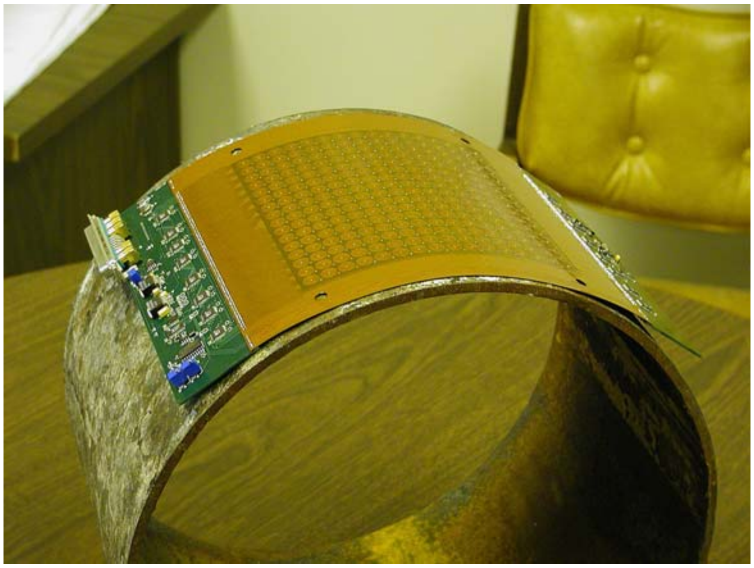
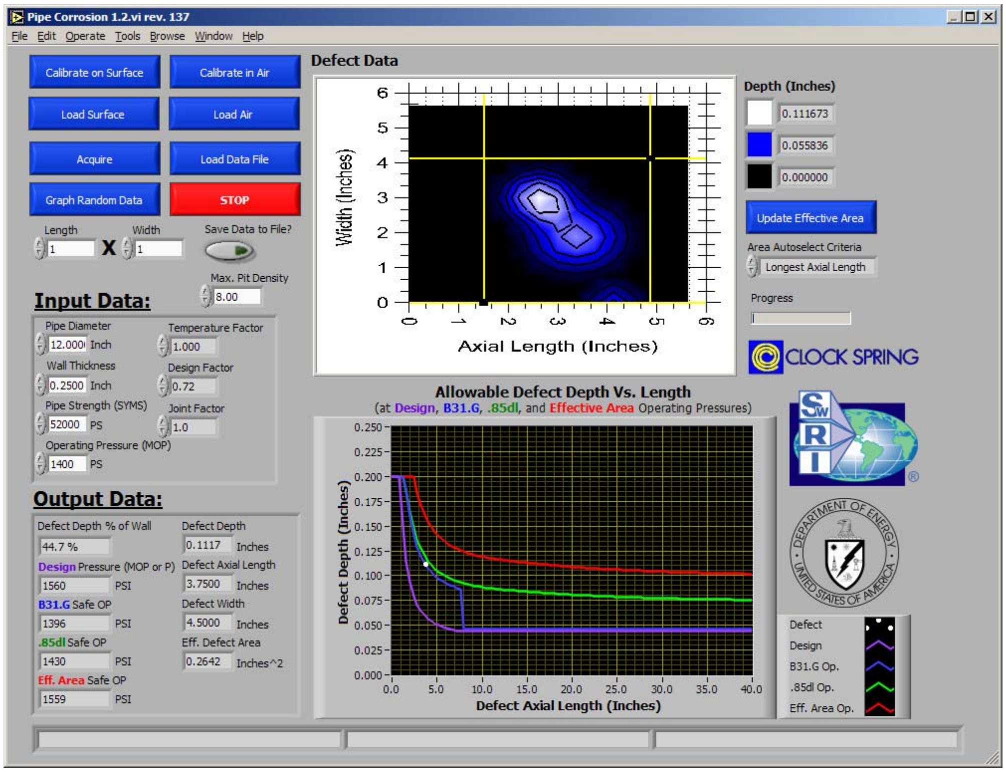


Figure 11. Array with circuit boards attached, placed on pipe specimen



Length 1 X Width 1

Max. Pit Density 8.00

Depth (Inches)

0.111673

0.055836

0.000000

Area Autoselect Criteria: Longest Axial Length

Input Data:

Pipe Diameter 12.000 Inch

Wall Thickness 0.2500 Inch

Pipe Strength (SYMS) 52000 PS

Operating Pressure (MOP) 1400 PS

Temperature Factor 1.000

Design Factor 0.72

Joint Factor 1.0

Output Data:

Defect Depth % of Wall 44.7 %

Design Pressure (MOP or P) 1560 PSI

B31.G Safe OP 1396 PSI

.85dl Safe OP 1430 PSI

Eff. Area Safe OP 1559 PSI

Defect Depth 0.1117 Inches

Defect Axial Length 3.7500 Inches

Defect Width 4.5000 Inches

Eff. Defect Area 0.2642 Inches^2

Figure 12. Sample display screen

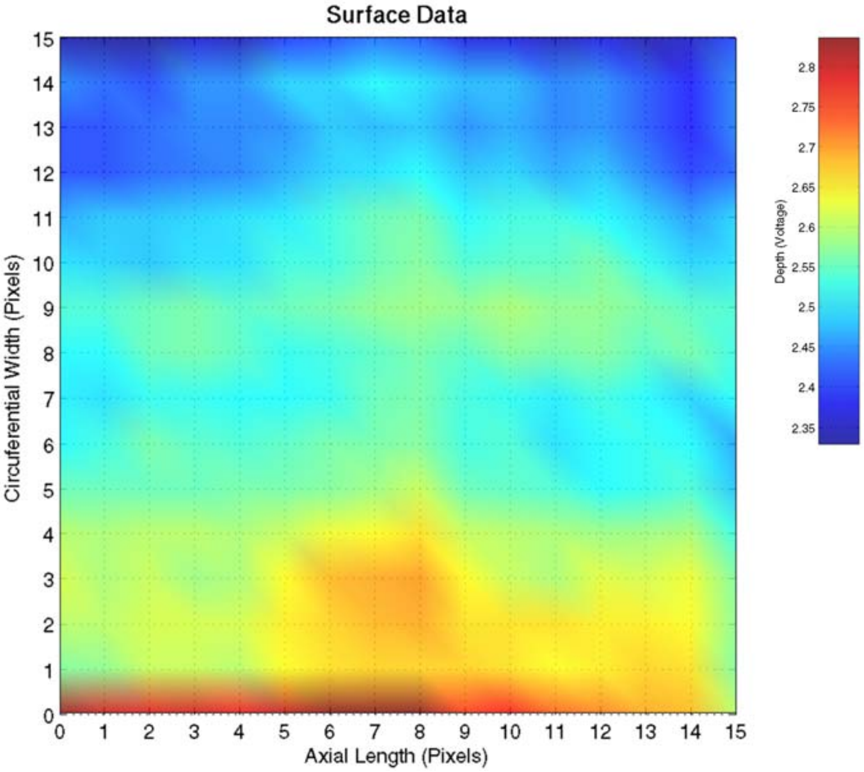


Figure 13. Typical pipe surface scan without corrosion

These arise because of resistance variations inherent in the multiplexer (vertical banding) and due to conductor length and array liftoff (horizontal banding).

While these differences are minimal, they should be removed to increase the accuracy of the array system. This normalization process is done using a standard method:

$$Norm = \frac{(D - S)}{(A - S)}$$

where D is the corrosion data, S is a surface scan, and A is an air scan. This normalization process results in data that are 0 on the surface and 1 at an infinite distance from a conductor.

The data must then be calibrated into units of inches, which is done through a linear interpolation fit to known calibration data. This process is explained in Section 3.4.

Once the data have been calibrated, the software will start an auto-boxing routine, which examines the corrosion data and creates islands of corrosion that have boundaries at a point of 10-percent wall loss. Once complete, the axial length of each island is computed, and interacting islands are grouped together. Currently, the software auto-boxes are based on one of two criteria, maximum pit depth and maximum axial length. The user can also manually select corrosion pits, but this may violate code.[1]

Once boxed, the data will be analyzed with three algorithms to determine the maximum allowable operating pressure. These algorithms are B31.G, a modified B31.G (.85dl), and effective area or RSTRENG. Explanation of the algorithms is outside the scope of this document.

This analysis allows for realtime visualization of corrosion data and decisions to be made in the field based on these results.

Once the analysis is complete, the data can be saved and loaded later either in Excel or the array software.

3.4 Calibration and Accuracy

To calibrate the array, a calibration block was designed and built. A picture of the block is shown in Figure 14, and a scan of the block is shown in Figure 15. The data acquired from this scan allow for a plot to be made of signal versus depth. This plot can be seen in Figure 16.

From these data, a linear interpolation fit is calculated and used to calibrate the acquired signals, resulting in an accuracy that is far from perfect. Future work will be aimed at better fitting this curve.

---

[1] J. F. Kiefner and P. H. Vieth, "A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe," Final Report on Project PR 3-805 to Pipeline Corrosion Supervisory Committee of the Pipeline Research Committee of the American Gas Association (Columbus, Ohio: Battelle, 1989) Section 10.8.2.2.4.

Figure 14. Calibration block

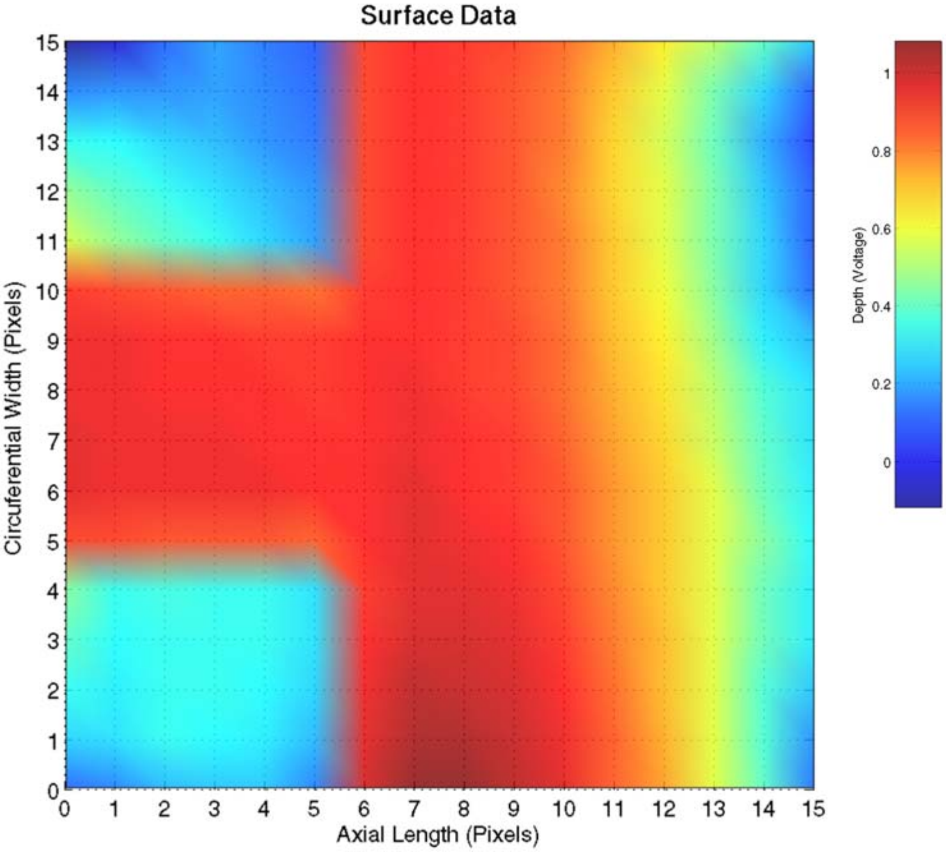


Figure 15. Data from calibration block

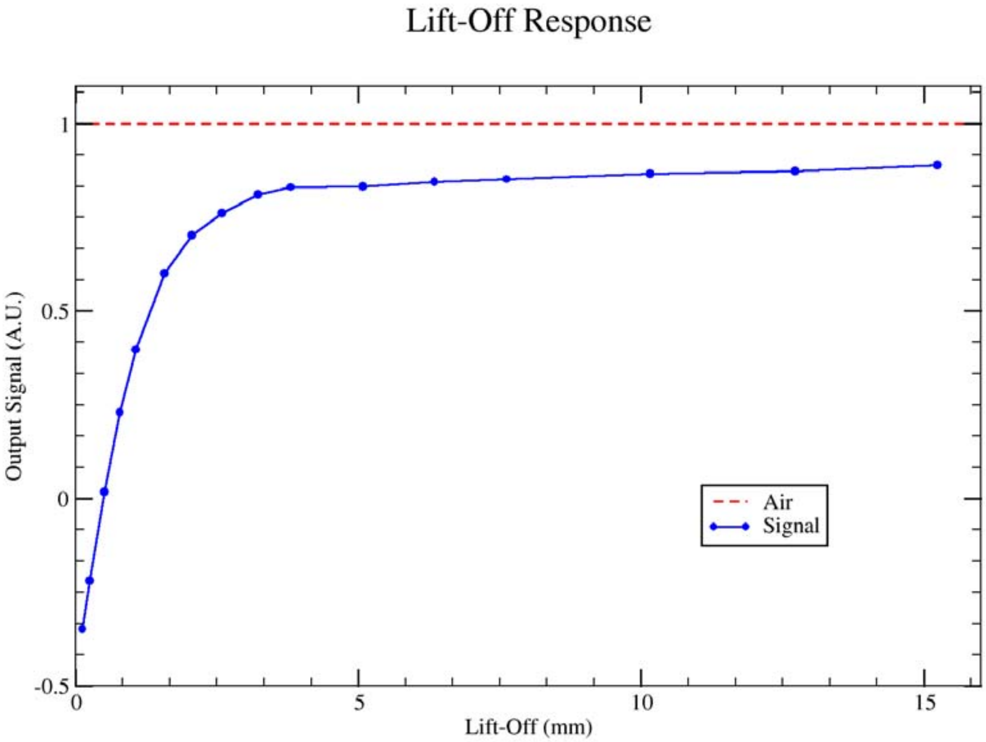


Figure 16. System liftoff response

4. RESULTS AND DISCUSSION

The prototype system can be used to measure external corrosion on the surface of a pipe that has not been thoroughly cleaned. Scan time with the present A/D circuit takes approximately 1 to 2 minutes. This time can be reduced to a few seconds, if necessary, by a different choice of A/D-computer interface.

Changes in the coil excitation-detection method made it possible to measure much deeper pits than were possible with the feasibility array.

Two corrosion assessment algorithms were implemented for processing the pit depth array data. B31.G and an RSTRENG-type calculation are both made automatically and the results displayed graphically for the operator's consideration.

4.1 Operating Procedure

The entire system (excluding laptop computer) is contained in an environment-proof case, herein referred to as the "suitcase." The suitcase contains the power supplies and data acquisition module plus storage space for the array and connecting cables. The suitcase is powered from 120 VAC.

Prerequisites for use of the system include cleaning of the pipe in the corroded area to assure that no coating or dried mud extends above the profile of the corrosion patch. Coating or mud down in the pitting is acceptable and should not affect the depth reading. Another requirement is that 120-VAC power should be available on site.

For corrosion that extends beyond the boundaries of a 150-mm square, there is a template for marking the pipe for multiple measurements. A transparent vinyl overlay with index holes is provided. The overlay is placed over the corrosion in such a position that multiple array readings can cover the whole corrosion. A paint pen is used to mark the pipe through the index holes.

The array is connected to the suitcase cable and the system power turned on. The laptop computer is connected to the USB connector on the suitcase panel. The laptop is booted up and the array software loaded and run.

The measurement array is placed on the pipe on a clean area away from the corrosion. The software command for normalization is then invoked to set all channels equal.

The array is then placed over the corrosion at the first index marks (if the corrosion takes more than one position for full coverage). The software is set up for the number of positions that will be required, and the "acquire" button is clicked. Following the on-screen prompts, the whole corroded area can be covered.

Data are merged on the screen, and either manual or automatic boxing will identify the length and width of the corrosion. The analysis will then be performed and maximum allowable operating pressures will be calculated, thereby allowing immediate action to be taken on the pipeline.

4.2 Field Testing

There were two components to the field tests, an initial test at SwRI and a subsequent test at the RTD Quality Services facility in Houston.

4.2.1 SwRI Field Test

After successful completion of the laboratory work, a prototype system was assembled to try the conformable array in the field. The first field measurement was made on a corrosion test specimen on the SwRI campus. A 24-inch-diameter pipe specimen from another project contains two external corrosion defects. The conformable array system was taken to this pipe specimen and used to map the two corroded areas. Figure 17 shows the “suitcase” used to transport and control the array.

There is also room in the suitcase lid for storing the conformable array PC board. For the SwRI measurements, the system was deployed from the trunk of a car, as shown in Figure 18. Approximately 10 m of connecting cable is provided between the control station and the pipe. This will allow the operator to position the system controls outside the bell hole in a field setup. For this test, the array was held onto the pipe surface by a strap and resilient pad, as shown in Figure 19.

In addition to the control box, the only other needed component is the laptop computer to operate the system and store the scan data. Figure 20 shows these components deployed in the car trunk.

Note in Figure 21 that the array is flexible enough to conform to the pipe surface without strapping. The strap and resilient pad are insurance to keep the liftoff to a minimum over the uncorroded pipe. The two corrosion defects are pictured in Figures 22 and 23, along with the conformable array data display. The display shows a map of the corrosion plus results of B31.G and RSTRENG-type calculations that indicate the maximum safe operating pressure for the defective pipe.

Figure 17. Control panel and cable storage in conformable array suitcase

Figure 18. Array deployment

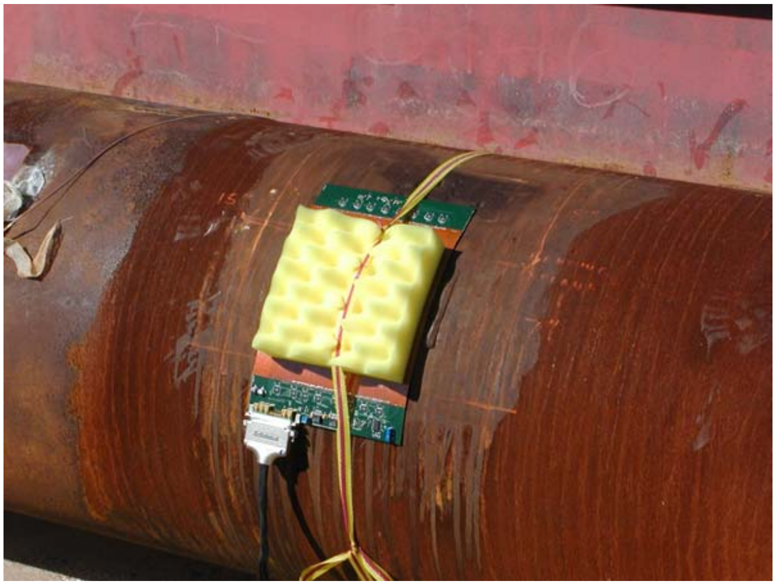


Figure 19. Array board held on pipe for measurement

Figure 20. Control box and laptop computer deployed in the trunk

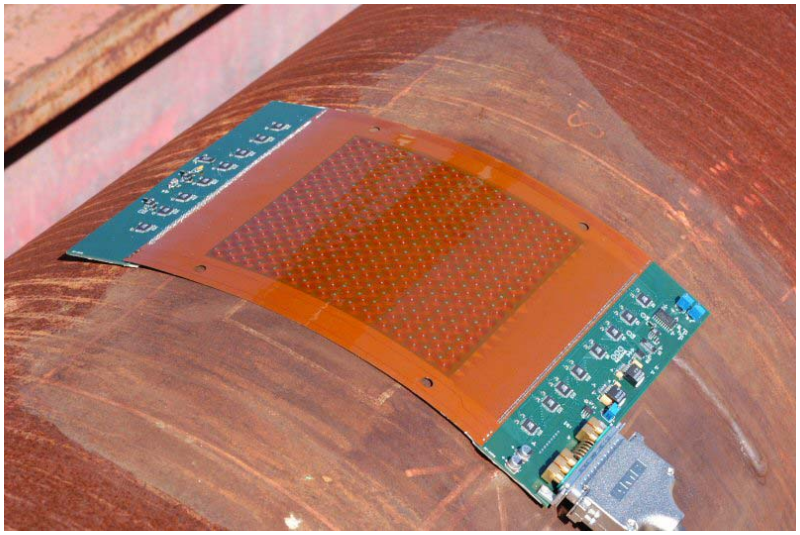
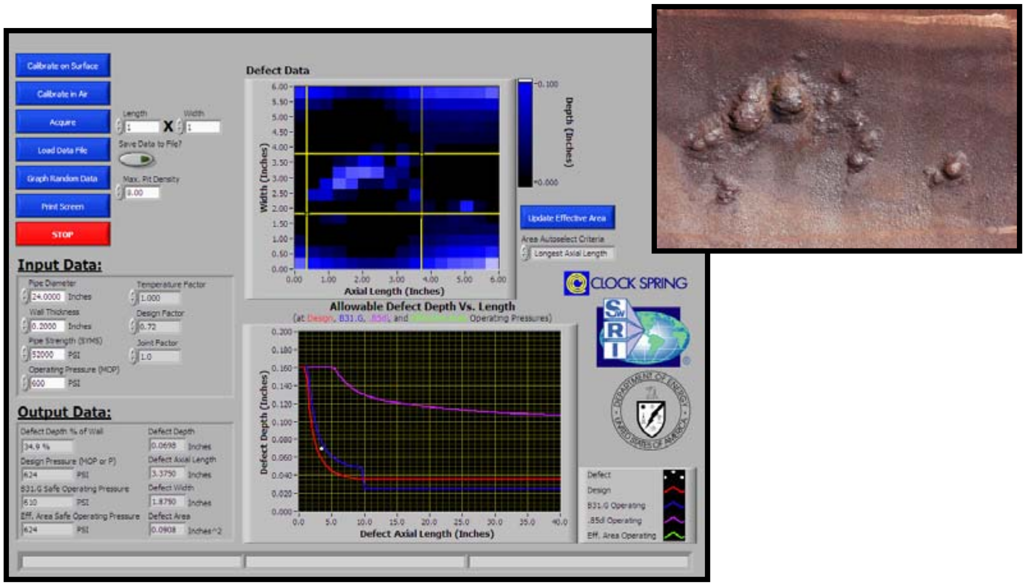


Figure 21. Conformable array on corroded pipe specimen



Length 1 X Width 1

Save Data to File?

Max. Pit Density 8.00

Input Data:

Pipe Diameter 24.0000 Inches

Wall Thickness 0.2000 Inches

Pipe Strength (SYMS) 52000 PSI

Operating Pressure (MOP) 600 PSI

Temperature Factor 1.000

Design Factor 0.72

Joint Factor 1.0

Output Data:

Defect Depth % of Wall 34.9 %

Design Pressure (MOP or P) 624 PSI

B31.G Safe Operating Pressure 610 PSI

Eff. Area Safe Operating Pressure 624 PSI

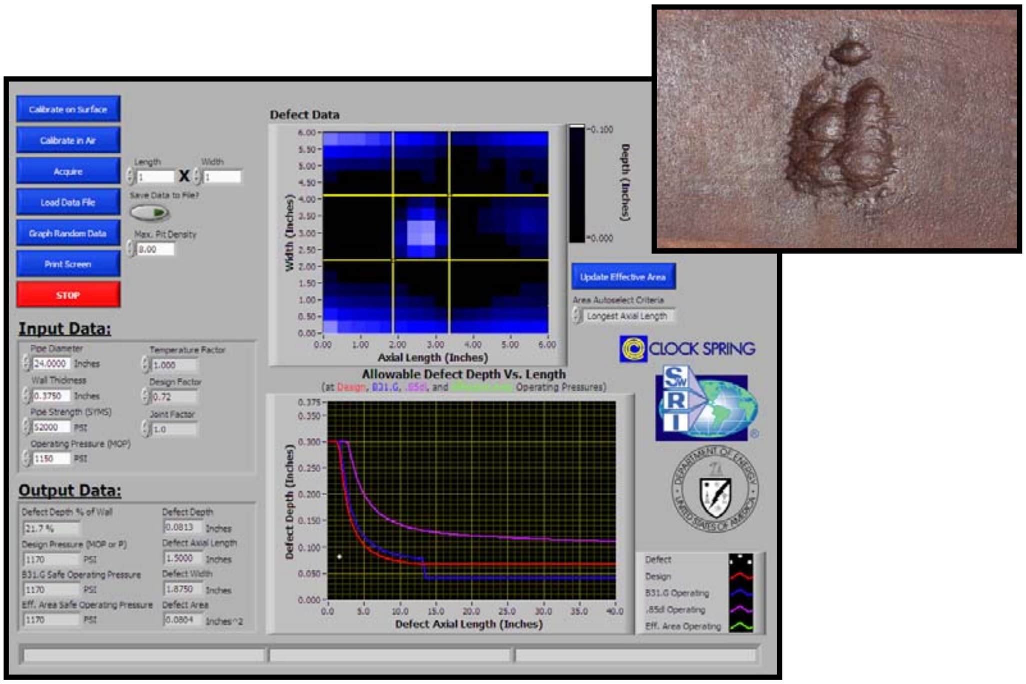
Defect Depth 0.0698 Inches

Defect Axial Length 3.3750 Inches

Defect Width 1.8750 Inches

Defect Area 0.0908 Inches^2

Figure 22. Data output for cluster of pits. Photo of defect is included.



Length 1 X Width 1

Save Data to File?

Max. Pit Density 8.00

Input Data:

Pipe Diameter 24.0000 Inches

Wall Thickness 0.3750 Inches

Pipe Strength (SYMS) 52000 PSI

Operating Pressure (MOP) 1150 PSI

Temperature Factor 1.000

Design Factor 0.72

Joint Factor 1.0

Output Data:

Defect Depth % of Wall 21.7 %

Design Pressure (MOP or P) 1170 PSI

B31.G Safe Operating Pressure 1170 PSI

Eff. Area Safe Operating Pressure 1170 PSI

Defect Depth 0.0813 Inches

Defect Axial Length 1.5000 Inches

Defect Width 1.8750 Inches

Defect Area 0.0804 Inches^2

Figure 23. Isolated pit together with photograph of defect

4.2.2 Test of BP Specimen

Our commercializing partner, Clock Spring Company, arranged for evaluation of the conformable array on a corroded pipe specimen belonging to the BP Company. This 20-foot pipe joint was at the RTD Quality Services facility on Rockley Road in Houston. The pipe joint is shown in Figure 24.

Of primary interest on this pipe was a 12-inch (305-mm) by 24-inch (610-mm) corroded area shown in Figure 25. Note that 6-inch-square contiguous areas have been drawn on the pipe to outline the eight separate areas to be scanned by the array.

To facilitate the alignment of the array, a transparent template was made with holes for marking index marks onto the pipe surface. Figure 26 shows the template in place on the pipe surface. Holes properly placed in the template are used to mark spots on the pipe where the corresponding holes in the conformable array are positioned. These holes make the array coils fall in exactly correct position for seamless stitching of the data from multiple scans.

In order to provide some level of calibration of the array, baseline readings can be taken from a smooth section of pipe, as shown in Figure 27. The baseline data can be used to normalize the response from the different coil channels. It also can be used with multiple scans to set the lower limit of accuracy due to pipe material variations.

After the baseline scans are recorded, the array is moved to the marked corrosion sections, which are scanned in sequence. The number of separate areas is entered into the system controller, and then prompts are provided for shifting from one to the next. At each area, the array is held firmly to the pipe surface, as shown in Figure 28.

System operation is monitored and controlled from the notebook computer, which is connected to the suitcase unit within 15 m of the array. The control station is shown in Figure 29.

After the eight corrosion areas were scanned and the data stitched together, it was ported to Excel for plotting. An Excel graph of corrosion depths is shown in Figure 30. Comparison between the RTD laser scan and the conformable array is shown in Figure 31.

Note the close correspondence of these two images. This is very encouraging evidence that the conformable array is reporting critical information about corrosion depth. The fact that it can do so quickly and affordably is an additional attractive feature.

Figure 24. BP test pipe in RTD facility

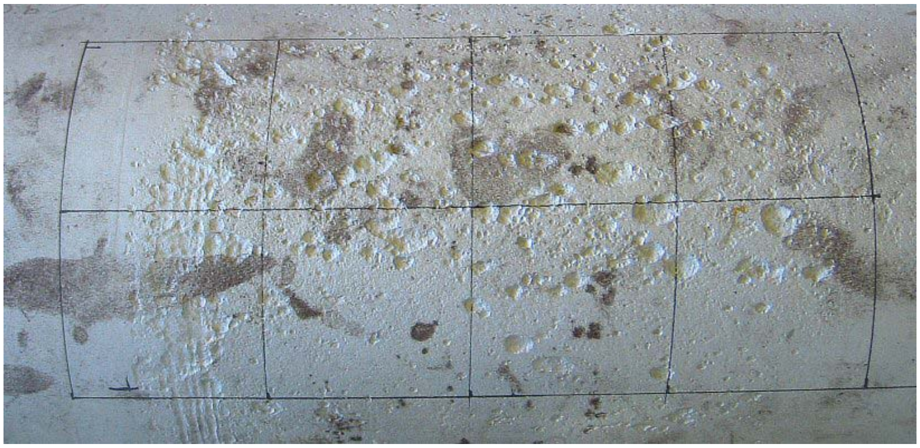


Figure 25. Corrosion test area on BP pipe specimen

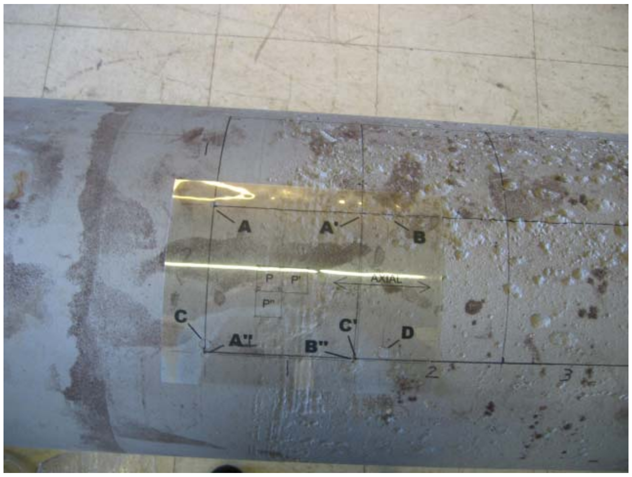


Figure 26. Template in place for marking array positions over contiguous corrosion areas

Figure 27. Baseline scans are taken on a smooth section of pipe surface

Figure 28. Contiguous areas are scanned in sequence under prompting from system software

Figure 29. Laptop and suitcase may be conveniently located anywhere within 15 m of the pipe

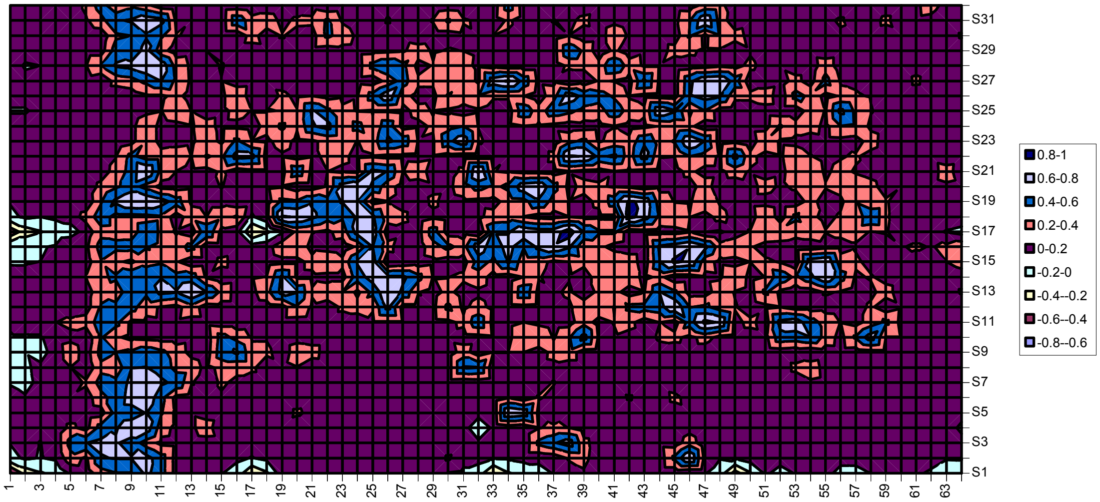


Figure 30. Conformable array graph of corrosion depths from 12-inch (305-mm) by 24-inch (610-mm) area on BP specimen

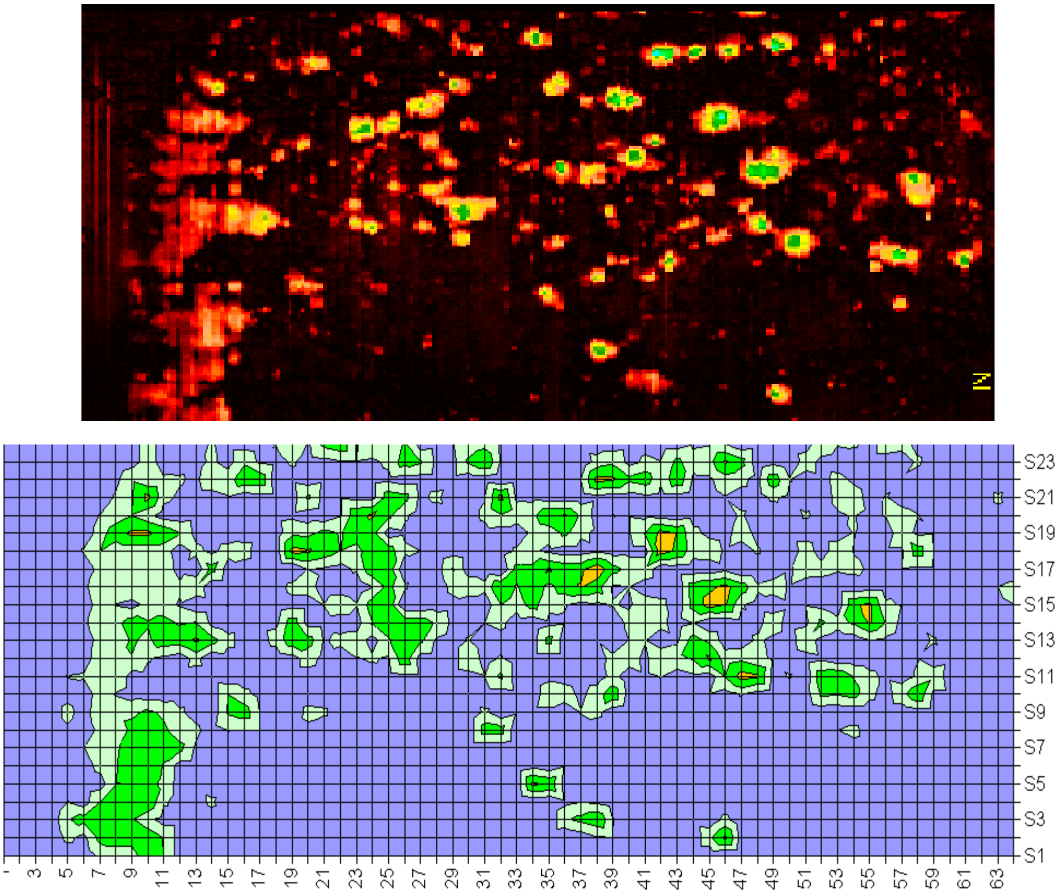


Figure 31. Comparison of RTD laser scan (top) and conformable array (bottom)

4.3 Follow-On Work

4.3.1 System Enhancements

The current conformable array system was designed to use National Instruments hardware. This decision was made to speed development work and lessen the chances of having a bug in the A/D hardware, but adds to the final array cost, increases the unit size, and requires AC power. Tests on the current system showed that DC power use was under 1 Watt and suggested that a future system design could be powered solely by the computer. A microcontroller with built-in A/D converter could be added to the array circuit board as well as a USB interface chip. These two chips, with an additional power inverter, should allow the array to be run solely off the computer's USB connection, thereby allowing the system to be truly portable. A side effect of these new chips would be that the system could acquire data samples in under 3 seconds and, with lower averaging, could display video frame rate data.

Other enhancements could be made to the calibration procedure. The measured calibration curves are not well understood, and further time should be spent characterizing them. This should allow for very accurate defect measurements.

4.3.2 Commercialization

The progress reached in this project will support a decision to proceed to a production design phase. The production design will incorporate some, if not all, of the enhancements described in Section 4.3.1. The authors of this report estimate that the production design will require new funding on the order of $100,000.

Commercialization has been assigned to the initial co-funder of the reported work, Clock Spring Company of Houston, Texas. Clock Spring is well positioned to market this product. They provide pipe remediation services to the pipeline industry with their Clock Spring composite banding. These bands are applied to return hoop strength to corroded pipe. It is logical and consistent that Clock Spring also provide an appliance for measuring corrosion and determining what remediation is recommended.

There are several modes of potential commercial use of the conformable array. First, the array may be offered as a saleable product. The cost of manufacture should be low enough that the system could be offered as a purchased product for a price that individual pipeline maintenance districts could afford. The array could be sold either with or without a laptop computer. Second, the array could be held by Clock Spring and its use offered as a service to the pipeline industry. Third, the array could be marketed by Clock Spring to a third party who would provide the service to pipeline companies. A company such as RTD Quality Services would be able to fulfill that role. Which mode of commercialization that is ultimately used will be up to Clock Spring Company.

5. CONCLUSION

The related prior project showed that it was feasible to use a multilayer printed array of eddy current coil pairs to map the depth profile of external pipeline corrosion. This project used the results of the earlier one to design and fabricate a new array and the associated electronics and software.

Enhancements in the measuring method made it possible to measure a much greater depth range than with the feasibility approach. The system, with its successful application to field corrosion, is now ready for commercialization. The only remaining task is to produce a commercial design that can be replicated for a cost that will be attractive to the market.