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EVALUATION AND VALIDATION OF ABOVEGROUND TECHNIQUES FOR COATING CONDITION ASSESSMENT

DTRS56-05-T-0004

PREPARED FOR

PHMSA
WASHINGTON, D.C.

PREPARED BY

CC TECHNOLOGIES, INC
GREGORY RUSCHAU, PH.D.
ANGEL KOWALSKI

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CC Technologies
A DNV COMPANY
Innovative Solutions

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Evaluation and Validation of Aboveground Techniques for Coating Condition Assessment

AUTHOR:

Gregory R. Ruschau, Ph.D. ______________________________ 02/23/06
Principal Investigator

REVIEWED BY:

C. Sean Brossia, Ph.D. ______________________________ 02/23/06
Director of Research

APPROVED BY:

Oliver C. Moghissi, Ph.D. ______________________________ 02/23/06
Senior Vice-President, Laboratories

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EXECUTIVE SUMMARY

The overall objective was to determine the accuracy, resolution, and limitations of equipment typically used for modern aboveground ECDA work with respect to locating holidays and disbondments with commonly used coatings with varying spatial relationships and geometrical configurations. The specific tasks of this program were the following:

1. Perform aboveground coating surveys on several underground pipelines using at least four (4) different survey techniques - DCVG, ACVG, PCM, C-scan, and Pearson surveys were performed.
2. Compare the results of the surveys with visual examinations of the coating defects after excavation of the surveyed pipelines.

Both DCVG and ACVG were the most accurate survey techniques, better able to resolve individual indications than the other surveys. DCVG and ACVG provided very similar data, with DCVG better able to size defects. Both techniques showed an ability to “pinpoint” a defect, after which some effort was necessary to determine defect size.

While the pinpointing provided more exact data, for long sections of pipe the voltage gradient surveys were more cumbersome than C-scan or PCM, which divided the pipe sections into discrete sections.

PCM appeared to be appropriate for large areas of disbondment. The DCVG and ACVG signals for these large disbonded regions appeared to indicate several defects rather than one large disbonded area. Beyond this example, PCM provided only non-specific data at uncertain locations along the pipe. C-scan was similar to PCM except that the option of a CICOS (close interval current only survey) to better pinpoint defect location was available with C-scan. The PCM equipment could be configured to read as a voltage gradient (ACVG) tool with the addition of the A-frame attachment.

The Pearson survey was clearly the weakest survey technique as it failed to locate any defects on one section and provided very inconsistent results on the second section. Clearly, the more recently developed voltage gradient technologies are an improvement over the Pearson survey method.

In no cases were false positives indicated, although the location of the defects varied by several feet in some cases. This was most likely due to the accuracy of the dig stake reference. Even when the coating defects were not clearly visible, as was the case for defects under which calcareous deposits were found, further investigation revealed that the indications were legitimate. This suggested that aboveground surveys can be more accurate than visual surveys, a counter-intuitive result. However, visual examinations were able to find several coating faults not detected by surveys, so there are advantages and disadvantages to each.

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INTRODUCTION

Multiple options exist for aboveground surveys to identify areas of disbonded coating on pipelines, all of which are valuable tools for external corrosion direct assessment (ECDA) of pipelines. The selection of a particular evaluation technique is often based on the operator's skill and experience with the technique and the anticipated findings. Some techniques are known to be better for locating and sizing only large disbonded areas, others are better for detecting smaller disbonded areas but may not be able to accurately size holidays.

Other significant factors which will affect accuracy include cathodic protection system type and current output, stray current interference, orientation of the coating defects, and environmental conditions (soil type, moisture, etc.). Limited information regarding the usefulness, accuracy, and flexibility of each technique is available, and a side-by-side comparison of each technique on a real pipeline with visual confirmation of the results would provide a valuable informational resource to the industry. Beyond this, the knowledge of which holidays are detectable with accuracy and which may be missed or misinterpreted by any or all techniques is a critical component for proper tool selection and interpretation of ECDA surveys.

CC Technologies has previously worked with the operators to validate the ECDA process. This work showed that the process was able to discriminate between pipeline locations with respect to both coating and corrosion damage. Validation efforts by others have shown similar correlation. A study of the merits of individual techniques with regard to accuracy and resolution was the focus of this investigation.

BACKGROUND

Aboveground survey techniques for pipeline assessment include the following:

Direct Current Voltage Gradient (DCVG): Close interval over-the-pipeline potential survey, where the rectifier on, instant off and the voltage gradient are measured between a half cell over the pipeline and one placed 1.5 to 2 meters to the side of the pipeline, simultaneously. The direction and magnitude of current flow through the soil are determined and correlated to coating defect size and location.

Alternating Current Voltage Gradient (ACVG): A traditional pipe locator is used to detect an a.c. current (typically 4 Hz) applied to the pipeline. Signal losses are correlated to the fault size. The primary distinction between ACVG and DCVG is that a signal generator is used to impart the signal to the pipeline for ACVG surveys.

Pearson Survey: An alternating current is passed from the pipe metal to the soil through defects in the coating, with a signal receiver transformed into an audible tone which is detected by the surveyor through earphones.

Pipeline Current Mapper (PCM): A trade name of a device from Radiodetection, Inc., PCM is an instrument for which an extremely low, "near d.c." frequency (4 Hz) is used to mirror as closely as possible the d.c. current generated by the cathodic protection. Integral datalogging functions store the current data so that current loss versus distance can be plotted.

C-Scan: The basic principle of the C-Scan AC Attenuation System is to use inductive coupling between the pipeline and the antenna to measure the strength of the signal current remaining on the line at each survey point. From this, the rate of loss (Logarithmic attenuation) of the signal from any previously stored survey point can be determined to give an indication of average coating condition on the section between those points. The attenuation value is independent of the applied signal and is an index of the coating condition. It can provide a clear indication as to whether faults are present in the section without surveying every foot of the pipeline.

The close interval survey (CIS) is not classified as a coating assessment tool and rather is a cathodic protection system assessment tool, but data from CIS work is used in coating condition assessments. CIS is the measurement of pipe-to-soil potentials at regular intervals along a pipeline. When insufficient potentials are identified from a system which has been verified to be intact (rectifiers and anodes functioning properly), one possible cause of this is excessive current demand from the pipe due to coating defects.

The DCVG, ACVG, and Pearson Surveys can all be classified into the category of voltage gradient techniques, while the PCM and C-Scan surveys can be generally classified as current attenuation techniques. The operating principles of each type will be described in more detail.

Voltage Gradient Techniques (DCVG, ACVG, Pearson)

The principle involved is that of impressing an alternating (Pearson and ACVG) or direct (DCVG) current between the pipe and the earth, and then detecting high potential drop in the neighborhood of a coating holiday.

On a Pearson survey a team of two people walk the line about 20-feet apart. Each person wears a pair of contact plates on their shoes; the potential difference between the two individuals' 20-feet apart is thus measured. The amplified signal can be heard in earphones and is indicated on a meter. As a holiday is approached, a rise in signal intensity is observed, which reaches a maximum when the front man is directly over the holiday. Another maximum is heard when the rear person passes the same point.

The ACVG is performed by attaching a device called an "A-Frame" to the PCM receiver to measure voltage gradients along the pipeline. A-Frame spikes are pushed into the ground and a reading is taken, a numerical value is displayed in dB microvolt and if a coating fault is in the vicinity an arrow is also displayed indicating the direction towards the fault. The operator follows the direction along the pipeline at approximately 3-foot intervals until the arrow display reverses indicating that the operator passed the coating fault. To determine the severity of the coating faults, readings are taken at 90 degrees to the pipeline starting at 3 feet from the pipeline at the fault position and moving away at 1-foot intervals. The maximum value obtained is then recorded.

To perform a DCVG survey the existing cathodic protection system of the pipeline or a temporary DC current source system is interrupted to produce a pulsed DC current applied to the pipeline. The current flow from the anode bed to the metallic structure exposed at coating faults generates a voltage gradient in the soil that can be traced in the soil surface above the pipeline by observing the out-of-balance between two half-cells connected to a special voltmeter.

AC Current Attenuation Techniques (PCM and C-SCAN Tools)

When an electrical current is applied to a perfectly coated buried pipeline, its magnitude decreases gradually as it travels away from the injection point, this is called "current attenuation", see Figure 1.

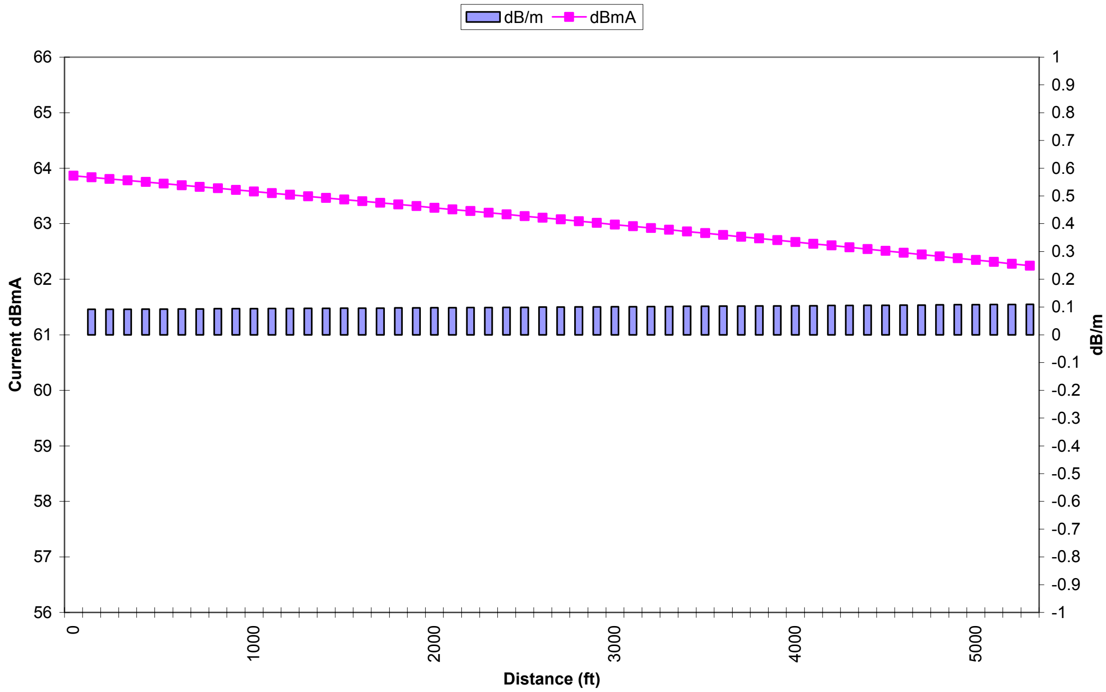


Figure 1: Current attenuation behavior of a buried pipeline with external coating in excellent condition

The current decline rate (current attenuation) follows a logarithmic behavior and therefore a parameter is calculated [dBmA, dBmA = log (current in mA) * 20] to plot current against the pipeline distance as a straight line. The current attenuation in miliBells per foot (mB/ft) is represented by the slope of the line obtained from plotting current (in mBmA) versus distance. As can be seen on Figure 1, a perfect coating will have a constant value determined by the following parameters: pipe diameter and wall thickness, AC current frequency and coating dielectric constant.

When a discontinuity is found in the coating of a buried pipeline the current attenuation changes abruptly because the dielectric constant of the coating has changed. Figure 2 shows the current attenuation plot of an underground pipeline with coating deterioration on a single section.

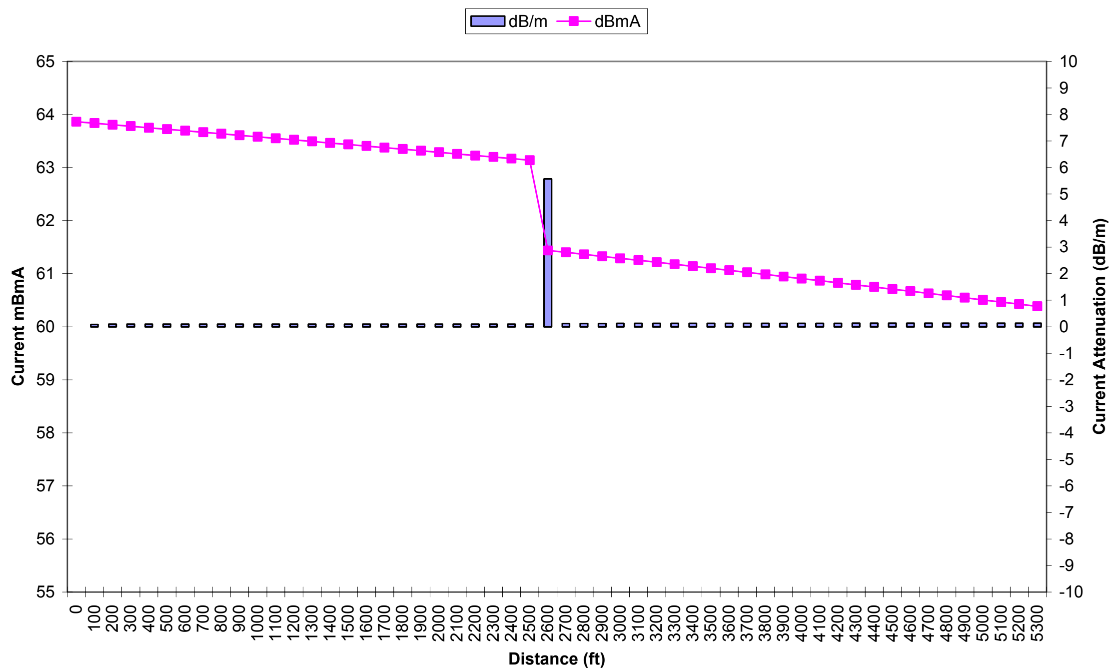


Figure 2: Example of the current attenuation behavior of an underground pipeline with coating deterioration on one section

Current attenuation tools determine the current magnitude by measuring the strength of the electromagnetic field radiated by the coated pipeline; any perturbation on the radiated electromagnetic field will induce error on the current readings. Examples shown in figures 1 and 2 represent ideal conditions and are based on the premise that the electromagnetic field is not disturbed, however in the real world the current attenuation results are affected by many factors such as:

- Existence of a coating holidays
- Aboveground and underground metallic structures in close proximity of the target pipeline,
- AC power transmission lines,
- CP system ground beds, grounding devices
- Others (grounding used to install current transmitter)

The interpretation of current attenuation results requires understanding the principles of the technique and the equipment limitations.

In practice, current attenuation tools are generally used to evaluate the average coating condition over underground pipe sections of 150 feet or more (as per C-Scan survey procedure manual). When readings are taken at a closer spacing, the current attenuation data may show inconsistency as current magnitude variations with distance are within the same range of the equipment precision. The current attenuation results in Figure 3 vary randomly from negative to positive values with no valid interpretation other than the presence of a perturbed magnetic field. Additionally the magnetic field could be affected by the current flow through the damaged coating or distorted by other elements such as an abrupt change in pipe depth or a bend.

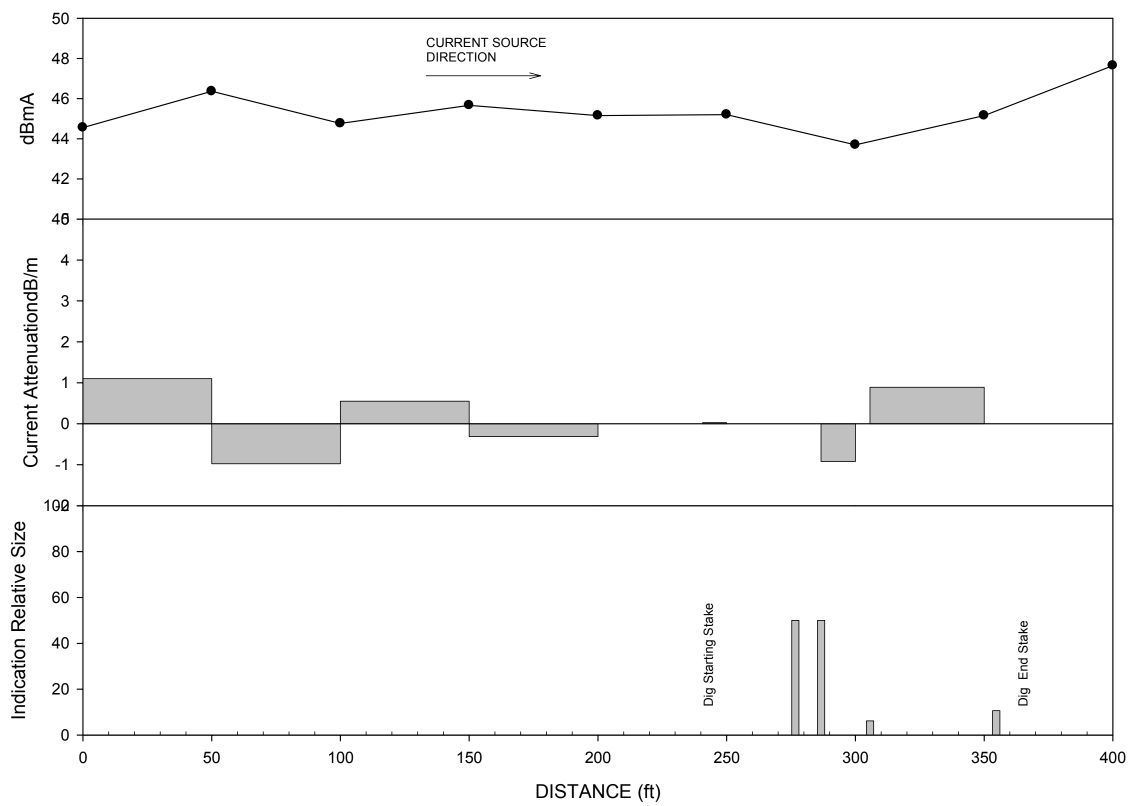


Figure 3: Current Attenuation results obtained with PCM tool calculating attenuation from current readings at 50 ft intervals

After analyzing the data shown above and using current readings at 150 ft spacing to calculate current attenuation values a more consistent curve was obtained and is presented in Figure 4.

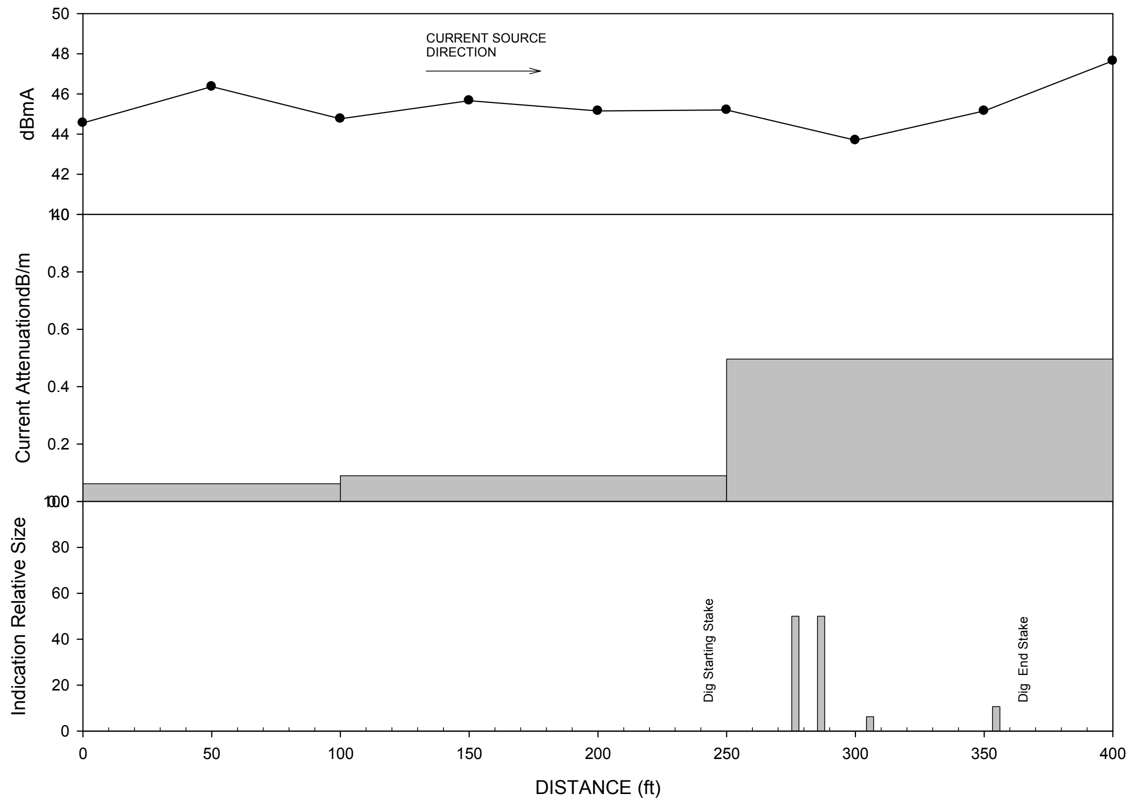


Figure 4: Current Attenuation results obtained with PCM tool calculating attenuation from current readings at 150 ft intervals

Equipment manufacturers recommend starting a survey with a minimum spacing between readings if coating quality is unknown. Current attenuation tools can be used to pin point coating holidays using very close spacing (10 ft) to evaluate underground pipeline sections with poor coating conditions when the induced magnetic field is known to be free of any external perturbation other than current flow through the coating holidays.

OBJECTIVES

The overall objectives were to determine the accuracy, resolution, and limitations of equipment typically used for modern aboveground ECDA work with respect to locating holidays and disbondments in the common coatings with varying spatial relationships and geometrical configuration. The specific tasks of this program were the following:

1. Perform aboveground coating surveys on several (three) underground pipelines on the selected pipeline system by at least four (4) different aboveground survey techniques
2. Compare the results of the four techniques with visual examinations of the coating defects after excavation of each of the surveyed pipelines

Based on the results of the visual examinations, the defects that were correctly identified and sized, those that were false positives/false negatives, and those that were missed were used to evaluate the performance of the survey methods.

PROCEDURES

Site Selection

The selection of the three survey sites was based on variations in the following characteristics:

- Coating type: Two locations had an asphalt enamel coating; the third had a coal tar enamel coating.
- Coating condition: One location was known to be in very poor condition, based on historical data. The second location was judged to be in good to fair condition, the third was thought to have pockets of isolated coating damage.
- Soil conditions: One location was buried in an extremely rocky trench with very wet conditions, a second was buried in a clay/loam/chalk mix, and the third primarily a clay soil.
- Proximity to other pipelines: Two of the locations were single cross-country lines, and the third was a “spur” pipeline consisting of 32-inch and 22-inch lines, each with a parallel 6-inch line in the same trench, in an urban/commercial setting.

DCVG, ACVG, and PCM surveys were conducted on several miles of operating liquid transmission pipelines in South Carolina during the fall of 2004, and again on separate sections in Virginia during the Summer of 2005. C-Scan was conducted on several sections in this same area, while a Pearson survey was performed in Virginia only. Areas were initially selected based on variations in the aforementioned characteristics, then final selections were made based on final access, i.e., locations for which the pipe was to be excavated in a time frame which enabled visual inspection without interfering with the rehabilitation process.

After the surveys were completed, only the sections of pipe which were scheduled for excavation during that time frame were further evaluated for coating defect size/location. Three different sites were selected, two of which had two separate sections that were excavated.

Site Characteristics

The first site was a 128-foot section known to have wet, rocky soil, located near Spartanburg, South Carolina. The 24-inch diameter pipeline was coated with asphalt enamel.

The second site was two separate excavations 203 feet and 125 feet long, separated by about 500 feet of unexcavated line. The soil in this region was a mix of clay, loam, and chalk. The 24-inch diameter pipeline in this region was also coated with asphalt enamel, and was located approximately 10 miles from the first site, close to the South Carolina / North Carolina border.

The third site was located in the Fairfax, Virginia area. Two segments, one 22-inch diameter, the other 32-inch diameter, were surveyed. Both of these segments were paralleled by a separate six-inch diameter line, approximately 2-3 feet away, which was not part of the survey. These two separate segments were later excavated, one excavation being 100 feet long, the second 203 feet long.

Visual examinations took place over a 24-hour period at each location. First, the indications identified by the aboveground surveys were located and visually examined. Next, the pipelines were examined for other coating disbondment and holidays, which were catalogued and photographed. In this way, the results of the exploratory visual exam (what do we see?) could be kept separate from the results of a specific exam in which a certain location was being examined (do we see what we're looking for?).

Survey Procedures

For the present work, available pipeline information consisting of close interval survey (CIS) data along with cathodic protection (CP) annual surveys, both performed by other personnel, over the test segment was analyzed and cathodic protection test stations and DC current sources were identified and located. Table 1 summarizes the test site characteristics.

For the application of each survey technique several signal transmitters set up configuration were tested and the surveys were performed at the best available set up configuration found.

Table 1. Test Segment Data Summary

Test Site	Coating Type	Pipe ID Number	Pipe Φ in inches	Distance in feet
1	Asphalt Enamel	N 4	36	128
2a	Asphalt Enamel	N 4	36	203
2b	Asphalt Enamel	N 4	36	125
3a	Coal Tar Enamel	Line 4	32	100
3b	Coal Tar Enamel	28A	22	210

Pipe Location, Depth of Cover, PCM and ACVG

The pipeline route was located with a Radiodetection Pipeline Current Mapper (PCM) with transmitter and receiver in ELF (extra low frequency) mode. The transmitter was connected to a ground and to the pipe and an adequate PCM current output was set. Marking flags were placed at convenient spacing, nominally 10 feet, and labeled with a numeric chain number. Pipe depth readings were recorded every 50 feet and PCM current magnitude and direction were recorded at every flag (Figure 5).

Following the PCM, the ACVG survey was performed attaching the A-frame to the PCM receiver and placing the probes over the line parallel to the pipeline route (Figure 6). The dB magnitude and direction was observed and followed until an indication was located (direction reversal). The magnitude of the indication was obtained by measuring the maximum amplitude of the signal in dB when moving the A-frame perpendicularly away from the pipeline direction. The distance from the indication to the closest chain flag was measured and recorded.

Figure 5: PCM survey

Figure 6: ACVG survey

DCVG SURVEY

A DCVG interrupter was installed at a DC source to generate an adequate DCVG signal over the test segment; the signal was measured at test stations upstream and downstream of the test segment to verify the level. If the level was not acceptable the DC current output was raised until an adequate level was achieved.

The operator with a DCVG receiver and probes walked along the pipeline segment (Figure 7) following the magnitude and direction of the analog DCVG meter. When a reversal on the needle deflection was observed the operator moved back and forth until a null deflection was obtained. At this point the operator repeated the procedure at a 90° angle from the pipeline axis. The intersection of the perpendicular lines of the two null points indicated the epicenter of the DCVG indication. The distance from the indication epicenter is measured to the closest chain flag and recorded. After recording the DCVG indication location four perpendicular readings are taken at fixed spacing and recorded in the field book; these readings define the shape of the indication. The voltage gradient from the epicenter of the indication to remote earth was obtained by measuring and adding the consecutive voltage gradients as the operator moved away and perpendicular from the pipeline longitudinal axis; the voltage gradient readings were recorded in the field book.

After completing all the readings from an indication the surveyor continued the survey first with short probe spacing while under the influence of the previous indication. The above procedure was repeated until the segment length was covered.

Figure 7: DCVG survey

PEARSON SURVEY

The transmitter (audio oscillator) was placed along the pipeline at test station located close to the segment under study, the lead wire was connected to the terminal marked “PIPE” and a wire was connected between the terminal labeled “GROUND” and a grounding pin driven into the earth at approximately 30 ft from the pipe at right angle.

A 12 volt battery was connected to the terminals and the voltage output selector was set to 2.5 volt and the fine adjustment to maximum. The interrupter switch was turned off and the power switch was turned on. The output voltage selector was increased until the LED indicator turned red, then the fine adjustment was moved until the LED indicator turned green, indicating a suitable audible signal. Finally the interrupter was switched to on.

The operators connect the receiver, cables and probes and adjust the audible signal and traverse along the pipeline (Figure 8). When an indication was located the midpoint between the operators was marked and the distance was reduced between them to accurately locate the indication. The indication distance was measured to the closest chain flag and recorded in the field book.

Figure 8: Pearson Survey

C-SCAN SURVEY

The C-Scan transmitter was placed at a test station close to the segment under study. The electromagnetic signal was established by connecting the equipment to a temporary ground and to the pipeline through the cathodic protection test station terminal. The survey interval was established accordingly with the segment total length. The average coating conductance of the sections was measured using the C-Scan receiver (Figure 9). Then a Close Interval Current Only Survey (CICOS) was conducted over the test section to determine if it contained separable areas of coating degradation and/or single events (anomalies). A CICOS was conducted by using the C-Scan receiver to measure the remaining current in the pipeline using very short spacing between readings (9 ft 9 inches, 3 meters). The results were plotted against distance and the resulting plot analyzed.

Figure 9: Cscan survey

SURVEY TOOL SET UP PARAMETERS

Table 2 outlines the individual tool setups for the voltage gradient surveys. Table 3 outlines the setups employed for the current attenuation surveys. The Pearson equipment was not available when sites 1 and 2 were surveyed.

VISUAL EXAMINATIONS

For the visual examination of the pipe after inspection, the procedures were as follows:

1. The locations of the start and end of the dig segment, with respect to the survey data, were verified. In several cases, the start/end were marked directly on the pipe by the excavation crew, in other cases landmarks (fences, test stations, etc.) were cited and used as consistent reference points.
2. Using a measuring wheel, the distances along the pipe at which indications were noted by the surveys were marked with chalk on the pipe.
3. The indication spots were visually located, photographed, marked with chalk or marker, and measured.
4. A second visual examination was then performed on the pipeline segment to locate defects apart from the survey indications.

Holiday detectors were not used to verify the continuity of any coating fault examined. In many cases, the coating fault was further examined using a pocket knife to look for adjacent disbondment and under-coating calcareous deposits.

Table 2. Setup parameters for voltage gradient –type surveys

SITE	DCVG			ACVG		PEARSON		
	SIGNAL MAGNITUDE mV		DC SIGNAL SUPPLY					
	START	END		TRANSMITTER LOCATED AT	CURRENT OUTPUT (AMPS)	TRANSMITTER LOCATED AT	VOLTAGE OUTPUT (VOLTS)	FINE CONTROL %
1	232	226	CP RECTIFIER	CP RECTIFIER	1	NO SURVEY PERFORMED	NO SURVEY PERFORMED	
2-a	790	760	CP RECTIFIER	CP RECTIFIER	1	NO SURVEY PERFORMED	NO SURVEY PERFORMED	
2-b	615	600	CP RECTIFIER	CP RECTIFIER	1	NO SURVEY PERFORMED	NO SURVEY PERFORMED	
3-a	182	184	CP RECTIFIER	CP RECTIFIER	2	TEST STATION	100	30
3-b	125	113	CP RECTIFIER	CP RECTIFIER	2	TEST STATION	100	90

Table 3. Setup parameters for current attenuation-type surveys

SITE	C-SCAN		PCM	
	TRANSMITTER LOCATED AT	CURRENT OUTPUT	TRANSMITTER LOCATED AT	CURRENT OUTPUT
1	COULD NOT SURVEY	COULD NOT SURVEY	CP RECTIFIER	1
2-a	CP RECTIFIER	600	CP RECTIFIER	1
2-b	CP RECTIFIER	600	CP RECTIFIER	1
3-a	TEST STATION	336	CP RECTIFIER	2
3-b	TEST STATION	105	CP RECTIFIER	2

RESULTS

The sites that were surveyed and later excavated are shown in Figures 10-13. Table 2 is the legend which explains the presentation of the tabular results for the surveys, which are provided in Tables 3-5.

(a) (b)

Figure 10: Site #1 (a) before excavation, and (b) after excavation

(a) (b)

Figure 11: Site #2 (a) first excavation and (b) second excavation.

(a) (b)

Figure 12: Site 3, first excavation (a) during survey, and (b) after excavation

(a) (b)

Figure 13: Site 3, second excavation (a) during survey, and (b) after excavation

Table 4. Description of data in tables 3-5

<table>
<tr><th rowspan="2">Reference</th><th rowspan="2">Distance from Dig Stake 1</th><th colspan="2">DCVG</th><th>ACVG</th><th>PCM</th><th>C SCAN</th></tr>
<tr><th>%IR[1]</th><th>O'clock Position</th><th>DB [1]</th><th>mA</th><th>µS/m2 [3]</th></tr>
<tr><td rowspan="4">Indication number</td><td rowspan="4">In feet from initial dig stake</td><td>0-15 = insignificant</td><td rowspan="4">Based on analog clock position on the pipe</td><td><50 = very small indication</td><td rowspan="4">Current detection based on position along the pipeline. The greater the current loss between adjacent sections, the larger the coating holiday</td><td rowspan="4">Coating quality</td></tr>
<tr><td>15-35 = maybe recommended for repair</td><td>50-65 = small indication</td></tr>
<tr><td>36-70 = recommended for repair</td><td>66-80 = medium indication</td></tr>
<tr><td>70-100 = recommended for immediate repair</td><td>81-100 = large indication</td></tr>
<tr><td colspan="7">[1] From proposed NACE standard on Aboveground Survey Techniques for the Evaluation of Coating Faults</td></tr>
<tr><td colspan="7">[2] From NACE RP 0502, Pipeline ECDA Methodology</td></tr>
<tr><td colspan="7">[3] From NACE TM0102, Measurement of Protective Coating Electrical Conductance on Underground Pipelines</td></tr>
</table>

Table 5. Comparison of techniques at Site 1 (C-scan not available)

Reference	Distance from Dig Stake 1	DCVG		ACVG	PCM
		%IR	O'clock Position	DB	MA
Dig Stake 1	0				
Indication 1	36	60	5-7	56	
Indication 2	46	63	5-7	56	182
Indication 3	65	65	5-7	52	153
Indication 4	114	59	5-7	55	181
Dig Stake 2	128				

Table 6. Comparison of techniques at Site 2

(a) First excavation

Reference	Distance from Dig Stake 1	DCVG		ACVG	PCM	C SCAN
		%IR	O'clock Position	dB	mA	µS/m2
Dig Stake 1	0					
Indication 2A-1	1	27	5-7	80	411	197
Indication 2A-2	12	35	5-7	78	411	197
Indication 2A-3	23	41	3-9	79	411	197
Indication 2A-4	33	N/a	N/a	75	409	197
Indication 2A-5	103	32	5-7	81	411	197
Indication 2A-6	115	35	5-7	75	411	197
Indication 2A-7	128	31	5-7	72	411	197
Indication 2A-8	154	36	5-7	76	411	197
Indication 2A-9	175	38	5-7	82	150	197
Dig Stake 2	203					

(b) Second Excavation

Refeference	Distance from Dig Stake 3	DCVG		ACVG	PCM	C SCAN
		%IR	O'clock Position	dB	mA	µS/m2
Dig Stake 3	0					
Indication 2B-1	56	29	5-7	79	404	3.88
Indication 2B-2	61	44	5-7	73	402	3.88
Indication 2B-3	91	27	5-7	73	386	3.88
Dig Stake 4	125					

Table 7. Comparison of techniques at Site 3

(a) First excavation

Reference	Distance from Dig Stake 1, ft	DCVG		ACVG	PCM	C SCAN	Pearson
		%IR	O'clock Position	dB	mA	µS/m^2	
Dig Stake 1	0						
Indication 3a-1	5.6	48.74%	12	-	800	1260	Indication
	6.8	N/A	12	76.0	800	1260	-
Indication 3a-2	44.0	51.31%	12	76.0	800	6573	-
Indication 3-3	50	N/A	N/A	N/A	633	6573	Indication
Dig Stake 2	100						

(b) Second excavation

Reference	Distance from Dig Stake 3, ft	DCVG		ACVG	PCM	C SCAN
		%IR	O'clock Position	dB	mA	µS/m^2
Dig Stake 3	0					
Indication 3b-1	101	42.88%	12	62	74	162
Indication 3b-2	115	38.92%	12	61	84	162
Indication 3b-3	120	N/A	N/A	N/A	52	162
Indication 3b-4	131	N/A	N/A	N/A	80	162*
Dig Stake 4	203					

*Indication was from a close interval current only survey (CICOS)

The indications in Table 5 correlate with the photos in Figures 14-16. The indications in Table 6 correlate with the photos in Figures 17-26. Indications 2A-3, 2A-8 and 2B-2 were under pipe saddle supports and thus could not be visually examined. Figures 27-29 are defects which were not detected by the surveys (false negatives) from site 1, and Figures 30-35 are defects which were not detected by the surveys from site 2.

Figures 36-43 are the indications from site 3, listed in Table 7. Figures 44-49 were false negatives from site 3, found upon visual examination.

Figure 14: Indications 1 & 2: From dig stake distances 36' to 46', coating was entirely disbonded on the underside of the pipe.

Figure 15: Indication #3: There were 3 small (~3" diameter) disbonded patches just above the 6 o'clock position on the pipe

Figure 16: Indication #4: A large disbonded area about 1 square foot total, from 6 o'clock to 9 o'clock on the pipe.

Figure 17: Indication 2A-1: 2 small gash marks at the 7 o'clock position

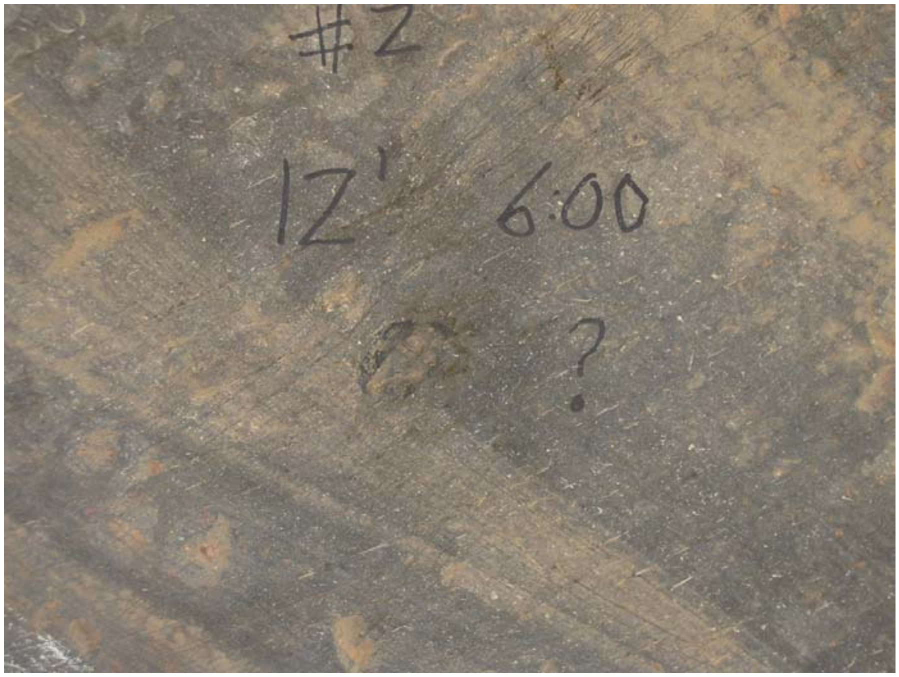


Figure 18: Indication 2A-2: One mark at 6 o'clock position

Figure 19: Indication 2A-4: Two marks at the 7 and 8 o'clock positions

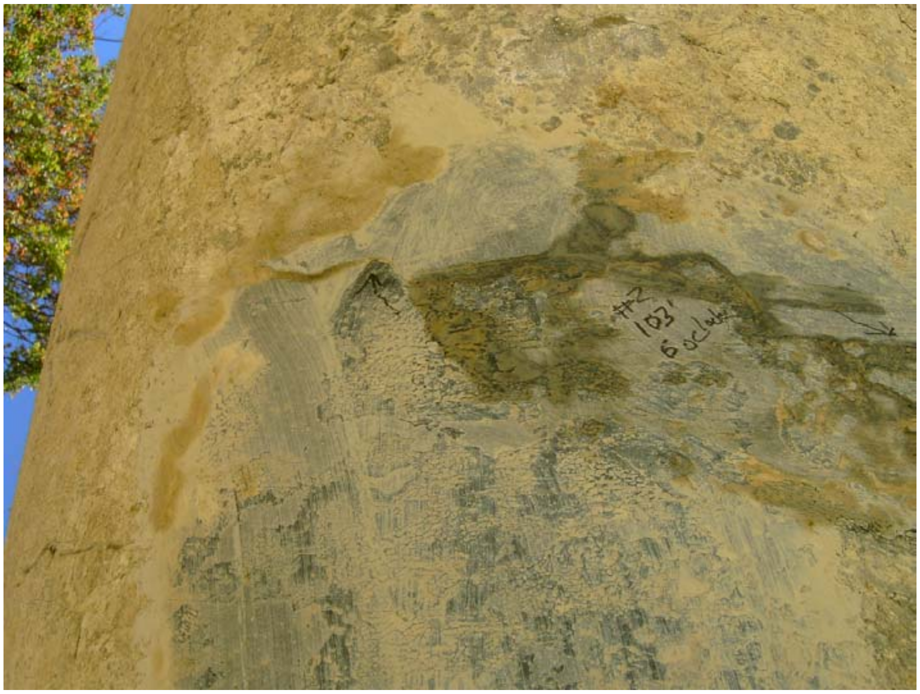


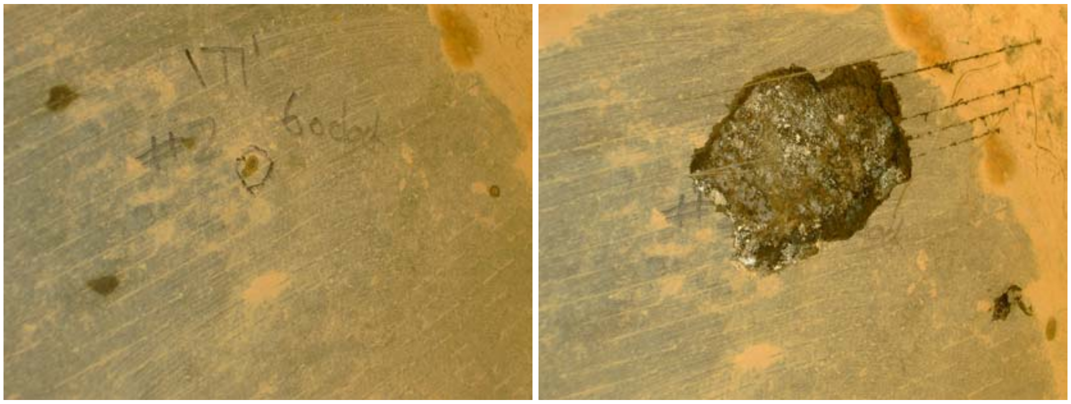
Figure 20: Indication 2A-5: A seam was noticed at 6 o'clock, but no obvious holiday

Figure 21: Indication 2A-5, after the coating was removed by a pocket knife.

Figure 22: Indication 2A-6: small "ding" at 6 o'clock

(a) (b)

Figure 23: Indication 2A-7 (a) as-noted, and (b) calcareous deposits noted after coating removal



(a) (b)

Figure 24: Indication 2A-9 (a) as-noted, and (b) calcareous deposits noted after coating removal

(a) (b)

Figure 25: Indication 2B-1 (a) as-noted, and (b) calcareous deposits noted after coating removal

(a) (b)

Figure 26: Indication 2B-3 (a) as-noted, and (b) calcareous deposits noted after coating removal

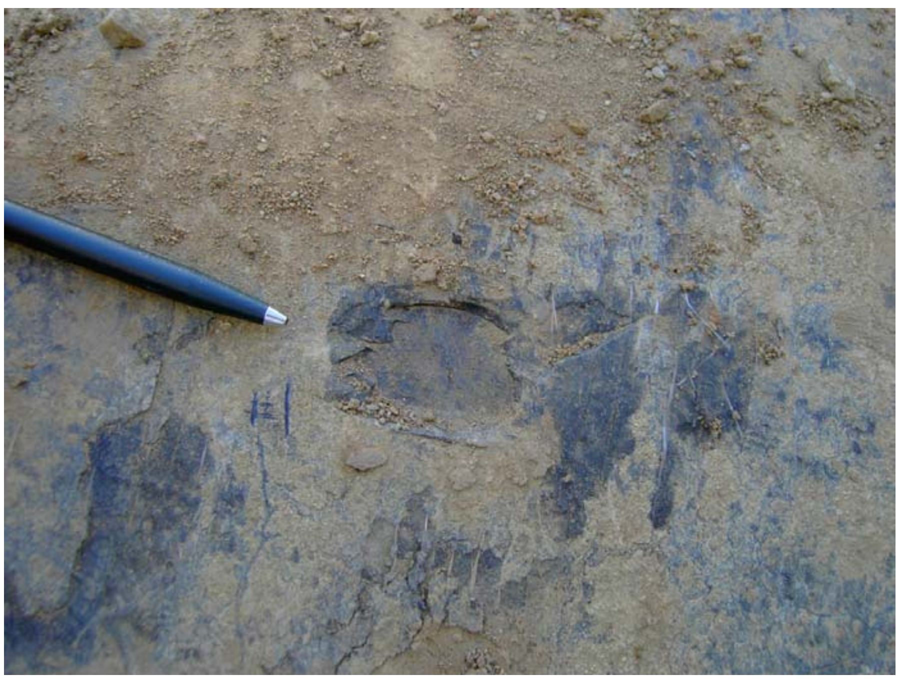


Figure 27: Site 1, undetected holiday, 1" diameter hole at 1 o'clock, 125'

Figure 28: Site 1, undetected holiday, 2 o'clock position, 72' from dig stake

Figure 29: Site 1, undetected holiday, 3 o'clock position at 50'

Figure 30: Site 2a, undetected holiday, 10 o’clock position, ¼” diameter holiday @ 3’

Figure 31: Site 2a, undetected holiday, 11 o’clock position, 1” diameter at 8’ from dig

Figure 32: Site 2a, undetected holiday, 1” diameter hole at 7 o’clock, 44’ from dig stake

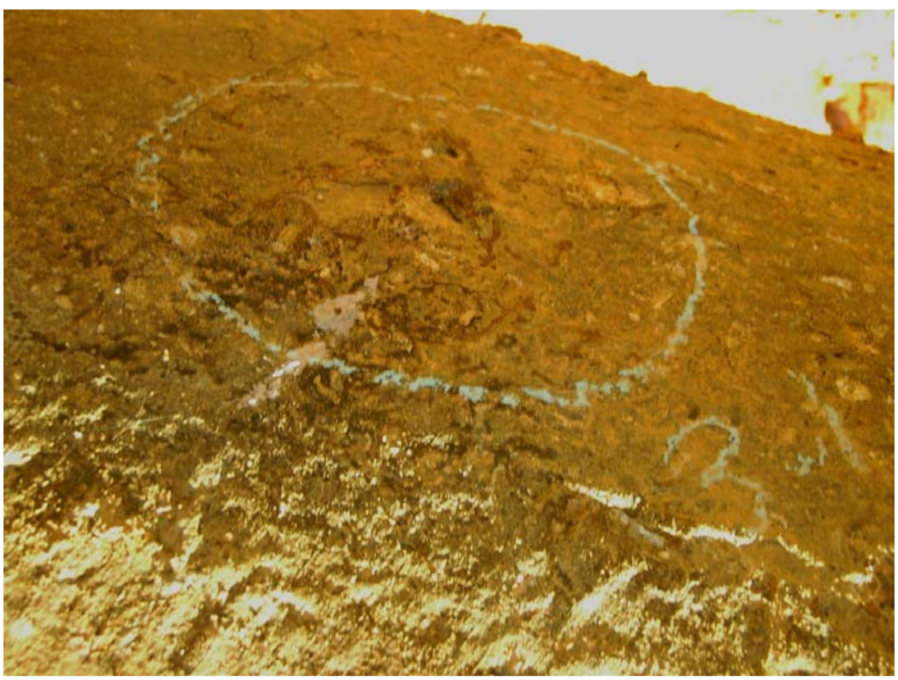
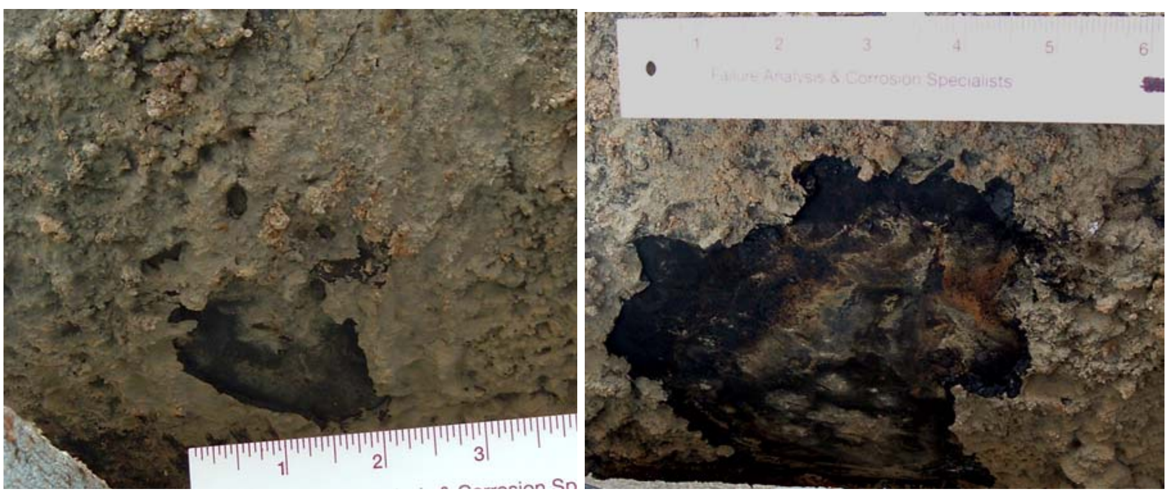


Figure 33: Site 2b, undetected holiday, 7 o’clock position, ¼” gouge at 9’6” from dig stake

Figure 34: Site 2b, undetected holiday, 7 o’clock position , ¼” gouge, 17’ from dig stake

Figure 35: Site 2b, undetected holiday, 5 o’clock position, 2 parallel gouges at 47’ from dig stake

Figure 36: Holiday indication 3a-1 (indicated by DCVG, ACVG) at 10 o'clock position



(a) (b)

Figure 37: Holiday indication 3a-2 (indicated by DCVG, ACVG, Pearson) at 6 o'clock position (a) as-found after excavation, and (b) after removing unbonded coating

(a)

(b)

(c)

Figure 38: Indication 3a-3, a coating overpatch near the 6 o'clock position, (a) as uncovered, (b) after prodding, and (c) after patch was removed

Figure 39: Holiday near 3b-1 found by DCVG, ACVG, 2 o'clock position

Figure 40: Defects found near 3b-1 indication, 8 o'clock position

Figure 41: Indication 3b-2 at 114', 9 o'clock position

Figure 42: Indication 3b-3, 12 o'clock position

Figure 43: Indication 3b-4, 10 o'clock position

Figure 44: Holiday from site 3a not indicated during survey, 10 o'clock position (14')

Figure 45: Site 3a undetected holiday at 28', 8 o'clock position

Figure 46: Site 3a undetected holiday at 52', 9 o'clock position

Figure 47: Site 3a large circular holiday not detected by survey, 9 o’clock position (possible patch?) at 18’

Figure 48: Site 3b undetected damage found at 53’, 8 and 10 o’clock positions

Figure 49: Site 3b undetected damage found at 140', 7 o'clock position

DISCUSSION

Visual Observations

The visual examinations performed at all sites were, in some cases, misleading. The "apparent" size of each defect did not always correlate to the bare area on the pipe which was discharging current during the surveys. This is best represented in Figures 20-21. In Figure 20, the coating fault appeared to be very small and did not appear to expose bare steel. After removing some poorly bonded coating at this location, calcareous deposits were noted on the steel underneath, implying that there was in fact bare exposed steel in this location which was drawing CP current, despite the lack of visual evidence of an "open" holiday. Similar observations were noted at multiple indications.

The use of a holiday detector during the visual examinations likely would not have produced any different results, because the bare steel area was not directly exposed to the soil, as shown schematically in Figure 50.

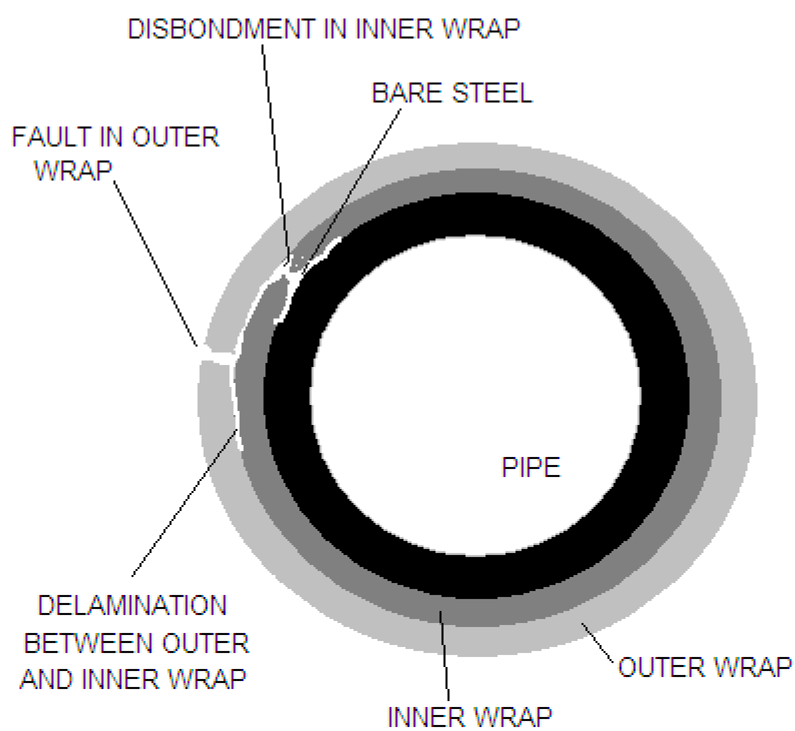


Figure 50: Representation of common coating fault in double layer wrap (asphalt enamel and coal tar enamel) systems

Groundwater took a tortuous path to reach the steel, and unless the groundwaters were still present during the visual examination, the electrical conductive pathway necessary to detect a holiday would not have been present. This would be typical for both asphalt enamel and coal tar enamel systems.

Survey Data

Tables 8-9 are side-by-side comparisons of the results obtained with different survey techniques on each of the sites. Figures 51-55 are illustrations of the overall results, what was predicted based on the surveys versus what was eventually found based on the excavations for all of the individual surveys.

PCM appeared to be appropriate for large areas of disbondment, such as that shown in Figure 51. The DCVG and ACVG signals for these regions appeared to indicate several defects rather than the one large disbonded area that was present. Beyond this example, PCM provided only non-specific data at uncertain locations along the pipe. Observing PCM results on Test Sites 2a and 2b suggests that 50 ft spacing for current readings generated inconsistent current attenuation data and thus did not pin point individual coating indications.

C-scan was similar to PCM except that the option of a CICOS (close interval current only survey) to better pinpoint defect location was available with C-scan. The coating classification established by C-Scan was not consistent with coating condition observed during excavation. Coating section classified as “Excellent” by C-scan in fact had significant coating holidays.

Also, the current attenuation values (mB/m) obtained by PCM and C-Scan tools did not coincide with observed coating condition and no consistent relationship could be established. However, on test Site 3a (Figure 54) the PCM survey reported 2 indications not reported by the other tools that were validated during excavation. On this Test Site C-Scan on close interval current mode also reported an indication not reported by the other tools and was validated during excavation.

DCVG and ACVG provided very similar data, with DCVG better able to size defects. ACVG coating fault ranking did not show a proportional relationship with the area of bare metal exposed to the electrolyte, thus making defect sizing difficult. Both techniques were better able to “pinpoint” a defect, after which some effort was necessary to determine defect size. While this provided more exact data, for long sections of pipe the survey was more cumbersome than C-scan or PCM, which divided the pipe sections into larger discrete sections.

The %IR DCVG coating fault categories were consistent with the coating faults found in the digs as the majority were classified as needing repair (Categories 3 and 4). However the %IR did not show a proportional relationship with the area of bare metal exposed. This inconsistency may be a result of the assumption of a linear attenuation of the DCVG signal between test points; when the distance between test points is big and the coating condition is poor the above assumption may not be as accurate as desired. This condition was observed at test site 2.

The Pearson survey was clearly the weakest survey technique as it failed to locate any defects on one section and provided very inconsistent results on the second section. Clearly, the more recently developed voltage gradient technologies are an improvement over the Pearson technique.

In no cases were false positives indicated, although the location of the defects varied by several feet in some cases. This was likely more due to the accuracy of the dig stake reference. Even when the coating defects were not clearly visible, as was the case for defects under which calcareous deposits were found, further investigation revealed that the indications were legitimate.

Figure 56 shows the relative performance of each technique from a sizing/locating perspective. From this graph the accuracy of DCVG appeared to be the highest. ACVG tended to overestimate the size of most of the defects, and also did not differentiate size as well. The current attenuation techniques, PCM and C-scan, were “all-or-nothing” indicators which essentially indicated either intact coating or poor coating, with little in between.

The large area of disbondment at site #1 was underestimated by all the surveys, though PCM and C-scan were more accurate, and the inability to generate a signal strong enough for C-scan hinted at this type of damage. However, it is also possible that the coating was so weakly bonded that it literally fell off of the pipe when excavated. This would create the visual image of a bare pipe, while the disbondment of the coating before excavation was not as extensive.

One thing that cannot be determined in this investigation is whether or not the defects which were not identified by the surveys were actually created by the excavation process. In all cases, these defects (false negatives) were relatively small and when the pipe surface in the area surrounding the defect was investigated, there was little evidence of calcareous deposits under the coating. This could be due to one or more of these possibilities:

1. The defect was created during the excavation process, due to shovel or backhoe impact
2. The defect was created in an area of well-bonded coating, so cathodic disbondment, calcareous deposits, and associated current loss off of the pipe was minimized

3. The defect was created recently, so the cathodic disbondment, calcareous deposits, and associated current loss off of the pipe had not yet reached levels which were readily detectable.
4. The defect was shadowed by nearby defects which created a situation for which defect identification was difficult
5. During the survey, the soil next to the defect was dry and thus minimal current loss would be expected

Table 8. Summary performance of voltage gradient surveys

	SITE #	1	2-a	2-b	3-a	3-b
CHARACTERISTICS	LENGTH (ft)	123	203	125	100	210
	PIPE Ø	36	36	36	22	32
	COATING	Asphalt Enamel	Asphalt Enamel	Asphalt Enamel	Coal Tar Enamel	Coal Tar Enamel
DCVG	# OF INDICATIONS DETECTED	Four (4) indications reported	Eight (8) indications reported	Three (3) indications reported	Two (2) indications reported	Three (3) indications reported
	MAGNITUDE OF INDICATIONS	All indications fall on Category 3, and repair is recommended	Two (2) indications fall on "Category 3", and repair is recommended, Six (6) indications fall on "Category 2", and repair may be recommended	One (1) indication falls on "Category 3", and repair is recommended, Two (2) indications fall on "Category 2", and repair may be recommended	All indications fall on "Category 3", and repair is recommended	Two (2) indications fall on "Category 3", and repair is recommended, One (1) indication falls on "Category 1" , and repair is not usually recommended
ACVG	# OF INDICATIONS DETECTED	Four (4) indications reported	Nine (9) indications reported	Three (3) indications reported	Two (2) indications reported	Three (3) indications reported
	MAGNITUDE OF INDICATIONS	The magnitude of indications is reported in decibels (dB); all indications between 52 and 56 dB	The magnitude of indications is reported in decibels (dB); all indications between 72 and 82 dB	The magnitude of indications is reported in decibels (dB); all indications between 73 and 79 dB	The magnitude of indications is reported in decibels (dB); the magnitude of both indications 76 dB	The magnitude of indications is reported in decibels (dB); One (1) indication 46 dB, and the remaining two (2) 61 and 62 dB respectively
PEARSON	# OF INDICATIONS DETECTED	Not performed	Not performed	Not performed	Two (2) indications reported	No indications reported
	COMMENTS	Not included as survey tool on this site	Not included as survey tool on this site	Not included as survey tool on this site	No means of classification available	No indications reported

Table 9. Summary performance of current attenuation surveys

	MAGNITUDE OF INDICATIONS	The magnitude of indications is reported in decibels (dB); all indications between 52 and 56 dB	The magnitude of indications is reported in decibels (dB); all indications between 72 and 82 dB	The magnitude of indications is reported in decibels (dB); all indications between 73 and 79 dB	The magnitude of indications is reported in decibels (dB); the magnitude of both indications 76 dB	The magnitude of indications is reported in decibels (dB); One (1) indication 46 dB, and the remaining two (2) 61 and 62 dB respectively
C-SCAN RESULTS	AVERAGE CURRENT ATTENUATION (mB/m)	Could not perform survey	1.79	0.10	9.23	1.41
	Coating Condition Classification	Could not perform survey; transmitter could not generate adequate signal level	197 µS/m2, classified as "Good coating" (1) , no close interval current survey was performed	3.88 µS/m2, classified as "Excellent", no current survey at close interval was performed	6573 µS/m2, classified as "poor coating", close interval current survey performed at 10 ft intervals, single indications between 40-50 ft and 70-80 ft from test site start stake. Poorest coating condition on section between 40 to 80 ft, most likely associated with presence of single indications	166 µS/m2, classified as "good coating", close interval current survey performed a 10 ft intervals; three indications were reported. Two classified as "degraded coating over distance", one from test site start stake for 10 ft and the second starting 140 ft from test site start stake for 10 ft; the third indication is reported as "Single event" located 165 ft from test site start stake
PCM	AVERAGE CURRENT ATTENUATION (mB/m)	4.08	0.00	0.66	1.17	3.34
	CLOSE INTERVAL CURRENT READINGS	current survey performed at 50 ft interval, located one (1) indication approximately 60 ft from test site stake	current survey performed at 50 ft interval, located one (1) indication approximately 150 ft from test site stake	current survey performed at 50 ft interval, no indications found	current survey performed at 10 ft interval, One (1) indication reported at 50 ft measured from test site start stake; the most significant indication.	current survey performed at 10 ft interval, 6 indications reported at 10, 30, 50, 70, 100 and 120 ft from test site start stake; the most significant indication located at 120 ft

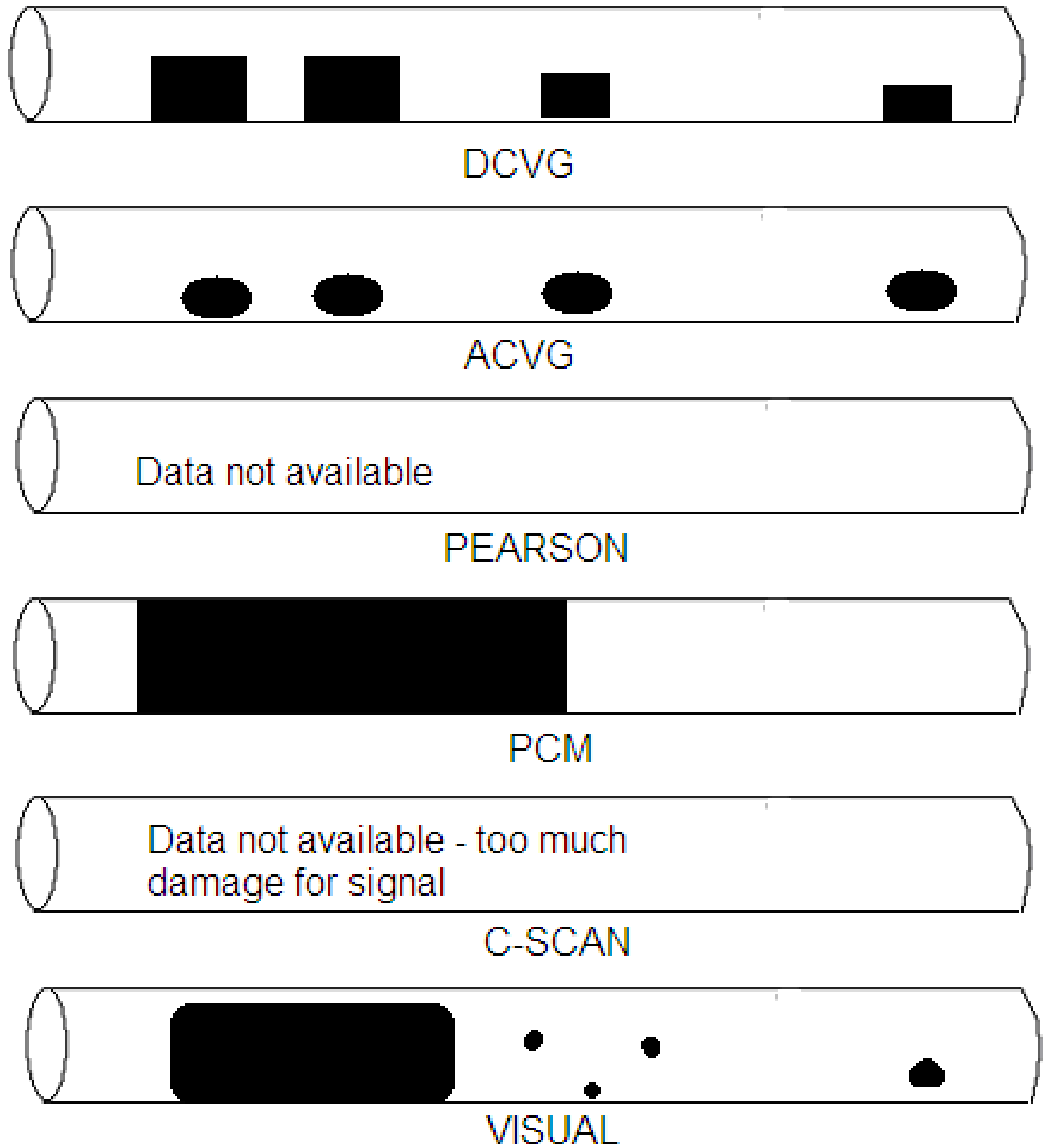


Figure 51: Comparison of techniques from Site 1. The black areas represent either the size of the coating fault (from surveys) or the area of exposed steel (from visual exam).

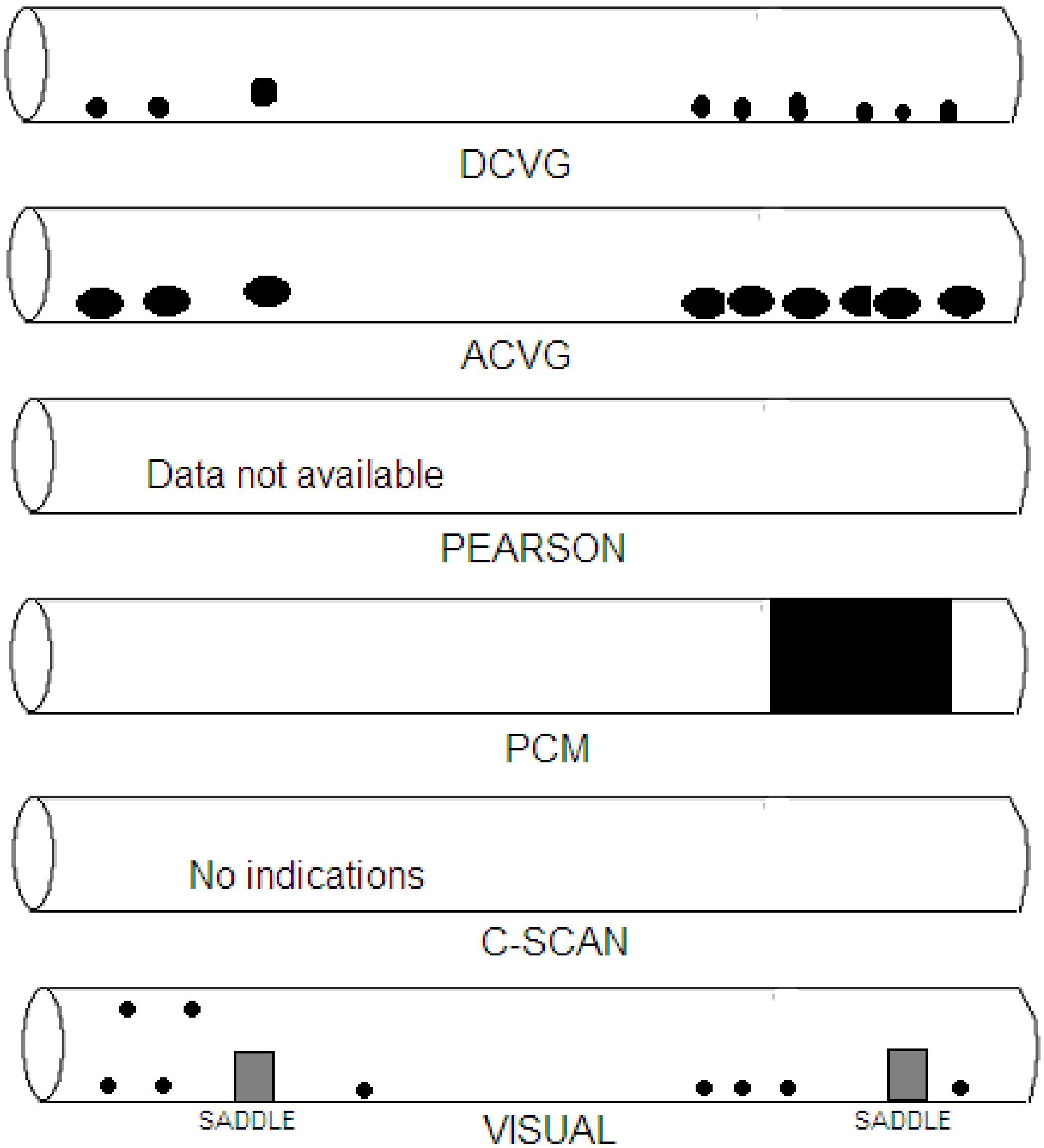


Figure 52: Comparison of techniques from Site 2a. The black areas represent either the size of the coating fault (from surveys) or the area of exposed steel (from visual exam).

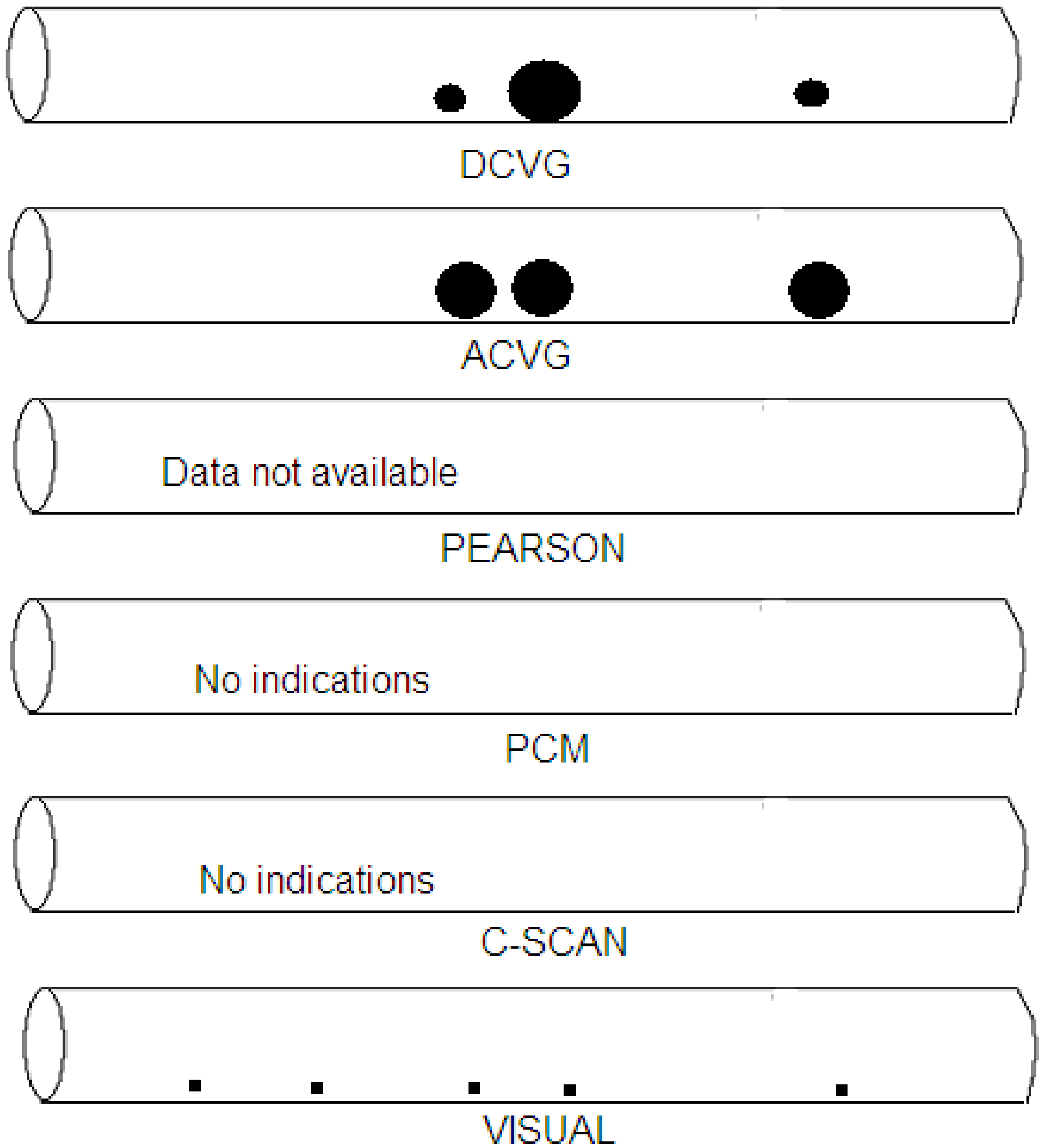


Figure 53: Comparison of techniques from Site 2b. The black areas represent either the size of the coating fault (from surveys) or the area of exposed steel (from visual exam).

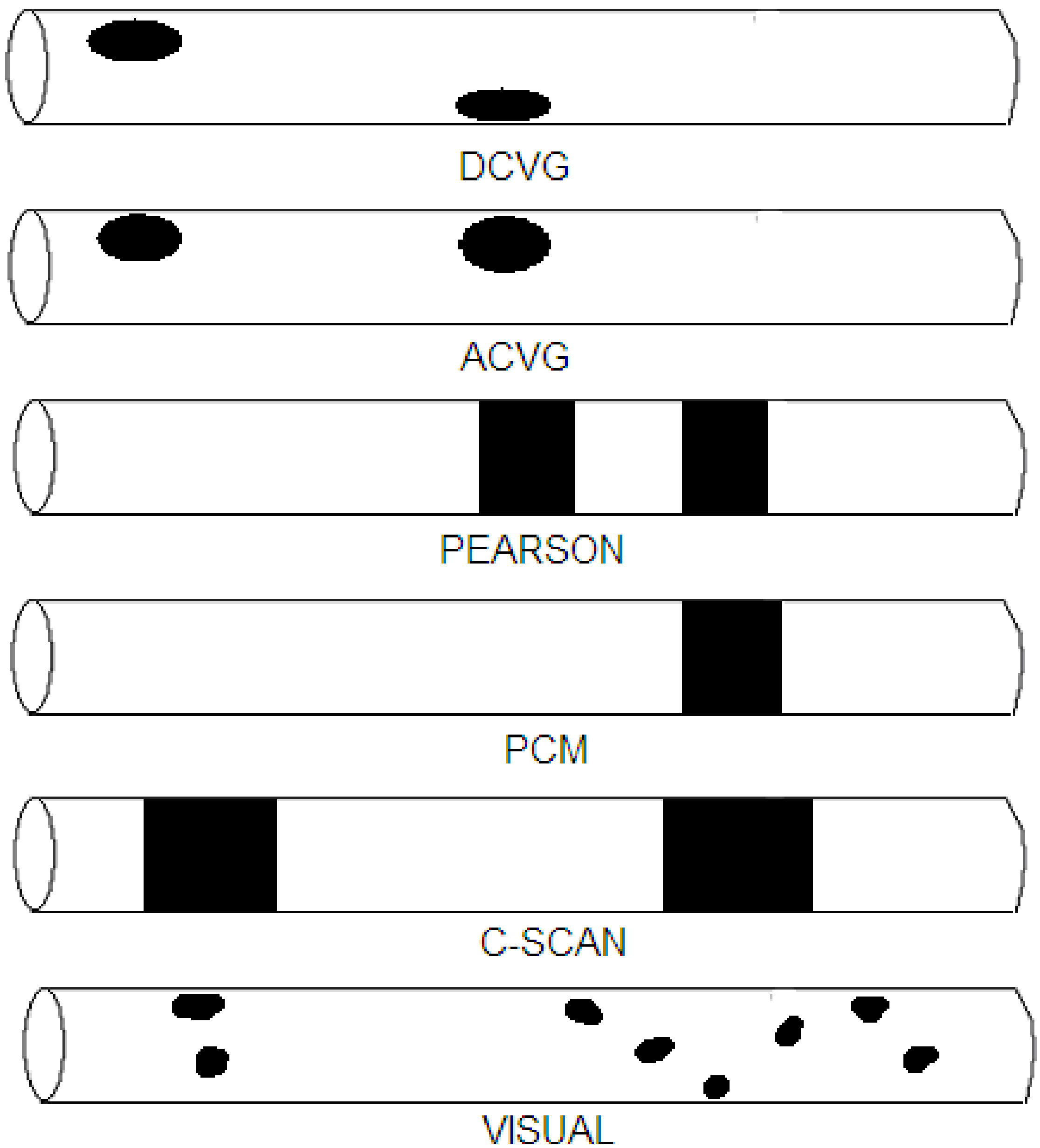


Figure 54: Comparison of techniques from Site 3a. The black areas represent either the size of the coating fault (from surveys) or the area of exposed steel (from visual exam).

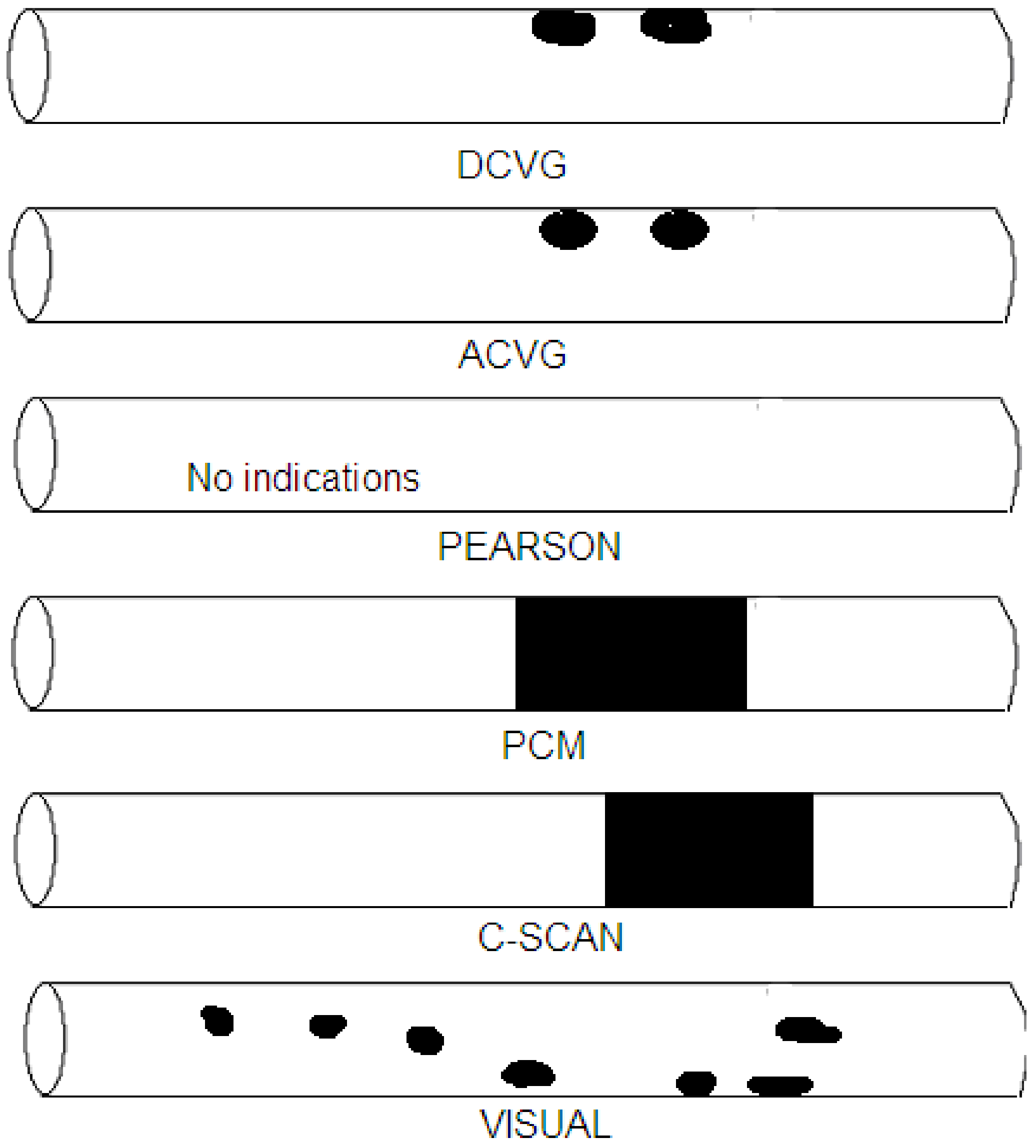


Figure 55: Comparison of techniques from Site 3b. The black areas represent either the size of the coating fault (from surveys) or the area of exposed steel (from visual exam).

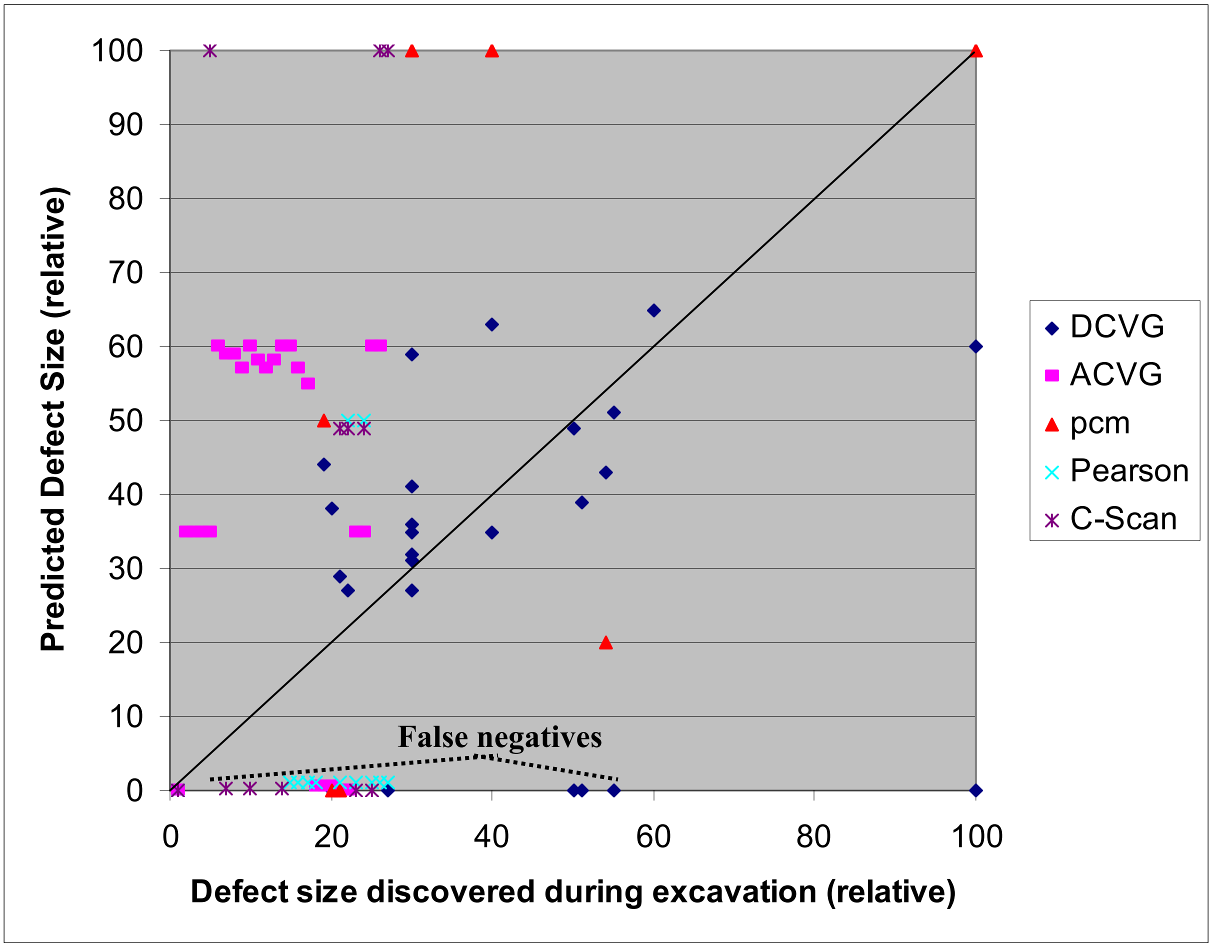


Figure 56: Graphic comparison of the performance of each technique with respect to defect sizing (points close to 45° line indicate high degree of accuracy).

CONCLUSIONS

For the pipelines studied in this investigation, the DCVG and ACVG surveys performed similarly, with DCVG better able to size defects. PCM and C-scan were able to detect "generally" bad coating and thus provided a more rapid indication of the overall state of the pipeline. DCVG and ACVG were better able to pinpoint individual defects. Pearson survey results were very poor, and thus not recommended if other survey tools are available.

Some specific observations regarding aboveground surveys:

- Average current attenuation coating classification in mB/m or mS/m2 did not provide any guidance to decide which sections required excavation.
- The spacing used between current reads on a current attenuation survey affects the validity of the data.
- Current attenuation tools used at 10 ft intervals were able to pin point coating holidays, however false indications were reported. (This suggests that these tools can be used on this mode when no additional perturbation to the magnetic field exists other than the one produced by the coating faults. This could be achieved by surveying various sections before performing the closed spaced survey)
- C-Scan could not perform survey over a section of pipe with very poor coating quality
- Plotting attenuation current (in mBmA) versus distance at adequate spacing is a good procedure to determine were coating deterioration may exist; however detailed information about coating faults requires the use of intensive surveys such as ACVG, DCVG, or current attenuation at 10 ft intervals where the electromagnetic field is not disturbed.
- Voltage Gradient techniques were found to be useful tools when individual coating fault determination is required. No false positives were reported, however coating faults not reported by these tools were found during the dig examination. No calcareous deposits were found so uncertainty exists regarding these defects (e.g. they may have been created during excavation work).
- It is known that coating faults that generate voltage gradients with large magnitudes and extensions can impede detection of smaller faults in close proximity. This effect may also account for the coating faults not reported by these techniques.

- It was observed that coating faults in close proximity located at different o'clock positions could be reported as a single indication by the voltage gradient techniques
- It was observed that voltage gradient tools were able to locate coating damage bellow the outer coating layer when a current path is available.

SUGGESTIONS FOR FURTHER WORK

The results of this work suggest that a wide number of variations in possible defect configurations, variations in coating type and condition, and other parameters which affect survey results. While more sites could be surveyed and a larger database of information gathered, each field site visit would have the natural limitations of coating type and defect configuration based on the limited number of permutations and combinations on a given pipeline.

A natural follow-on to this work would be the construction of a specific test site for which all of the possible variations in pipeline conditions, such as coating type, soil type, defect size and distribution, could be simulated. This test site would utilize the findings in the present study as well as the input from others in the industry who have performed surveys and who manufacture survey equipment.

Such a test site would enable further research on survey technologies, proof testing for new equipment, and training for industry professionals. Additional field survey data could also be gathered in a similar fashion, providing good feedback to the test site as part of the deliverables of the follow-on project.