APPENDIX A

FINAL PROJECT SUMMARY REPORT

PROJECT IDENTIFICATION INFORMATION

1. BUSINESS FIRM AND ADDRESS

HD Laboratories, Inc.
1595 NW Gilman Blvd, #14
Issaquah, WA 98027

2. DOT SBIR PROGRAM

2006 PHASE I

3. DOT CONTRACT NUMBER

DTRT57-07-C-10004

4. PERIOD OF PERFORMANCE

From 11/20/06 To 10/31/07

5. PROJECT TITLE

MEIS System for Pipeline Coating Inspection

SUMMARY OF COMPLETED PROJECT

The data in this final report shall not be released outside the Government without permission of the contractor for a period of four years from the completion date (10/31/07) of this project from which the data were generated.

An advanced pipe coating inspection system utilizing above-ground sensors has been developed and tested. The system uses Magnetically-assisted Electrochemical Impedance Spectroscopy (MEIS) to detect coating properties. A unique feature of the system is the use of a frequency response analyzer (FRA) for implementing MEIS. This design represents a substantial improvement over previous MEIS technology.

The MEIS system measures the complex electrical impedance of the pipe-to soil interface. The coating condition can be directly ascertained from this impedance data. Phase I results indicate that the method can both detect and size coating disbonds, and can also determine the type of fill medium in the disbond (air, water, or corrosion product).

The Phase I results will serve as a strong basis for Phase II system development. The Phase II system would be directed at rapid in-service inspection of pipelines.

APPROVAL SIGNATURES

1. PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR (Typed)	2. PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR (Signature)	3. DATE
THOMAS J. DAVIS	Thomas J. Davis	10-25-07

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MEIS SYSTEM FOR PIPELINE COATING INSPECTION

1.0 INTRODUCTION

Coating disbond on buried pipelines continues to be a major problem world-wide. A disbonded coating impairs the protection offered by cathodic protection on the pipe. Moreover, moisture ingress behind the disbonded coating can cause corrosion and/or stress corrosion cracking. Early detection of disbond can result in substantial cost savings, since only the coating and not the pipe needs repair.

One pigging method currently exists for detecting coating disbonds [1]. It uses EMAT-generated ultrasound. However, other techniques are needed for non-piggable pipes. MEIS (Magnetically-assisted Electrochemical Impedance Spectroscopy) offers the potential for inspecting these pipes. It should be substantially less costly than the pig-based methods.

MEIS was developed under funded research at Johns Hopkins University over a number of years [2, 3, 4, 5]. That work was directed at both measuring corrosion rate and assessing disbonds. PRCI funded much of this work with emphasis on disbond inspection.

MEIS is implemented from above ground using magnetometers. It measures the complex impedance of the pipe-to-soil interface at a number of test frequencies. The resulting data from a segment of pipe can then be analyzed using standard EIS (Electrochemical Impedance Spectroscopy) [6]. The analysis reveals substantial information on the condition of the coating.

HD Laboratories has recently developed and field-tested a potentiostat-based MEIS system for an oil company who is a member of PRCI. These field tests yielded some first-ever baseline data on pipe coatings. The Phase I work reported herein was conducted under a technology evaluation license granted to HD Laboratories by PRCI.

Previous MEIS systems have been based on potentiostats of the type used by the work at Johns Hopkins. These devices are generally intended for laboratory EIS work, and were not highly amenable to field MEIS operation. The design reported herein utilizes a frequency response analyzer (FRA) to perform the impedance measurements. It offers substantially more advantages for field implementation of MEIS.

2.0 SUMMARY OF RESULTS

An MEIS system utilizing an FRA for performing pipe coating impedance measurements was successfully developed, and was refined during laboratory testing. This system is described in Section 5 of this report, while detailed test results are contained in Section 6. The MEIS laboratory test bed is described in Section 7.

The FRA-based system was used to test a number of pipe-coating conditions in the laboratory test bed. The test bed provided conditions virtually identical to those of operation field pipes. It was assembled using recently-measured coating properties from an operational FBE-coated pipe in the field. Simulated pipe lengths ranged from 6 to 40 yards of a 20-inch diameter, FBE-coated pipe.

The system was able to measure the disbond-sensitive coating parameters on all simulated pipe lengths with an overall accuracy of:

- 3.5% for pipe-to-soil resistance
- 2.4% for pipe-to-soil capacitance.

These accuracies allow MEIS to readily detect disbonds and quantify whether the disbond is filled with air, water of corrosion product. Some reduction in accuracy may be encountered for field conditions, but improvements contemplated for the next generation Phase II system should remedy this.

Sizing of the disbonds should also be practical with MEIS. The percent of disbonded area in the pipe segment under test will be available from the data. We project that a Phase II system could characterize disbonds as small as 10% of of the total area of the pipe segment being inspected. This would translate to a 9 square-foot disbond on a 6 yard section of 20-inch pipe.

We recommend that a Phase II project be initiated to further these results and develop a next generation MEIS system. We have a potential Phase III sponsor who is also interested in co-funding Phase II work. The intended final result would be a vehicle-mounted, rapid deployment MEIS system for in-service inspection. In addition, the previously-mentioned oil company for whom we developed the earlier MEIS system is interested in being a party to this work. They would make some of the new intellectual property available to the project.

3.0 PHASE I TECHNICAL OBJECTIVES

The objectives of this Phase I SBIR were:

1. Test an advanced method for implementing MEIS which will form the foundation of Phase II and III systems.
2. Quantify the ability of MEIS to characterize disbonded coating.

This work was directed at answering the following questions:

1. Can commercially available Frequency Response Analyzers (FRA's) successfully replace the more cumbersome potentiostats used for earlier MEIS work?
2. Can MEIS successfully quantify the degree of disbond in a pipe section?
3. Can MEIS successfully detect the type of fill in the disbond volume?

4.0 PHASE I WORK PLAN

The original work plan called for burying calibration pipes with various degrees of simulated disbond and testing them with the Phase I MEIS system. However, the work plan was redirected to a more practical approach during the course of the project. This was due to the following factors:

1. HD Laboratories recently conducted successful field tests on operational pipelines with an older, potentiostat-based MEIS system. These tests provided the first-ever baseline data on properties of bonded Fusion-Bonded Epoxy (FBE) coating. Specifically, we were able to measure the actual values of pipe-to-soil capacitance and conductance per unit-area of pipe surface for FBE-coated pipe.
2. Our Phase I findings showed that use of buried calibration pipes with synthetic disbonds was impractical for the project. Larger and longer pipe sections than originally anticipated would be required for the Phase I work. This was beyond the financial scope of the Phase I project.

The work plan was consequently revised to take advantage of these findings. A laboratory test bed was constructed which fully and accurately simulated all the test conditions needed for Phase I. The field-measured FBE coating parameters (mentioned above) allowed us to directly simulate various lengths of pipe and disbond conditions. Ultimately, we believe the MEIS technology has been advanced further by this work than originally planned

The laboratory test bed consisted of a tape-wrapped pipe section connected to electrical loads that precisely simulated the various coating conditions. The system magnetometer was used to sense on-pipe current. It was positioned to at a stand-off of 36 inches from the pipe to simulate a 3-foot cover-soil layer. It is described in Section 7.0.

5.0 THE NEW MEIS SYSTEM

Photographs of the FRA-based MEIS system are included as Figures 1 - 4. The Phase I MEIS instrument appears in Figures 1 and 2. This instrument both houses the FRA and contains apparatus for switching between MEIS and calibration modes. The calibration mode serves to calibrate the system magnetometer.

The system magnetometer is shown in Figure 3. It is a rugged, highly sensitive, and expensive device that can measure on-pipe current from above ground. It has a null feature to cancel the response to the earth's magnetic field. The earth-field signal, if not canceled, can swamp out the smaller signal from the on-pipe current. These devices are originally intended for naval operations.

The complete electronic system (exclusive of the magnetometer) is shown in Figure 4. It includes the Phase I MEIS instrument, a power amplifier for driving the pipe circuits, and a computer for operating the FRA.

The system connects to a pipe in the manner shown in Figure 5. Further information on MEIS principles are contained in references 2-5.

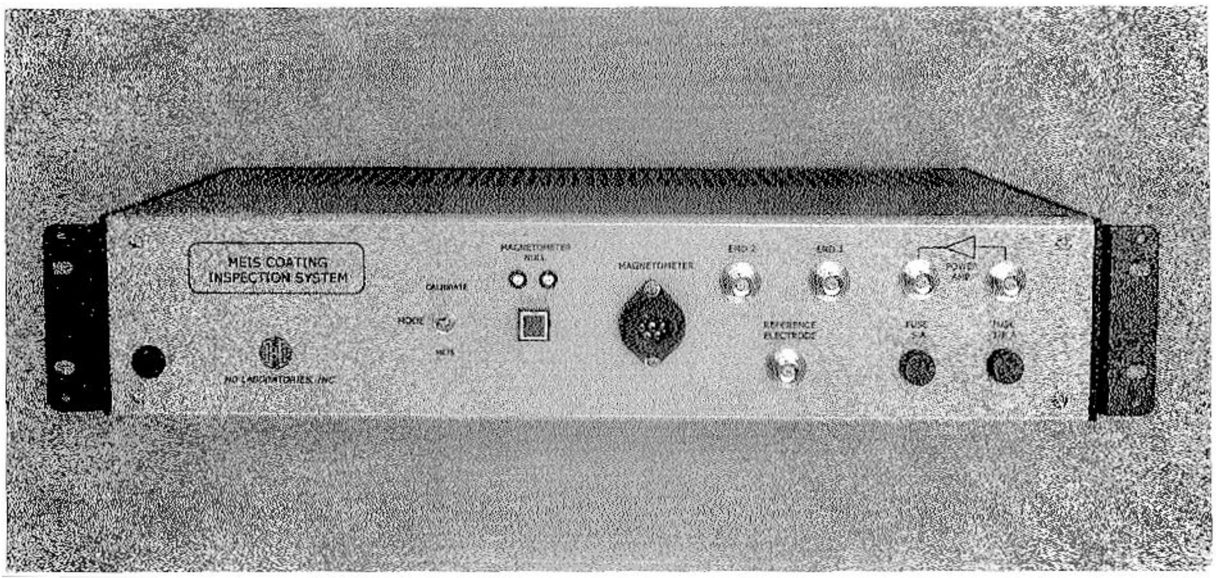

Figure 1. The new MEIS instrument. It houses the FRA and interfaces to all other system components.

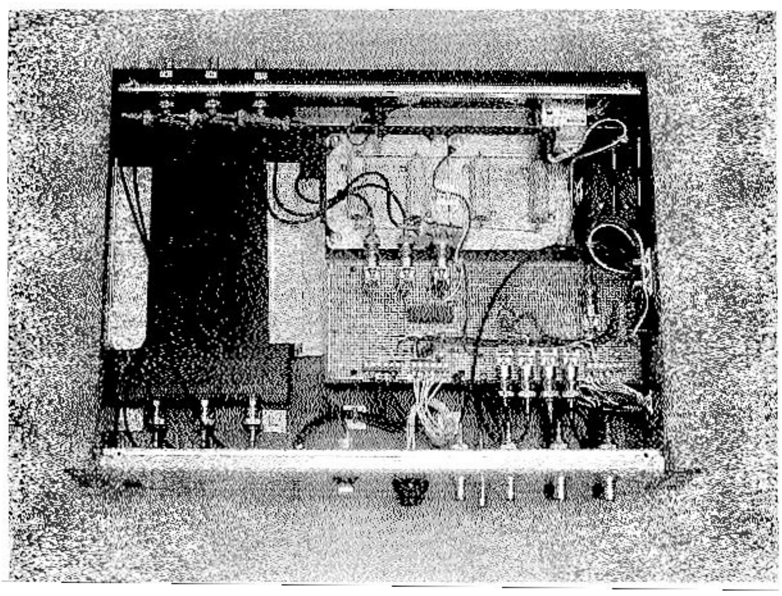

Figure 2. Internal view of the Phase I MEIS instrument. The FRA appears at the left. The gold-colored objects are power resistors that form the sense resistor for magnetometer calibration

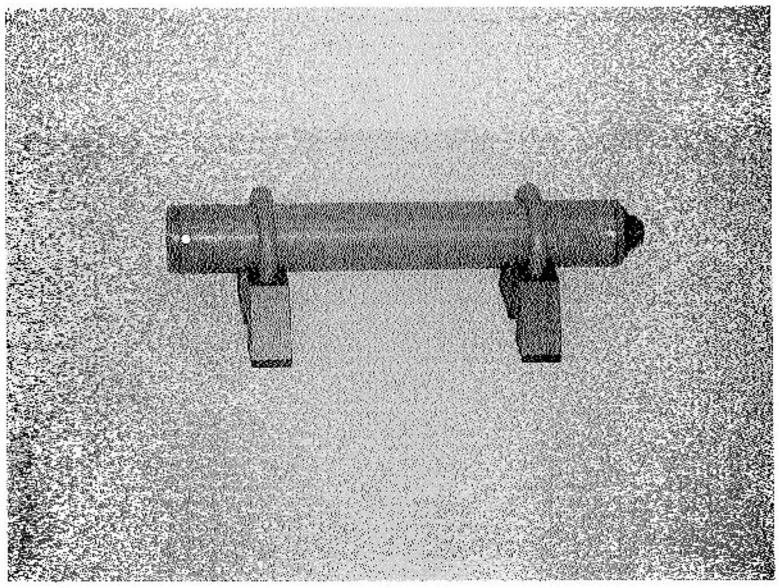

Figure 3. The system magnetometer. The feet are intended to keep its internal field sensor aimed at the pipe.

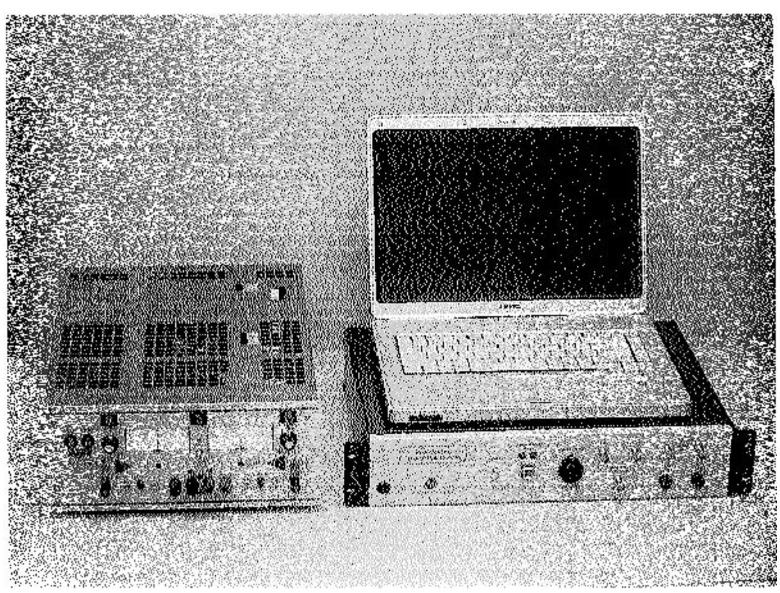

Figure 4. Major system components. The power amplifier at left is used to drive the pipe circuit, and the computer controls the FRA through a USB port.

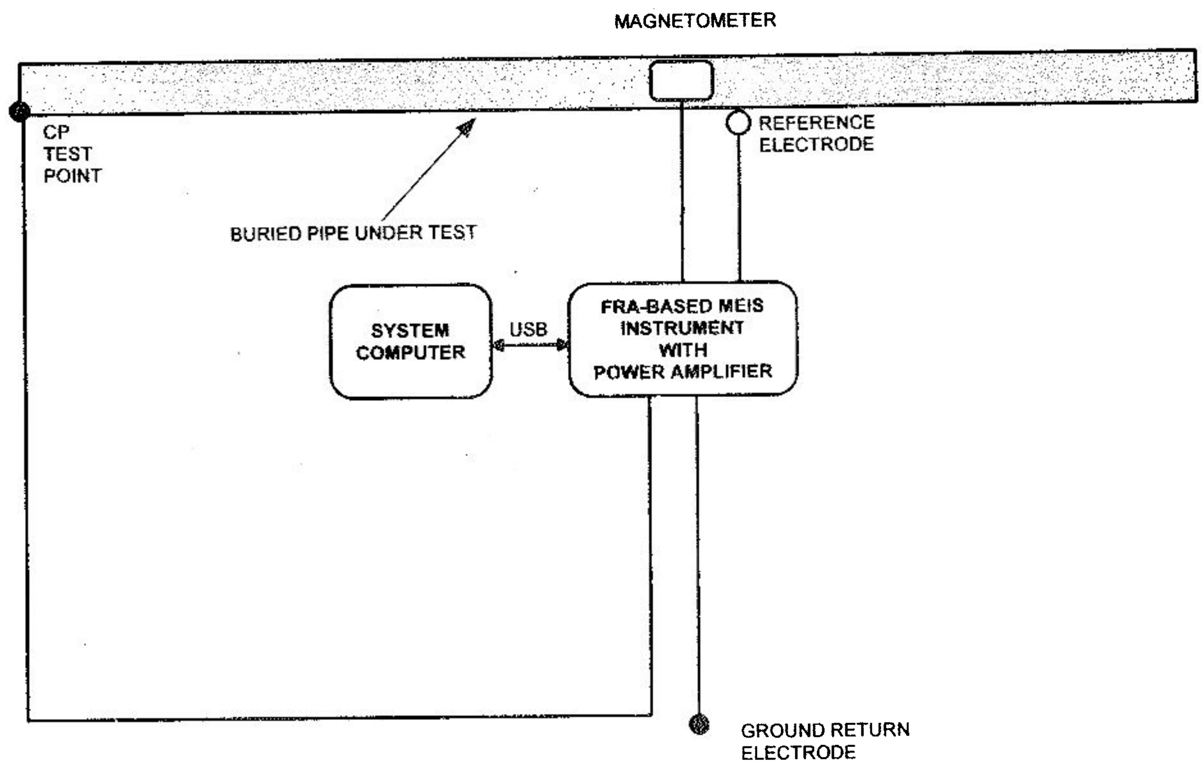

Figure 5. A MEIS system utilizing a frequency response analyzer. The drive signal is injected at a CP test point.

Phase II and III systems would use a remote signal injector, thereby eliminating the wire link to the pipe shown above.

6.0 DETAILED TEST RESULTS

We first provide a short overview on pipe coating parameters in Section 6.1. The test results follow in Section 6.2, with all numeric data contained in Table 1. Selected Nyquist plots of the data appear in Section 6.3 for those wishing more information. These show how the pipe coating values are estimated. Also, the air-filled disbond shows a unique signature.

6.1 BASICS OF PIPE COATINGS

MEIS assesses pipe coating condition by measuring two circuit elements of the pipe segments pipe-to-soil impedance. These are the capacitance (C_1) and resistance (R_1) from the pipe metal to the soil. These circuit elements are illustrated in Figure 1, which is a standard Randles circuit for a coated interface. Both of these values will be affected by the coating condition.

The other element shown is the earthing resistance (R_{SOIL}) of the pipe section. This is the actual resistance from the outer surface of the coating to mother earth. It is a function of soil resistivity, and the depth, length and diameter of the pipe section.

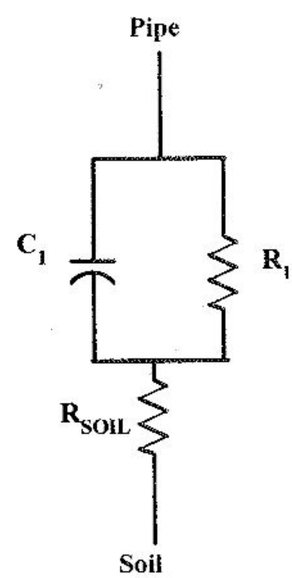

Figure 6. The electrical circuit of a pipe-to-soil interface.

MEIS can measure the value of all three circuit elements shown. The procedure is to measure on-pipe current with a magnetometer at two locations bounding the pipe segment of interest. The differential AC impedance as a function of frequency between the two locations is then computed. The circuit element values can be computed from this data.

The properties of the coating interface can be determined from the values of R_I and C_I in the following manner.

- Resistor R_I is a function of the electrical resistivity of the interface. Thus a disbond with air or dry corrosion-product would increase this resistance relative to a good bond. However, disbonds with water ingress or wet corrosion product or bonds with microcracking or holidays could decrease the resistance.
- Capacitor C_I is a function of the dielectric coefficients of the media between the pipe and soil. Thus a disbond with air or dry corrosion product would decrease the capacitance relative to a good bond. However, disbonds with water ingress or wet corrosion product would increase the capacitance.
- The size of the disbond would be indicated by the deviation of R_I and C_I from the normal values encountered for the specific pipeline.

6.2 TEST RESULTS

We set up a laboratory test bed using a tape-wrapped pipe to deliver current to a simulated pipe segment. This setup is described in Section 7.0. The pipe segment parameters were based on our recent field observations of capacitance and conductance per unit area for FBE-coated pipe.

The per unit area values we observed on FBE-coated pipe were:

- Capacitance: 11.1 picofarads/cm^2
- Conductance: 4.7 E-8 mhos/cm^2.

Conductance is 1/R and provides a measure of mhos/unit area. It is the real component of complex admittance. Resistance may be used directly but the units are ohms*unit area.

These numbers allow us to calculate R_I and C_I for any bonded segment of pipe as a function of its surface area. The remaining value to be computed is R_{SOIL}. This value (the earthing resistance of the pipe section) was computed from Dwight's equations [7] using an assumed soil resistivity of 18,370 ohm-cm.

We used this information to design a set of simulated pipe segments, including disbonds. The simulated pipe lengths ranged from 45 yards down to 6 yards of a 20-inch diameter FBE-coated pipe. Each used a Randles circuit with the values calculated from the information above. Earthing resistances of 1 and 2 ohms were used for the balance-of-pipe impedance represented by the rest of the long pipe. This is consistent with field findings for the FBE-coated pipe.

The disbonds were on simulated pipe segment lengths of 13 yards, and were configured as 100% (of the surface area) disbonds.

The test data is shown in Table 1.

PIPE SEGMENT LENGTH, yards	CONDITION	R_1 (Ohms) Actual	R_1 (Ohms) Reported by MEIS	C_1 (Microfarads) Actual	C_1 (Microfarads) Reported by MEIS
45	Bonded	32.5	34	6.78	6.86
31	Bonded	47.5	49	4.85	4.76
19	Bonded	77.9	81	2.9	2.92
13	Bonded	114	119	1.97	1.96
6	Bonded	247	255	0.97	0.92
13	Air-filled Disbond	Open	Open	1.97	2.00
13	Water-filled Disbond	114	112	3.88	3.85
13	Corrosion Product in Disbond	247	242	0.97	0.94

Table 1. MEIS system test results. Resistance units are ohms, capacitance units are microfarads. The "actual" R_1 and C_1 values correspond to a 20-inch diameter pipe segment of the length indicated. They are based on parameters obtained from recent field measurements with an older potentiostat-based MEIS system.

The RMS measurement errors were 3.5% for R_1 and 2.3% for C_1. This data is quite encouraging and can readily permit accurate assessment of pipe coating quality. The various simulated bond and disbond conditions are readily discernible to a high degree of accuraccy in the above data.

As indicated earlier, we project from these results that a Phase II MEIS sysetm using an FRA could report disbonds as small as 10% of the surface area of the pipe segment under test.

In summary, the data show that the following information is available from MEIS inspection of pipe coating:

- Bonded or disbonded
- Disbond Area
- Type of fill in Disbond
    - Air
    - Water
    - Corrosion Product

This performance listed above was obtained using a value of two ohms for the balance-of-pipe load. The error approximately doubled when a value of one ohm was used for the balance-of-pipe load. Error can be lowered in the field by using higher pipe-drive currents and by using advanced signal processing.

6.3 SELECTED NYQUIST PLOTS

The actual values of the circuit elements shown in Figure 6 are commonly extracted using Nyquist plots of the data, followed by curve fitting. A Nyquist plot is shown in Figure 7.

Nyquist plots from two each of the bonded and disbonded conditions are included as Figures 8-11.

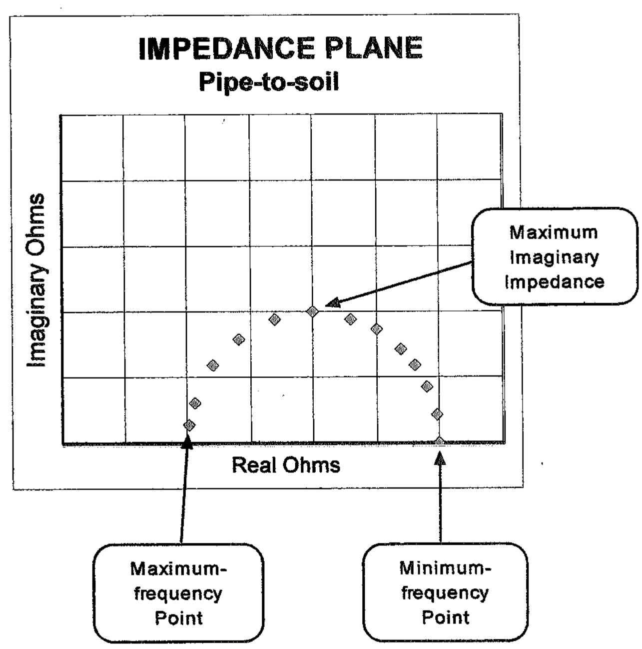

Figure 7.

A Nyquist plot of the circuit in Figure 6.

The impedance at the minimum frequency is the sum of R_1 and R_{SOIL}, while that at the maximum frequency is equal to R_{SOIL}. Capacitor $C_1 = 1/[2(pi)fR_1]$, where f is the frequency at maximum imaginary impedance occurs.

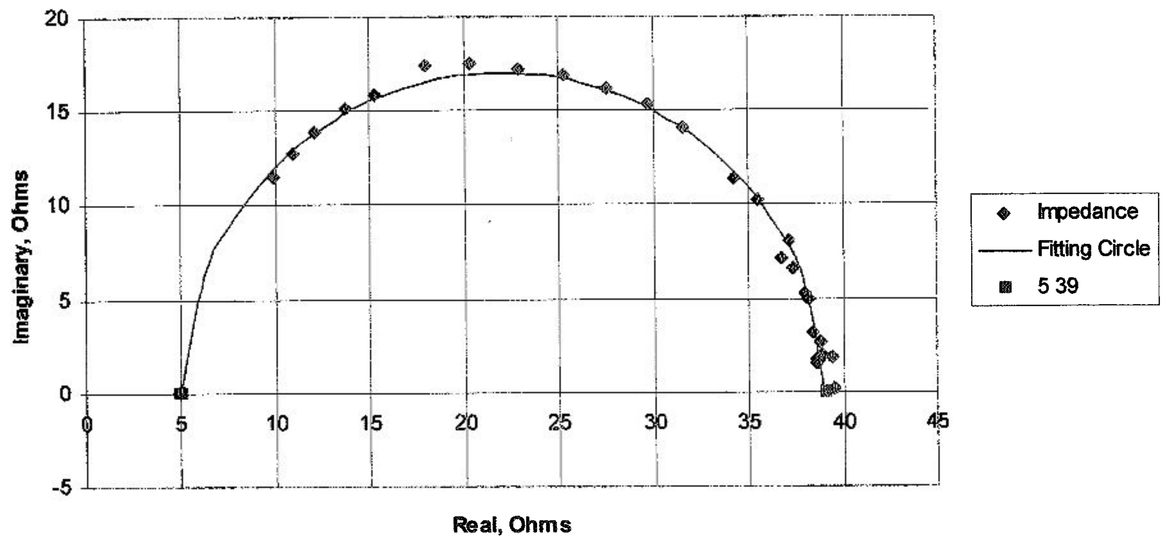

Figure 8. Nyquist plot of 45 yard bonded pipe segment. This is the cleanest data because of the lower values associated with the long segment length.

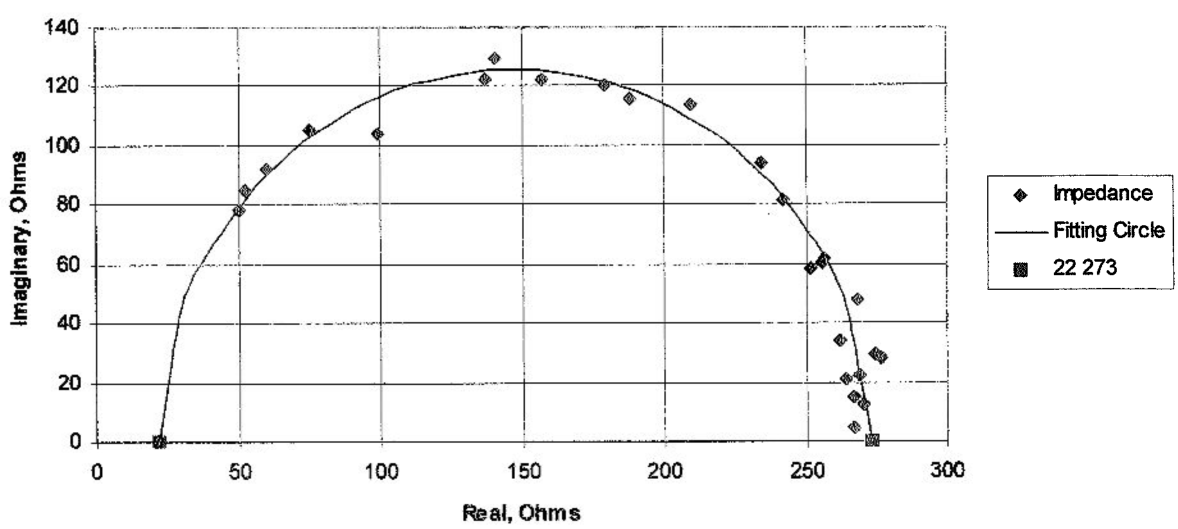

Figure 9. A 6 yard bonded pipe segment. The data is noisier because the values are large compared to the 2-ohm balance-of-pipe earthing resistance used.

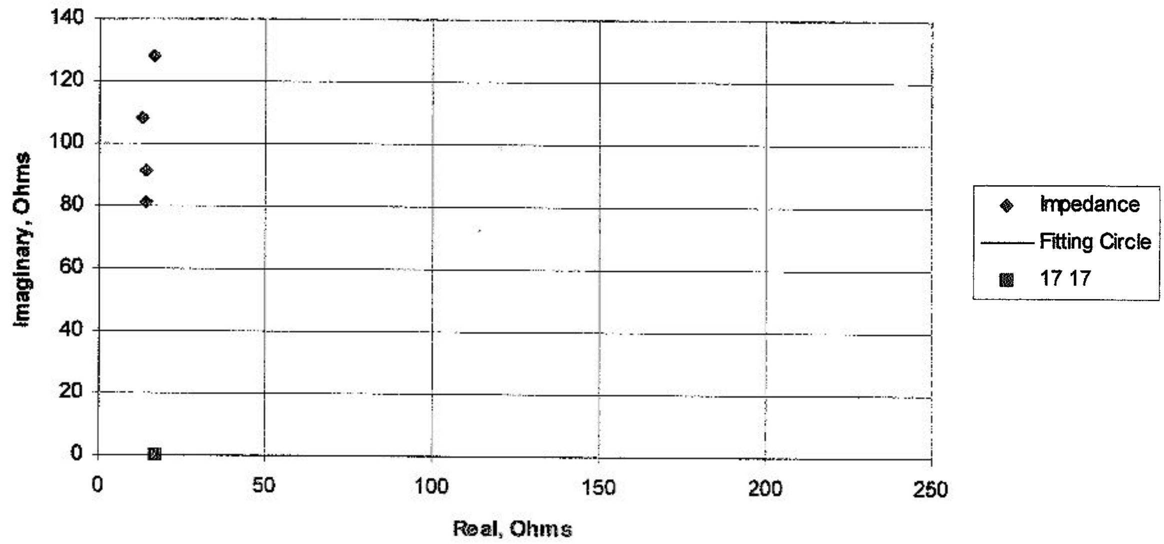

Figure 10. Simulated 13 yard air-filled disbond. Only the high frequency points are needed to characterize the disbond. The ciruit is a capacitor in series with R_{SOIL}. Its impedance will increase vertically with decreasing frequency.

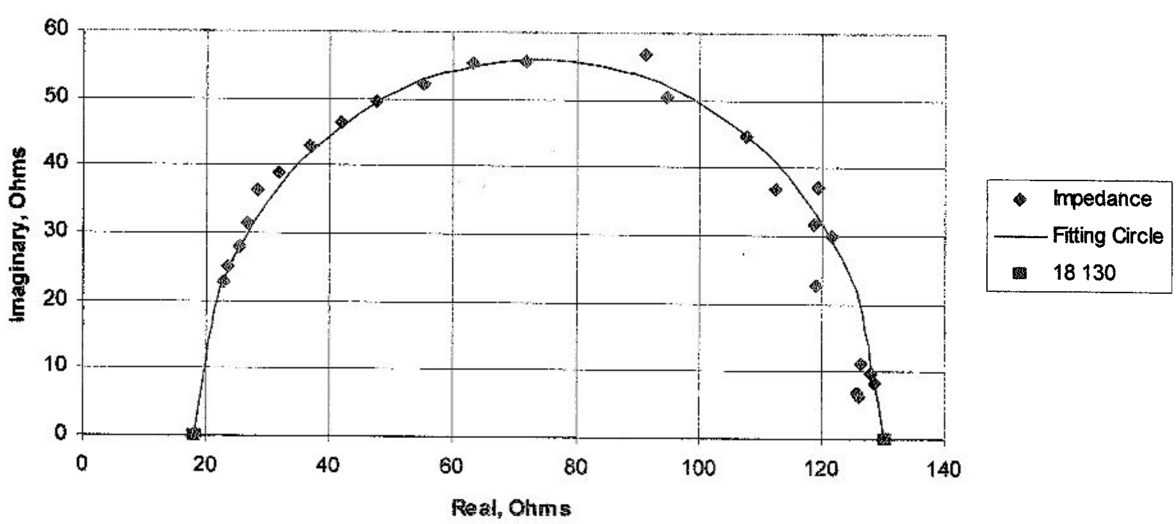

Figure 11. Simulated 13 yard water-flled disbond. It has the same shape as a bonded segment but has different values of R_1 and C_1.

7.0 LABORATORY TEST BED

A laboratory test bed was set up to thoroughly and accurately simulate field conditions for MEIS inspection of buried pipe. A block diagram of the test bed is shown in Figure 12.

The test bed produces the exact same magnetometer and pipe-to-soil voltages that would occur for a segment of buried pipe with the simulated impedances shown. As noted previously, the values of R_l and C_l for the simulated pipe segment were computed using recently-measured pipe coating parameters in the field. The values of R_{SOIL} were calculated from Dwight's equation [7] for the pipe depth, diameter, segment length, and the assumed soil resistivity.

The magnetometer was placed 36 inches above a 10 foot pipe in the laboratory through which the test current passed. This simulated field conditions with a 3 feet of cover soil.

Magnetometer readings are collected for each of the two switch positions. In one case the current measured is that flowing to mother earth through both the balance of the pipe and the segment coating under test. This corresponds to placing the magnetometer at the input side of the segment. In the other case, the current is only that flowing in the balance of the pipe. This corresponds to placing the magnetometer at the downstream side of the segment.

This procedure implements exactly the MEIS measurement scheme described by Srinivasan in Reference 3.

We used balance-of-pipe earthing resistances of 1 and 2 ohms for the tests. Recent field experience indicated that these numbers are consistent for FBE-coated pipes. As noted, the data reported in Section 6 is for two ohms. A value of 12 ohms was used for the earthing resistance of the ground rod. This number is arbitrary and is based on the number of rods used, their depth, and the soil resistivity.

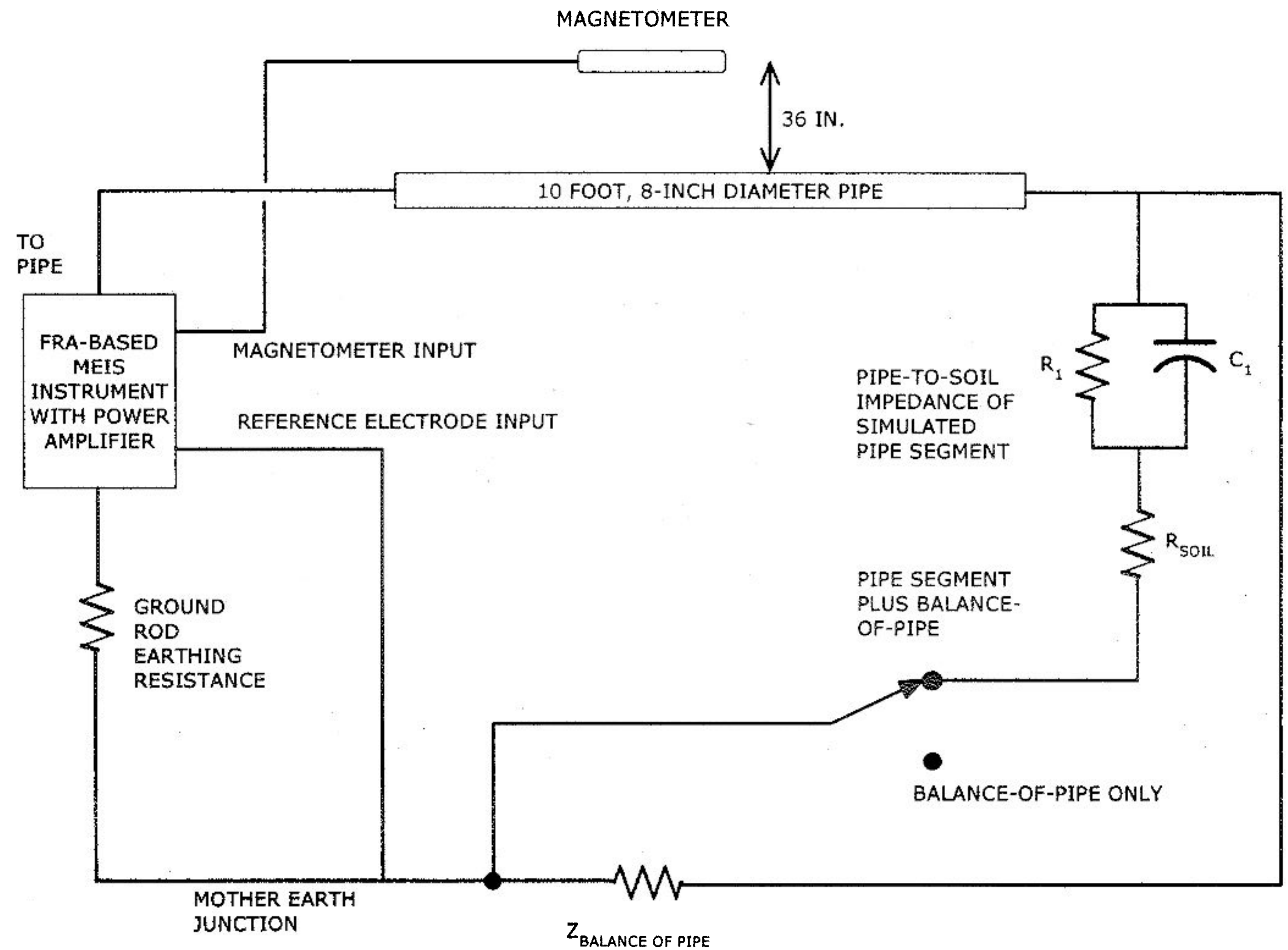

Figure 12. Laboratory test bed used for experiments.

8.0 RECOMMENDATIONS FOR FUTURE WORK

It is recommended that a Phase II project be initiated to continue this work and develop the next generation MEIS system. This system would be intended for rapid field deployment and would be vehicle mounted. This design would be intended for production and sales, but primarily for in-service inspection.

The work would commence with extensive field testing with the Phase I system to prove up MEIS. Initially we would connect the existing test bed to an operational pipe more to provide an actual balance-of-pipe impedance. We would then construct longer calibration pipes with actual disbonds and bury them for testing. This would be followed by tests on operational pipelines and or pipe farms with disbonded pipe, concident with post-test excavation to verify results. Development of the next generation system would then commence.

As mentioned previously, a potential Phase III sponsor is very interested in these results, and may wish to co-fund a Phase II project. Moreover, the oil company for which HD Laboratories developed a potentiostat-based MEIS system is interested in making their intellectual property available for such a project.

9.0 REFERENCES

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