CONFORMABLE ARRAY FOR MAPPING CORROSION PROFILES

Final Report
August 21, 2001–November 21, 2002

Prepared by

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November 2002

DOE Contract No. DE-FC26-01NT41153
SwRI® Project 14.04996

Prepared for

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

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Written by	*Approved by*
______________________	______________________
Alfred E. Crouch	Glenn M. Light, Ph.D.
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ABSTRACT

This report describes work to determine the feasibility of a new method for field measurement of external corrosion on pipelines. The method used an array of spiral-shaped eddy current coils to map the corrosion contours using the eddy-current liftoff response. Laboratory work described in the report includes experiments to select coil size, coil spacing, and excitation frequency. The selected array parameters were used to fabricate two breadboard arrays, which were used to collect data from a machined pit plate as well as several steel pipe coupons containing natural corrosion. It was concluded from this project work that it is feasible to use a flexible array of eddy current coils to measure external pipeline corrosion in the field, as envisioned at the start of the project.

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EXECUTIVE SUMMARY

This report describes work to determine the feasibility of a new method for field measurement of external corrosion on pipelines. The report describes methods currently in use and points out the relative advantages of the proposed method. Current methods include an extension gage with bridging bar, laser range finding, and ultrasonic scanning. The proposed method will use an array of spiral-shaped eddy current coils that will map the corrosion contours using the eddy-current liftoff response. Data display will be a color contour map on which the operator will be able to select pit regions for application of assessment calculations.

The laboratory work in support of this feasibility investigation included experiments to select coil size, coil spacing, and excitation frequency. Also evaluated was the choice of single coils versus exciter-receiver pairs. The results of the laboratory work suggested that the design should have the following characteristics: coil pairs using spiral coils in the range of 6 to 10 mm in diameter, excitation frequency of 100 kHz, coil spacing in the same range as the coil diameter, and isolated connections to the individual array elements to avoid sneak-path problems.

A steel test plate was designed and fabricated to test the response of all the candidate coils and operating parameters. The plate contains multiple rows of spherical-section machined pits. All pits in a single row have the same surface diameter, but different depths. Pit surface diameters varied from 6 mm to 25 mm. Depths varied from 1 mm to 12 mm. Using a computer-driven scanner, it was possible to scan a row of pits of constant diameter and observe the effects of changing pit depth.

The selected array parameters were used to fabricate two breadboard arrays, a small one with 4.3-mm-diameter coils and a larger one with 7.1-mm-diameter coils. These arrays were used to collect data from the machined pit plate as well as several steel pipe coupons containing natural corrosion. The report shows pipe coupon data from one array, displayed as a color contour map.

It was concluded from this project work that it is feasible to use a flexible array of eddy current coils to measure external pipeline corrosion in the field as envisioned at the start of the project. A field-worthy array was not planned as part of this project, but follow-on work has been approved to fabricate such an array in a separate 12-month project. This project's cofunding partner, Clock Spring Company, L.P., will participate in that project as well and plans to commercialize the array after successful demonstration of the field version.

1. INTRODUCTION

The objective of this project was to determine the feasibility of measuring external pipeline corrosion with an eddy current array in a flexible form that could be wrapped around the pipe and scanned electronically without extensive operator involvement. If multiple coils could be provided in a wrap-around sheet, then conceivably an entire corrosion patch could be measured in a single setup. Scanning and multiplexing circuitry could be used which would activate one coil at a time and record the measurement data before moving to the next coil. In a reasonably short time, then, a significant area could be covered.

1.1 Corrosion Defect Assessment Algorithms

In the late 1960s, pipeline operators were faced with both an aging infrastructure and the development of inspection technologies that could detect corrosion or other wall loss defects in the body of the pipe. Methods were required to predict the remaining pressure strength of pipelines containing defects. The experimental work done by Battelle Memorial Institute and the report “Summary of Research to Determine the Strength of Corroded Areas in Line Pipe,” July 10, 1971, was the result of this industry need.

ASME subsequently published the work in 1984 as the B31G “Manual for Determining the Remaining Strength of Corroded Pipelines” that supplements the B31 Code for Pressure Piping. This manual provides the primary assessment tool for external defects found in pipelines and is typically the approach embedded in the codes. (Analyses that are more complex are allowed and typically reference “acceptable engineering assessment” or words to that effect). B31G requires the user to input pipe attributes of diameter, wall thickness, and grade. After operating conditions of maximum operating pressure (MOP) and design factor are entered, the user must enter basic defect information. This assessment requires only the defect depth and the axial length. Based on the information provided, a safe pressure can be calculated as well as maximum defect depth for a given length and maximum length for a given depth. B31G provides a conservative assessment.

A modified version of this defect assessment tool was introduced in the mid- 1990s. This method is generally referred to as RSTRENG (Remaining Strength). The RSTRENG criterion was developed to address the conservatism embodied within B31G and provides a more accurate assessment of a corroded area. This assessment tool requires more accurate defect profiles and uses less conservative values for specified minimum yield stress (SMYS) and the Folias factor. The defect must be measured on an established grid to provide depth vs. axial position information. This then allows a “river-bottom” profile to be developed that in turn can provide a less conservative assessment of the defect.

As integrity programs and defect assessment evolved, it became apparent that defects in close proximity to each other must be considered. Rules had to be established to determine the full axial and circumferential extent of multiple defects separated by a thin ligament of sound pipe. These interaction rules vary slightly from code to code. Canadian Standards Association Z662–89, “Oil and Gas Pipeline Systems,” provides a typical definition of interaction:

> “Corroded areas in close proximity shall be considered to interact if the distance between them is less than the longitudinal length of the smallest defect.”

If defects are found to interact, then they are considered a single defect, and the axial extent or length of the defect shall be the full length measured axially along the pipe. Measuring the defect is an important requirement of any assessment technique.

1.2 State of the Art in Corrosion Measurement

Several approaches to the problem of field measurement of corrosion have evolved. The simplest type of corrosion is a single isolated pit. Field measurement of an isolated pit can be accomplished with a scale. The scale can be used directly to measure the length of the corroded area. An extension gage (pit gage) can be placed over the pit (assuming the base of the gage is broader than the pit) and the pit depth read and recorded. Typically, only the maximum depth is recorded. A more complicated case is that of several overlapping pits or a corroded patch. In this case, the length can still be read from a scale, but the pit gage may not span the corroded patch to rest on the pipe surface, so the depth measurement will not be correct. In this case, a bridging bar is often used. The bar is long enough to span the corrosion area and provide a pipe surface reference from which a depth gage can measure the corrosion depth. A field deployment of a bridging bar is shown in Figure 1.

When the corrosion is extensive, it is not always obvious from visual inspection which location is the deepest, or which path is the correct river-bottom track. In those cases, a grid on the pipe surface is often employed to help construct a map of the corrosion. A rectangular pattern of measurement points on a uniform spacing is painted onto the pipe surface, including the corroded area. A bridging bar or ultrasonic probe is used to make measurements at each grid node. From this array of measurements, either manual or computer-aided processing may be used to construct a corrosion map. All of these manual methods are laborious and time-consuming. It can take most of a day to make all the grid measurements on a corrosion patch. Furthermore, rain, cold, and other inconveniences can take a toll on operator attention and the resulting accuracy of measurement. This is particularly true if the corrosion patch is on the bottom of the pipe. So, there has been industry interest in automating the measurement process.

Figure 1. Bridging bar with dial depth gage

Two solutions that will be described here are the Edison Welding Institute's laser range-finding system marketed by RTD and an ultrasonic aid marketed by the Integrity Assessment Pipeline Group (IAPG). Either of these systems will automatically scan a corroded area and collect very accurate data of the corrosion depth.

The laser system, marketed under the name LPIT, is shown in Figure 2. The LPIT provides probably the most accurate depth measurements possible with an automated system. Further, it collects data on a very high-resolution grid, yielding a very detailed description of the pitted surface. In addition to these very positive aspects of the laser gage, there are some characteristics of its operation that need to be carefully considered by the user. First, the pipe surface needs to be quite clean. Any dirt or residual pipe coating will cause the measurements to fall short of the true depth. In addition, the apparatus will require some care in its use in awkward locations such as on the bottom of a pipe.

Figures 3 and 4 from SwRI laboratory measurements show that the laser gaging method can provide a very descriptive display of a corroded area on a pipeline.

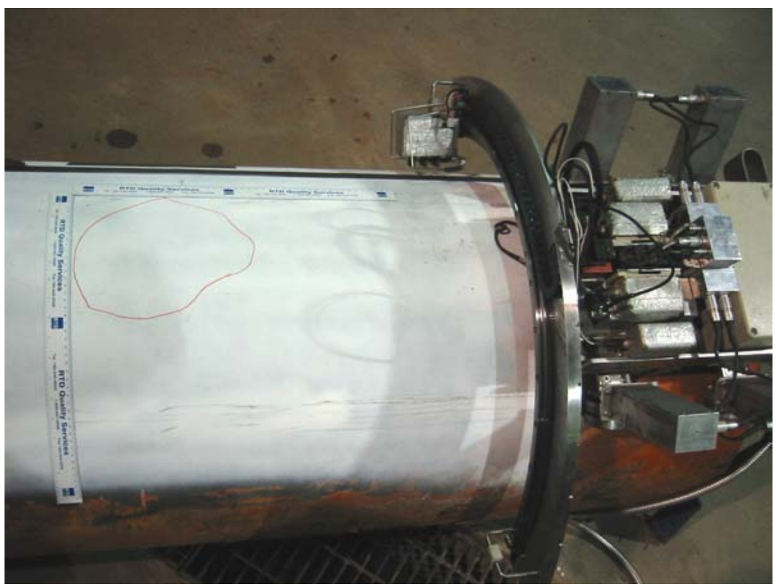

Figure 2. LPIT laser gage for corrosion mapping

Figure 3. Photograph of corrosion patch coupon

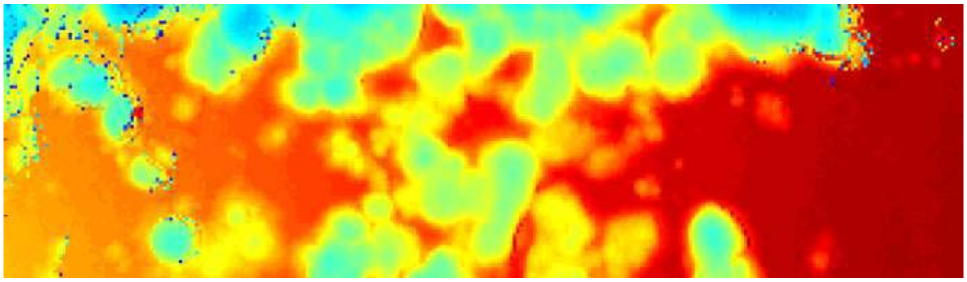

Figure 4. Laser map of corroded surface

IAPG's Advanced Digital Ultrasonic Mapping (ADUM) is an ultrasonic system that can map internal or external corrosion on a predetermined high-resolution grid. The advantage of the ultrasonic approach over the laser is the ability to measure far-surface (internal) defects. Figure 5 shows the ADUM clamped onto a pipe. IAPG offers training for the use of the ADUM and supports its operation. A wide range of software is available to implement several assessment methods directly from the ultrasonic data.

While the proposed conformable array will not match the above systems in resolution and precision of measurement, it is expected to be adequate for B31 and RSTRENG calculations. Additionally, it should be simple and rugged enough that pipeline maintenance personnel could use it in the "pipeline ditch" environment in a wide range of ambient conditions. Further, the target price of the conformable array system will make it practical to have units at pipeline district maintenance facilities.

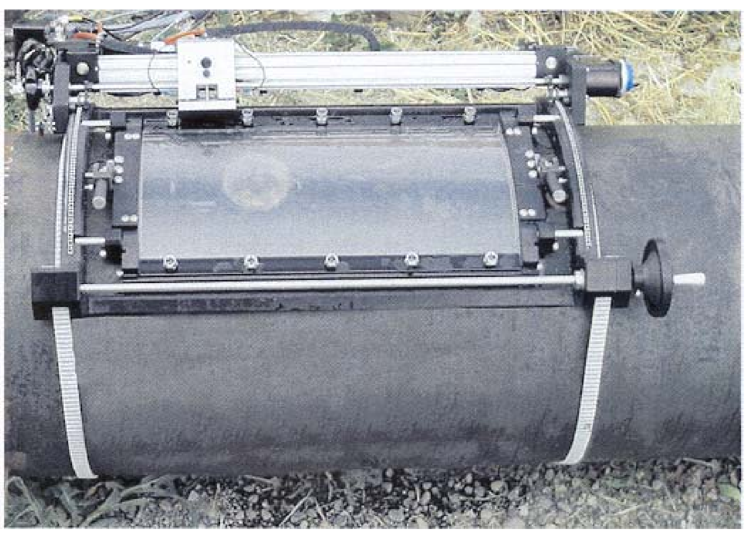

Figure 5. Advanced Digital Ultrasonic Mapping (ADUM) system

1.3 SwRI Background

SwRI has developed specialized eddy current test (ECT) probes for displacement measurement applications. One application involved the use of very small coils [e.g., 1.5 mm (0.06 inch) diameter] for the dynamic measurement of small gaps between automotive engine pistons and cylinder walls. A second application was a probe that measures the height and orientation of a second flaw detection probe above a surface. This was used to keep the proper probe orientation and position as the probe was scanned with a robotic device.

The displacement measurement technology can, in principle, be used for corrosion depth measurement; however, the systems are intended for flat test piece surfaces. The accuracy will be affected when the surface is irregular.

1.4 NYGAS Graphitic Corrosion Measurement

SwRI was approached by the New York Gas Group (NYGAS) to help produce a device to measure graphitic corrosion in cast iron gas mains. Graphitic corrosion leaves a brittle deposit in pits in the cast iron. The deposit is nonmetallic and has no significant strength. Visual inspection cannot tell how extensive the corrosion is, so it is difficult to make a decision about repairing or replacing the pipe. In SwRI's investigation of electromagnetic methods to determine corrosion depth, it was discovered that there was already a single-coil hand probe on the market in Japan. SwRI acquired this device and redesigned the sensing coil to improve its ability to accurately measure small pits. The redesign was based on earlier work that SwRI had done on another inspection system. The modification was successful.

1.5 Clock Spring Company, L.P.

Cofunding was provided by SwRI's industrial partner, Clock Spring Company, L.P., of Houston, Texas, who manufacture composite repair and reinforcement systems for pipelines. "Clock Spring®" refers to a family of related fiber glass-and-resin matrix products used to repair blunt defects in pipes or arrest ductile fractures in high-pressure gas pipelines. The system operates by transferring the hoop stress from the defect, through high compressive strength filler, to the composite sleeve wrapped around, and bonded to, the pipe.

Clock Spring Company, L.P., felt that the conformable array, if it were successful, would be a good addition to their product line. Accordingly, they contributed both cash and in-kind work to this project.

2. BACKGROUND

2.1 Eddy Current Basics

If a coil of wire (Figure 6) carrying an alternating current is placed near an electrically conductive material, the magnetic field from the coil will cause currents to flow in the conductive material in a reverse direction to those in the coil, as shown in Figure 7.

The magnitude and phase of these secondary currents are influenced by the geometry of the arrangement (which includes the spacing between coil and conductive material) and the conductivity and magnetic permeability of the part. 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. Figure 8 illustrates such a coil pair.

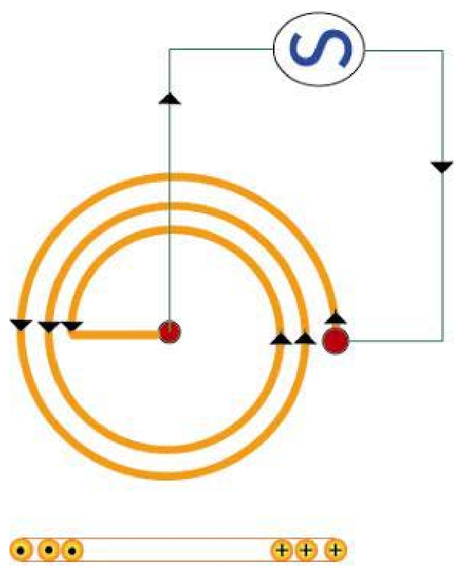

Figure 6. Spiral eddy current coil

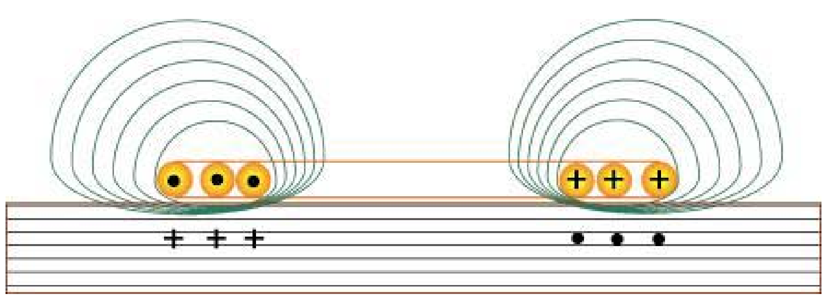

Figure 7. Reaction currents generated in conductive workpiece

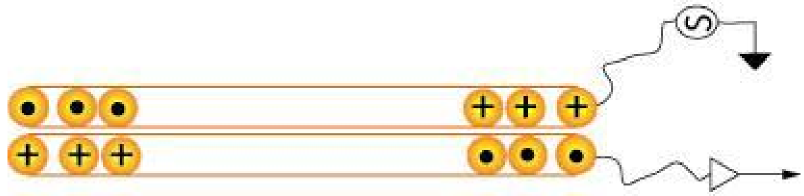

Figure 8. Two-coil eddy current configuration

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. (See the double arrow in Figure 9.) When the coil is close to the test piece, the coupling is strong and 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 10. Similar approaches have been investigated by scanning a single coil to map the surface or find the maximum depth.

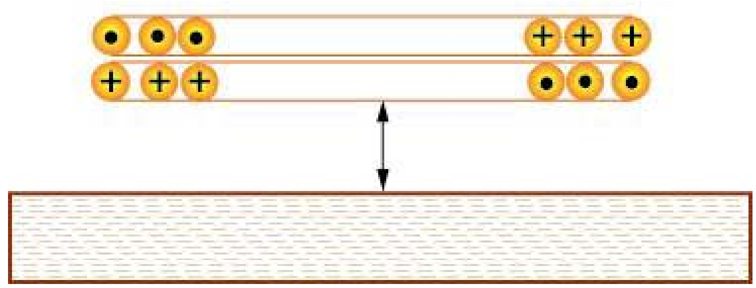

Figure 9. Two coil arrangement and definition of liftoff

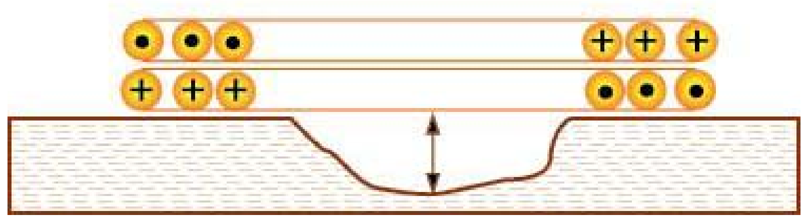

Figure 10. Coil pair measures pit depth using liftoff signal

With suitable instrumentation and signal processing, the coil-to-workpiece spacing can be measured. This "liftoff" carries information about corrosion depth, so the liftoff signal component is the one that is retrieved.

The approach used in this project was to use an array of ECT probes to map the corrosion over a relatively large area without the need to perform extensive scanning of a single probe. By employing a flexible substrate for mounting the probes, the substrate can be flexed to conform to the original pipe surface, and the localized corrosion depth can be measured with respect to the probe substrate at each probe position. By using printed circuit techniques, a flexible coil array can be produced relatively inexpensively.

3. WORKSCOPE

3.1 Task List

The following tasks were part of this program.

3.1.1 Research Management Plan

A work breakdown structure and supporting narrative were developed that concisely addressed the overall project, as set forth in the agreement. A concise summary of the technical objectives and technical approach for each task and. where appropriate, for each subtask, was provided. Detailed schedules and planned expenditures for each task, including any necessary charts or tables, and all major milestones and decision points, were provided.

3.1.2 Determine State of the Art

Examine previous eddy current systems—There has been a significant amount of work done at SwRI with eddy current inspection technology. Many different sensor types have been developed for various purposes, including measurement of pit depth. Those previous projects were reviewed to determine applicability to this project. An on-line search was also conducted to determine if related work had been done by others, or if patents may have been awarded for this application.

3.1.3 Parameter Determination

Determine minimum sensor size and accuracy—The ability to measure the depth of a small-diameter pit with an eddy current coil depends on the diameter of the measuring coil. A design goal of minimum pit diameter was established and then the required coil size determined. Experiments were performed to determine how the depth measurement accuracy varied with pit size and whether that accuracy was sufficient for corrosion assessment methods.

***Determine data acquisition requirements*—**In order to measure a corrosion patch, the array of eddy current sensors should ideally be larger than the patch. This may require as many as 100 separate eddy current sensor coils in the array. Connection to the coils must be made in a way that a scanning or multiplexing circuit can record their outputs quickly and store the data for analysis. This subtask was to determine what type of switching circuit would be used and what its operating parameters would be.

3.1.4 Design and Fabricate Breadboard Array

Lay out sensor printed array—Computer-aided drafting was used to lay out the printed array.

Fabricate and check out array—SwRI has in-house printed circuit fabrication capability, but the line widths and spacing required on the eddy current array required a precision that pushed the capability of the in-house shop, so it was decided to go outside to fabricate the boards.

Assemble interface electronics—The required electronics included an oscillator driver for the array and a multiplexing system to handle the coil signal outputs. The electronic complement for this project was assembled as much as possible from laboratory instruments. The project budget did not permit design and fabrication of custom circuitry.

3.1.5 Evaluate Array on Laboratory Specimens

Scan selected corrosion specimens—SwRI had been given, by a gas pipeline company, a number of corrosion coupons cut from defective line pipe. They span the range from isolated pits to general corrosion in depth range from almost zero to 100 percent of the wall.

Using the breadboard array and assembled instrumentation, SwRI scanned selected specimens to test the operation of the eddy current array. Already on hand were laser scans of several of the specimens to serve as comparison to the eddy current measurement.

3.1.6 Specify Display Software

Determine display approach—Even though the primary function of the conformable array is to create a data file that can be input into an assessment algorithm, it was anticipated that a display of the system output would be needed for operator feedback and to save as a visual permanent record. This subtask considered the basic parameters of the display approach.

Specify software requirements—This subtask was not addressed, but was deferred to the follow-on project.

3.1.7 Project Management and Reporting

Reporting and presentations—SwRI produced the required reports on the DOE reporting schedule. With DOE concurrence, the project team also made the industry aware of progress through papers and technical presentations at industry conferences, including a paper at the 2002 International Pipeline Conference in Calgary, Canada.

Documentation for technology transfer—Once the eddy current sensor design had been finalized and the SwRI prototype array fabricated, SwRI made all the design specifications available to Clock Spring Company, L.P., who was slated to be a continuing partner to this work.

3.2 Schedule

The project term was 12 months with an additional 3-month no-cost extension.

3.3 Personnel

The project was carried out by SwRI with participation of Clock Spring Co. Project Manager was Al Crouch, Principal Investigator was Gary Burkhardt, and Clock Spring Company, L.P., Investigator was Patrick Porter.

4. EXPERIMENTS WITH RESULTS

4.1 Frequency Selection

Laboratory work was performed to determine the response of a small coil to the liftoff from external corrosion. The coil is a hexagonal spiral made by photo etching a conductive layer on a nonconductive substrate. Figure 11 shows the coil. First it was placed on a flat steel plate and moved to different amounts of liftoff by inserting nonmetallic shims between the coil and the plate. Figure 12 through Figure 15 show how the coil electrical impedance changes with liftoff for four different test frequencies.

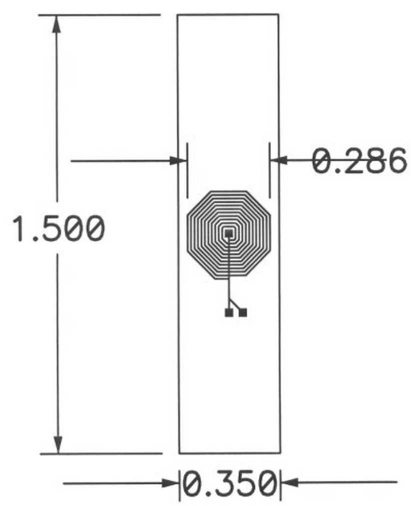

Figure 11. Printed circuit test coil (dimensions in inches)

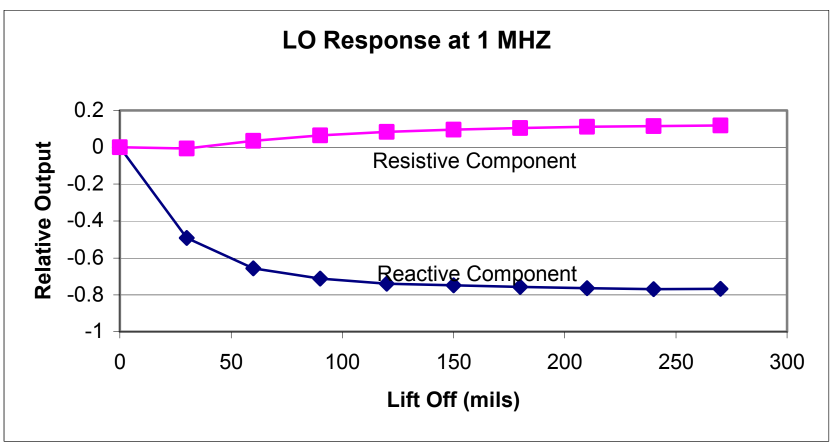

Figure 12. Liftoff signal response at 1 MHz

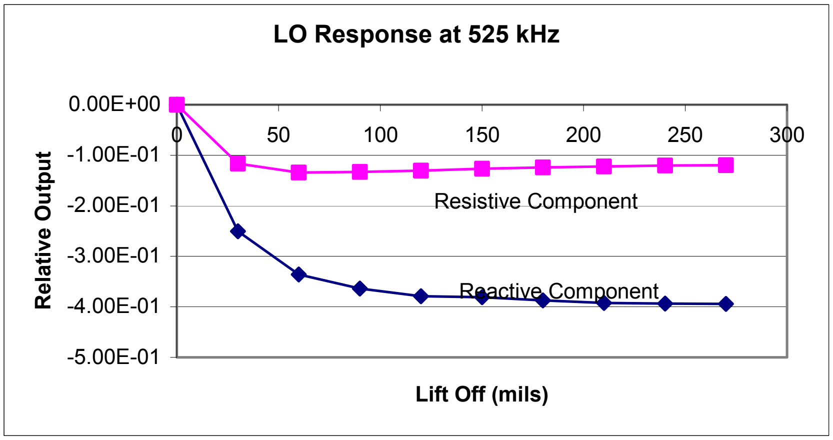

Figure 13. Liftoff signal response at 525 kHz

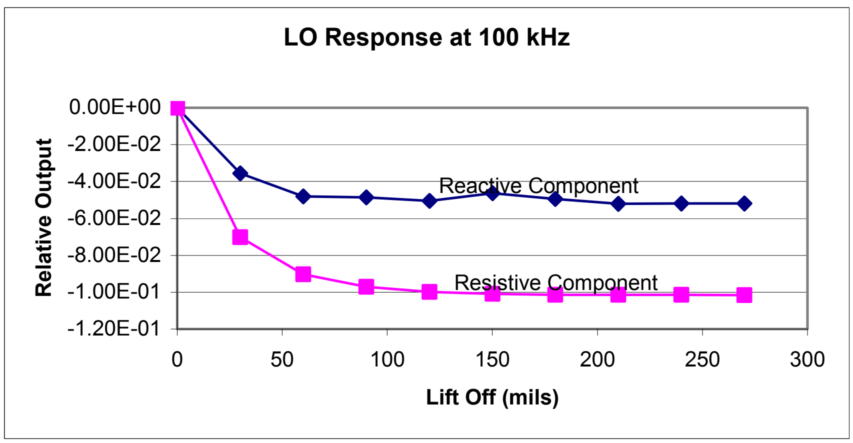

Figure 14. Liftoff signal response at 100 kHz

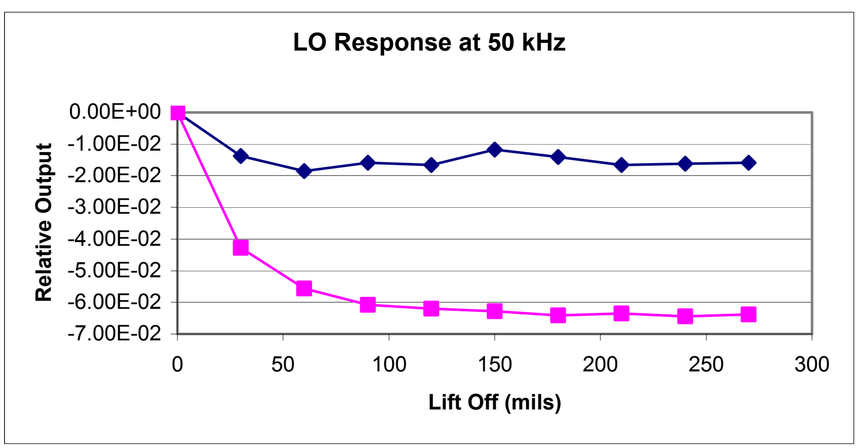

Figure 15. Liftoff signal response at 50 kHz

According to the results in the variable frequency liftoff test, an operating frequency of 100 kHz was chosen. Since there was liftoff information in the outputs at all the tested frequencies, the choice was made based on considerations of potential cross-talk problems at the higher frequencies.

The impedance measurements showed that all the pits that were larger than the sensing coil yielded impedance data that laid on a single monotonic curve, as shown in Figure 16. The data from the smaller pits formed a curve parallel to the large pit curve and displaced slightly from it (Figure 17). The fact that the response from all pits larger than the coil lies on a single curve suggests that the pit diameter effect is not significant for pits whose diameters are larger than the coil diameter.

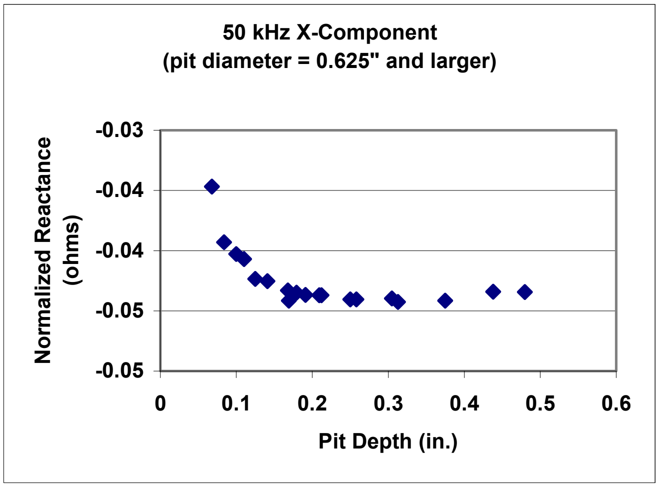

Figure 16. Impedance response of large pits

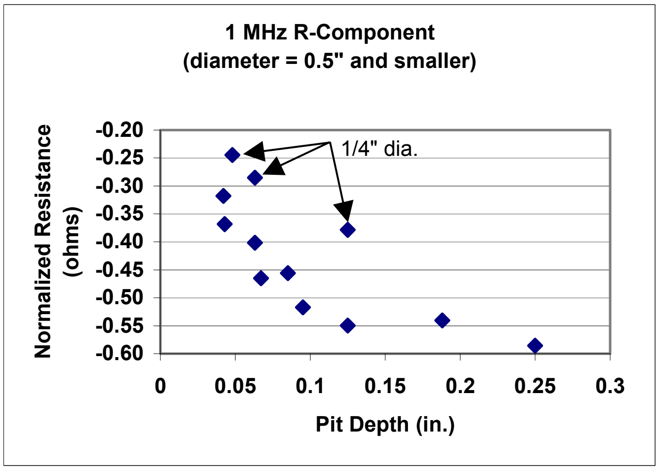

Figure 17. Impedance curves for smaller pits

Impedance measurements are not the most convenient method for sensing liftoff in a corrosion measuring system. A more reasonable approach is to have exciter-sensor coil pairs wherein one coil is energized and another identical coil detects the field from that excitation. As the coil pair is subjected to varying amounts of liftoff, coupling between the coils changes and the output from the sensor coil can be measured by, for example, an analog-to-digital converter. To evaluate the performance of this approach, we made a coil pair from two coils identical to the one used for the impedance measurements. The coils were individually printed on thin flexible printed-circuit boards. Two coils were placed in registration with the boards in intimate contact, as shown in Figure 18. A computer-driven scanner was used to scan the pair down the center of one after another of the rows of pits (Figures 19 and 20). Data were collected on a high-resolution interval so the profile of response across a pit could be measured.

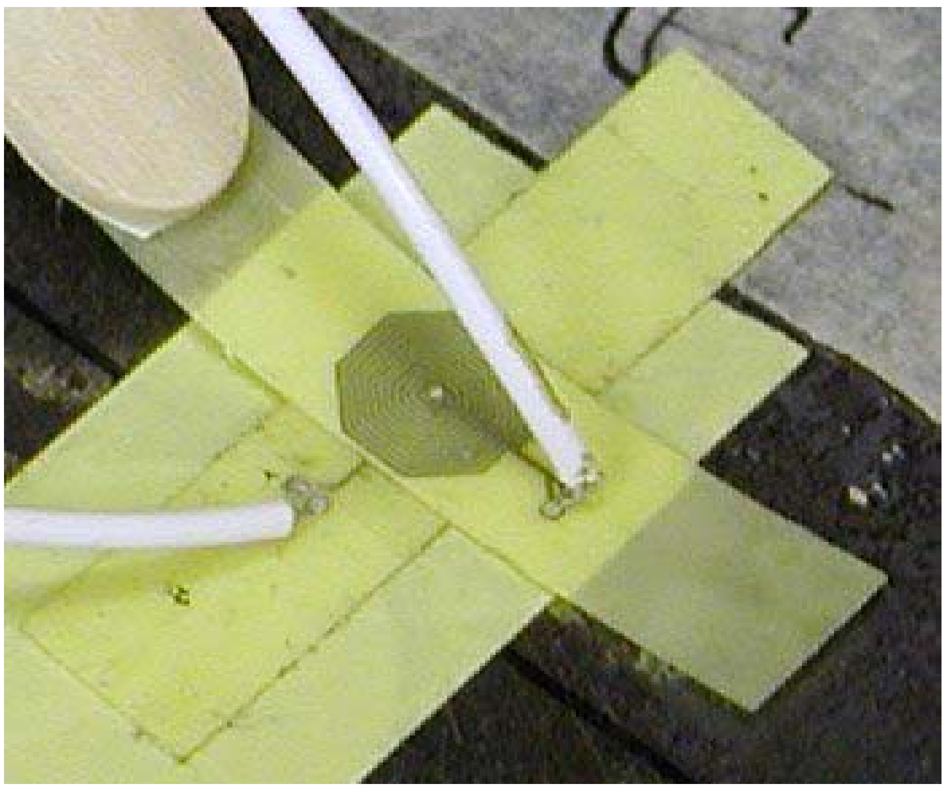

Figure 18. Coil pair using octagonal spiral coils

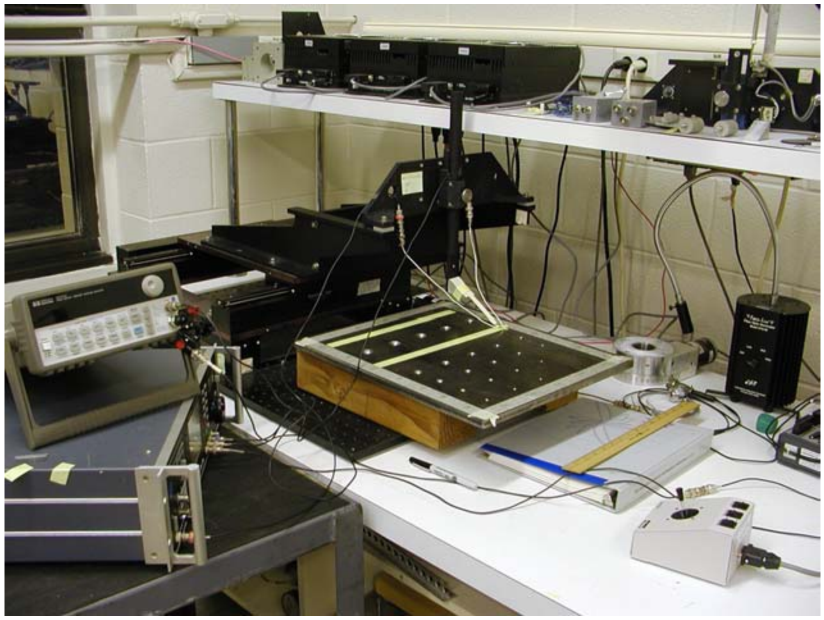

Figure 19. Bench test arrangement showing test plate, computer-driven scanner, frequency source, and lock-in amplifier

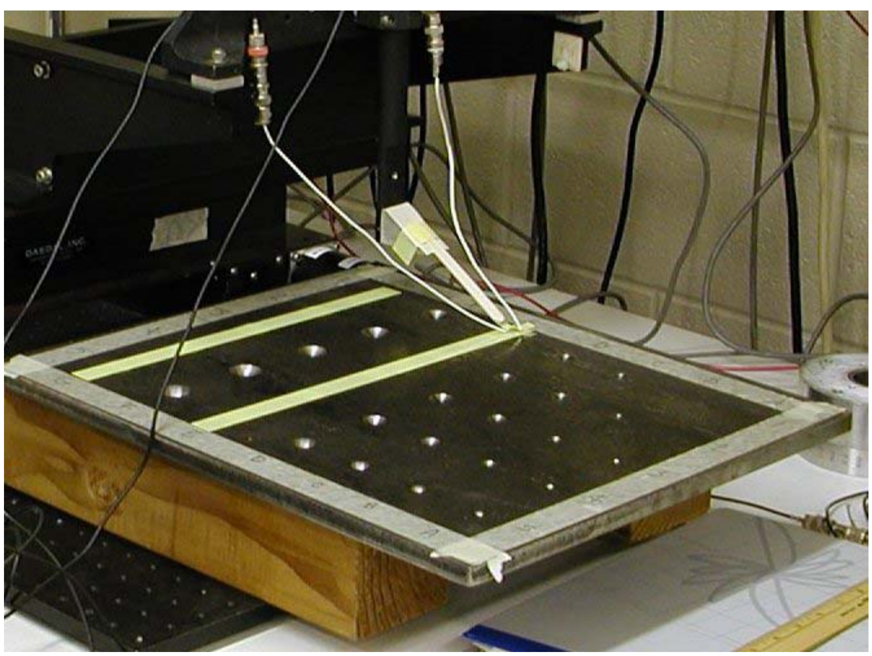

Figure 20. Detail of test plate

4.2 Pit Test Plate

Subsequent experiments used the coil to make impedance measurements at the centers of 31 machined pits in a 13-mm (0.5-inch)-thick steel plate that was approximately 380 × 460 mm in size (15 × 18 inches). The pits were put into the plate in rows of constant surface diameter and varying depth, as shown in Figure 21. The depths and diameters are shown in Table 1.

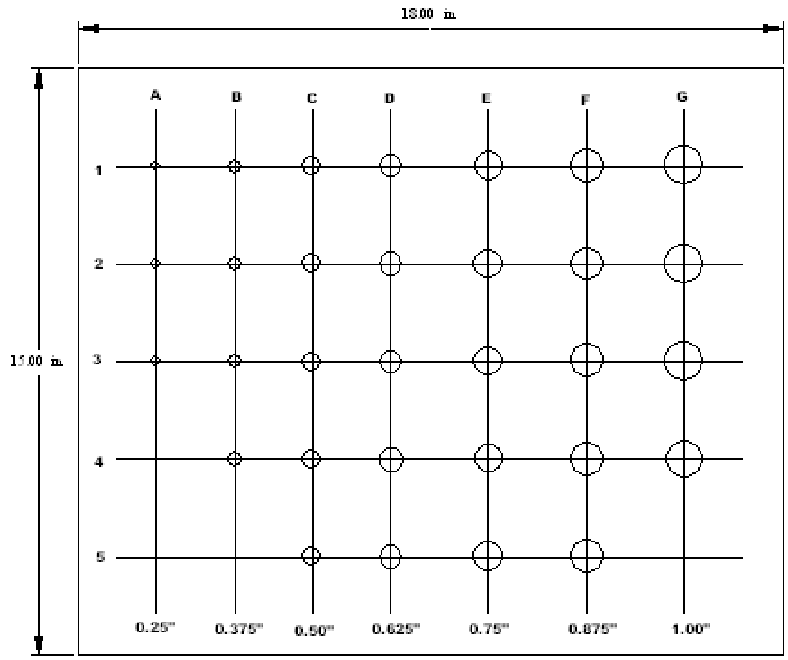

Figure 21. Layout of steel pit plate

Table 1. Range of pit diameters and depths in test plate

Column	No. of Pits	Diameter (mm)	Minimum Depth (mm)	Maximum Depth (mm)
A	3	6.35	1.22	3.18
B	4	9.53	1.07	4.78
C	5	12.70	1.09	6.35
D	5	15.88	1.73	7.95
E	5	19.05	2.54	9.53
F	5	22.23	3.58	11.13
G	4	25.40	4.85	12.19

The exciter-receiver coil pair shown in Figure 18 was used to scan across rows of constant diameter pits in the pit test plate shown in the laboratory setup photograph in Figure 19. Rows of pits varied in depth, but kept the same diameter at the plate surface. A computer-driven scanner drove the coil pair at a constant speed along the centerline of a row of pits while data were collected for each millimeter of travel. Figure 22 shows the pit response for three rows of pits. The peak pit signals for these three pit diameters are shown in Figure 23. Note that the response flattens out for pit depths greater than about 6 mm. A fairly uniform curve applies to all pits whose diameters are greater than the coil diameter.

Since the steel plate with simulated pits has rows of pits with constant surface diameter and varying depths, it was easy to collect data that isolated the depth variable by scanning down the center of a row of constant-diameter pits. Figure 22 illustrates the variation in depth sensitivity for three rows of pits. The peak values for each pit are shown in Figure 23. Note that there is increasing signal amplitude for increasing pit depth over the three diameters shown. Note also that there is signal saturation above depths of approximately 0.3 inches (7.6 mm).

4.3 Array Design

After deciding that the coil configuration would be sandwiched coil pairs, a small proof-of-concept array with 64 elements was developed. The design will later be extended to a larger scale array. The size of a single coil was chosen to be 4.32 mm and 7.11 mm in two separate arrays. Center-to-center spacing was 5.08 mm and 7.62 mm, respectively.

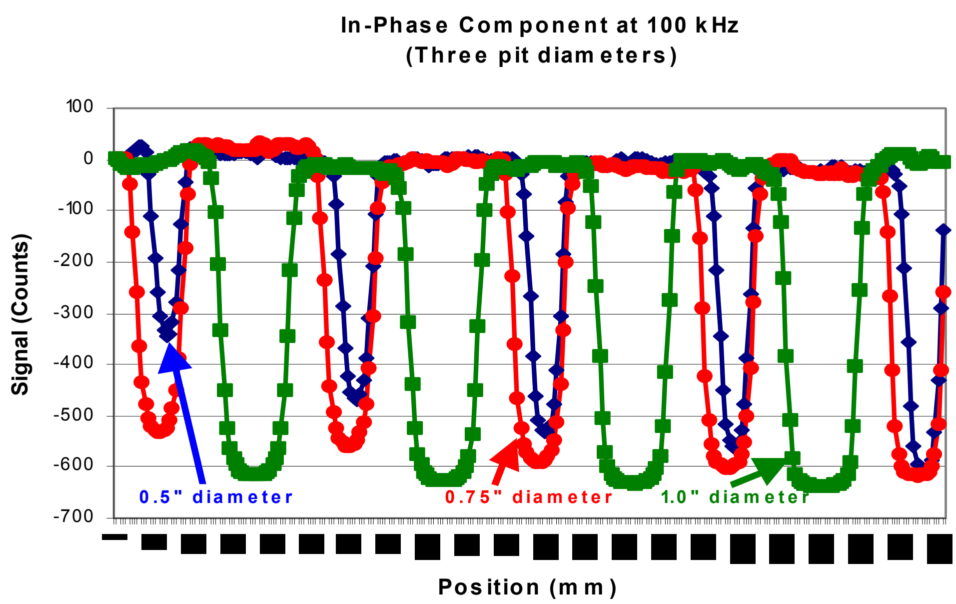

Figure 22. Eddy current signal from three rows of pits

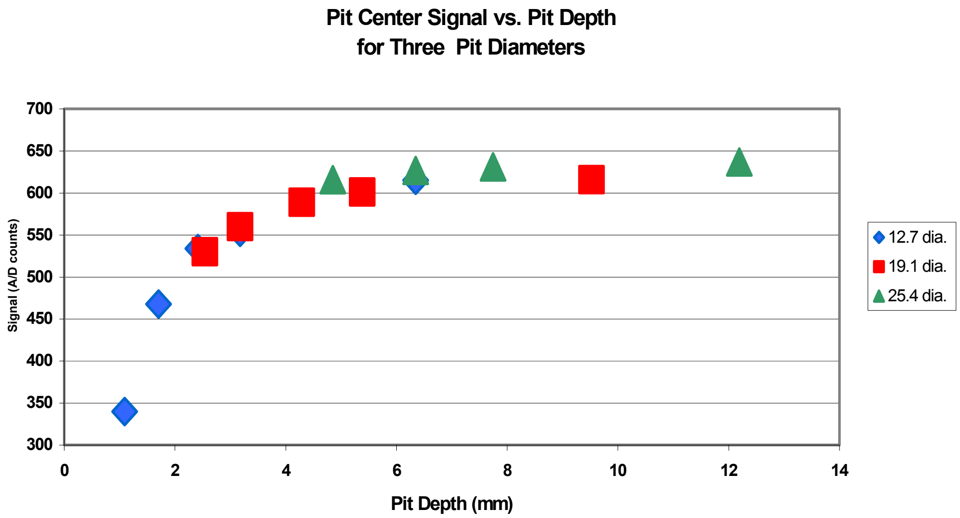

Figure 23. Peak signals for three pit diameters

Array size considerations—Laboratory measurements have pointed out the relationship between coil size and the signal from a pit of a certain size (see Figure 24). It is apparent from the pit response during scans across them that the array elements have a maximum distance between them to get acceptable response from all pits in a corrosion patch.

Among the key questions to be addressed is what the density (spacing) of the array needs to be to adequately map corroded areas. In the simplest case, the array will be placed onto one position on the corrosion patch and all data will be collected at that position. This means that the individual coils must be close enough that they do not miss the deepest corrosion. The assumption is that this requirement will result in coils no more than 6.4 mm apart. If the array must cover a corrosion patch that is 300 mm square, that will require over 2000 individual coils. Using modern printed circuit techniques, that is not prohibitive. Furthermore, array-addressing methods are available to handle data collection from that number of coils.

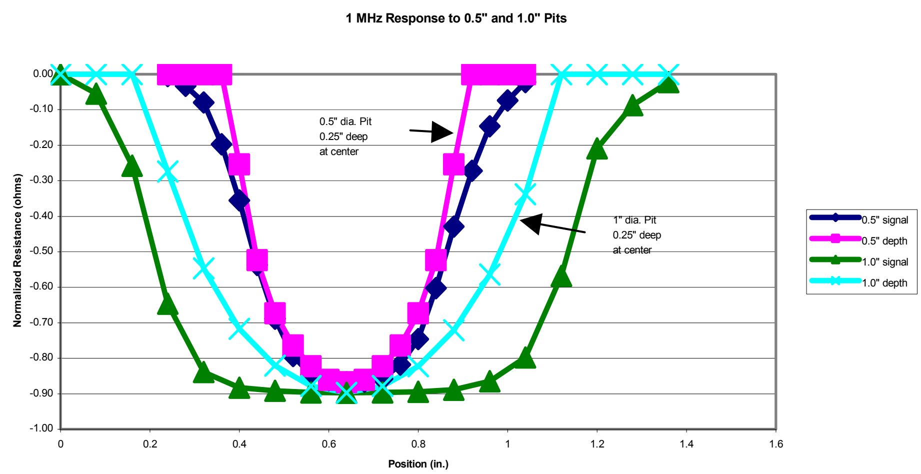

Figure 24. Fall-off of signal as coil is moved over the center of the pit

However, it may not be necessary to use this “brute force” approach. We are considering a movable array that can collect data quickly in one position, be shifted slightly, and collect data again. After several coordinated moves, sufficient data will be on hand to produce a contour map with significantly greater resolution than the native coil spacing would suggest. For example, an array with small coils spaced 13 mm apart could produce an image with resolution better than 6.5 mm if the data were collected at several different positions with respect to the corrosion.

The design of a breadboard array is shown in Figure 25. The exciters and receivers were printed on multiple-layer boards so that they remain in perfect registration with the connecting leads on opposite sides of the board from the coils.

A proposed circuit arrangement is shown in Figure 26.

The effects of array density are illustrated in Figures 27 through 32. Figure 27 is a photograph of a pitted pipeline coupon. Figures 28 through 32 show contour mapping of the coupon at varying resolutions from 2-mm measurement spacing to 32-mm measurement spacing. Note the progressive loss in detectability of the isolated pits.

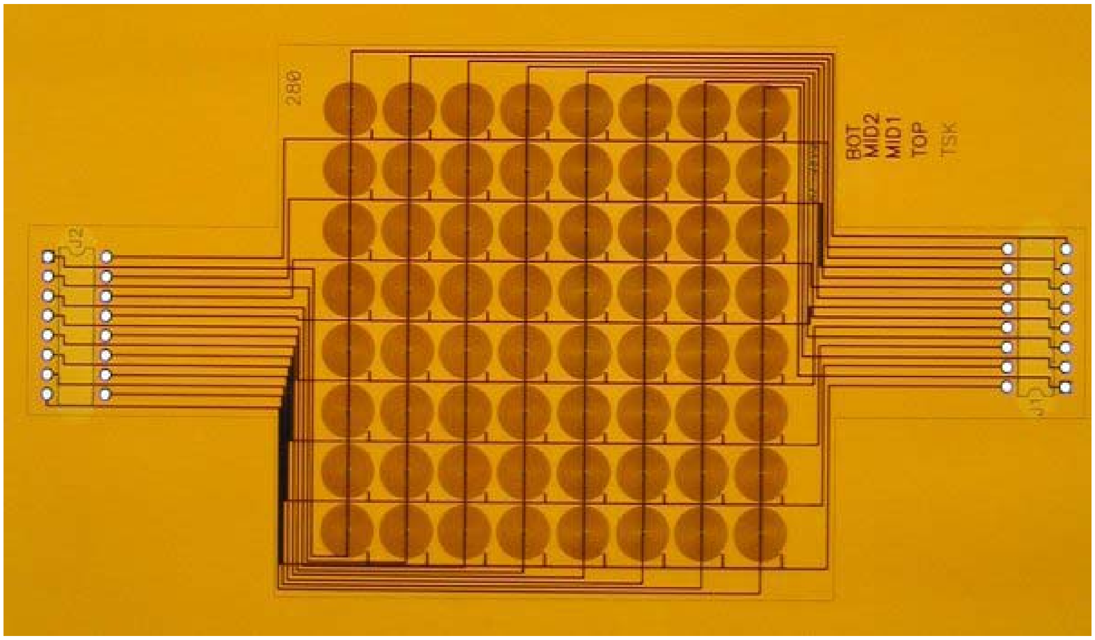

Figure 25. Breadboard array

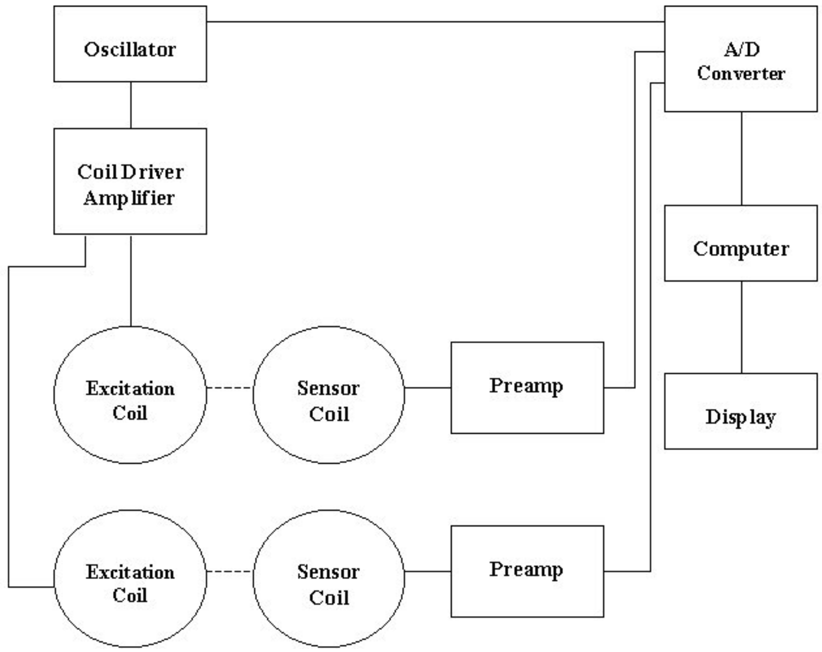

Figure 26. Proposed circuit arrangement for use with breadboard array

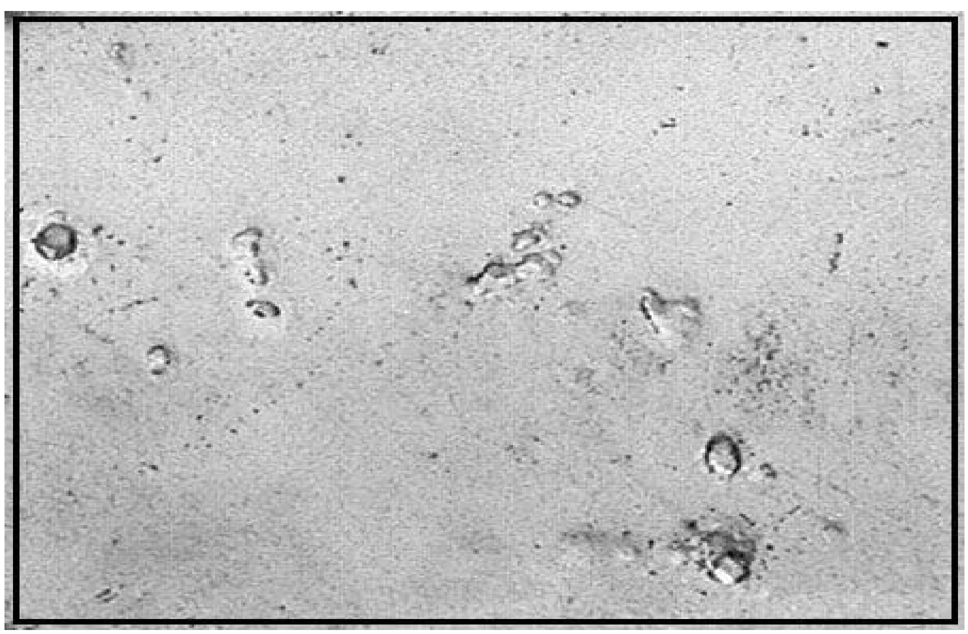

Figure 27. Photograph of isolated pitting

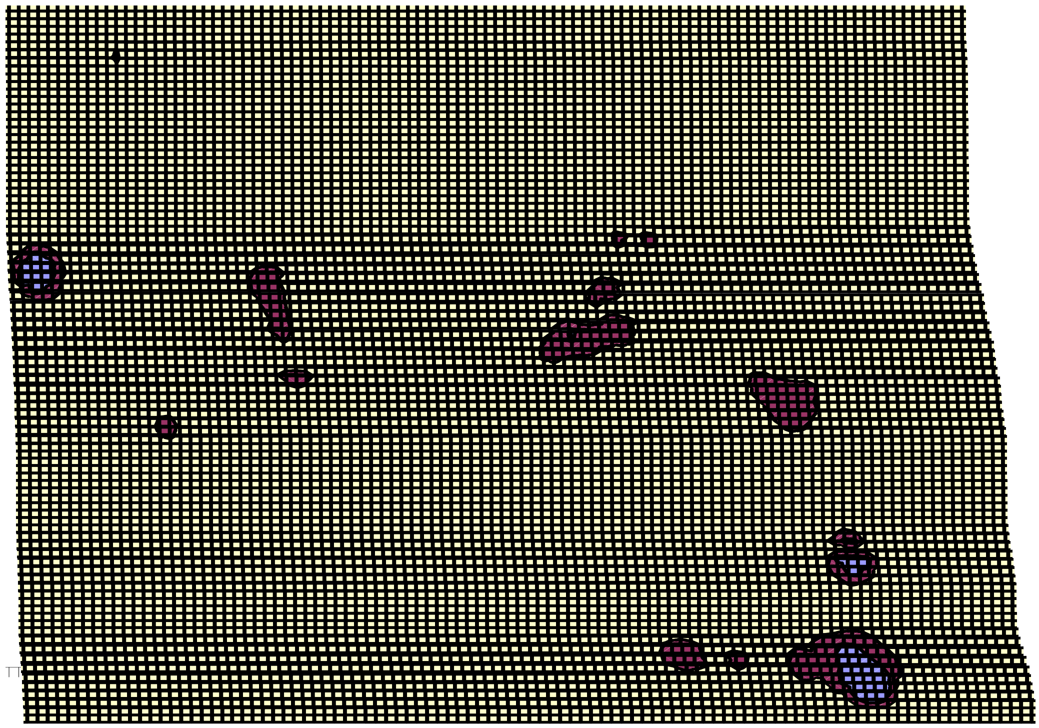

Figure 28. Color map with 2-mm resolution

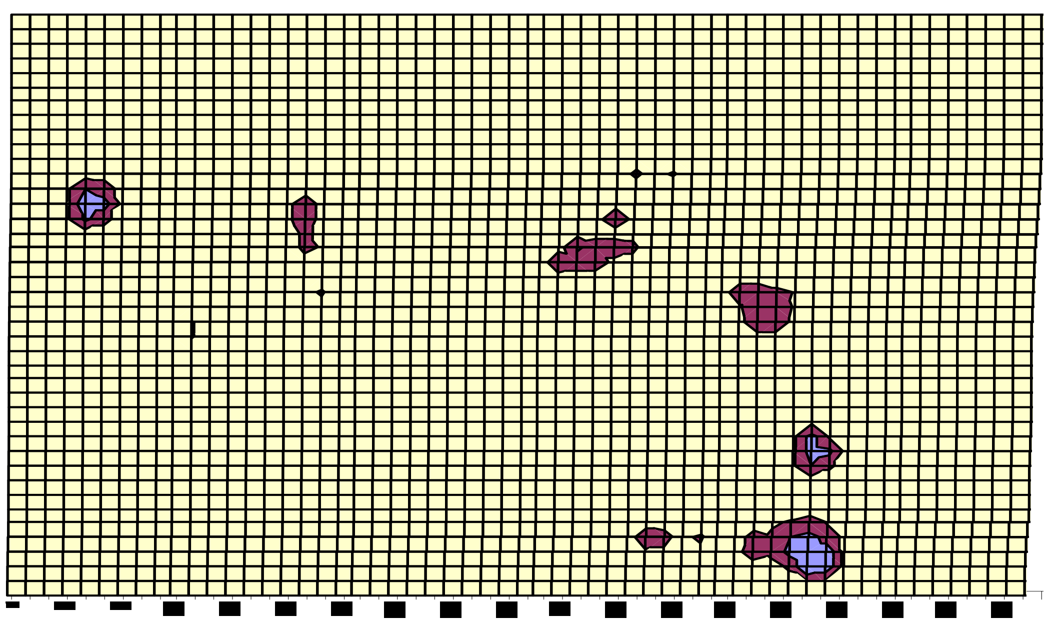

Figure 29. Color map with 4-mm resolution

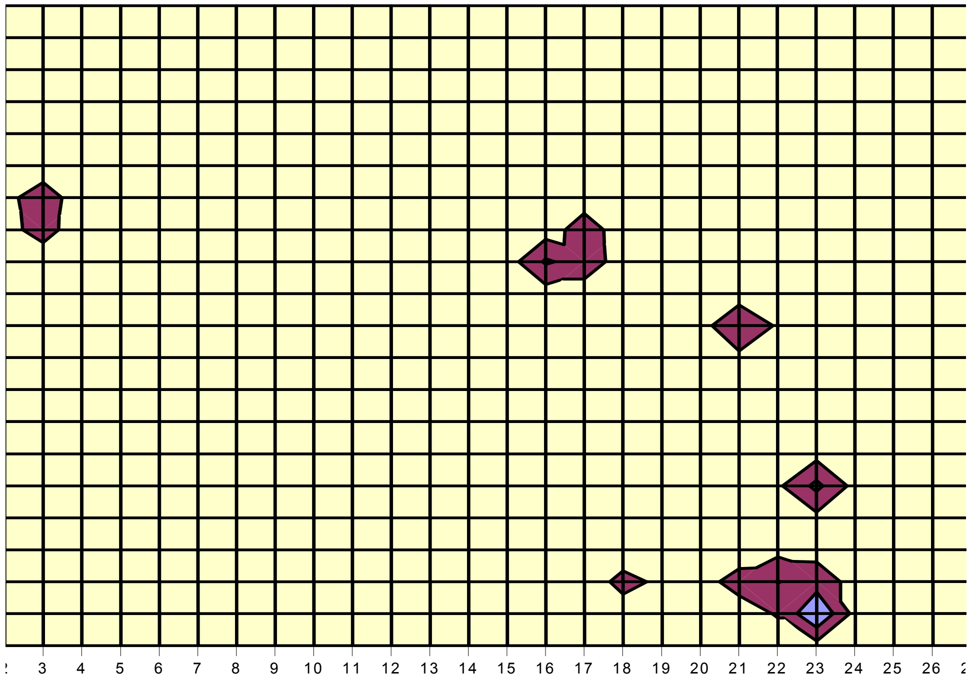

Figure 30. Color map with 8-mm resolution

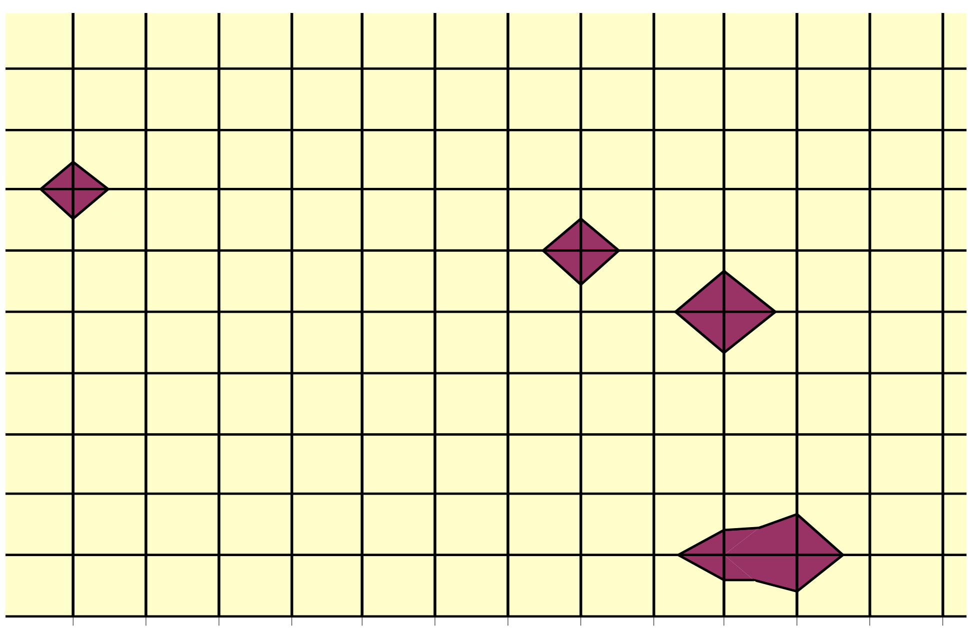

Figure 31. Color map with 16-mm resolution

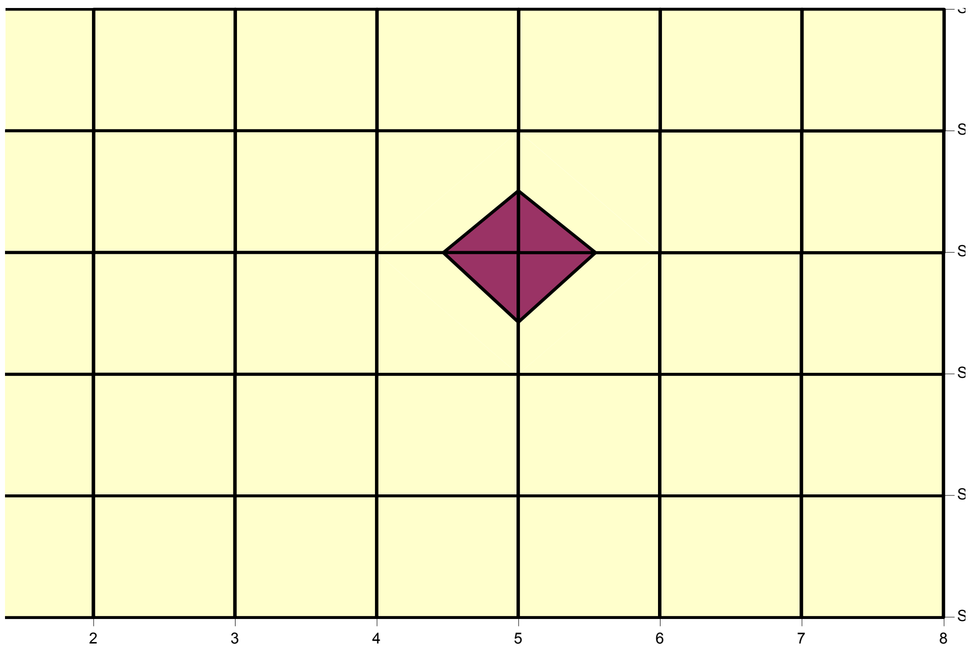

Figure 32. Color map with 32-mm resolution

4.4 Sneak-Path Problem

Figure 33 shows the response to Row D of pits with a single coil of the breadboard array. Contrast this with the waveforms shown in Figure 34, which is a single coil output when the row and column addressing was used with the array. The row and column addressing was thought to isolate a single coil pair so that it could be operated independently from the rest of the array. After the poor signal-to-noise ratio was seen (Figure 34), it was found that the single pair was not isolated, but rather all the other coils in the array were energized to some extent, and all the receiver coils were contributing to the output of the chosen coil. As a result, it was concluded that row/column addressing could not be used. Individual isolated leads would have to be brought out.

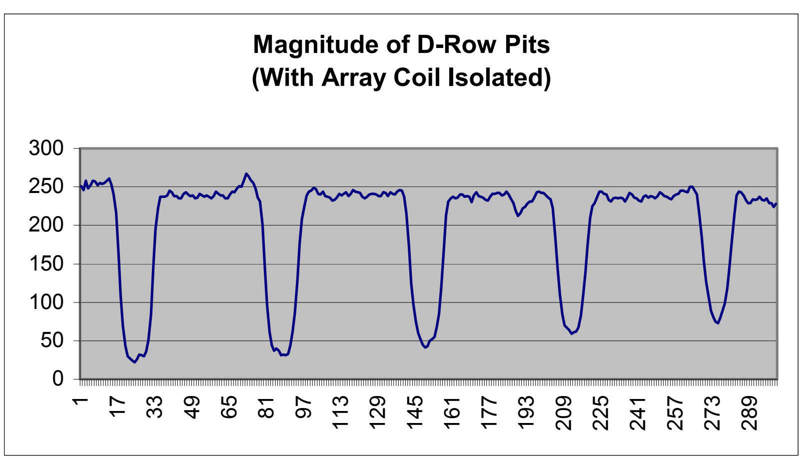

Figure 33. D-row pits scanned with a single isolated coil pair

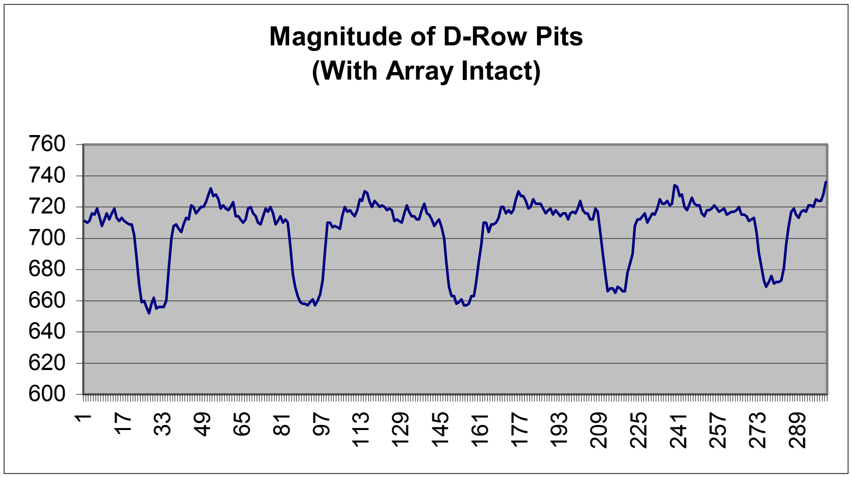

Figure 34. Output of single coil pair using unmodified array

Once the sneak-path problem had been identified and dealt with, work proceeded with the breadboard arrays, using isolated coils. The first measurement was to determine the liftoff response of the printed coil pairs. Figure 35 shows the result.

The liftoff response suggests that the small (4.3 mm) coil will not show depth response beyond about 2.5 mm, whereas the larger (7.1 mm) coil should continue to measure out beyond 3 mm. The response is somewhat better for pits. For example, Figure 33 shows that for pits whose diameter is 15.88 mm, there is depth response out to the deepest (7.95 mm) pit.

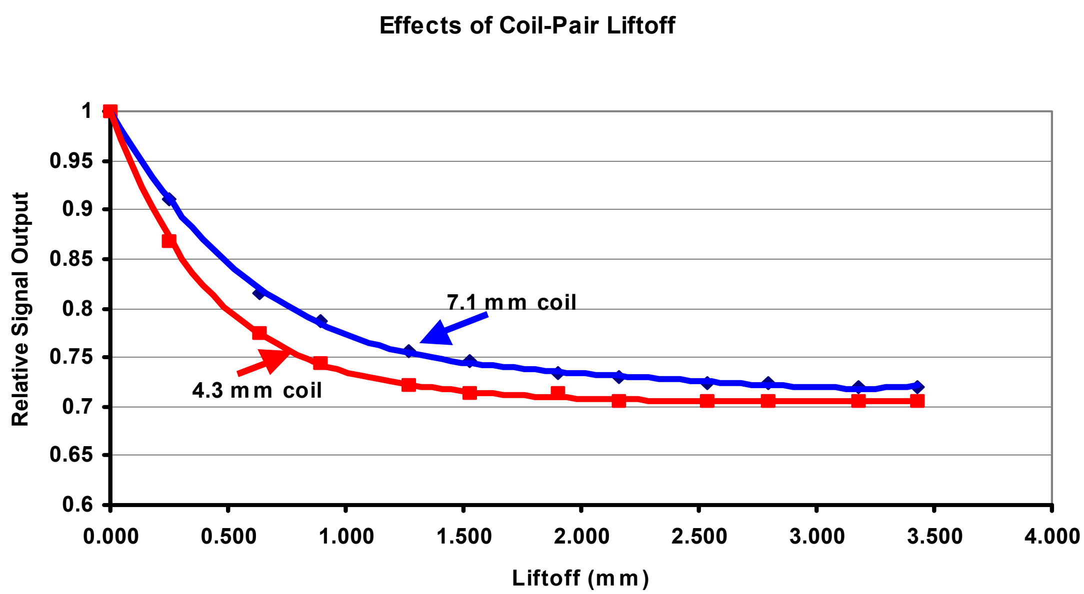

Figure 35. Liftoff response of printed arrays

4.5 Array Scans of Corrosion Coupons

One of the printed arrays was used to scan the corrosion specimen shown in Figure 36. Data were acquired on 1.25-mm resolution in both X and Y directions. Microsoft Excel was used to produce the color contour plat shown in Figure 37. Note the excellent agreement between the color map and the corrosion coupon.

Figure 36. Corrosion coupon with numerous pits

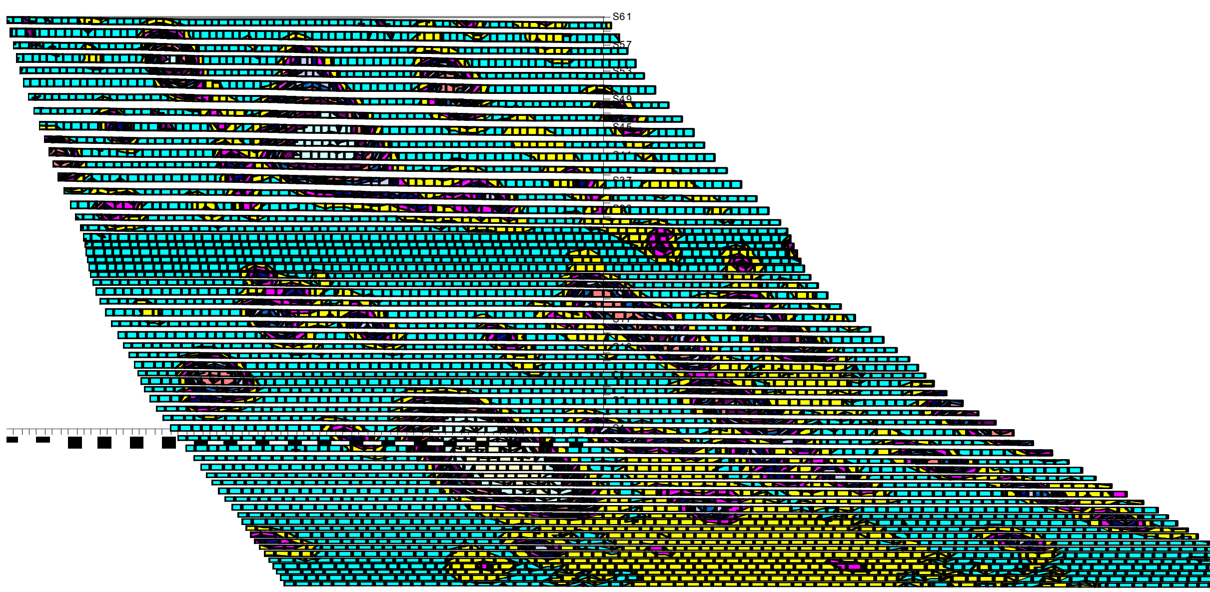

Figure 37. Color map of array o

5. CONCLUSIONS

5.1 Operating Procedure

The conformable array has two distinct applications—inspection tool calibration and defect assessment.

5.1.1 Tool Calibration

Pipeline integrity and defect detection generally involves the use of an in-line-inspection (ILI) tool. These tools are run through the pipeline with the flowing product, sensing and recording information on the condition of the pipe wall. Magnetic flux leakage is the most common technology used. This technology does not directly measure defects but rather the magnetic field that surrounds the defect. Defect geometry is deduced from the magnetic data. The magnetic data are influenced not only by defect geometry but also material properties of the pipe and the operating conditions of the tool. Data analysis can be improved by comparing tool performance to known defects.

The conformable array can provide a rich source of defect information that can be used to assess and qualify subsequent inspections. If a defect is measured and then repaired with a technology that does not affect the magnetic properties of the pipe, then that measurement information can be used on subsequent inspection to help calibrate the inspection. These data can also be used to ensure that the inspection company has complied with detection and sizing specifications outlined in the contract. It can qualify a tool run. This qualification aspect will become more important as inspection is imposed on the industry.

The following discussion represents the current status of development and may change as the development program moves to a field version.

The conformable array is a flexible pad, with properties similar in consistency and flexibility to a computer mouse pad. The sensors and conditioning electronics are printed within the pad but are transparent to the operator. The pad will contain a connector that will attach the measuring system to a laptop computer. The computer will contain the analog-to-digital converters and calibration software required for operation.

The sensing element within the pad is a two-dimensional, high-density array of eddy current sensors, typically on a 10-mm grid. An address generator multiplexes the sensors. Each exciter coil is energized in turn, and the signal from the corresponding sensor coil is routed to conditioning electronics. An amplifier driver will send the selected data channel to the AD converter in the computer. (See the system block diagram in Figure 38.)

The computer will acquire the data from each element of the array and calculate a calibration factor for that element. A two-dimensional calibration table will be built and stored. This calibration information is temporary in nature and only used to adjust the measurement data. After the measurement data have been compensated, the calibration table will be deleted.

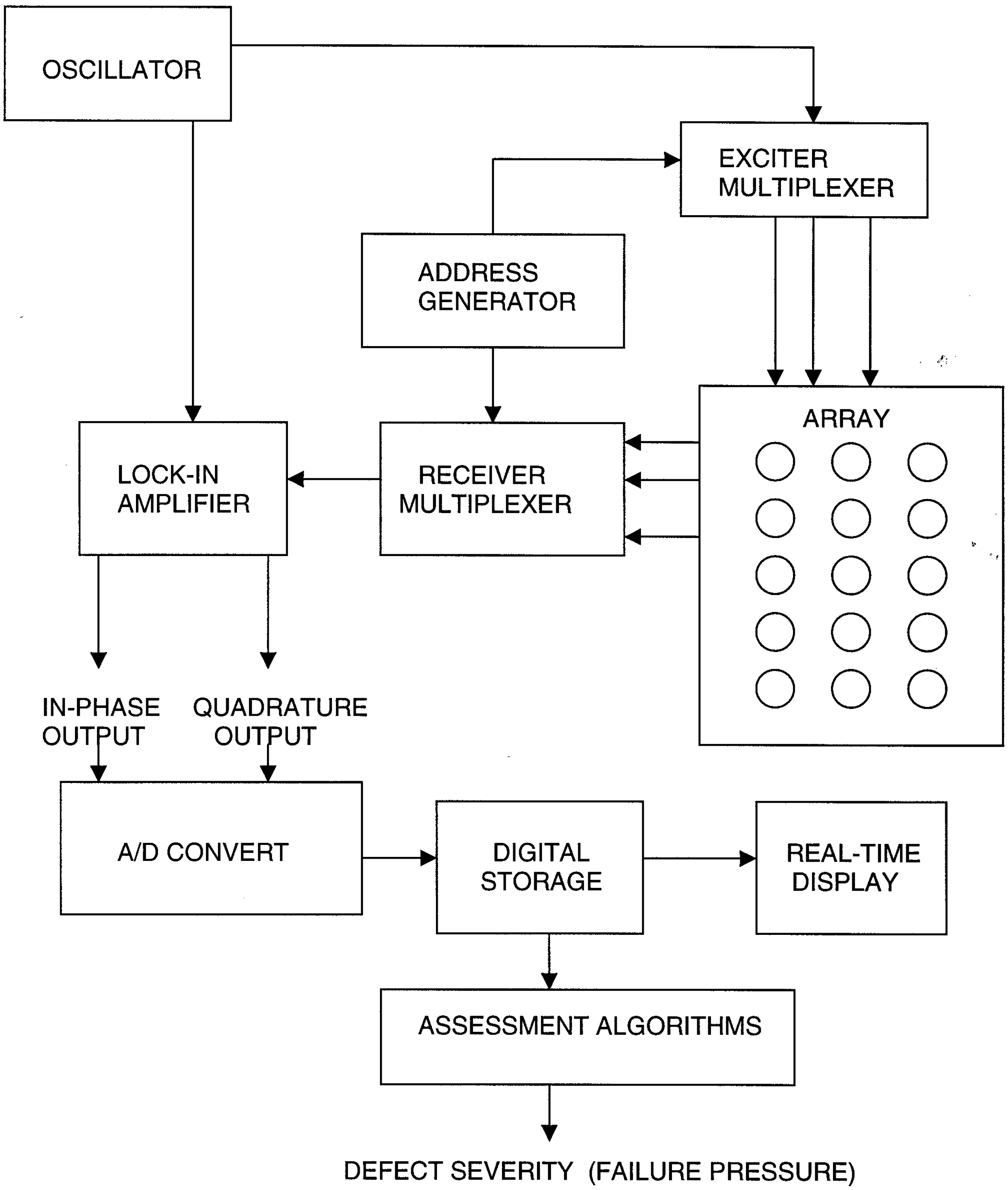

Figure 38. System block diagram

5.1.2 Defect Assessment

In operation (see Figure 39 for artist's concept), the defect to be assessed will be unearthed and cleaned. The conformable array will be placed on the pipe at a location where no defect exists. The operator will calibrate the device with a single keystroke, building the calibration array table. The array will then be placed over the defect to be assessed. Data from each measuring element will be acquired and compensated according to the corresponding location in the calibration array. The data will be stored in a measurement array and displayed on the screen in a color density plot. The two-dimensional measurement array contains both defect depth information from the sensing elements and location information from the physical location of the element within the array. This can be used to automatically assess the defect by one of several methods. B31G assessment can be calculated by simply finding the deepest point within the defect and the overall length of the defect. RSTRENG can be calculated based on a river-bottom profile selected by the analysis software. The data can be stored for future use and reference.

If the defect being measured is larger than the pad, then the pad will be indexed by marks provided for that purpose and a second set of measurements acquired. The display and analysis software will seamlessly splice the data.

The operator can assess defects and decide on repair alternative immediately. The digital data can be printed or filed for recordkeeping and future use.

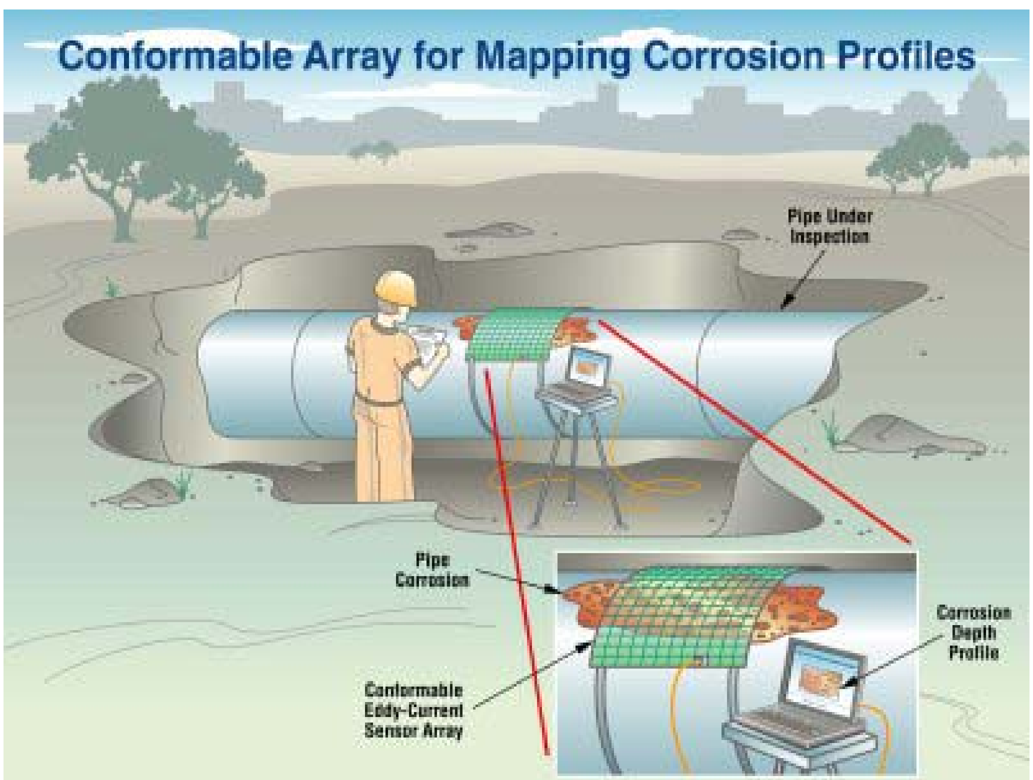

Figure 39. Artist's concept of field deployment of conformable array system

5.2 Limits of Performance

In order to determine the limits of accuracy of pit depth measurement, the large-coil array was used to scan the rows of pits in the pit test plate. Sensor signals were used to develop an equation of pit depth as a function of sensor output. That equation was then applied to the sensor signals from the test plate to produce the curve shown in Figure 40.

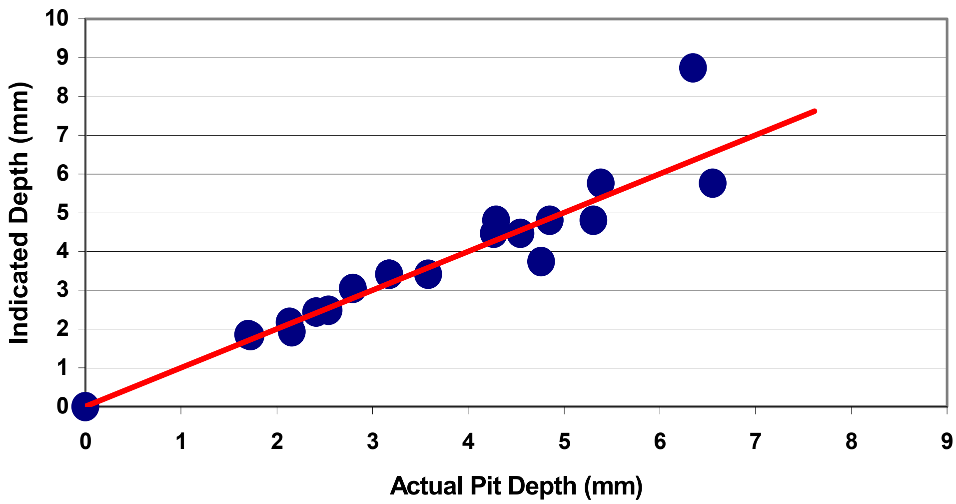

Figure 40. Pit depth measurement

Analysis of the data showed that significant errors were present when pit depths deeper than 7 mm were considered. The data on the graph represent a range of pit diameters from 10 mm to 25 mm. Note that all measurements with the exception of one are within 1 mm of the true depth.

5.3 Options for Coverage

The array used for these breadboard tests was about 65 mm square, containing 64 coil pairs in an 8 by 8 array. Typical corrosion patches that need to be measured are on the order of 300 mm square. The options for handling this difficulty are as follows.

(1) *Make a larger array.* To cover a 300-mm-square corrosion patch would require an array of approximately 900 coil pairs, using 10-mm-diameter coils. A printed array of that size is well within the limits of conventional printed circuit technology, although the chances for a defect in the board go up somewhat with the larger size. Also, since individual connecting leads have to be brought out of the array for each coil, crowding of the connecting lines can make the board design challenging.

(2) *Use multiple positions of a smaller high-resolution board with indexing.* A 300-mm-square area can be covered by a 150-mm-square board positioned in four successive locations. This would reduce the array coil count to 225 coil pairs. A smooth thin substrate with reference marks could be placed over the corrosion between the pipe surface and the array. The array would be put at those four positions in turn and data

acquired. The four data sets would be spliced to make one large data set, which would be displayed for examination by the operator.

(3) *Use multiple positions of a smaller high-resolution board with position tracking.* A small array could be outfitted with a position tracking feature so that reference marks would not be necessary. The operator could move the array in free-form scanning over the pipe surface while acoustic pulses or infrared light beams were used to track the array position with respect to a fixed, known reference position. Another tracking method that has been evaluated in the use of an optical computer mouse. The mouse has been shown effective on a wide range of surfaces, from a table top to a steel pipe surface. One shortcoming of the mouse is the lack of an absolute reference. If the mouse is lifted off the surface, it must be returned to a reference position and re-zeroed.