Delivery Reliability for Natural Gas -- Inspection Technologies

Technical Semiannual Progress Report

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ABSTRACT

The Remote Field Eddy Current (RFEC) technique is ideal for inspecting unpiggable pipelines because all of its components can be made smaller than the diameter of the pipe to be inspected. For these reasons, RFEC was selected as a technology to be integrated with the Explorer II robotic platform for unpiggable pipeline inspections. The research work is a continuation of a prior DOE-NETL project but is now directed towards a seamless integration with the robot. The laboratory set-up has been improved and data collection is nearly autonomous. With the improved collections speeds, GTI has been able to test more variables. Tests have been run on 6” and 12” seamless and seam-welded pipes. Testing on the 6” pipes have included using three exciter coils, each of different geometry. Two types of sensor coils have been tested. With a focus on preparing the technology for use on the Explorer II, improvements in power consumption have proved successful. Tests with metal components have been performed to check for interference with the electromagnetic field. The results of these tests indicate RFEC will still be able to produce quality inspections while on the robot. Mechanical constraints, power requirements, limited control and communication protocols, and potential busses and connectors have been addressed. A limited amount of work has gone into sensor module design.

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EXECUTIVE SUMMARY

The Remote Field Eddy Current (RFEC) Project (DE-FC26_04NT42266) supports the DOE-NETL Delivery Reliability for Natural Gas - Inspection Technologies program. This program seeks to enhance the integrity and reliability of the natural gas distribution and transmission systems across the United States to ensure the availability of clean, affordable energy for our homes, businesses and industries by developing technologies that improve the safety and delivery reliability of the natural gas infrastructure. This project is aimed at increasing safety and reducing unplanned operational outages by developing an inspection tool for “unpiggable” pipelines, which cannot be inspected with available technologies due to various restrictions in the pipeline. The inspection tool is envisaged as a combination of the Explorer II robot and a sensor technology. This project focuses on the Remote Field Eddy Current technology as the sensing technology and its development for integration with the robot. There are three phases, Design, Construction, and Integration and Demonstration, where the last phase integrates the RFEC inspection technology with the robot and proves the combined system’s efficacy in an operating pipeline. Currently, the project is halfway through the Design phase, Phase I.

The RFEC technology is well suited for unpiggable pipelines because its components can be made much smaller than the pipe diameter it is inspecting. The components can be easily adapted to inspect pipelines with multiple diameters, valve and bore restrictions, and tight bends. We are currently working on the mechanics, electronics, and sensor design to prepare RFEC for integration with the Explorer II robot.

We have completed all of our deliverables, including the Research Management Plan, Technology Assessment Report, and Initial Sensor/Platform Definition. We attended the Kickoff Meeting held at Carnegie Mellon University’s National Robotics Engineering Consortium. We also participated in multiple teleconferences to coordinate with other members of the program.

The laboratory is set up with seam welded and seamless pipes of 6” and 12” diameters. Each pipe has a set of 13 machined defects for testing and optimizing the technology for the robotic prototype. We have made significant improvements to the laboratory setup. At the start of the project, we could only test using one sensor coil. We built a multiplexer that can collect data from up to 16 sensor coils. We built a new test vehicle to mount multiple coils to and built an automatic winch system to pull the vehicle through the pipe in ¼” steps. We wrote LabVIEW programs to control the winch system and collect data from all the sensor coils. We can now inspect an entire pipe without an operator present in less time than it used to take us to scan a single defect. Additionally, we’ve obtained a Ferroscope from Russell Technologies that is capable of collecting data at the rate of travel achievable by the Explorer II robot. As a result, testing is much more efficient and allows us to test more variables in less time.

Some of the variables we have tested include exciter coil geometries. We tested three different exciter coils and two types of sensor coils. The optimal sensor coil is 20,000 turns of #46 copper wire wound on a 3/8” wide, ¾” diameter bobbin. The best results were achieved with an exciter coil of 1,355 turns of #26 copper wire wound 4.25” long on a 3.5” diameter spool. We were able to consistently detect defects as small as ½” diameter and 10% missing wall thickness. Because we can detect defects so much smaller than those that need to be detected in an operating pipeline, it is extremely unlikely that the RFEC technology would not detect a defect in the field that would require repairs. In addition, this particular coil only consumed 1.85 Watts. Earlier coils consumed as much as 10 Watts. We have made limiting power consumption an important criteria for exciter coils. This is significant because Explorer II is an untethered system with a limited power supply.

Preliminary module design has been promising. We expect to be able to build all of our

RFEC components into two robot modules as requested by the robotics developer. The first six months of this project have been very successful and productive. With continued success, the natural gas industry will realize an innovative and powerful inspection tool created from the combination of RFEC technology and Explorer II.

THE REMOTE FIELD EDDY CURRENT TECHNIQUE

The remote field eddy current (RFEC) technique was patented by W. R. McLean (US Patent 2,573,799, "Apparatus for Magnetically Measuring Thickness of Ferrous Pipe", Nov.6, 1951) and first developed by Tom Schmidt at Shell for down hole inspection (Schmidt, T. R., "The Casing Instrument Tool- …", Corrosion, pp 81-85, July 1961). The RFEC technology has many advantages including:

- A simple exciter coil that can be less than 50% the diameter of the pipe. The exciter coil does not need to be close to the wall.
- Simple and small (millimeter to centimeter diameter) sensor coils that do not need to contact the wall. Thus, the diameter of the coil array can be easily adjusted to match the pipe diameter yet pass through a small opening.
- Sensor coils close to the pipe wall provide sensitivity and accuracy comparable to standard MFL inspection tools. General pipe corrosion of 10% of the wall thickness or less is detected and measured with commercial units.
- Sensor lift-off, up to 0.75 inch can be automatically compensated for, though sensitivity and resolution will be compromised.

The technique is commercially viable for inspecting boiler tubes and pipe diameters up to 8 inches for several hundred feet. Recently, Russell Technologies developed an 18 inch device that can inspect production wells for several thousand feet. However, none of the current versions are collapsible to 50% of the pipe diameter or less, nor can any handle short-radius elbows and other obstacles. To adapt the technique for this application will require investigating variations such as transmitter coil angle and methods for either reducing the variations or sensitivity to them. Larger diameters should not be a problem since specialized tools can inspect the steel reinforcing of 12 foot diameter concrete water mains (Atherton, D. L., US patent 6,127,823, "Electromagnetic Method for Non-Destructive Testing of Prestressed Concrete Pipes for Broken Prestressed Wires", Oct. 3, 2000).

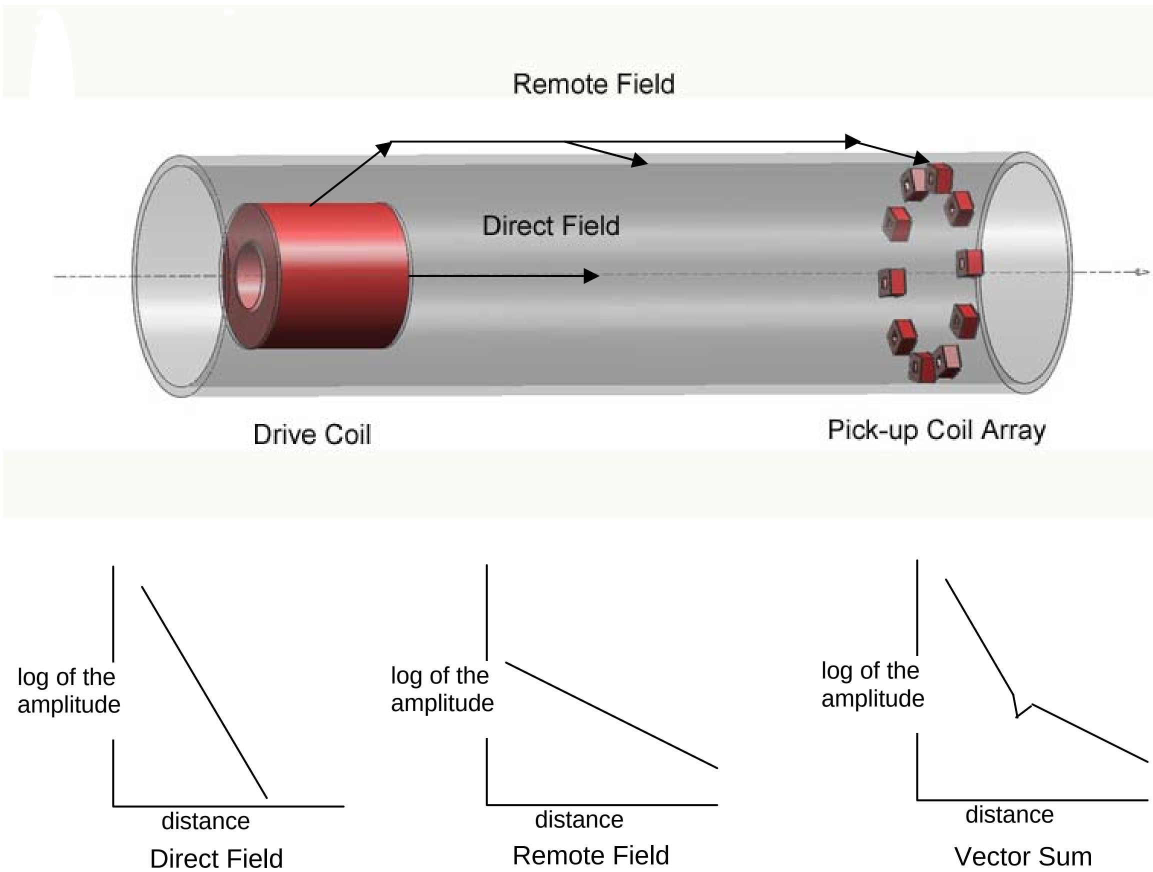

Figure 1: Variation of the amplitude of the near and remote eddy current fields with distance along a pipe.
The sum includes the effect of the phase difference between the direct and remote field vectors. In the presence of metal loss, the signal amplitude increases while the phase change decreases. Measurements far from the exciter coil are very sensitive to corrosion and insensitive to the direct field.

Figure 1 shows the basics of the remote field eddy current (RFEC) method. The exciter coils sends 20 Hz to 200 Hz electromagnetic waves propagating down the pipe and through the pipe wall. The electromagnetic waves traveling inside the pipe (direct field) are highly attenuated because they are well below the cutoff frequency for propagation in a wave-guide. As far as the electromagnetic waves are concerned, a pipeline is nothing more than a wave-guide. Approximately two pipe diameters from the source coil, these waves all but vanish. Meanwhile, the waves that have penetrated the wall (remote field) can penetrate back into the pipe as well. At about two pipe diameters from the exciter coil and beyond, these waves swamp the direct field waves attempting to propagate down the bore of the pipe and, therefore, can be detected and measured. This is the reason for the term “remote field eddy currents” (as opposed to the near or direct field currents from waves propagating down the bore of the pipe). This is exactly what is needed. Any pipeline flaws such as metal loss from corrosion or other causes that affect the propagation of these RFECs back into the pipe alter the detected signal so that the flaws may be detected and measured by the sensing coils.

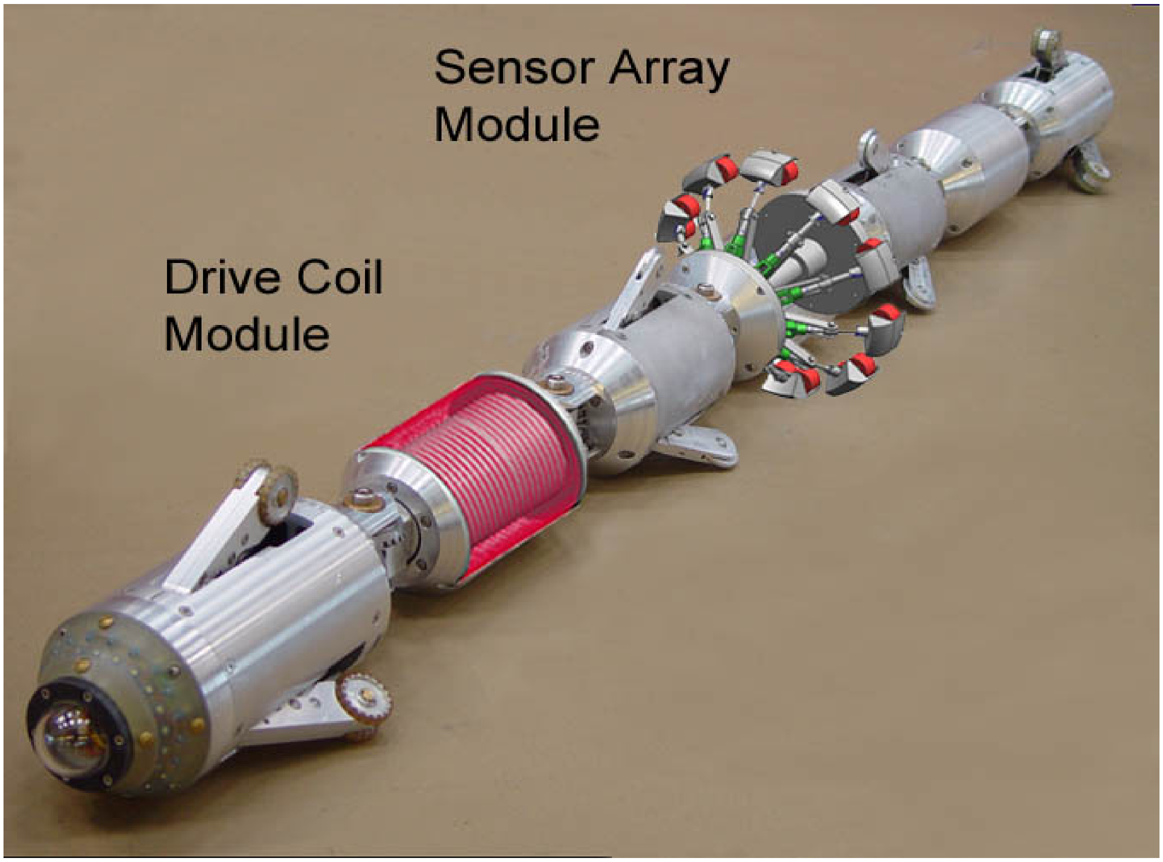

Figure 2: A drawing simulating the RFEC technology integrated to the Explorer I robot.

The RFEC frequencies need to be low since higher frequencies will not penetrate ferromagnetic conductors such as pipeline steel. Methods to increase penetration by lowering the magnetic permeability by magnetizing the pipe may not work well for unpiggable pipelines for the some of the same reasons that MFL inspection will not work well. The one disadvantage of the technique will therefore be slow inspection speeds. Other than that, the RFEC technique is the ideal in-line inspection technology for inspecting “unpiggable” pipelines. The transmitter and sensors can be designed to fit through anything that robots or any design of pig driving cups can pass through. Figure 2 shows a conceptual design for the proposed inspection device using Explorer II to propel the tool through a distribution main. The transmission coil can be much smaller than the pipeline diameter and mounted on a short module. Power and electronic modules, including possibly a recharging module, can be mounted ahead and between the transmitter and the sensors with additional modules, if needed, following behind these. Modules at each end of the RFEC in-line inspection tool can move the tool in either direction.

NON EXPERIMENTAL

GTI completed the Research Management Plan. The plan detailed the work to be performed as outlined in the Statement of Objectives and included the project schedule and staffing. The work will consist of three phases, Design, Construction, and Integration and Demonstration. GTI completed the Technology Assessment Report that described both the status of the RFEC technology and where it fit within available technologies for enhancing pipeline reliability. The feasibility of inspecting transmission pipelines using the RFEC technique was proven in a previous DOE project (DE-FC26-02NT41647). The technique can use small components making it ideal for its primary purpose of inspecting unpiggable pipe. The current project will demonstrate that capability in an operating pipeline or distribution main.

As part of this phase of the project, Task 6.0 requires us to have a preliminary module design. We have begun this task by participating in brainstorming and 3D modeling activities. We are currently exploring various designs for the sensor module(s) in an effort to limit all the sensor coils to one module as requested. We've also completed the deliverables for Task 3.0, which include our anticipated constraints, protocols, and requirements.

EXPERIMENTAL

Figure 3: RFEC laboratory setup.

Figure 3 shows the laboratory setup for performing RFEC research tasks. We machined defects sets into two 10' sections of 6" diameter pipe. One pipe is seamless, the other is seam welded. The seamless pipe is set up with a Kepco BOP, bipolar operational power supply, on the right, which drives the exciter coil and a PerkinElmer lock-in amplifier, on the left, which filters and amplifies the signal received by the sensing coil.

Originally, we started with an exciter coil made of 1000 turns of #29 copper wire wound 2" wide on a 1 ½" diameter spool. Electromagnetic waves for the remote field were generated by driving the coil at 8.6 V rms and 0.2 A rms by the BOP. The sensing coil was made of 20,000 turns of #46 copper wire wound on a 3/8" wide, ¾" diameter bobbin. The output of the sensing coil is filtered and amplified by the lock-in amplifier. The lock-in amplifier rejects all frequencies except that of its internal oscillator. The internal oscillator of the lock-in amplifier provides the signal that is amplified by the BOP to drive the exciter coil.

Figure 4: RFEC testing on 12" pipe samples.

Early in the project, we performed RFEC testing on 12" seamless and seam-welded pipes. Figure 4 shows the pipes and equipment tent. This testing was initially started in preparation for the DOE-NETL technology demonstration held at Battelle Laboratories in Ohio. The RFEC vehicle is shown in Figure 5.

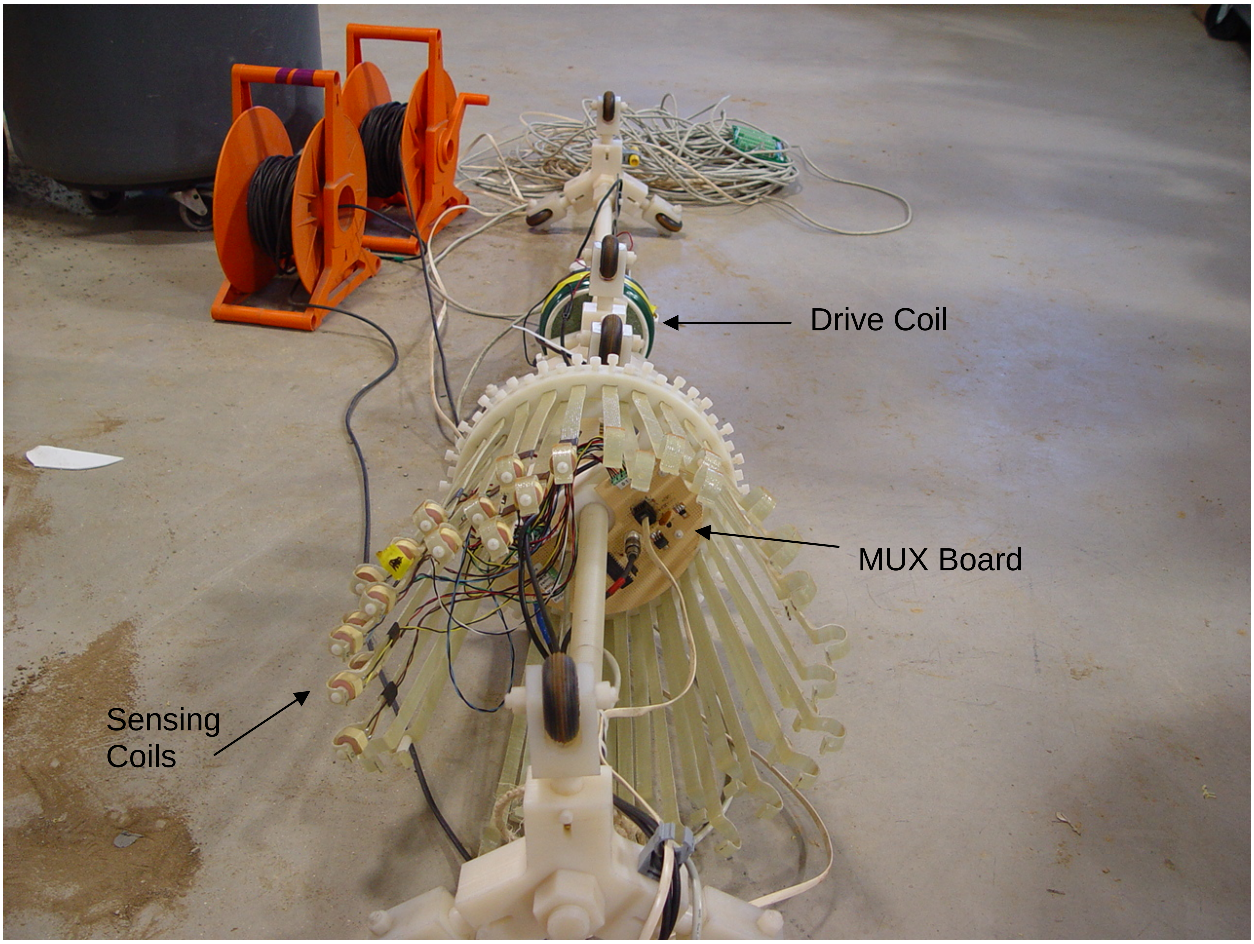

Figure 5: Testing vehicle for RFEC inspection of 12" pipes.

ELECTRONICS and DATA ACQUISITION IMPROVEMENTS

The vehicle features a 16-channel multiplexing board, MUX to be able to acquire data from 16 sensing coils. We also built a 16 channel MUX for use on the 6" pipes in the laboratory. In order to collect data for 16 sensor coils, we updated our LabVIEW data acquisition program to step through and record data from all 16 channels. In addition to sensor data, the addition of odometry to the vehicle required the LabVIEW program to also record position data from the odometer at acquisition locations.

Using the MUX board and LabVIEW significantly improved collection speeds. Manually, it would take close to two hours to inspect a single defect. Using the new system, all 13 defects along a 10' section of pipe can be inspected in an hour and a half without a researcher present. Further improvements in inspection speeds were seen when GTI purchased a Ferroscope and software from Russell Technologies, Inc. This is a much more sophisticated system as Russell has years of experience using the RFEC technique to inspect boiler tubes. The collection speeds on this setup are about 3 minutes for a 10’ length of pipe.

LAB APPARATUS

We’ve also made improvements in the 6” vehicle. The original vehicle had one coil mounted on an arm. To be able to mount multiple coils, we drilled equally spaced holes into a 6” disc and mounted three sets of 5 coils each at 120° locations. This new vehicle allowed us to scan all the defect sets at the same time using the BOP and lock-in setup. We also installed a motor-encoder mechanism to automate the data collection. In addition, a self-righting mechanism was put in place to prevent major rotations of the vehicle. This eliminates the need to “uncurl” the data during analysis.

GEOMETRIC & SYSTEM STUDIES

We have studied drive and sensor coils separation distance as a function of frequency. We obtained understandable results up to the 1-2 kHz range in frequency. We also studied defect detection at a set frequency as a function of sensor orientation to pipe axis. The results of these studies are discussed in the results section of this report. We also studied multiple exciter coils in both the 12” and 6” pipes. These studies have enabled us to reduce power consumption, which is important for use on the Explorer II robot which has limited power.

RESULTS AND DISCUSSION

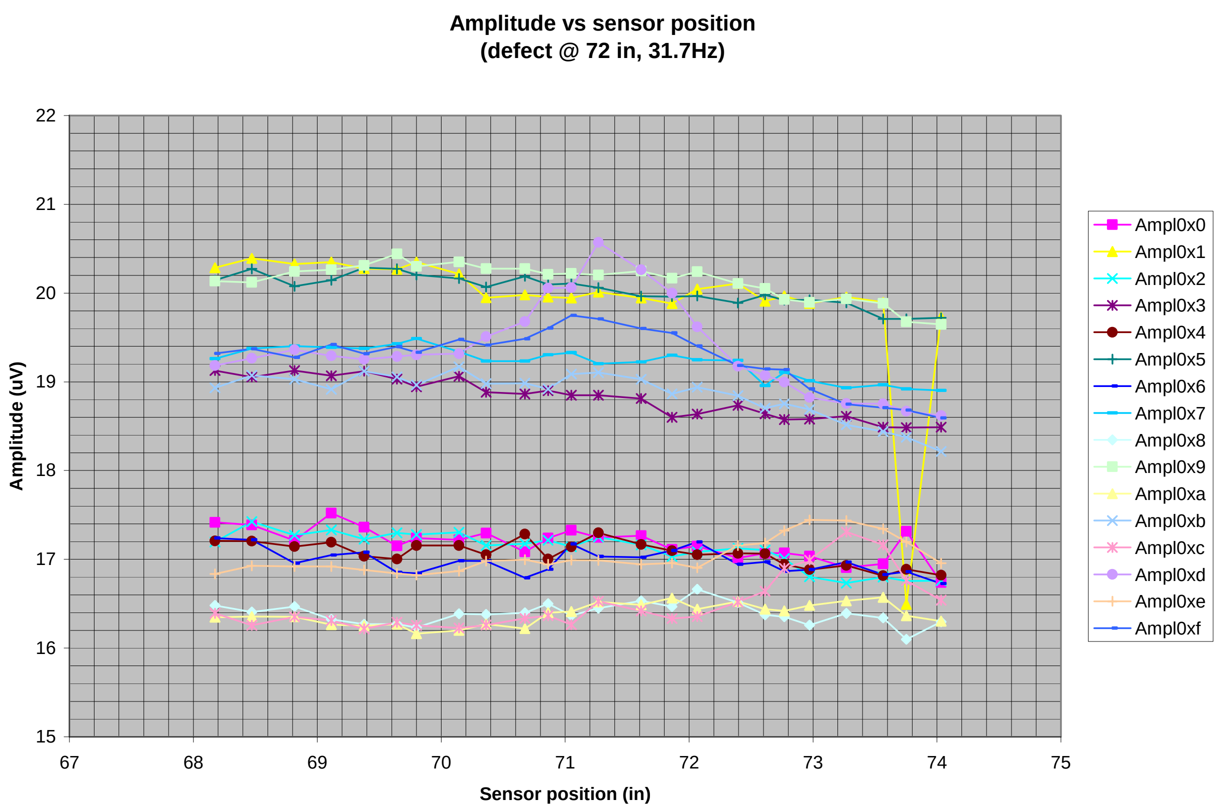

Figure 6: Amplitudes vs. Sensor Position Inside 12" Pipe

The graph in Figure 6 shows the amplitudes of the signals seen in all 16 channels while scanning a 6" section of the 12" test pipe. The 80% WT defect is nominally at 72" from the end of the pipe. The sensors labeled *Ampl0xd, Ampl0xf, Ampl0xc,* and *Ampl0xe* all indicate an increase in amplitude near the defect location. The horizontal axis indicates the position of sensors *Ampl0xd* and *Ampl0xf* along the pipe. *Ampl0xd* and *Ampl0xf* do not indicate exactly 72" because of systematic and correctable imprecision in their position. This is not due inherently to the technique but rather to position calibration constants. Due to mechanical constraints, the sensors *Ampl0xc,* and *Ampl0xe* are about 2" farther into the pipe[1], which is why they indicate a defect location about 2" farther than the other two sensors. The fact that multiple sensors indicate the defect allows for locating it circumferentially as well as axially.

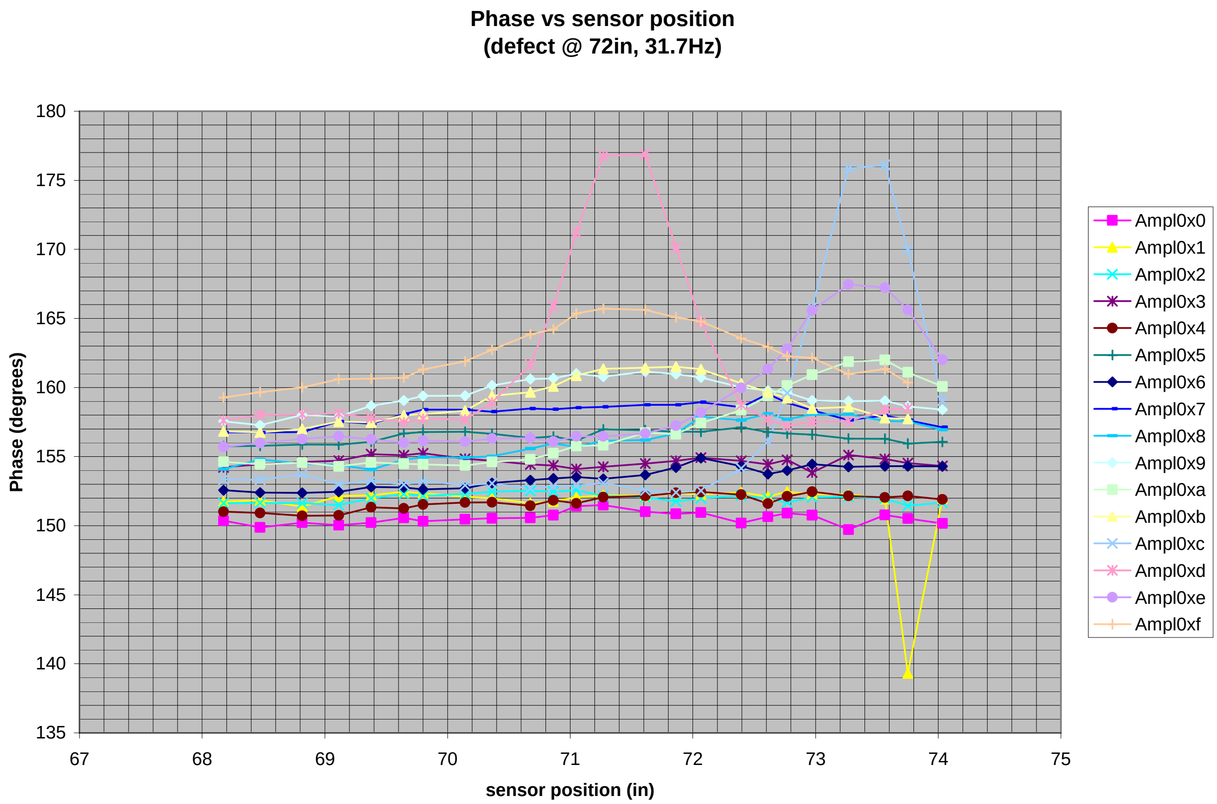

Figure 7: Phases vs. Sensor Position Inside Pipe

Figure 7 shows the phases of the signals seen in all 16 channels while scanning a 6" section of the 12" test pipe. The 80% WT defect is nominally at 72" from the end of the pipe. The sensors labeled *Ampl0xb, Ampl0xd, Ampl0xf,* and *Ampl0xa, Ampl0xc, Ampl0xe* all show an increase in phase near the point of the defect. The horizontal axis indicates the position of sensors *Ampl0xb, Ampl0xd, Ampl0xf*. The defect signals on channels *Ampl0xb, Ampl0xd, Ampl0xf* do not occur exactly at 72" because of systematic and correctable imprecision in their position. This is not due inherently to the technique but rather to position calibration constants. Due to mechanical constraints, the sensors *Ampl0xa, Ampl0xc, Ampl0xe* are about 2" farther into the pipe, which is why they indicate a defect location about 2" farther than the other two sensors. The fact that multiple sensors indicate the defect allows for locating it circumferentially as well as axially.

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1 This 2" separation between adjacent sensors is visible in Figure 5.

The graphs in Figures 6 and 7 are simple excel plots. One advance made in this segment of the project was the purchase of Adept Pro software from Russell Technologies. Figure 9 shows a screenshot of Adept Pro.

The Adept Pro display shows a strip chart of the phase angle on the left (ignore the analysis functions on the far left), followed by a C-Scan of the phase. Although the C-Scan provides a good overview of the defects, often as in this case, the strip chart is better for seeing the smaller defects. The magnitude information is displayed to the right of the phase information. The top right hand panel shows the Voltage Plane. The black spiral is the attenuation spiral: as the wall thickness increases, the remote filed eddy current signal strength decreases while the phase also decreases, resulting in a spiral in a polar plot. The blue curve on the plot is the signal from the defect at the marker that runs across the strip charts and C-scans. The two red lines on either side of the marker mark the range of data analyzed. The angle between the blue line and the spiral determines the defect depth, while the distance to the intercept with the attenuation spiral indicates the circumferential extent of the defect.

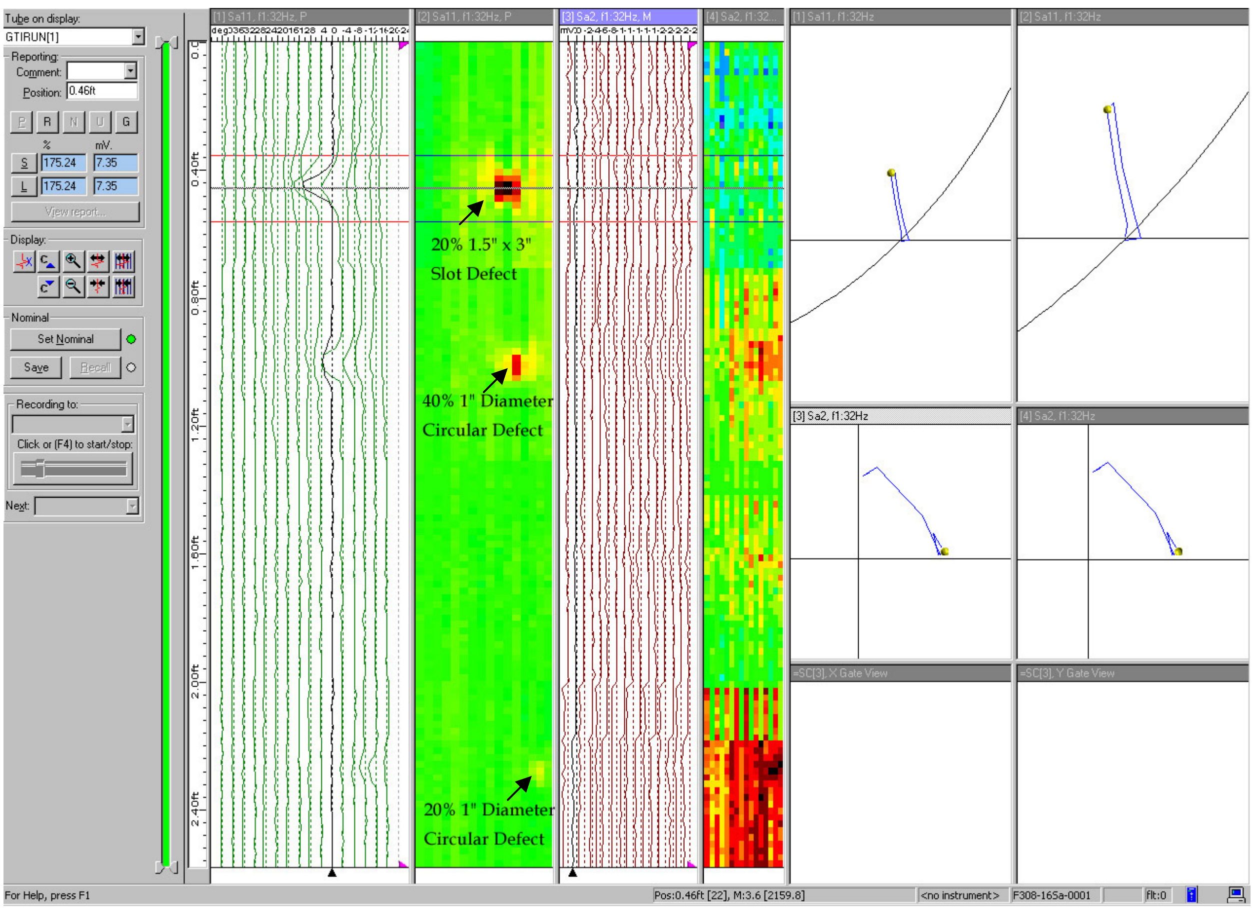

Figure 8: Screenshot of Adept Pro software showing defect locations in pipe.

Figure 8 is data analysis done on one defect line of a 12" seam welded pipe. Three of four defects were identified. The defect that was not detected was a 1" diameter circular defect of only 10% of the wall thickness.

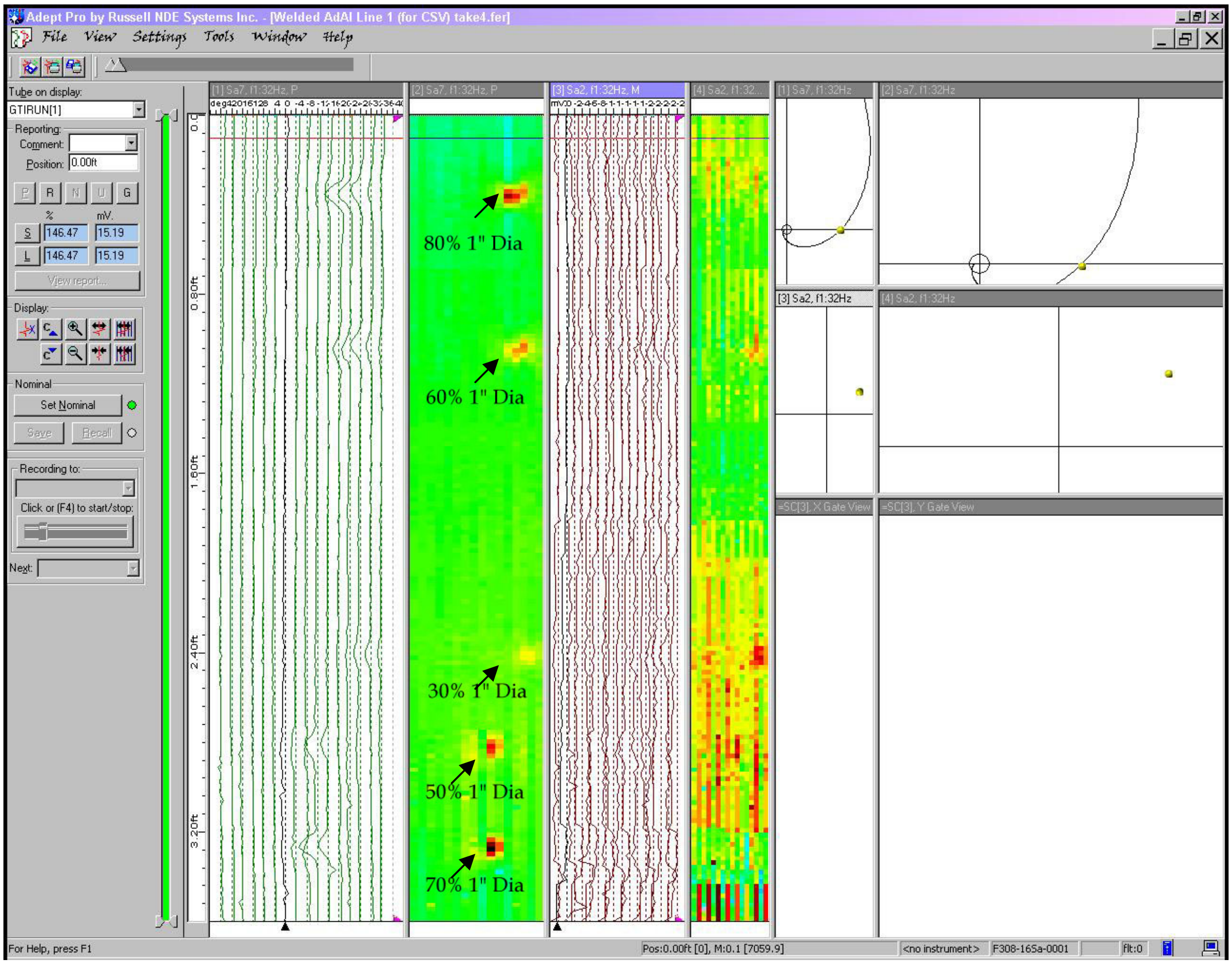

Figure 9: Screenshot of Adept Pro software showing defect locations in pipe along defect line 1.

Figure 9 is data analysis done on the first defect line of a 12" seam welded pipe with the second drive coil. Five of six defects were identified. The defect that was not detected was a 1" diameter circular defect of only 5% of the wall thickness.

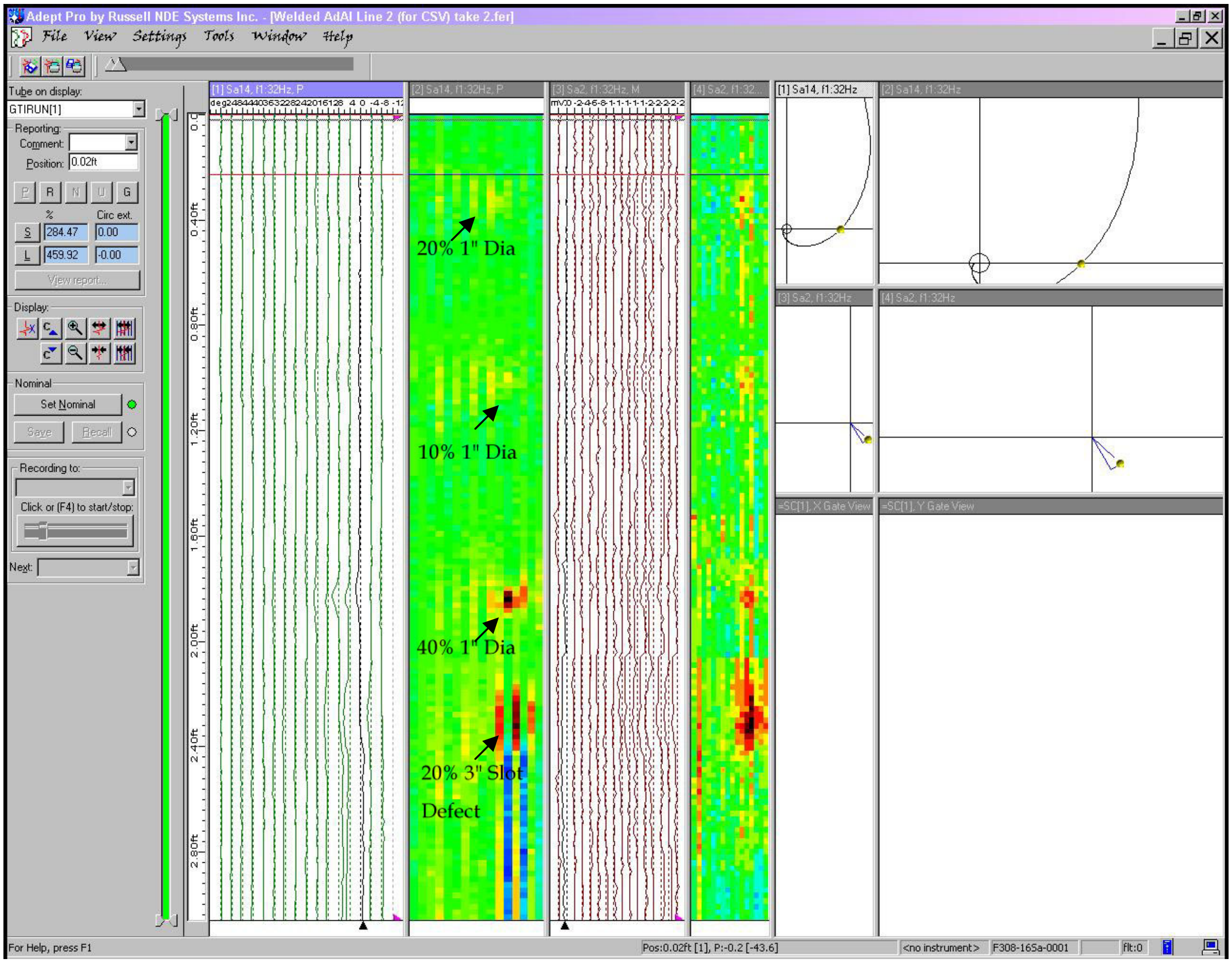

Figure 10: Screenshot of Adept Pro software showing defect locations in pipe along defect line 2.

Figure 10 is data analysis done on the second defect line of a 12” seam welded pipe with the second drive coil. Four of four defects were identified. The smallest defect that was detected was a 1” diameter circular defect of only 10% of the wall thickness.

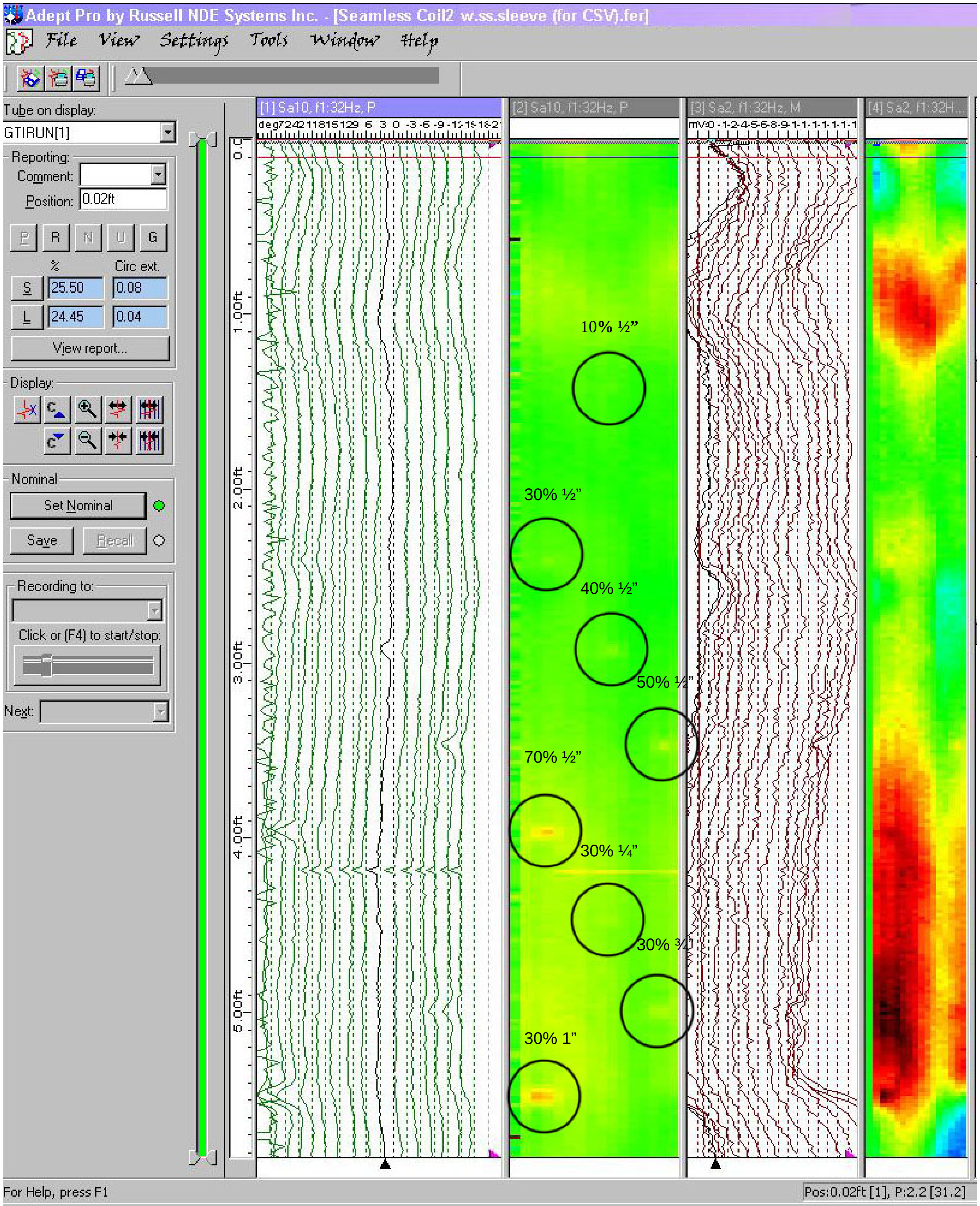

Figure 11: Screen shot of 6” seamless pipe scan from Adept Pro Software.

Figure 11 is a scan of the entire 6” seamless pipe. During this test, a stainless steel sleeve, was placed between the exciter and sensor coils. We were testing the effect of metal components on detection results since the Explorer II robot is metallic. Our concern is that the metal could disrupt the electromagnetic fields and produce poor results. In actuality, we obtained better results with the sleeve inserted. This scan covered 10 defects. Eight of them are identifiable in the strip chart to the left of the screenshot. The two defects that did not show in the data were a 5% ½” and a 30% ¼” defect. We suspect the 30% defect was not detected because we scan in ¼” steps. It is likely that we stepped right over that defect. The results seem to be very promising as the 10% ½” defect was found. We repeated this test with a chunk of aluminum of 3” diameter and 3” in length. The results were slightly noisier but there was no apparent drop in the amplitude of the signal. The smallest defect detected in this run was a 30% ½” round.

After completing the above testing with metal components, we performed a study of differential coils. Our differential coils consisted of two identical coils mounted close to each other on the same axis and were operated with each coil 180° out of phase with the other’s current. Data analysis included taking the absolute measurement of each coil then subtracting them to get the differential. Results of scanning the pipe along all three defect lines of the 6” seamless pipe are shown in Figure 12. The absolute measurements are plotted in red and orange and the differential measurement is plotted in yellow. The bright red vertical lines represent defect locations along the length of the pipe. The defects measured absolutely are indicated by significant increases in amplitude. A sharp drop followed by a sharp increase in amplitude indicates differential defects. These can be seen in Figure 12. The most obvious is the 80% deep defect located around 78” on Line 1. The differential coils do not appear to have any significant advantage over our standard sensor coils.

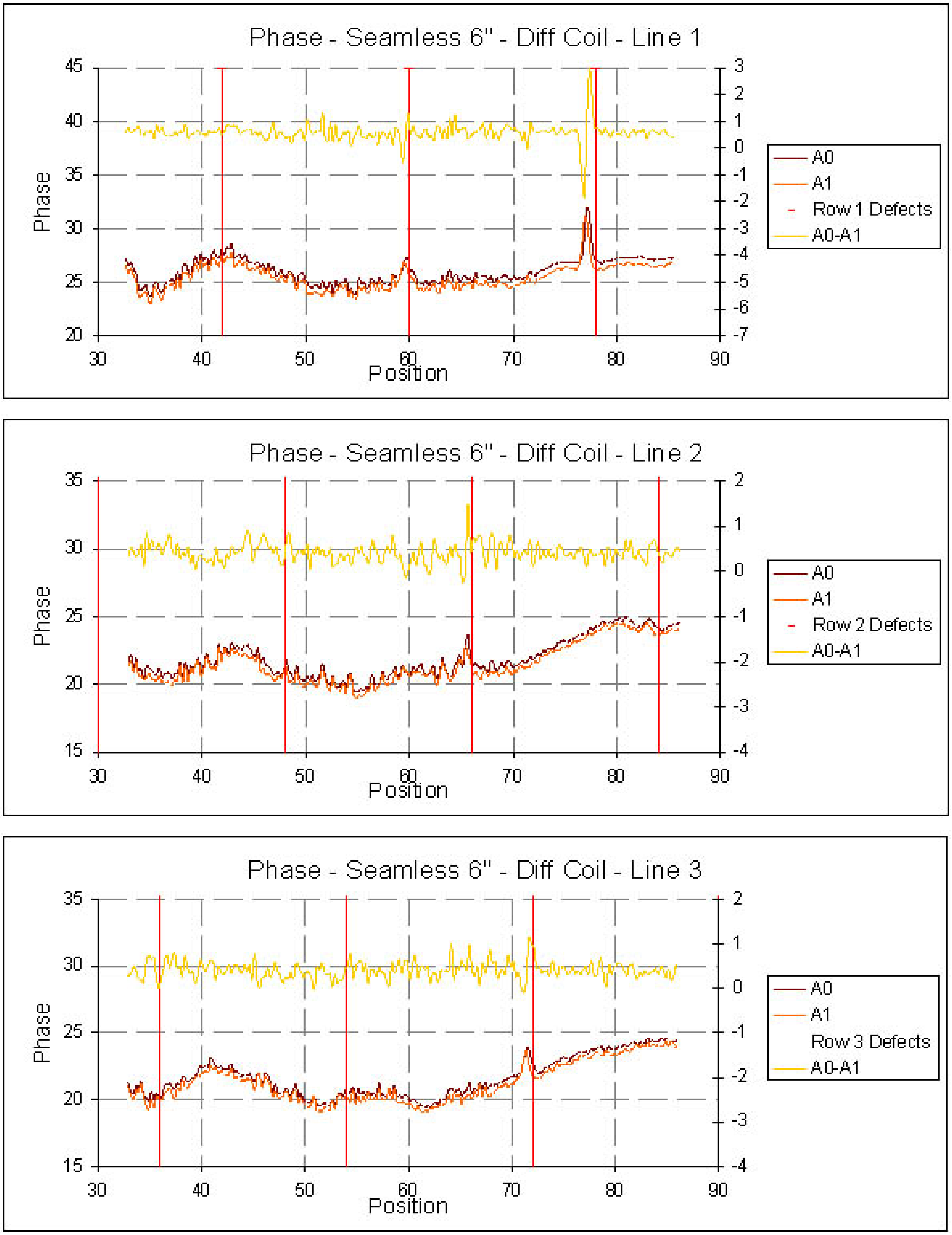

Figure 12: Results of scanning the 6” seamless pipe with differential coils.

To date, we have tested a total of three exciter coils. The data discussed thus far in the report in the 6" pipe has been results using Coil 2. We also tested Coil 4 and Coil 5. The specs of these coils are listed in Table 1 below. Of the three, Coil 4 was the most undesirable because of its weight and power consumption. A comparison of various tests using Coils 2 and 5 show that the magnitude of the sensed field is greater from Coil 5: 0.53mV versus .84mV.

Coil Name	Inner Diameter (")	Length (")	# of Turns	Wire Gauge	Weight (lb)	Power Consumption (W)
Coil 2	2.375	3.25	2000	29	1.03	1.06
Coil 4	2.375	1	750	29	.35	6.62
Coil 5	3.5	4.25	1355	26	1.85	1.85

Table 1: Specifications of exciter coils tested.

Comparisons of detection results between Coils 2 and 5 tend to favor Coil 5. Coil 5 consistently detected all defects except for the 30% ¼" and 5% ½". Coil 2 also did not detect these two defects but in addition, it did not consistently detect the 20% ½" or 30% ½" whereas Coil 5 did.

In addition to coil testing, we standardized our exciter coil - sensor coil center-to-center distance to 15" based on the dimensions of the Explorer II. Prior to this standardization, the center-to-center distance for each test was based on pullout results of the individual exciter coils.

CONCLUSION

We have accomplished all of our goals and have met all of our deliverables to date. Important points of our accomplishments include optimization of the exciter coil, acquisition of improved detection equipment, and preliminary module designs. All of these are important because they bring us closer to our goal of creating an innovative inspection tool for the natural gas industry. This tool will be capable of inspecting unpiggable pipelines. This sensor integrated Explorer II robot will address the need to inspect unpiggable lines in high consequence areas by one of the four methods mandated by the Pipeline Integrity Management Rule.

Because we have had much success in laboratory work, we remain confident that RFEC will in fact be well suited for use on Explorer II. We have been able to reduce power consumption of the exciter coil to a level compatible with the battery supply on the robot.

Through geometric changes and additional modifications, we were able to accomplish reducing the power consumption without compromising detection abilities. The acquisition of the Ferroscope and Adept Pro software from Russell Technologies will prove beneficial to the project since the Ferroscope can acquire data at the expected speed of travel of Explorer II. Preliminary module design shows that RFEC components are in fact small enough to work on a robotic platform capable of traversing unpiggable pipelines. We expect to be able to fit all of our equipment into the two designated robot modules while still being able to inspect all 360° of the pipe wall.

As a result of the work performed on this project during the first six months of the Inspection Technologies program, GTI has proven that the RFEC technology makes an outstanding partner for the Explorer II robotic platform. With continued effort and success, the natural gas industry will have a prototype tool capable of inspecting unpiggable pipelines by the close of this program.

REFERENCES

W.R. McLean, W. R., US Patent 2,573,799, “Apparatus for Magnetically Measuring Thickness of Ferrous Pipe”, Nov. 6, 1951

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TABLE OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

RFEC	Remote Field Eddy Current
GTI	Gas Technology Institute
BOP	Bipolar Operational Amplifier
V rms	Volts root mean square
A rms	Amps root mean square
MUX	Multiplexer
mV	Millivolt
W	Watt