FINAL REPORT

Benchmarking Emerging Pipeline Inspection Technologies

To

Department of Energy

National Energy Technology Laboratory (NETL)

DE-AP26-04NT40361

and

Department of Transportation

Research and Special Programs Administration (RSPA)

DTRS56-02-T-0002 (Milestone 7)

September 2004

Final Report

on

Benchmarking Emerging Pipeline Inspection Technologies

Cofunded by

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by

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BENCHMARKING EMERGING PIPELINE INSPECTION TECHNOLOGIES

This report provides the supporting documentation for the Contracting Officer Technical Representative (COTR) to assess the data obtained by pipeline inspection technology developers participating in an internal inspection demonstration held at Battelle's Pipeline Simulation Facility during the second week of September 2004. This report is divided into four main sections that document the pipe defect types, sizes, and locations inspected during the demonstration program. Section 1 provides a brief background of the internal inspection demonstration program and facilities used. Section 2 provides detailed information on both the manufactured corrosion defect set and the natural corrosion defect set used to benchmark some of the technologies. Section 3 provides detailed information for the mechanical damage defect sets and Section 4 provides detailed information for the Stress Corrosion Cracking (SCC) defect set also used to benchmark the various inspection tools.

SECTION 1. BACKGROUND

INTRODUCTION

DOE NETL and DOT RSPA are charged with improving natural gas delivery reliability by establishing a viable technology foundation for the natural gas transportation and delivery network. This objective is being achieved by developing technologies that enhance the integrity, operational reliability, safety and security of the nation's natural gas infrastructure. NETL and RSPA are collaborating with National Laboratories and the private sector in developing new inspection technologies. The combined research portfolio includes projects that address corrosion, stress corrosion cracking and mechanical damage.

Battelle, in association with NETL and RSPA have devised a program that will allow each developer to benchmark their sensor technology during a one-week pipeline inspection demonstration at Battelle's Pipeline Simulation Facility (PSF) in Columbus, Ohio. Battelle's PSF has unique facilities and pipes with representative defects that are ideal for use in the technology demonstration program. The defect sets include natural and artificial defects with a wide range of types and sizes in pipe segments of various wall thickness and diameters.

This demonstration was conducted the week of September 13th, 2004 and attended by the participants listed in Table 1-1.

Table 1-1. Participants in the Internal Inspection Demonstration

Company	Technology	Tool Diameter	Defects Examined
Battelle	Moving permanent magnet eddy current	12 inch	Corrosion
Battelle	Dual magnetization MFL	24 inch	Mechanical Damage
Gas Technology Institute (GTI)	Small diameter exciter remote field eddy current	12 inch	Corrosion
Los Alamos National Laboratory (LANL)	Deformation sensor	24 inch	Mechanical Damage
Oak Ridge National Laboratory (ORNL)	Circumferential EMAT	30 inch	SCC
Pacific Northwest National Laboratory (PNNL)	EMAT strain measurement tool	24 inch	Mechanical Damage
Southwest Research Institute (SwRI)	Collapsible coil remote field eddy current	12 inch	Corrosion
TeleTest	Guided wave	12 inch	Corrosion

Prior to the demonstration, each participant had been contacted directly to discuss the objectives of their sensor development programs and the constraints of current implementation. This information was taken into consideration when developing the demonstration program and associated documentation.

PIPELINE SIMULATION FACILITY

The Pipeline Simulation Facility was designed and built to conduct research and to develop and commercialize pipeline technologies. Its primary focus is in-line inspection technologies. The facility can be used for a wide range of inspection-related studies, from detailed analyses of defects in flat plates under idealized conditions to tests on the same defect geometries in a pressurized line operating under flowing conditions. Collectively, the Pipeline Simulation Facility offers a hierarchy of capabilities for developing and proving technologies.

Flow Loop

The flow loop is the largest and most significant part of the Pipeline Simulation Facility. The loop is a simulated operating pipeline in which research, development, and demonstrations can be conducted under realistic conditions. For inspection related developments, tests can be made using test bed vehicles or in-line inspection tools. The loop is approximately 4,700 feet long and 24 inches in diameter, and it allows both pressure and flow velocity to be controlled. It contains a number of typical pipeline features, such as bends, road crossings, underwater sections, and anchors. It can be used to complete the development of pipeline technologies and test the technologies without risking the integrity or throughput of an operating pipeline.

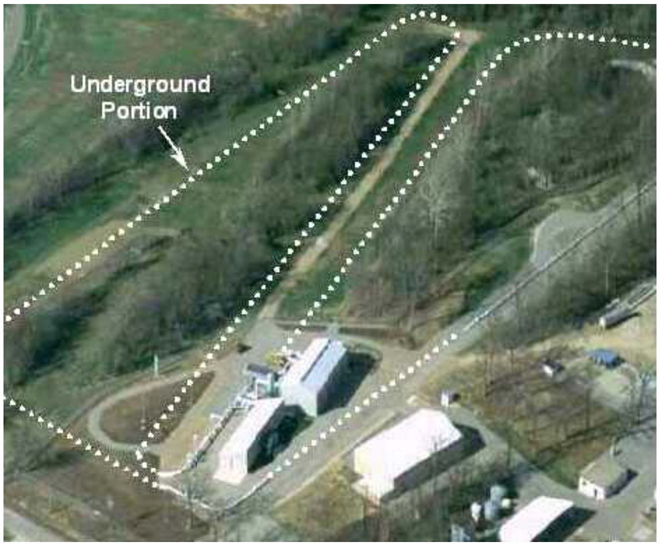


Figure 1-1. PSF Flow Loop

Pull Rig

The pull rig is used for tests of complete inspection systems under unpressurized conditions. It consists of four 300-foot long pipe runs with diameters of 12, 24, 30, and 36 inches. In-line inspection tools and test bed vehicles can be pulled through the pipe sections using the rig's winch. Depending on the tool, pull forces up to 56,000 pounds and speeds up to 25 mph can be achieved.

Figure 1-2. PSF Pull Rig

Sensor Development Sled

The sensor development sled is a moveable platform on which sensors and partial magnetizing or inspection assemblies can be installed and pulled along pipe segments at accurate velocities up to 10 mph. The sensor development sled can be used to measure the effects of velocity and sensor position on defect-to-signal relationships, and it can support virtually any nondestructive evaluation sensor technology.

Figure 1-3. Sensor Development Sled

Test Bed Vehicle

The test bed vehicles are generic in-line inspection platforms upon which inspection hardware can be mounted and tested. Two test bed vehicles are available: the magnetic flux leakage (MFL) vehicle, which is specialized for MFL technology, and the advanced sensor vehicle, which is specialized for high data-rate inspection technologies.

Figure 1-4. Test Bed Vehicle

Defect Sets

A number of existing defect sets are available for evaluation at the Pipeline Simulation Facility. These defect sets provide a common basis for correlating results from each facility component, thereby helping to ensure that the conclusions drawn are valid over a wide range of conditions. Removable metal-loss and mechanical damage defect sets are available for use in 24-inch pipe in the pull rig and flow loop. Similar defects are available in pipe segments for the sensor development sled. Natural corrosion samples are available in 12 and 24 inch diameter pipe. A stress-corrosion cracking defect set is available for the 30-inch pipe in the pull rig, and a section of 26-inch pipe that has been re-rounded to 24-inch diameter is also available for the pull rig. A set of weld-solidification cracks, and a matching set of notches made using electron discharge machining, are available for the flow loop. Additionally, for development of third party damage inspection tools, over 200 dents and gouges are available in 24 inch diameter pipe.

INTERNAL INSPECTION DEMONSTRATION CONFIGURATION

The configuration used to benchmark the emerging technologies consisted of the following pipe samples:

- One 12 inch seamless pipe sample with natural corrosion defects measuring 48 feet 2 inches in length with wall thickness ranging from 0.31 to 0.38 inches.
- One 12 inch seam welded pipe sample with manufactured corrosion defects measuring 32 feet in length with a wall thickness of approximately 0.358 inches.
- One 24 inch pipe sample with mechanical damage defects measuring 41.5 feet in length with wall thickness ranging from 0.266 inches to 0.292 inches (comprised of two separate pipe samples welded together).
- One 24 inch pipe sample with plain dent defects measuring approximately 40 feet in length with a wall thickness of 0.280 inches.
- One 30 inch pipe sample containing natural stress corrosion cracks (SCC) measuring approximately 20 feet 4 inches in length with a wall thickness of 0.343 inches

Each pipe configuration has the same defect characteristic philosophy; the detection and sizing of the defects range from simple to difficult. This helps to define both the current capability and future challenges for each of the inspection technologies.

At the current state of development, none of the technologies were ready for full pull rig testing. Rather, the pipe samples were placed within the pipeline testing lab, which is a 40 foot by 100 foot building with overhead doors. The two 12 inch diameter pipes, two 24 inch diameter pipes, and one 30 inch diameter pipe were placed parallel to each other with a separation distance between each pipe of approximately 4 feet. The exact layout of the pipe samples is shown in Figure 1-5.

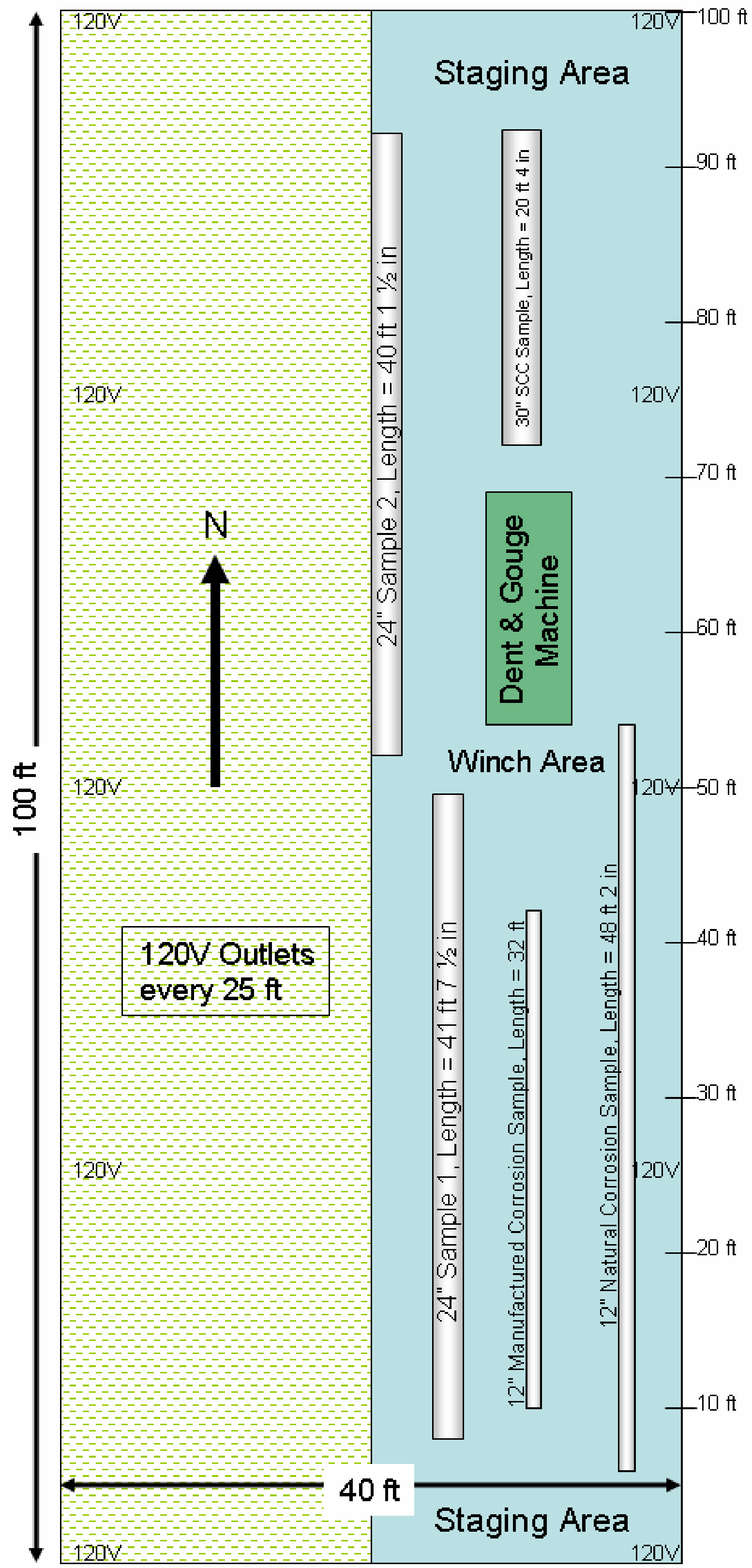


Figure 1-5. Layout of Building JS-5

In developing the internal inspection benchmarking program, the procedures were tailored to the needs of the specific inspection technologies. A general outline of the demonstration program is as follows:

1. The following items could be attached to the sensor carriage as requested by the sensor developer:
   a. A 100 foot tape measure at the center of the sensor to measure defect position; and
   b. A 115 Volt AC power cord.
2. Each inspection tool was pulled through the test pipes with a light duty winch.
3. In the relevant pipe samples, one to three pull through tests were performed for a specific sensor developer.
4. After the third pull, the winch was configured for the next sensor developer desiring a pull test.
5. After each technology developer had the opportunity to acquire data, the developers were allowed repeat runs to collect additional data following the same order.
6. The facility was open for use from Monday, September 13 to Friday, September 17, 2004 from 8 am to 5 pm. After hours access was limited because of safety and security rules.
7. The results obtained by each participant are to be submitted to NETL representatives for review and assessment of capability.

Battelle established a list of specific distances and positions along the pipe on which each participant was to report. The locations may or may not have had defects, enabling detection capability and false call rates to be assessed. Each technology is at a different level of maturity, and therefore this must be considered when evaluating results. While a more mature technology may provide better performance in this assessment, over time a less mature technology may be better suited for the needs of the pipeline industry.

REPORTING

Prior to the demonstration, Battelle selected specific axial locations on which the developers were to report their inspection results. This information was given to each developer for review and comment approximately two weeks prior to the start of the demonstration. Following the demonstration, each participant subsequently reported to their COTR where defects were detected and included any sizing or assessment information in their documentation. The COTR is to subsequently perform the comparison of inspection results to the defects documented in this report.

The information provided in Sections 2, 3, and 4 of this report consist of:

- Corrosion Defects: Section 2 documents the maximum depth and surface extent for each manufactured corrosion defect. For natural corrosion defects comprised of more than one pit, multiple maximum depths are reported.
- Dents and Gouges: Section 3 provides the depth of each dent at the center to an accuracy of +/- 0.020 inches and the axial length as determined by a 0.020 inch departure from a straight edge placed on top of the dent.

- Dents: Section 3 provides the dent depth and relative severity based on dent fabrication loads and denting tool geometry. Dent severity is the most subjective to assessment.
- SCC: Section 4 provides a magnetic particle map showing the location and length of natural SCC.

SUMMARY

The Pipeline Simulation Facility has unique facilities and pipes with representative defects to assess the capabilities of a number of inspection technologies. This benchmarking demonstration of emerging pipeline inspection technologies should help to define progress and future direction for research and development efforts.

SECTION 2. CORROSION INSPECTION TECHNOLOGY ASSESSMENT

INTRODUCTION

The current focus of corrosion inspection projects is to develop technologies that can work in unpiggable pipelines. These lines typically have bore restrictions, low pressure or other conditions that make pigging with existing technologies impractical. These new inspection techniques will eventually be mounted on crawlers being developed under separate programs. These crawlers will act as the propulsion units to escort the new sensor technologies through the pipeline. While each technology will have the potential to work in an unpiggable pipeline, the current development is focused only on detecting and sizing corrosion defects. Therefore, the capability of passing bore restrictions was not evaluated at this time.

Each corrosion inspection technology uses electromagnetic energy to interrogate the pipeline for defects. A common requirement for three of the four technologies is that

- a full circumference pipe is needed; the technology will not work on coupons cut from pipe,
- the sending and receiving units need to be separated by 2 to 3 pipe diameters, and
- the defects must be at least four pipe diameters from an open end to avoid end effects that may influence results (end effects are not a problem in actual pipelines).

These technologies are an adaptation of boiler tube inspection technology and more applicable to smaller diameter pipelines. These technologies can be scaled up to diameters more common in distribution mains that operate at pressures that would mandate inspection. The pipe fabrication process is an important variable that affects inspection and was considered when selecting the pipe samples. Pipe in diameters 26 inches and less can be categorized into two basic types, seam-welded and seamless. Seam-welded pipe starts with flat plate which is formed into a cylindrical geometry. The edges are joined by welding processes that include electric resistance weld (ERW) and arc welding. Seamless pipe starts with round bar stock; a piercing tool is used to form the pipe. Welded seam pipe formed from plate stock has a uniform wall thickness, with the wall thickness tolerance typically ranging from 0 to 5 percent greater than the specified wall thickness. Seamless pipe can have wall thickness variations of greater than +/-10 percent of nominal. These variations in wall thickness, while acceptable as long as the minimum wall thickness is achieved, can complicate detection and sizing of corrosion. The advantage of seamless pipe is that there is no seam weld; certain weld processes can have defects that affect integrity and may require detection using inspection methods.

Battelle’s Pipeline Simulation Facility has a 12 inch diameter seamless pipe sample with large natural corrosion defects. Additionally, Battelle has recently acquired a section of seam-welded pipe in which a number of machined corrosion defects were placed. The report sections below discuss the demonstration plan for the corrosion inspection tools and provides an “answer key”

(Table 2-1) for the data sheets filled out by the corrosion inspection tool developers during the demonstration. Additional information and photographs are provided in Figures 2-1 through 2-5 describing the maximum depths, surface extent, and locations for all of the corrosion defects.

12-INCH CORROSION DEFECT DEMONSTRATION PLAN

The demonstration plan for the 12-inch corrosion defect test configuration is as follows:

1. The technologies benchmarked included:
   - 1.1. SwRI: Collapsible coil remote field eddy current
   - 1.2. GTI: Small diameter exciter remote field eddy current
   - 1.3. Battelle: Moving permanent magnet eddy current
2. Total length of the pipe samples will be 40-80 (TBD*) feet
3. The pipe will be 12-inch inside diameter
4. The demonstration samples will be comprised of two pipes:
   - 4.1. Pipe 1 specifications are as follows:
     - 4.1.1. The length will be up to 60 (TBD) feet long, seamless construction.
     - 4.1.2. The nominal wall thickness will be 0.325 inches; the natural variations of seamless pipe will exist.
     - 4.1.3. The pipe will have natural corrosion defects.
     - 4.1.4. The pipe will also have 3-5 machined metal loss defects.
       - 4.1.4.1. The defects will have the following dimensions:
         - 4.1.4.1.1. Length (in): >= 1 inch and <= 3 inches
         - 4.1.4.1.2. Width (in): >= 1 inch and <= 3 inches
         - 4.1.4.1.3. Depth (% wall thickness): >= 20% and <=80%
       - 4.1.4.2. Up to 2 more will be defined at installation.
     - 4.1.5. The machined defects will be aligned in a single row.
   - 4.2. Pipe 2 specifications are as follows:
     - 4.2.1. The length will be up to 40 feet (TBD).
     - 4.2.2. The nominal wall thickness will be 0.375 (TBD) inches.
     - 4.2.3. The pipe will have up to 10 machined metal loss defects.
       - 4.2.3.1. The defects will have the following dimensions:
         - 4.2.3.1.1. Length (in): >= 1 inch and <= 3 inches
         - 4.2.3.1.2. Width (in): >= 1 inch and <= 3 inches
         - 4.2.3.1.3. Depth (% wall thickness): >= 20% and <=80%
       - 4.2.3.2. Up to 3 more multiple pits will be defined at installation.
       - 4.2.3.3. The separation between defects (or defect clusters) will be nominally 3 pipe diameters.

* To be determined. When used after a number, the value can vary 25 percent.

12 inch Corrosion Assessment Data

Benchmarking of Inspection Technologies
Detection of Metal Loss - Page 1

Name:	
Date:	
Company:	
Sensor Design:	

CALIBRATION DATA

	Calibration Metal Loss Location	Metal Loss Length & Width	Depth of Metal Loss	Radius of Curvature	Measured Length & Width of Defect	Measured Depth of Defect	Comments
	inches from end A	inches	inches	inches			
Natural Corrosion Pipe Sample (48' 2")							
Calibration T1:	60"	1"	0.3"	0.557"			
Calibration T2:	96"	1.475"	0.21"	1.417"			
Calibration T3:	401"	1.475"	0.21"	1.417"			
Manufactured Metal Loss Pipe Sample (32')							
Groove Defect 1:	55"	0.5"	0.09"	0.25"			
Groove Defect 2:	329"	0.5"	0.14"	0.25"			
Calibration MC01:	90"	1.2" long x 3" wide	0.29	0.933			

TEST DATA

Pipe Sample:	**Manufactured Corrosion Sample**
Defect Set:	12" Diameter, 0.358" Wall Thickness Pipe Sample with Manufactured Metal Loss

LINE 1

Defect Number	Search Region (Distance from End A)	Start of Metal Loss Region from Side A	End of Metal Loss Region from Side A	Total Length of Metal Loss Region	Width of Metal Loss Region	Maximum Depth of Metal Loss Region	Comments
	inches	inches	inches	inches	inches	inches	
MC02	126" to 138"	**130.5"**	**133.5"**	**3"**	**1.2"**	**0.13"**	**Radius of curvature tool used to create defect - 1.417"**
MC03	144" to 156"	***	***	***	***	***	**Blank**
MC04	162" to 174"	***	***	***	***	***	**Blank**
MC05	186" to 198"	**191.4"**	**192.6"**	**1.2"**	**2"**	**0.21"**	**Radius of curvature tool used to create defect - 0.933"**
MC06	210" to 222"	***	***	***	***	***	**Blank**
MC07	234" to 246"	**239.15"**	**241.85"**	**2.7"**	**1.1"**	**0.17"**	**Radius of curvature tool used to create defect - 0.933"**
MC08	264" to 276"	***	***	***	***	***	**Blank**
MC09	282" to 294"	**287"**	**289"**	**2"**	**1.5"**	**0.29"**	**Radius of curvature tool used to create defect - 1.417"**
MC10	306" to 318"	***	***	***	***	***	**Blank**

Table 2-1. 12 inch Corrosion Inspection Technology Data Sheet "Answer Key"

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 2							
Name:							
Date:							
Company:							
Sensor Design:							
TEST DATA							
Pipe Sample:		**Manufactured Corrosion Sample**					
Defect Set:		12" Diameter, 0.358" Wall Thickness Pipe Sample with Manufactured Metal Loss					
		LINE 2					
Defect Number	Search Region (Distance from End A)	Start of Metal Loss Region from Side A	End of Metal Loss Region from Side A	Total Length of Metal Loss Region	Width of Metal Loss Region	Maximum Depth of Metal Loss Region	Comments
	inches	inches	inches	inches	inches	inches	
MC11	78" to 90"	***	***	***	***	***	**Blank**
MC12	102" to 114"	**106.5"**	**109.5"**	**3"**	**1.4"**	**0.18"**	**Radius of curvature tool used to create defect - 2.726"**
MC13	138" to 150"	***	***	***	***	***	**Blank**
MC14	174" to 186"	***	***	***	***	***	**Blank**
MC15	198" to 210"	**203.25"**	**204.75"**	**1.5"**	**1.5"**	**0.20"**	**Radius of curvature tool used to create defect - 1.417"**
MC16	222" to 234"	***	***	***	***	***	**Blank**
MC17	246" to 258"	**251.3"**	**252.7"**	**1.4"**	**3.3"**	**0.27"**	**Radius of curvature tool used to create defect - 2.726"**
MC18	272" to 284"	***	***	***	***	***	**Blank**
MC19	288" to 300"	**293.3"**	**294.7"**	**1.4"**	**3"**	**0.09"**	**Radius of curvature tool used to create defect - 2.726"**

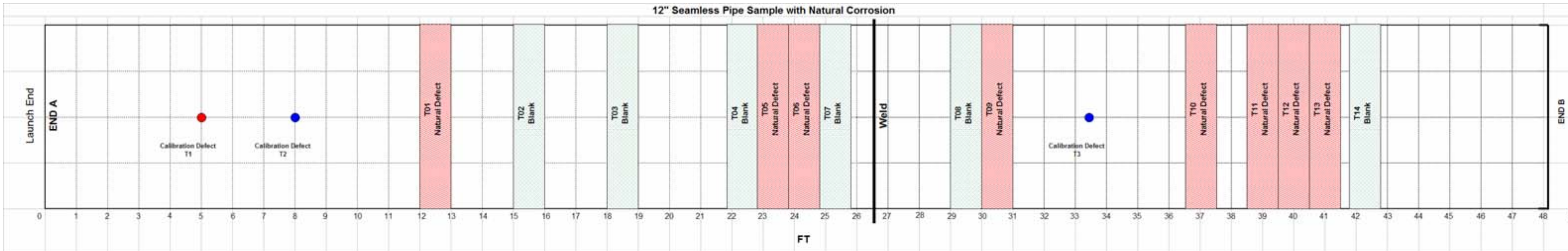
Table 2-1 (cont). 12 inch Corrosion Inspection Technology Data Sheet "Answer Key"

Benchmarking of Inspection Technologies **Detection of Metal Loss - Page 3**	
Name:	
Date:	
Company:	
Sensor Design:	
TEST DATA	
Pipe Sample:	**Natural Corrosion Sample**
Defect Set:	12" Diameter, 0.31" to 0.38" Wall Thickness Pipe Sample with Natural Corrosion

Defect Number	Search Region (Distance from End A)	Start of Metal Loss Region from Side A	End of Metal Loss Region from Side A	Total Length of Metal Loss Region	Width of Metal Loss Region	Maximum Depth of Metal Loss Region	Comments
	inches	inches	inches	inches	inches	inches	
T01	144" to 156"	**T01a = 147.1"** **T01b = 153.4"**	**T01a = 149"** **T01b = 156.6"**	**T01a = 1.9"** **T01b = 3.25"**	**T01a = 0.9"** **T01b = 0.8"**	**T01a = 0.13"** **T01b = 0.15"**	**Two regions: T01a and T01b**
T02	180" to 192"	***	***	***	***	***	**Blank**
T03	216" to 228"	***	***	***	***	***	**Blank**
T04	260" to 272"	***	***	***	***	***	**Blank**
T05	272" to 284"	**273.7"**	**284.3"**	**10.6"**	**1.1"**	**0.12"**	
T06	284" to 296"	**T06a = 285.3"** **T06b = 295.5"**	**T06a = 294.8"** **T06b = 196.5"**	**T06a = 9.5"** **T06b = 1"**	**T06a = 1.3"** **T06b = 1"**	**T06a = 0.15"** **T06b = N/A**	**Two regions: T06a and T06b**
T07	296" to 308"	***	***	***	***	***	**Blank**
T08	348" to 360"	***	***	***	***	***	**Blank**
T09	360" to 372"	**363"**	**367"**	**4"**	**1.3"**	**0.20"**	
T10	438" to 450"	**T10a = 440.3"** **T10b = 447.4"**	**T10a = 443.8"** **T10b = 448.6"**	**T10a = 3.5"** **T10b = 1.25"**	**T10a = 0.9"** **T10b = 0.4"**	**T10a = 0.15"** **T10b = N/A**	**Two regions: T10a and T10b**
T11	462" to 474"	**T11a = 462.8"** **T11b = 469.2"**	**T11a = 467.2"** **T11b = 472.8"**	**T11a = 4.4"** **T11b = 3.6"**	**T11a = 0.8"** **T11b = 1.1"**	**T11a = 0.13"** **T11b = 0.16"**	**Two regions: T11a and T11b**
T12	474" to 486"	**T12a = 474"** **T12b = 482.6"**	**T12a = 480"** **T12b = 485.4"**	**T12a = 6"** **T12b = 2.75"**	**T12a = 2"** **T12b =0.9"**	**T12a = 0.18"** **T12b = N/A**	**Two regions: T12a and T12b**
T13	486" to 498"	**T13a = 487.4"** **T13b = 492.9"**	**T13a = 488.6"** **T13b = 495.1"**	**T13a = 1.25"** **T13b = 2.25"**	**T13a = 0.5"** **T13b = 0.4"**	**T13a = 0.15"** **T13b = 0.10"**	**Two regions: T13a and T13b**
T14	500" to 512"	***	***	***	***	***	**Blank**

Table 2-1 (cont). 12 inch Corrosion Inspection Technology Data Sheet "Answer Key"

12 INCH NATURAL CORROSION PIPE SAMPLE DOCUMENTATION



	To Center of Defect		Pipe Wall Thickness =			0.375
Defect Number	Approx. Distance from Side A (inches) to Center of Region	Approx. Distance from Side A (feet)	Approx. Length of Defect (in)	Approz. Width of Defect (in)	Max Depth of Metal Removed (in)	% Metal Loss
T01a	148	12.3	1.9	0.9	0.13	35%
T01b	155	12.9	3.25	0.8	0.15	40%
T02	186	15.5	-	-	-	0%
T03	222	18.5	-	-	-	0%
T04	266	22.2	-	-	-	0%
T05	279	23.2	10.6	1.1	0.12	32%
T06a	290	24.1	9.5	1.3	0.15	40%
T06b	296	24.6	1	1	N/A	N/A
T07	302	25.2	-	-	-	0%
T08	354	29.5	-	-	-	0%
T09	365	30.4	4	1.3	0.20	53%
T10a	442	36.8	3.5	0.9	0.15	40%
T10b	448	37.3	1.25	0.4	N/A	N/A
T11a	465	38.8	4.4	0.8	0.13	35%
T11b	471	39.3	3.6	1.1	0.16	43%
T12a	477	39.8	6	2	0.18	48%
T12b	484	40.3	2.75	0.9	N/A	N/A
T13a	488	40.7	1.25	0.5	0.15	40%
T13b	494	41.2	2.25	0.4	0.10	27%
T14	506	42.2	-	-	-	0%

Calibration Defects						
	Tool Radius	Width	Length	% Metal Loss	Depth of Metal Loss (inches	Distance from End A
Calibration T1	0.557	1	1	80%	0.3	60"
Calibration T2	1.417	1.475	1.475	55%	0.20625	96"
Calibration T3	1.417	1.475	1.475	55%	0.20625	401"

% Metal Loss	Depth of Metal Removed (inches)
25% (yellow)	0.09
35% (green)	0.13
48% (dark green)	0.18
50% (cyan)	0.19
55% (blue)	0.21
60% (slate)	0.23
75% (orange)	0.28
80% (red)	0.30

Figure 2-1. 12-inch Natural Corrosion Pipe Sample Defect Map

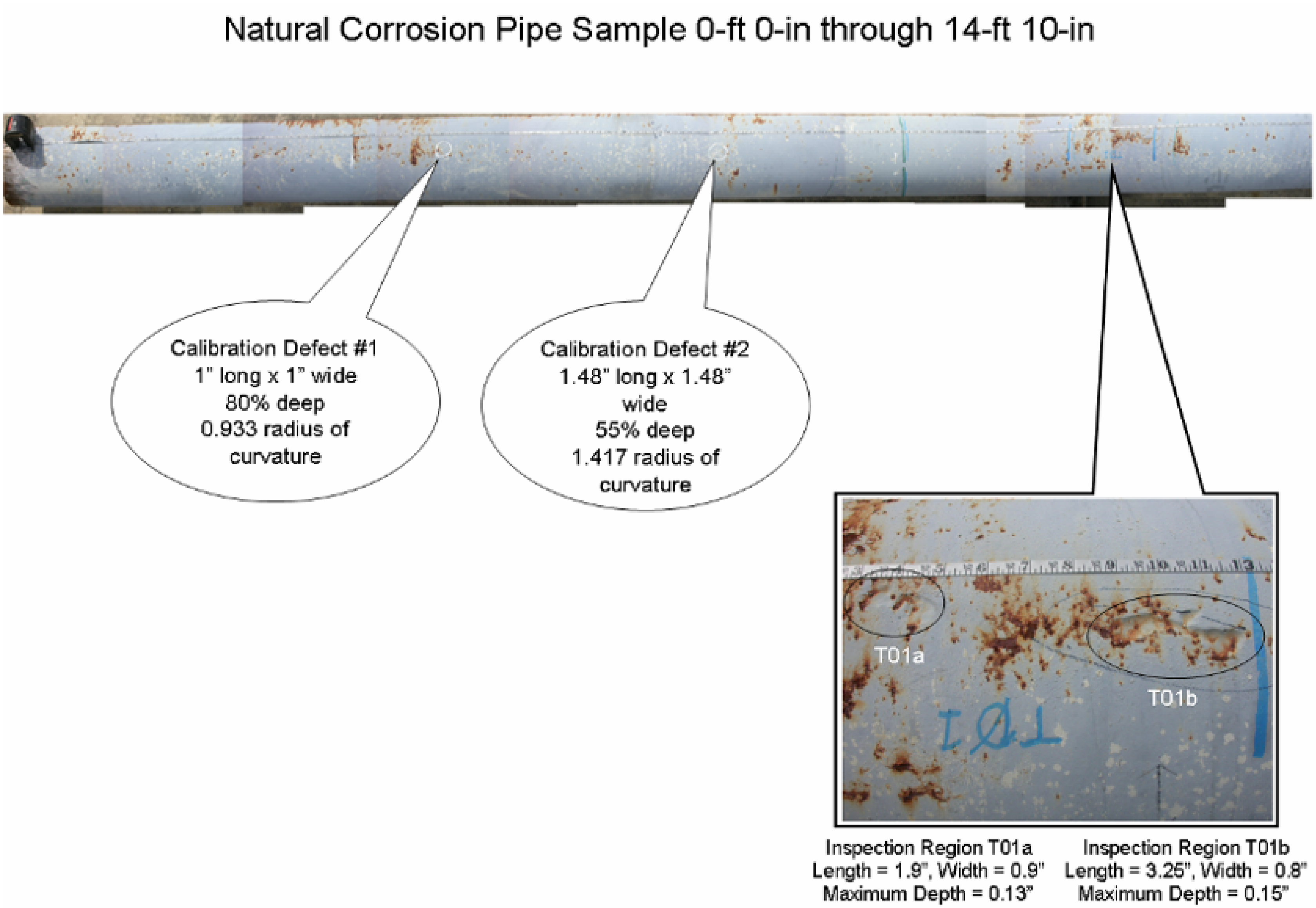


Figure 2-2. 12 inch Natural Corrosion Pipe Sample Defect Parameters 0 ft to 14 ft 10 in

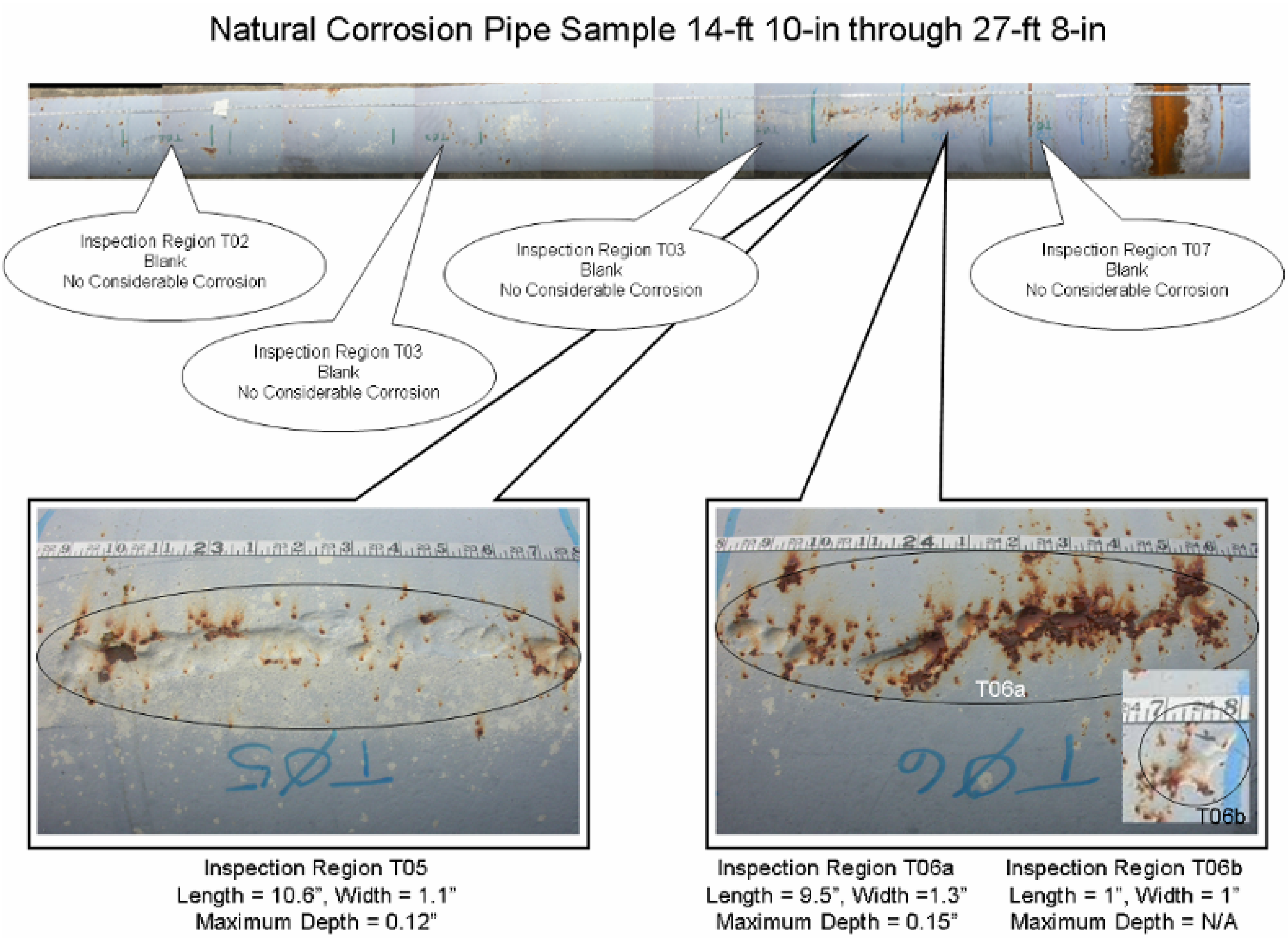


Figure 2-3. 12 inch Natural Corrosion Pipe Sample Defect Parameters 14 ft 10 in to 27 ft 8 in

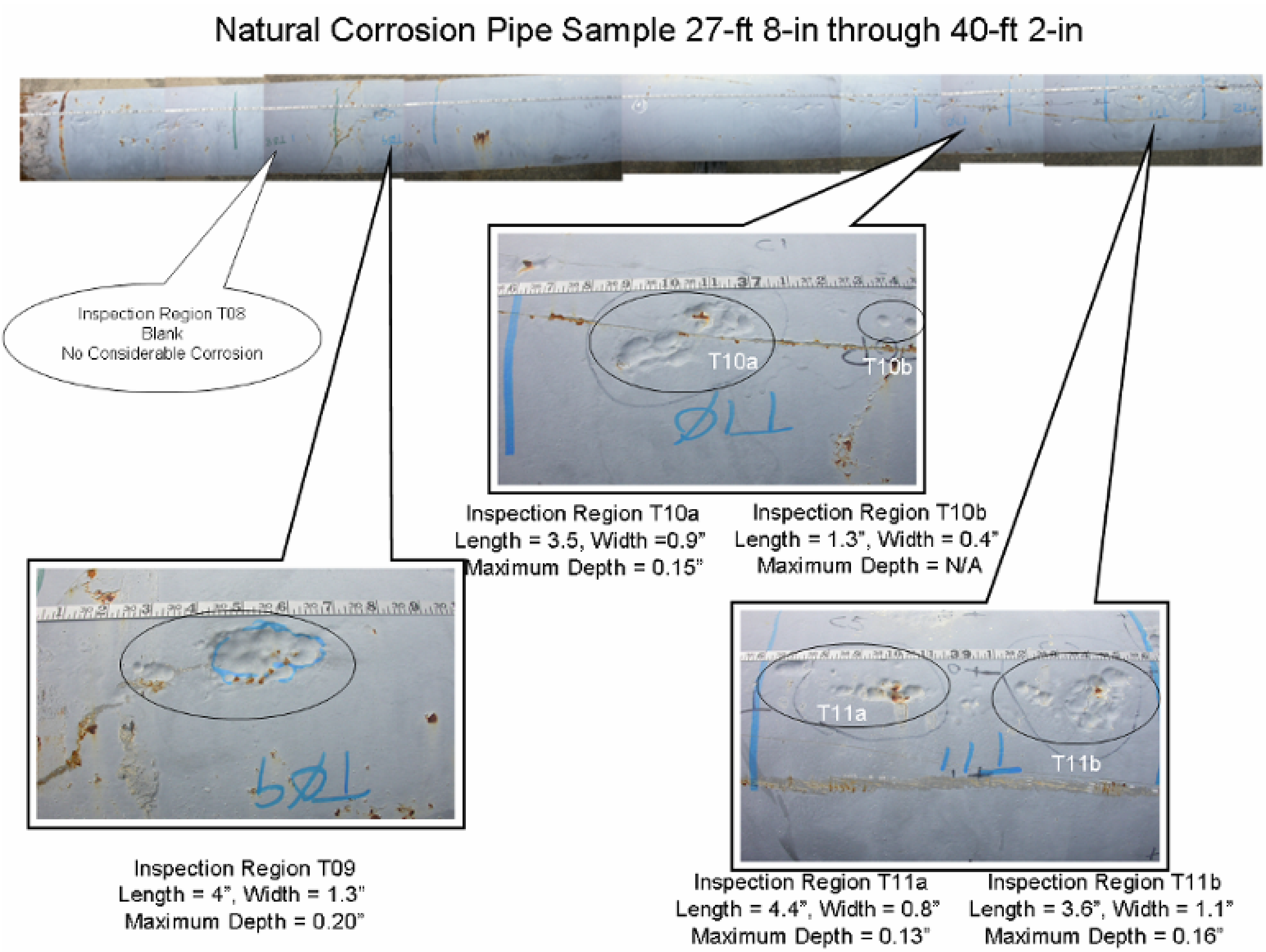


Figure 2-4. 12 inch Natural Corrosion Pipe Sample Defect Parameters 27 ft 8 in to 40 ft 2 in

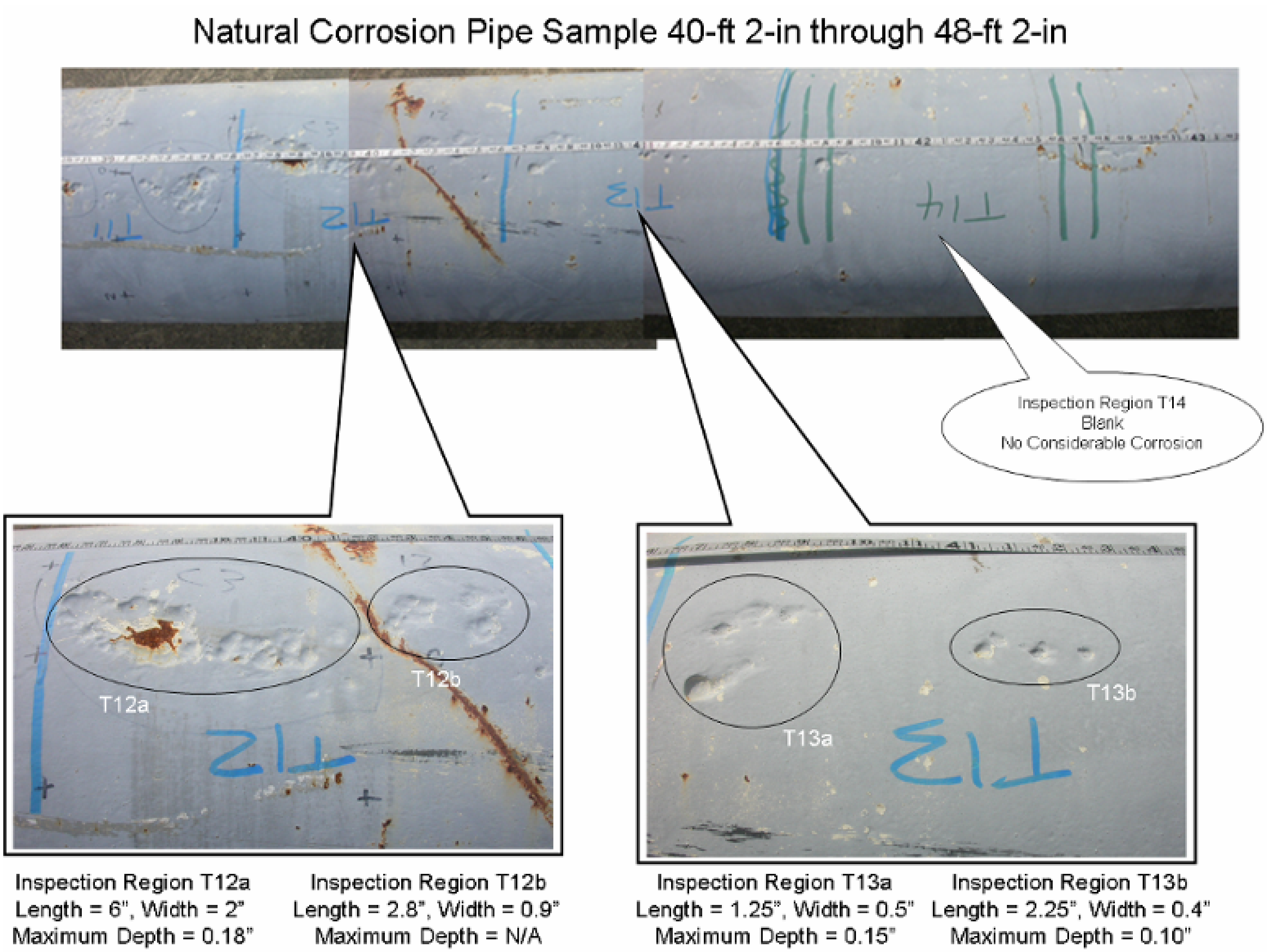
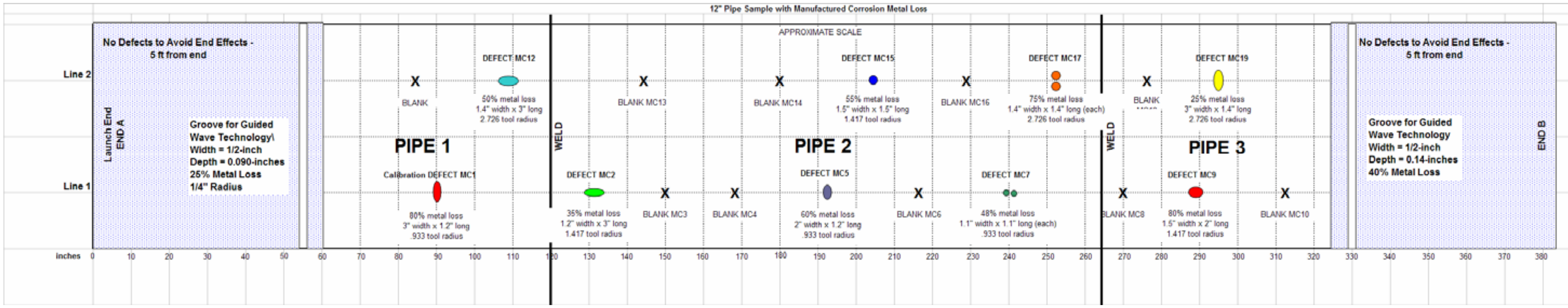


Figure 2-5. 12 inch Natural Corrosion Pipe Sample Defect Parameters 40 ft 2 in to 48 ft 2 in

12 INCH MANUFACTURED CORROSION PIPE SAMPLE DOCUMENTATION



	To Center of Defect						
Defect Number	Distance from Side A (inches)	Distance from Side A (feet)	Length of Defect (in)	Width of Defect (in)	Depth of Metal Removed (in)	% Metal Loss	Radius of End Mill Tool
PIPE 1 Line 1							
Calibration DEFECT MC1	90	7.5	1.2	3	0.28	80%	0.933
PIPE 2 Line 1							
DEFECT MC2	12	1	3	1.2	0.13	35%	1.417
Blank MC3	30	2.5	-	-	0.00	0%	-
Blank MC4	48	4	-	-	0.00	0%	-
DEFECT MC5	72	6	1.2	2	0.21	60%	0.933
Blank MC6	96	8	-	-	0.00	0%	-
DEFECT MC7	120.5	10.04167	2.7	1.1	0.17	48%	0.933
PIPE 3 Line 1							
Blank MC8	6	0.5	-	-	0.00	0%	-
DEFECT MC9	24	2	2	1.5	0.29	80%	1.417
Blank MC10	48	4	-	-	0.00	0%	-
PIPE 1 Line 2							
Blank MC11	84	7	-	-	0.00	0%	-
DEFECT MC12	108	9	3	1.4	0.18	50%	2.726
PIPE 2 Line 2							
Blank MC13	24	2	-	-	0.00	0%	-
Blank MC14	60	5	-	-	0.00	0%	-
DEFECT MC15	84	7	1.5	1.5	0.20	55%	1.417
Blank MC16	108	9	-	-	0.00	0%	-
DEFECT MC17	132	11	1.4	3.3	0.27	75%	2.726
PIPE 3 Line 2							
Blank MC18	12	1	-	-	0.00	0%	-
DEFECT MC19	30	2.5	1.4	3	0.09	25%	2.726

% Metal Loss		Depth of Metal Removed (inches)
	25%	0.09
	35%	0.13
	48%	0.17
	50%	0.18
	55%	0.20
	60%	0.21
	75%	0.27
	80%	0.29

Figure 2-6. 12 inch Manufactured Corrosion Pipe Sample Defect Map

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Manufactured Metal Loss Defect Photos

Figure 2-7. Calibration Defect MC01

Figure 2-8. Defect MC02

Figure 2-9. Defect MC05

Figure 2-10. Defect MC07

Figure 2-11. Defect MC09

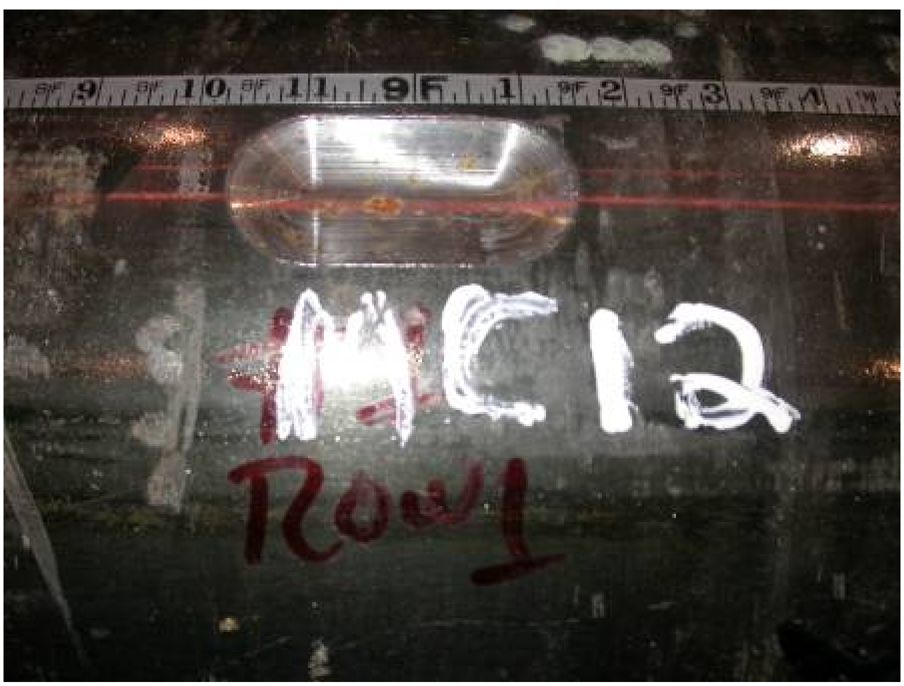


Figure 2-12. Defect MC12

Figure 2-13. Defect MC15

Figure 2-14. Defect MC17

Figure 2-15. Defect MC19

Figure 2-16. Calibration Groove 1

Figure 2-17. Calibration Groove 2

Figure 2-18. Tools Used to Machine Metal Loss Defects

SECTION 3. MECHANICAL DAMAGE INSPECTION TECHNOLOGY ASSESSMENT

INTRODUCTION

The current NETL and RSPA developments for mechanical damage inspection technologies are not restrictive of pipe diameter. However, prior DOT RSPA projects involved fabricating defect sets in 24 inch diameter pipe. Therefore when selecting the specimens and data for the mechanical damage defect set the use of the existing 24 inch diameter pipe samples was the most practical. An additional advantage of using the existing 24 inch defect sets is that they have already been inspected using MFL technology under a DOT contract. As such, magnetic flux leakage signals from these defects can be made available upon request.

One of the technology developers has requested only smooth dents without gouges on the external surface. Another is only examining internal surface geometry. One pipe sample exists that meets the smooth dent requirement; however another defect set with minimal gouging is also included in the demonstration to assess the future potential of each technology. For completeness, this second pipe sample is configured in a pipe with previously manufactured dents and gouges.

The following report sections discuss the demonstration plan for the mechanical damage inspection tools and provides an “answer key” (Tables 3-1 and 3-2) for the data sheets given to the developers during the demonstration. It should be noted that two distinct data sheets had to be created for the mechanical damage benchmarking due to the differences in how PNNL records their data for smooth dents. Additional information and photographs are provided in Figures 3-1 through 3-29 describing how the dents were manufactured, the maximum dent depths, dent lengths, and locations for all of the mechanical damage defects.

24-INCH MECHANICAL DAMAGE DEMONSTRATION PLAN

The test plan for the 24-inch dent and third party damage defect test configuration is as follows:

1. The technologies to be benchmarked will include:
   1.1. PNNL: Strain measurement tool
   1.2. LANL: Deformation sensor
   1.3. Battelle: Dual magnetization MFL
2. Total length of the pipe sample will be 120 (TBD) feet
3. The pipe will be 24-inch outside diameter
4. A rail or guide wire will be available for installation on the inside the pipe at the bottom to minimize rotation, as needed by sensor developers

5. The test sample will be comprised of two pipes:
    5.1. Pipe 1 specifications are as follows:
        5.1.1. The length will be up to 40 (TBD) feet seam welded pipe
        5.1.2. The nominal wall thickness will be 0.280 inches
        5.1.3. The pipe will contain between 10 to 15 smooth dents without gouges
        5.1.4. Up to 3 dents will be available for calibration, the rest will be blind
    5.2. Pipe 2 specifications are as follows
        5.2.1. The length will be up to 80 feet (TBD)
        5.2.2. The nominal wall thickness will be 0.325 (TBD) inches
        5.2.3. The pipe will contain multiple dents with some gouges in 3 to rows.

LOS ALAMOS 24 INCH MECHANICAL DAMAGE ASSESSMENT DATA

LANL Benchmarking of Inspection Technologies
Detection of Mechanical Damage - Page 1

Name:	
Date:	
Company:	
Sensor Design:	

CALIBRATION DATA

		Calibration Dent Location	Length	Depth	Measured Length	Measured Depth	Smooth or Gouged?	Comments
		inches from end A to center of dent	inches	% Diameter	inches	% Diameter		
Mechanical Damage Pipe SAMPLE 1 (41' 5.5")								
Calibration Dent Q01:		117"	6	6%				
Calibration Dent Q02:		82"	2	3%				
Calibration Dent Q03:		46"	0	6%				
Mechanical Damage Pipe SAMPLE 2 (40' 1.5")								
Calibration Dent R01:		42.25"	3.5	1.2%				
Calibration Dent R02:		73.25"	8.5	0.8%				

TEST DATA

Pipe Sample:	**SAMPLE 1**
Defect Set:	24" Diameter Pipe with Mechanical Damage

Defect Number	Search Region (Distance from End A)	Start of Dent from Side A	End of Dent from Side A	Total Length of Dent	Depth of Dent (% Dia.)	Smooth or Gouged Dent?		Comments
	inches	inches	inches	inches	%			
Q1	406" to 430"	**414.4"**	**414.7"**	**0.25"**	**6%**	☐	Smooth	**Gouge ~25% loss in wall thickness**
						☑	**Gouged**	
						☐	None	
Q2	370" to 394"	***	***	***	***	☐	Smooth	**Actually has only a gouge measuring 2" in length with ~5% loss in wall thickness**
						☐	Gouged	
						☑	**None**	
Q3	334" to 358"	**343"**	**349"**	**6"**	**3%**	☐	Smooth	**Gouge ~5% loss in wall thickness**
						☑	**Gouged**	
						☐	None	
Q4	298" to 322"	**307"**	**309"**	**2"**	**3%**	☐	Smooth	**Gouge ~5% loss in wall thickness**
						☑	**Gouged**	
						☐	None	
Q5	262" to 286"	**270.9"**	**271.1"**	**0.25"**	**3%**	☐	Smooth	**Gouge ~5% loss in wall thickness**
						☑	**Gouged**	
						☐	None	
Q6	226" to 250"	***	***	***	***	☐	Smooth	**Blank**
						☐	Gouged	
						☑	**None**	

Table 3-1. LANL 24 inch Mechanical Damage Inspection Technology Data Sheet "Answer Key"

LANL Benchmarking of Inspection Technologies Detection of Mechanical Damage - Page 2	
Name:	
Date:	
Company:	
Sensor Design:	

TEST DATA	
Pipe Sample:	**SAMPLE 2**
Defect Set:	24" Diameter Pipe with Mechanical Damage

Defect Number	Search Region (Distance from End A)	Start of Dent from Side A	End of Dent from Side A	Total Length of Dent	Depth of Dent (% Dia.)	Smooth or Gouged Dent?	Comments
	inches	inches	inches	inches	%		
R03	96" to 120"	**107.25"**	**111.25"**	**4.0"**	**1.21%**	☑ **Smooth** ☐ Gouged ☐ None	**R03 = Calibration Dent R01 = R06**
R04	132" to 156"	**139"**	**149"**	**10.0"**	**0.96%**	☑ **Smooth** ☐ Gouged ☐ None	**R04 = R08 = R10**
R05	168" to 192"	**178.75"**	**187.25"**	**8.5"**	**0.83%**	☑ **Smooth** ☐ Gouged ☐ None	**R05 = Calibration Dent R02 = R07 = R09**
R06	204" to 228"	**215"**	**219"**	**4.0"**	**1.21%**	☑ **Smooth** ☐ Gouged ☐ None	**R03 = Calibration Dent R01 = R06**
R07	240" to 264"	**248.75"**	**257.25"**	**8.5"**	**0.83%**	☑ **Smooth** ☐ Gouged ☐ None	**R05 = Calibration Dent R02 = R07 = R09**
R08	276" to 300"	**284.5"**	**294.5"**	**10.0"**	**0.96%**	☑ **Smooth** ☐ Gouged ☐ None	**R04 = R08 = R10**
R09	312" to 336"	**320.75"**	**329.25"**	**8.5"**	**0.83%**	☑ **Smooth** ☐ Gouged ☐ None	**R05 = Calibration Dent R02 = R07 = R09**
R10	348" to 372"	**355.5"**	**365.5"**	**10.0"**	**0.96%**	☑ **Smooth** ☐ Gouged ☐ None	**R04 = R08 = R10**
R11	384" to 408"	*******	*******	*******	*******	☐ Smooth ☐ Gouged ☑ **None**	**Blank**

Table 3-1 (cont). LANL 24 inch Mechanical Damage Inspection Technology Data Sheet "Answer Key"

PNNL 24 INCH MECHANICAL DAMAGE ASSESSMENT DATA

PNNL Benchmarking of Inspection Technologies Detection of Mechanical Damage - Page 1						
Name:						
Date:						
Company:						
Sensor Design:						
CALIBRATION DATA						
		Calibration Dent Location	Length of Dent	Depth of Dent	Dent Severity	Comments
		inches from end A to center of dent	inches	% Diameter	0 = No dent 1 = Least Severe 2 = Moderate Severity 3 = Most Severe	
Mechanical Damage Pipe SAMPLE 1 (41' 5.5")						
Calibration Dent Q01:		117"	6	6%	3	
Calibration Dent Q02:		82"	2	3%	2	
Calibration Dent Q03:		46"	0	6%	1	
Mechanical Damage Pipe SAMPLE 2 (40' 1.5")						
Calibration Dent R01:		42.25"	3.5	1.2%	1	
Calibration Dent R02:		73.25"	8.5	0.8%	2	

TEST DATA	
Pipe Sample:	**SAMPLE 1**
Defect Set:	24" Diameter Pipe with Mechanical Damage

Defect Number	Search Region (Distance from End A to Center of Dent)	Dent Severity	Commments
	inches	0 = No dent 1 = Least Severe 2 = Moderate Severity 3 = Most Severe	
Q1	416.5"	**1**	**This dent is similar to calibration defect Q03**
Q3	347"	**3-**	**This dent is similar to calibration defect Q01 but is only 3% deep rather than 6%**
Q4	309.5"	**2**	**This dent is similar to calibration defect Q02**
Q5	272"	**1-**	**This dent is similar to calibration defect Q03 but is only 3% deep rather than 6%**
Q6	239.5"	**0**	**Blank**

Table 3-2. PNNL 24 inch Mechanical Damage Inspection Technology Data Sheet "Answer Key"

PNNL Benchmarking of Inspection Technologies Detection of Mechanical Damage - Page 2			
Name:			
Date:			
Company:			
Sensor Design:			
TEST DATA			
Pipe Sample:			**SAMPLE 2**
Defect Set:			24" Diameter Pipe with Mechanical Damage
Defect Number	Search Region (Distance from End A to Center of Dent)	Dent Severity	Comments
	inches	0 = No dent 1 = Least Severe 2 = Moderate Severity 3 = Most Severe	
R03	109.25"	**1**	**R03 = Calibration Dent R01 = R06**
R04	144"	**3**	**R04 = R08 = R10**
R05	183"	**2**	**R05 = Calibration Dent R02 = R07 = R09**
R06	217"	**1**	**R03 = Calibration Dent R01 = R06**
R07	253"	**2**	**R05 = Calibration Dent R02 = R07 = R09**
R08	289.5"	**3**	**R04 = R08 = R10**
R09	325"	**2**	**R05 = Calibration Dent R02 = R07 = R09**
R10	360.5"	**3**	**R04 = R08 = R10**
R11	397"	**0**	**Blank**

Table 3-2 (cont). PNNL 24 inch Mechanical Damage Inspection Technology Data Sheet "Answer Key"

MECHANICAL DAMAGE DEFECTS – PIPE SAMPLE 1

The defects in mechanical damage Pipe Sample 1 were installed using the dent & gouge machine featured in Figure 3-1. The machine is designed to move a damage tool (indenter) into or along the pipe wall. In Figure 2-1, the damage tool is in the center of the photograph, immediately above the pipe. The machine has two hydraulic actuators to press the indenter into the pipe. A vertical actuator applies radial compression, and a horizontal actuator pushes the tool along the pipe axis.

Figure 3-1. Dent and Gouge Machine

During installation of defects, the radial and axial movements of the indenter are effected independently. The indenter is first moved into the pipe, creating a dent. Then, the indenter is moved along the pipe at a constant dent depth. Finally, the indenter is retracted.

Some difficulties were encountered when installing the defects, which caused the defects made early in the program to be less repeatable than those made later. Pipe movement along the axis of the machine reduced the defect length relative to the target length. Riding up of the indenter over the pipe wall thickness affected gouge depth. These effects can generally be seen in the defect photos.

Indenters

Several different indenting tools were used to create the mechanical damage defects, as shown in Figure 3-2. In all cases, the protruding tooth was 1-inch wide and was extended to create a gouge with a target depth (in percent wall thickness). Measurements indicate that the target dent depth (in percent of the diameter) was repeatable using this tool, but the actual gouge depth was highly variable and not well correlated with the target depth. Other defect parameters include length (in inches) and pressure at installation (in percent specified minimum yield stress).

Figure 3-2. Spherical Denting Tool

Typical Defects

Shown in Figure 3-3 are four defects made with the spherical indenter. Several features should be noted. First, the contact area between the ball and the pipe can be large, often extending several inches on either side of the gouge. Second, the socket for the indenter produced a circular mark on the pipe at the start of each defect (this is most clearly seen in the upper left defect). Third, there is some asymmetry to the defects, with the protruding tooth grabbing more on one side than on the other. Finally, there is evidence of slip-stick, which is discussed later.

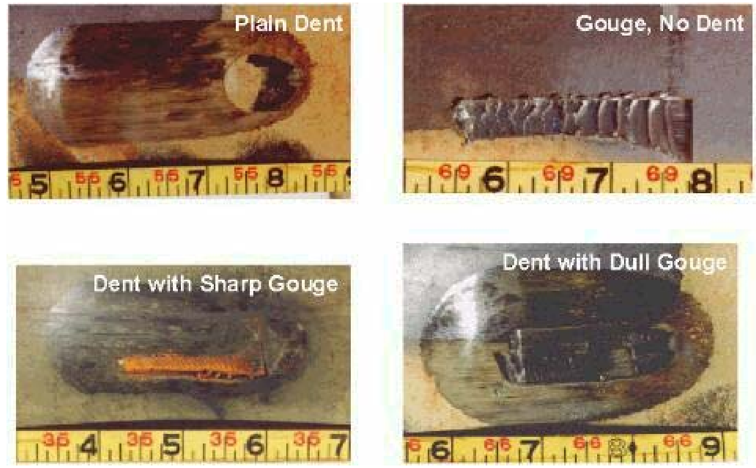


Figure 3-3. Defects Created with Spherical Indenter

Defect Set Layout

The defect set was assembled from two individual pieces of pipe containing defects at several locations, as shown in Figure 3-4. The overall length of the section is approximately 40 feet. Description and properties of the various sections, where known, are given in Table 3-3.

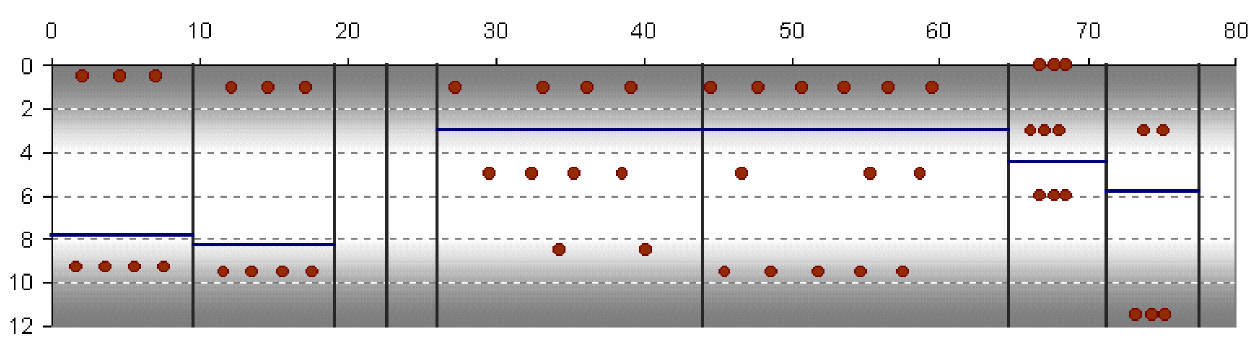


Figure 3-4. Defects Created with Spherical Indenter

Section	Start (ft)	Finish (ft)	Grade	Thickness	Comments
1	0	9.54	X70	0.300	7 defects; mostly dents; some installed at no pressure
2	9.54	19.17	X60	0.300	7 defects; mostly dents; some installed at no pressure
3	19.17	22.58	NA	NA	Pup piece
4	22.58	26.04	NA	NA	Pup piece
5	26.04	43.92	X52	0.292	10 defects; dents, gouges, and dents with gouges; installed under pressure
6	43.92	64.63	X42	0.266	14 defects; dents, gouges, and dents with gouges; installed under pressure
7	64.63	71.21	X70	0.344	9 defects; dents, gouges, and dents with gouges; some installed at no pressure
8	71.21	77.48			5 defects
9	77.48	79.94	NA	NA	Pup piece

Table 3-3. 24 inch Mechanical Damage Pipe Properties

The target dimensions of the defects are shown in Table 3-4. "Depth" is the maximum dent depth during installation in percent of the defect. "Length" is the length of the gouge in inches. "Pressure" is the internal pipe pressure in percent of specified minimum yield strength. "Defect #" is an arbitrary number identifying each defect.

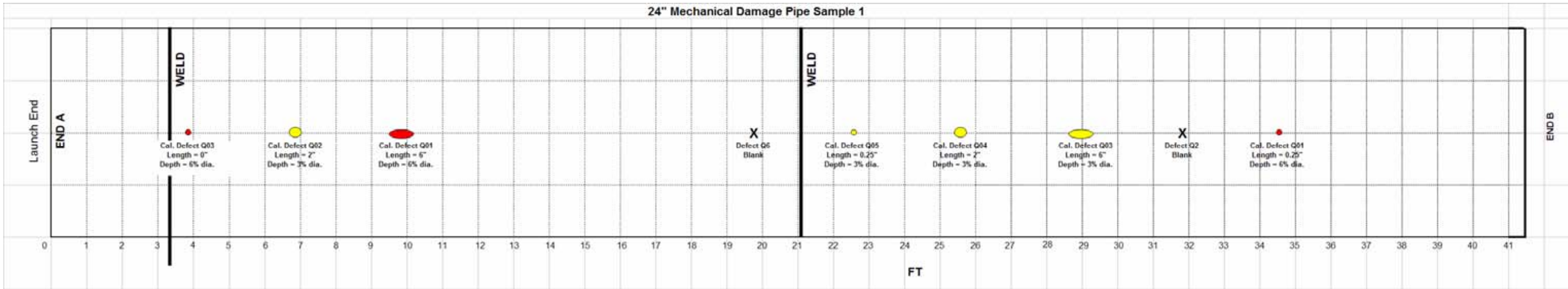
Defect #	Dent Depth (% diameter)	Length (inches)	Gouge Depth (% thickness)	Pressure (% SMYS)
33	6	0.25	10	60
36	0	6	5	60
39	6	2	R5	60
42	3	2	0	60
45	3	6	R5	60
48	3	0.25	25	60
35	6	6	10	60
44	6	2	10	60
Q5 (34)	3	0.25	5	60
Q4 (37)	3	2	R5	60
Q3 (40)	3	6	5	60
Q2 (43)	0	2	5	60
Q1 (46)	6	0.25	25	60
15	3	0	0	60
12	6	6	R10	60
9	0	0.25	5	60

Defect #	Dent Depth (% diameter)	Length (inches)	Gouge Depth (% thickness)	Pressure (% SMYS)
6	6	2	0	60
3	3	2	25	60
8	6	2	25	60
2	6	6	0	60
Calibration Dent Q03 (13)	6	0	0	60
Calibration Dent Q02 (10)	3	2	5	60
Calibration Dent Q01 (7)	6	6	R5	60
4	3	2	10	60
1	0	6	5	60

Table 3-4. Target Dimensions of Defects

Legend:

- Defect # is an arbitrary number identifying each defect
- Depth is the dent depth in percent of the diameter.
- Length is the total length of the gouge in inches.
- Gouge Depth is the target depth of the gouge; where an "R" precedes the number, the indentor tooth was rounded.
- Pressure is the internal pipe pressure in percent of specified minimum yield strength.
- Test Defects
- Calibration Defects



Pipe Wall Thickness =			0.292	
Defect Number	Approx. Distance from End A (inches) to Center of Region	Approx. Distance from End A (feet)	Approx. Length of Defect (in)	Dent Depth % Dia.
Cal Q03	46	3.8333	0	6%
Cal Q02	82	6.8333	2	3%
Cal Q01	117	9.75	6	6%
Q6	237	19.75	-	0%
Q5	271	22.583	0.25	3%
Q4	308	25.667	2	3%
Q3	346	28.833	6	3%
Q2	380	31.688	-	0%
Q1	415	34.542	0.25	6%

% Diameter Depth	
(green)	0%
(yellow)	3%
(red)	6%

Figure 3-5. 24 inch Mechanical Damage Pipe Sample 1 Defect Map

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Mechanical Damage Pipe Sample 1 Defect Photos

Figure 3-6. Defect Q1 (46)

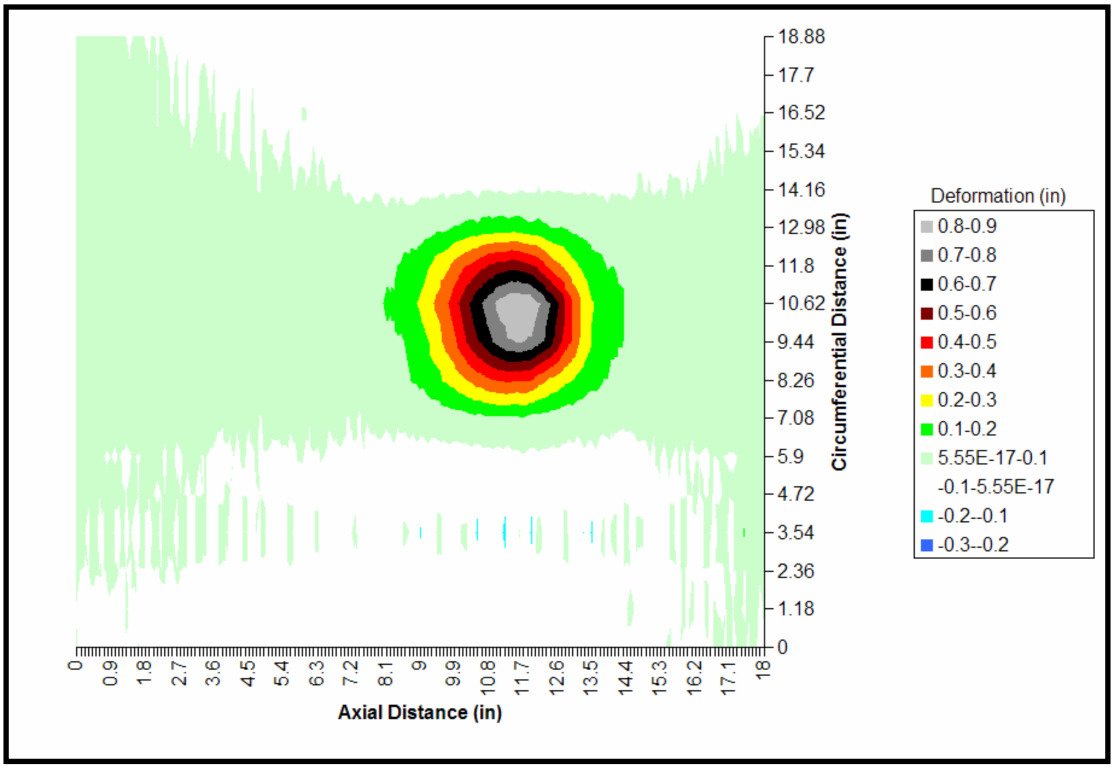

Figure 3-7. Deformation Data for Defect Q1 (46)

Figure 3-8. Defect Q2 (43)

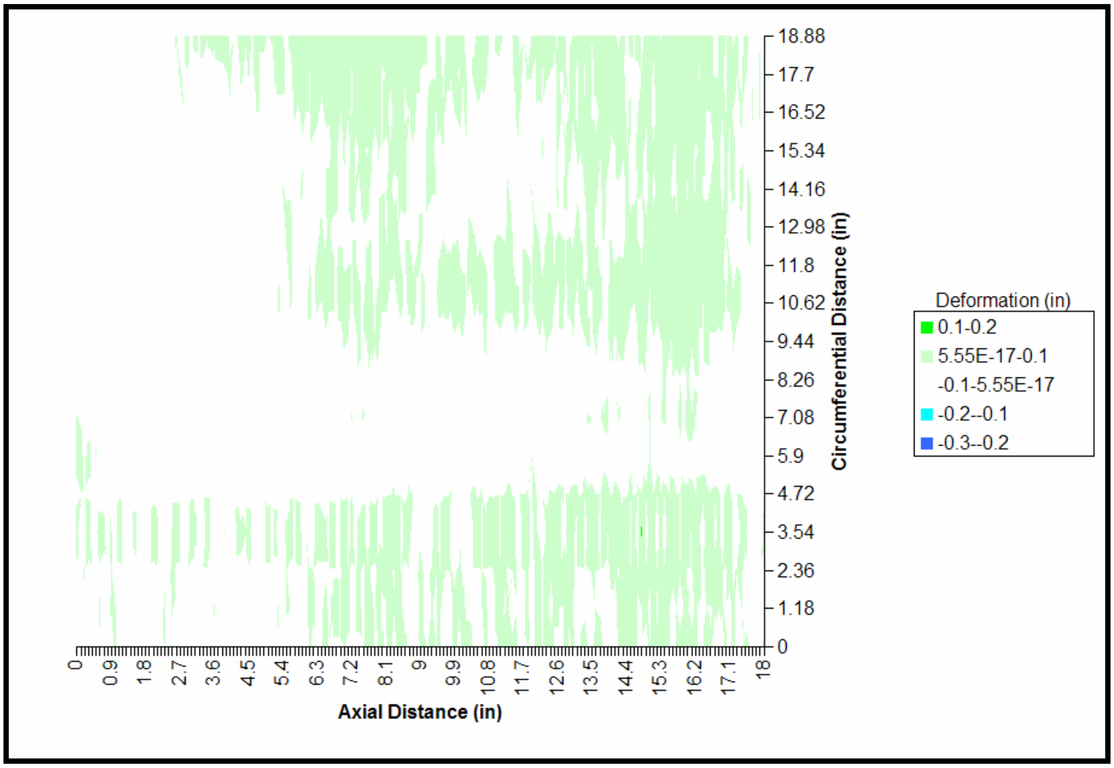

Figure 3-9. Deformation Data for Defect Q2 (43)

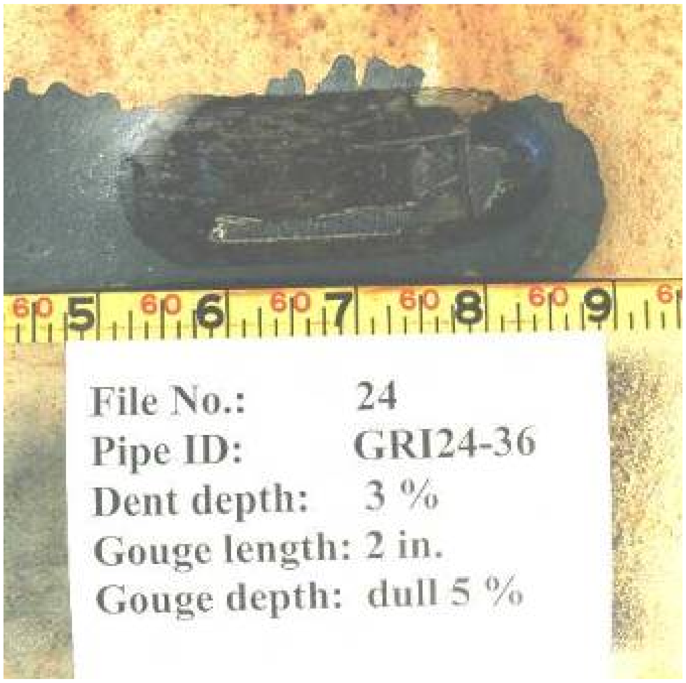

Figure 3-10. Defect Q3 (40)

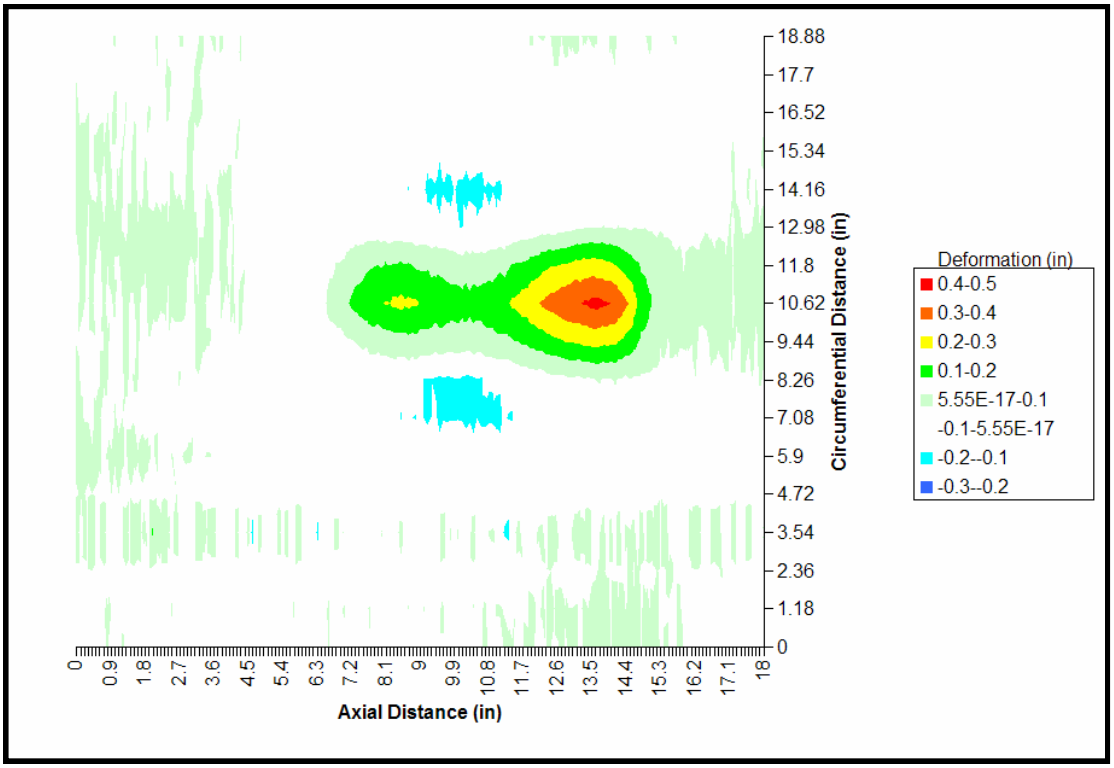

Figure 3-11. Deformation Data for Defect Q3 (40)

Figure 3-12. Defect Q4 (37)

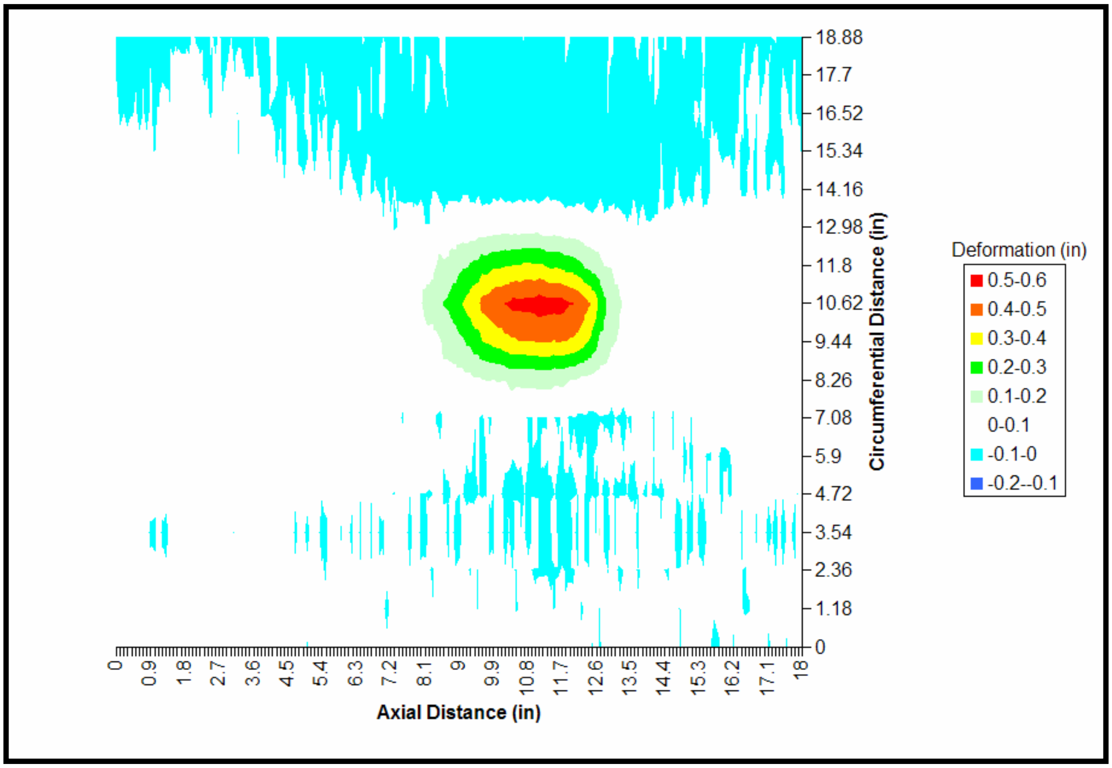

Figure 3-13. Deformation Data for Defect Q4 (37)

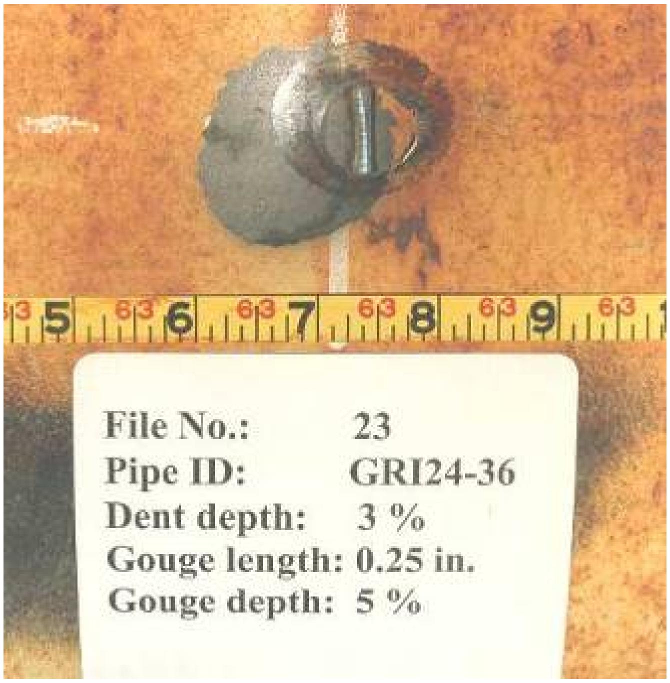

Figure 3-14. Defect Q5 (34)

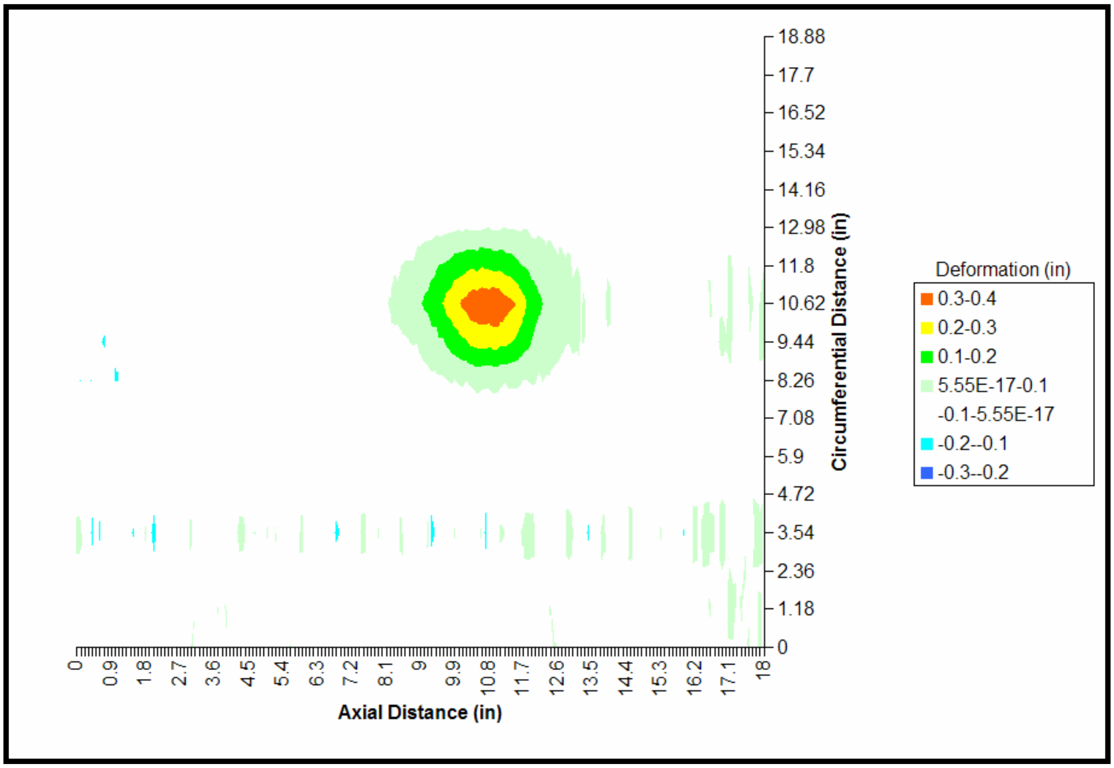

Figure 3-15. Deformation Data for Defect Q5 (34)

Figure 3-16. Calibration Defect Q01 (7)

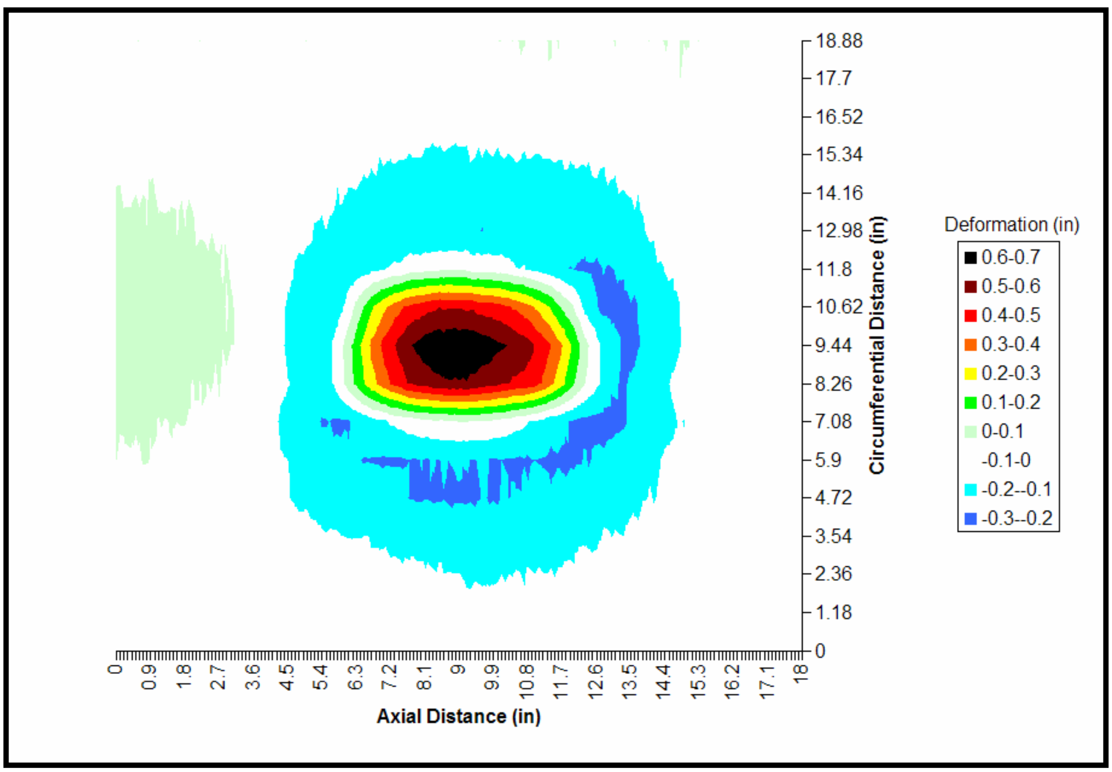

Figure 3-17. Deformation Data for Calibration Defect Q01 (7)

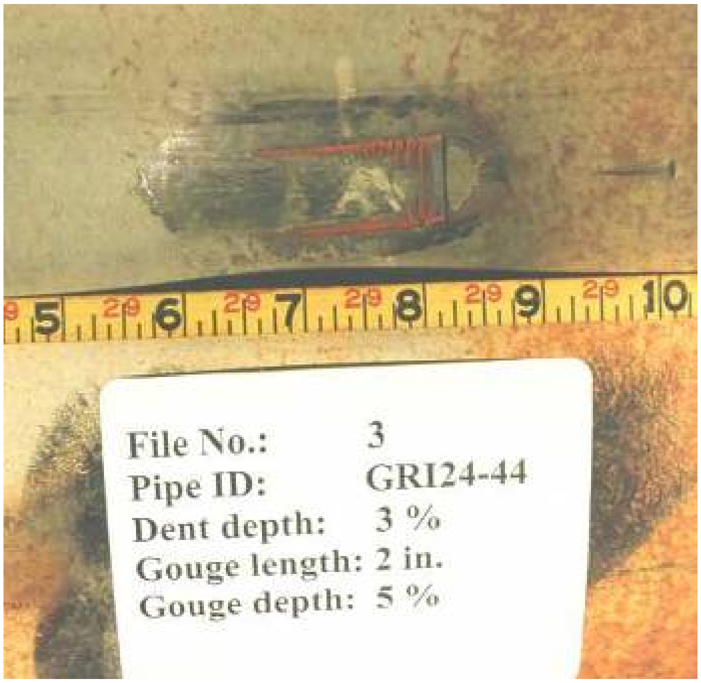

Figure 3-18. Calibration Defect Q02 (10)

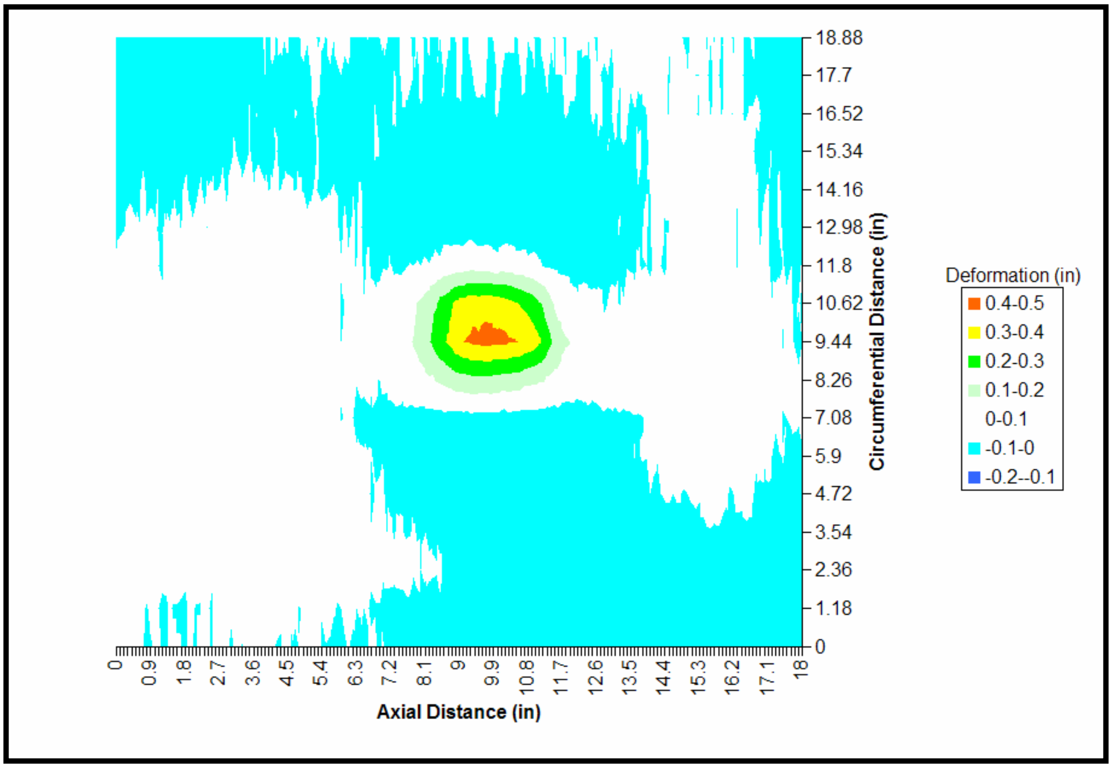

Figure 3-19. Deformation Data for Calibration Defect Q02 (10)

Figure 3-20. Calibration Defect Q03 (13)

MECHANICAL DAMAGE DEFECTS – PIPE SAMPLE 2

Plain dents represent the other fundamental part of mechanical damage where the natural cylindrical shape of the pipe is distorted. The dents in mechanical damage Pipe Sample 2 were made without gouging, so that the response of inspection systems to dents could be examined without compensation for the geometry changes, such as removed metal, and stresses caused by the gouge process.

This section describes the methods and equipment used to fabricate the dent-only defects. The description is followed by detailed information of each dent and photographs.

Test Configuration

The procedure for the incremental denting and data collection was a follows:

1. Pressurize the 24-inch diameter, 0.280-inch wall pipe to 600 psi, or about 40 percent of specified minimum yield stress (SMYS) of the this X60 pipe
2. Acquire baseline MFL data prior to denting, but with denting apparatus positioned (about one percent of maximum dent load was applied to hold reaction frame in place)
3. Apply hydraulic pressure to indent the pipe in increments of 0.5 percent of the pipe diameter (0.120 inches)
4. Acquire axial MFL data with the indenter in place to keep the dent from rebounding
5. Repeat steps 3 and 4 until a maximum dent depth of 2 percent is a attained
6. Allow the dent to rebound 0.5 percent of the pipe diameter, matching the indenting steps
7. Acquire MFL with the indenter in place to keep the dent from further rebounding
8. Repeat steps 6 and 7 until the denting load is zero indicating the dent has finished rebounding.

The equipment for the experiments is described in the three subsections that follow. The first subsection describes a denting apparatus with a hydraulic actuator and reaction frame. The second subsection describes the flanged pipe sample with components that enable a MFL inspection pig to be launched, pulled back and forth during the dent forming process, and accessed between inspections. The third subsection describes the axial MFL inspection pig as modified for data collection.

Denting Apparatus

The apparatus used to dent the pipe in a controlled manner is illustrated in Figure 3-21. The operation of the equipment is simple. A hydraulic cylinder is extended between a pipe sample and a stiff reaction frame. The reaction frame was a previously used I-beam with the web reinforced to minimize deformation during the application of the denting load. A 1-inch thick plate was welded to the beam for support of the hydraulic cylinder. The weakest component of the apparatus is the pipe wall that is in contact with the indenter. As the hydraulic load increases, the pipe deforms.

To determine the amount of deformation, two measurements are made by linear cable extension transducers, commonly referred to as “string pots.” The first string pot measures the extension of indenting tool. The second string pot measures the separation between the pipe and the reaction frame, which increases during the formation of the dents since the many components elastically bend and extend. The depth of the dent is established by the difference between the

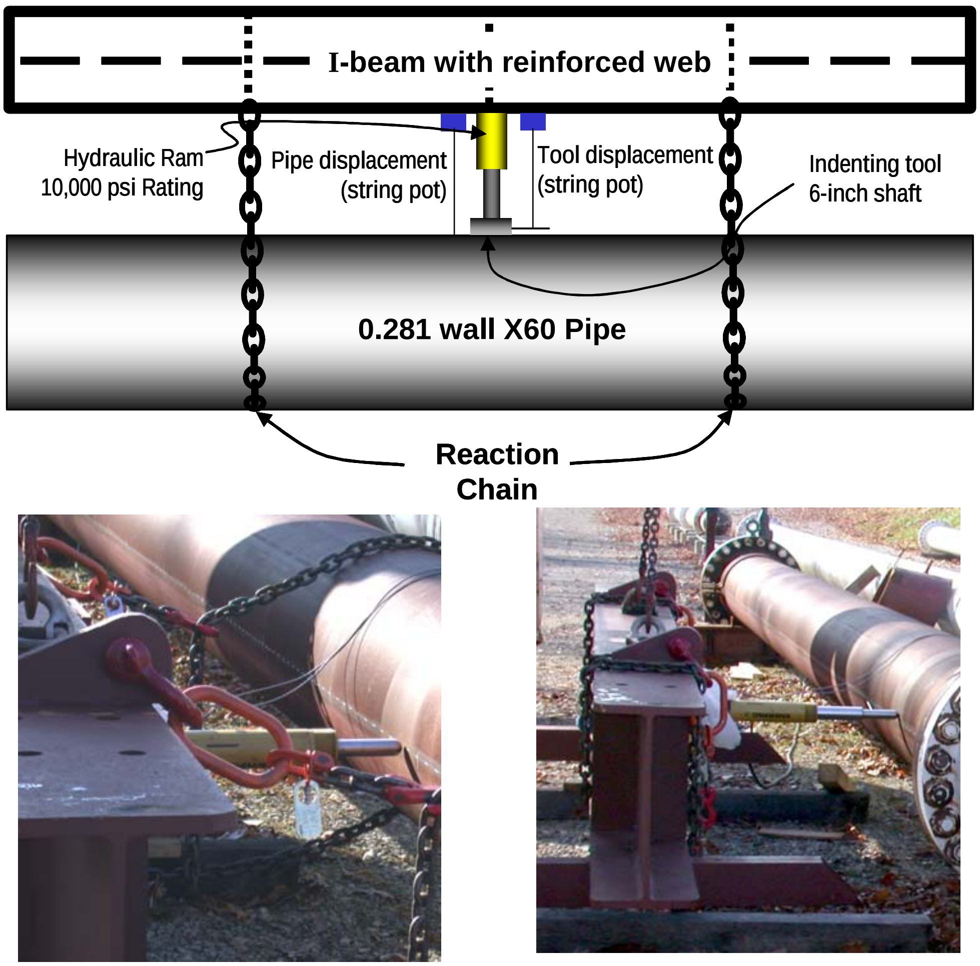

Figure 3-21.   Denting apparatus configuration including reaction frame, hydraulic actuator displacement transducers, pipe sample and load reaction chains.

two measurements. The dents were formed by slowly increasing the pressure until depth was attained. The denting process took between 2 and 3 minutes. Since the pipe was pressured to 600 psi, the pump was located 150 feet from the actuator for safety concerns.

Pressurized Pull Rig

To evaluate leakage signals from dents as they form and rebound under internal pressure, a method was established to acquire flux leakage at multiple pressures repeatedly at multiple magnetization levels. The experimental configuration, shown in Figure 3-22, is essentially a pressurized version of a pull rig. The components include:

- A new pipe sample configured with flanges on either end. This was a 0.281-inch wall thickness, 24-inch diameter, 60 ksi yield pipe.
- A pig launching barrel for insertion of the circumferential magnetizer and data recorder. This was a 0.5-inch wall thickness, 24-inch diameter, 60 ksi yield pipe from existing pipe inventory.
- A hinged pressure door for insertion and access to the magnetizer and data recording equipment.
- Two rods for pulling the magnetizer and data recording equipment in either direction.
- Rod seals to hold pressure as the equipment is pulled. These seals are commonly used in oil well pumping operations.
- A pressure relief valve to prevent over pressurizing. This was required to adequately address safety concerns.

After each increment of dent depth, the MFL inspection pig was pulled from one end of the pipe sample and back to the return position. During the pulling of the pig, leakage in the rod seals would cause a drop in internal pressure in the pipe. Lubricating the rod with light oil reduced wear on the seal, minimizing pressure losses to less than 5 psi or 1 percent on each pull.

Three indenters were used to dent the pipe. Each indenter was made from a non-ferromagnetic 300 series stainless steel. Each shaft was 6 inches long to keep the ferromagnetic hydraulic actuator sufficiently away from the pipe to minimize interference with the flux leakage inspection equipment. Figure 3-23 shows a spherical indenter made from 1.5-inch diameter rod, photographed during the denting process. Figure 3-24 shows the two longer indenters. The radius of the rounded indenter matches the spherical indenter radius of 0.75 inches. The sharp indenter is rounded to a radius of 0.125 inches to provide a more concentrated load, but avoid piercing. The length of the long rounded indenter and the long sharp indenter is 4.5 inches. The shape changes were chosen to facilitate comparison of results. For the spherical and long rounded indenter, the radius is the same but the contact shape is changed from a sphere to a cylinder. For the two longer indenters, the length was the same, but the contact shape is changed from gradual to abrupt.

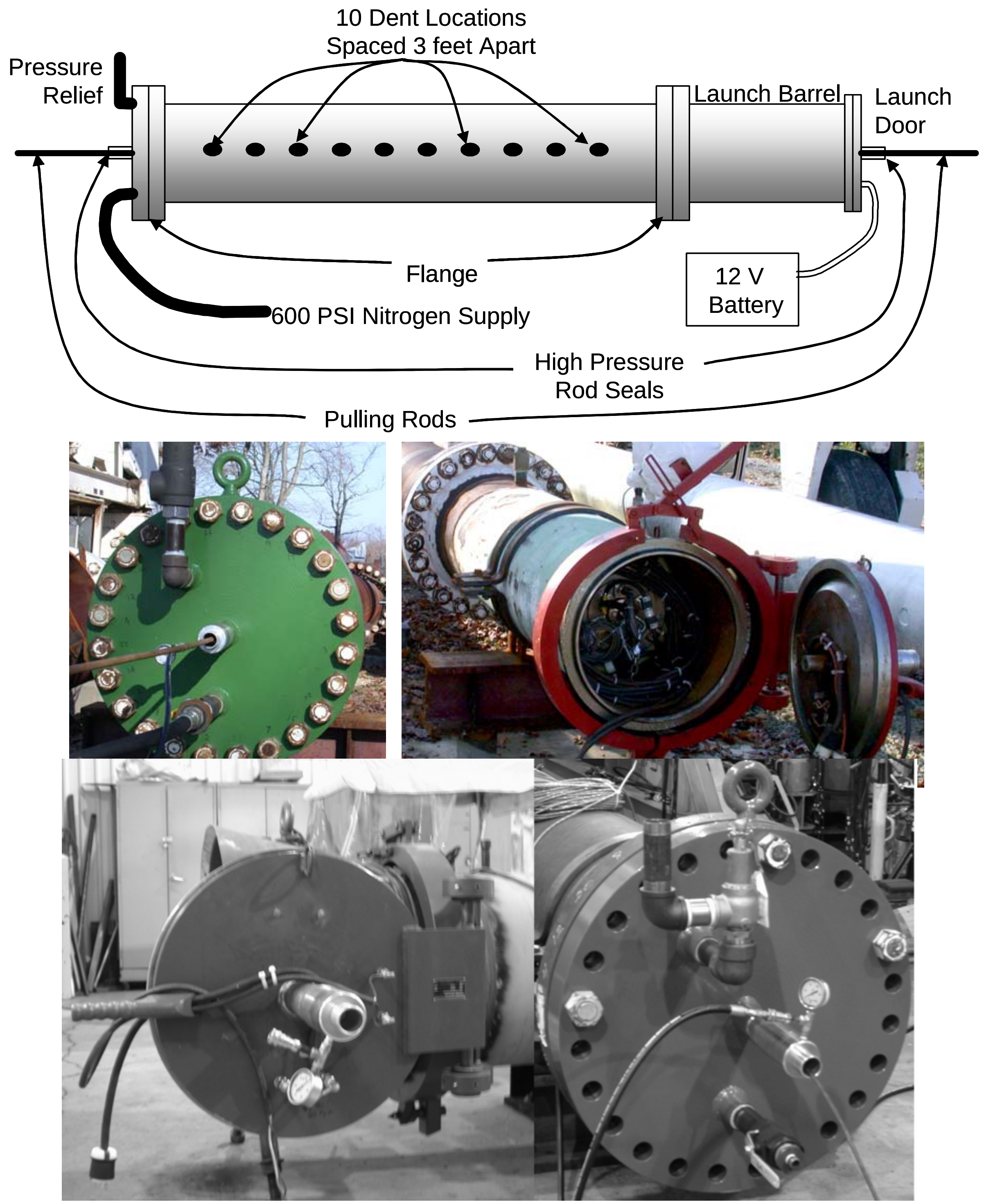

Figure 3-22. Pressurized pull rig for acquisition of MFL data during incremental denting and rebounding.

Figure 3-23. The spherical indenter, made from a non-ferromagnetic material, photographed while holding a 2 percent dent.
Note the connections for the two linear cable extension transducers.

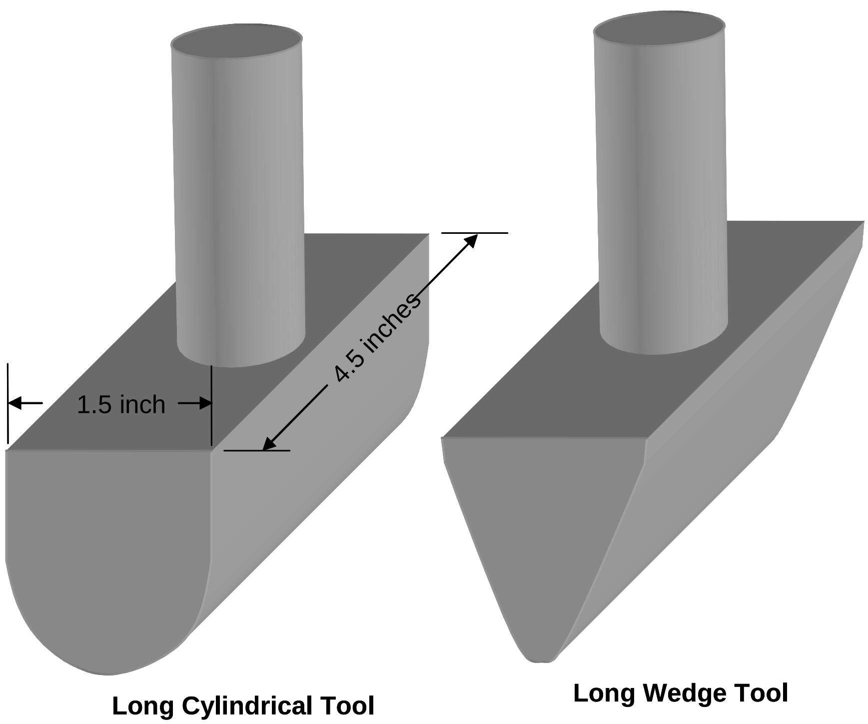

Figure 3-24. Diagram of two other indenters used in incremental denting and data recording experiments.

Axial MFL Tool

The axial MFL test bed vehicle was used to collect the data after each denting increment. The single directional cups were exchanged for bidirectional disks. Because of excessive drag concerns, the battery module was omitted. An external battery was used to provide power to the data recorder and Hall effect sensors. This electrical power was fed through the pressure door. A cable connected the pig to the feed though connector. The MFL test bed vehicle required modifications to work under pressurized conditions. Even though the data-recording module is contained in a pressure vessel, small leaks at the electrical connections did cause pressurization of the unit. Any pressure sensitive components such as capacitors were replaced. Since there were many sources of electrical energy outside the pressure vessel that could introduce an ignition spark, the pipe was pressurized with nitrogen for safety.

Plain Dent Defects

A total of 10 defects were made with three indenters at two magnetization levels, as shown in Table 3-5.

#	Indenter	Magnetization	Comment
Calibration Dent R01	Spherical	High	Good data
Calibration Dent R02	Long Cylindrical	High	50 psi Pressure drop
R03	Spherical	High	100 psi Pressure drop
R04	Long Wedge	High	Good data
R05	Long Cylindrical	High	Good data
R06	Spherical	Low	Good data
R07	Long Cylindrical	Low	Good data
R08	Long Wedge	Low	Good data
R09	Long Cylindrical	Low	Sensor noise problem
R10	Long Wedge	Low	Sensor noise problem

Table 3-5. Incremental dent defects

The MFL pig was configured for high magnetization, nominally 150 oersted, for the first set of tests; then magnets were removed and shunts to reduce magnetic field were installed to produce a low magnetic field, nominally 70 oersted. The six runs provided quality data with no variables. The pressure drops in the second and third runs may have reduced stress effect and rerounding extent; these were used only for general comparisons. During the last two defect installations, a sensor appeared to short circuit, causing noise in neighboring sensors serviced by the sample analog to digital converter. The noise appeared as an offset greater than the largest defect signal. The noise was not continuous, and many signals were noise free. When the noise was absent, the signals were used for verification of results.

Table 3-6 shows the final dimensions of the dents used for the primary comparisons of the high and low magnetization signals. Since dents do not have distinct start and end points, measurements can be subjective; the length measurements for defect 5 are illustrated in Figure 3-18. The total length and width were defined by a 0.025-inch departure from the nominal shape of the pipe. The reround lengths were defined by a more abrupt departure from the nominal shape of the pipe. The surface length is the length that the indenter was in hard contact with the pipe. Because of irregularities of the pipe shape itself, the accuracy of the length and width measurements is ±0.5 inch and the accuracy of the depth measurement is ±0.010 inch.

#	Indenter	Signal	Dent Dimension (inches)					% W.T. Depth
			Total Length	Reround Length	Surface Length	Width	Depth	
R01	Spherical	High	6.5	3.5	1.5	5.0	0.290	1.21%
R02	Long Cylindrical	High	12.0	8.5	4.5	6.0	0.200	0.83%
R03	Spherical	High	6.5	3.5	1.5	5.0	0.290	1.21%
R04	Long Wedge	High	13.5	9.5	4.5	5.5	0.200	0.83%
R05	Long Cylindrical	High	12.0	8.5	4.5	6.0	0.200	0.83%
R06	Spherical	Low	7.5	4.3	1.5	5.0	0.290	1.21%
R07	Long Cylindrical	Low	12.0	8.5	4.5	6.5	0.180	0.75%
R08	Long Wedge	Low	14.5	10.5	4.5	6.5	0.230	0.96%
R09	Long Cylindrical	Low	12.0	8.5	4.5	6.5	0.180	0.75%
R10	Long Wedge	Low	14.5	10.5	4.5	6.5	0.230	0.96%

Table 3-6. Dimensions of the dents used for the primary comparisons of the high and low magnetization signals.

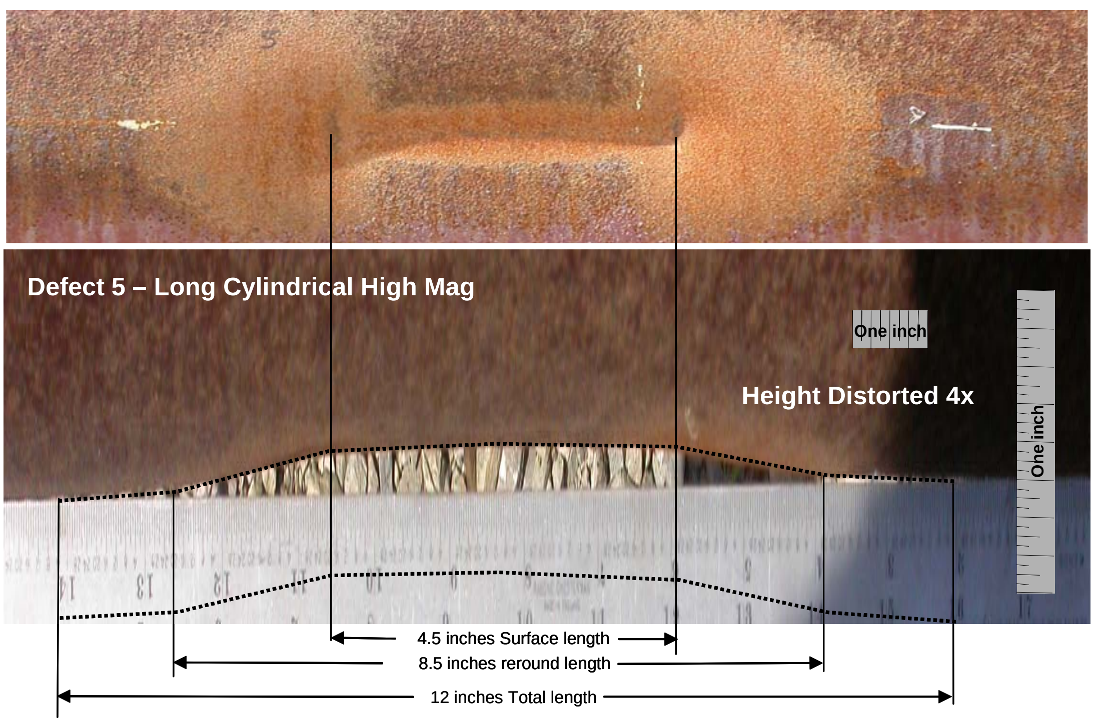

Figure 3-25. Dent length measurements for the long cylindrical indenter.

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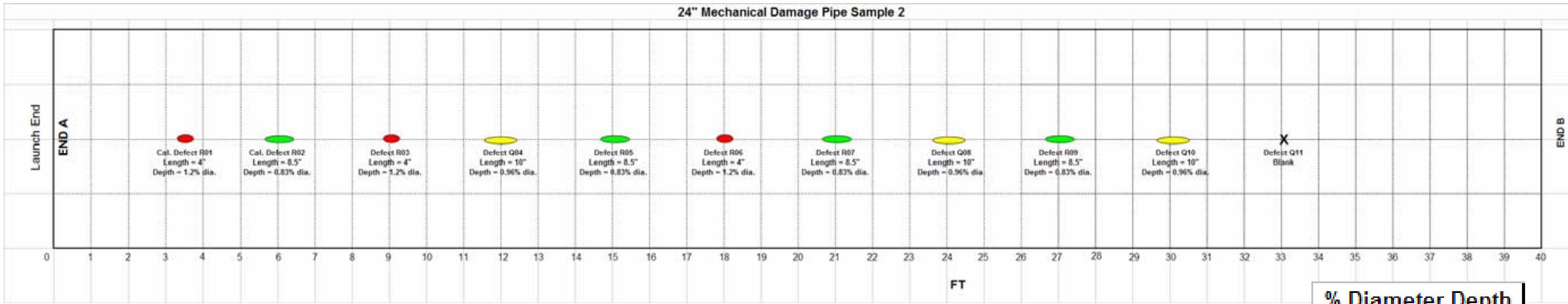

% Diameter Depth	
(green)	0.83%
(yellow)	0.96%
(red)	1.21%

Pipe Wall Thickness =			0.28	
Defect Number	Approx. Distance from End A (inches) to Center of Region	Approx. Distance from End A (feet)	Approx. Length of Defect (in)	Dent Depth % Dia.
Cal R01	42	3.5208	4	1.21%
Cal R02	73	6.1042	8.5	0.83%
R03	109	9.1042	4	1.21%
R04	144	12	10	0.96%
R05	183	15.25	8.5	0.83%
R06	217	18.083	4	1.21%
R07	253	21.083	8.5	0.83%
R08	290	24.125	10	0.96%
R09	325	27.083	8.5	0.83%
R10	361	30.042	10	0.96%
R11	397	33.083	-	0.00%

Figure 3-26. 24 inch Mechanical Damage Pipe Sample 1 Defect Map

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Mechanical Damage Pipe Sample 2 Defect Photos

Figure 3-27. Calibration Defect R01

Figure 3-28. Calibration Defect R02

Figure 3-29. Defect R03

Figure 3-30. Defect R04

Figure 3-31. Defect R05

Figure 3-32. Defect R06

Figure 3-33. Defect R07

Figure 3-34. Defect R08

Figure 3-35. Defect R09

Figure 3-36. Defect R10

Figure 3-37. Blank R11

SECTION 4. SCC INSPECTION TECHNOLOGY ASSESSMENT

INTRODUCTION

The focus of the SCC assessment projects is developing ultrasonic technologies that can work in natural gas pipelines. Crack detection technology for liquid pipelines is already commercially available. However, transmitting ultrasonic energy into and out of the pipe without the use of a liquid coupling agent is necessary for the practical inspection of natural gas transmission pipelines. Stress corrosion cracks are more common in larger diameter pipelines because typical operating pressures produce sufficient stress in the pipe wall to initiate and grow cracks. From an inspection technology viewpoint, the sensors have a relatively large footprint. A typical sensor footprint, without engineering to make them smaller, is on the order of 10 cm (4 inches) per quarter. Pipe samples also appear to be more readily available in larger diameter pipes. Therefore, for these practical and implementation reasons, the capability of SCC detection technology is initially focused on pipe diameters greater than 24 inches.

The Pipeline Simulation Facility has available a large number of SCC defects in 30 inch diameter pipe. One of the technology developers has already used pipe samples at the Pipeline Simulation Facility. These pipe samples were not part of the test. The external coating on the pipe itself is a significant variable and therefore only pipe without coating was made available for the demonstration.

The report sections below discuss the demonstration plan for the SCC inspection tool and provides an “answer key” (Table 4-1) for the data sheets filled out by the SCC inspection tool developer during the demonstration. Additional information and photographs are provided in Figures 4-1 through 4-15 which show the magnetic particle maps and the locations and lengths of the natural SCC defects.

30-INCH STRESS CORROSION CRACK DEMONSTRATION PLAN

The test plan for the 30-inch stress corrosion crack test configuration is as follows:

1. The technology(s) to be benchmarked will include:
   1.1. ORNL: Strain measurement tool
2. Total length of the pipe sample will be 80 (TBD) feet
3. The pipe will be 30-inch outside diameter
4. The test sample will be comprised of one pipe:
   4.1. Pipe 1 specifications are as follows:
      4.1.1. The length will be up to 20 (TBD) feet of seam welded pipe

4.1.2. The nominal wall thickness will be 0.343 inches
4.1.3. The pipe will contain 10 (TBD) stress corrosion crack colonies
4.1.4. Up to 3 notches will be available for calibration
4.1.5. The pipe will not have an external coating

30 INCH SCC PIPE 1093 ASSESSMENT INFORMATION

Benchmarking of Inspection Technologies Detection of SCC - Page 1	
Name:	
Date:	
Company:	
Sensor Design:	

CALIBRATION DATA						
	Calibration Crack Location	Length	Depth	Measured Length	Measured Depth	Comments
	inches from end A	inches	% wall thickness			
Manufactured Crack 1:		1	25%			
Manufactured Crack 2:		1	50%			
Manufactured Crack 3:		1	75%			
Blank Area:						

TEST DATA	
Pipe Sample:	1093
Defect Set:	30" Diameter Pipe with Stress Corrosion Cracks

LINE 1

Defect Number	Search Region (Distance from End A)	Start of Crack Region from Side A	End of Crack Region from Side A	Type of SCC		Comments
	inches	inches	inches			
SCC1 **(11)**	60" to 70"	**63"**	**63"**	☑	**Isolated Crack**	**1 crack; ~1/4" long**
				☐	Colony of Cracks	
				☐	None	
SCC2 **(8)**	70" to 80"	**75"**	**75"**	☑	**Isolated Crack**	**1 crack; ~1/4" long**
				☐	Colony of Cracks	
				☐	None	
SCC3 **(7)**	80" to 90"	**82"**	**84.5"**	☐	Isolated Crack	**2 cracks; 1 crack ~ 2" long**
				☑	**Colony of Cracks**	
				☐	None	
SCC4 **(Blank 1)**	90" to 100"	*****	*****	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	
SCC5 **(Blank 2)**	110" to 120"	*****	*****	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	
SCC6 **(1 & 2)**	130" to 140"	**137"**	**138"**	☐	Isolated Crack	**2 cracks; 1 crack ~ 1" long**
				☑	**Colony of Cracks**	
				☐	None	

Table 4-1. 30 inch SCC Inspection Technology Data Sheet "Answer Key"

Benchmarking of Inspection Technologies Detection of SCC - Page 2						
Name:						
Date:						
Company:						
Sensor Design:						
TEST DATA						
Pipe Sample:	1093					
Defect Set:	30" Diameter Pipe with Stress Corrosion Cracks - LINE 2					
	LINE 2					
Defect Number	Search Region (Distance from End A)	Start of Crack Region from Side A	End of Crack Region from Side A	Type of SCC		Comments
	inches	inches	inches			
SCC7 **(12)**	60" to 75"	**61"**	**67"**	☐	Isolated Crack	**Large colony of cracks**
				☑	**Colony of Cracks**	
				☐	None	
SCC8 **(Blank 3)**	75" to 90"	***	***	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	
SCC9 **(Blank 4)**	90" to 105"	***	***	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	
SCC10 **(Blank 5)**	105" to 120"	***	***	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	
SCC11 **(Blank 6)**	120" to 135"	***	***	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	

Table 4-1 (cont). 30 inch SCC Inspection Technology Data Sheet "Answer Key"

Benchmarking of Inspection Technologies Detection of SCC - Page 3						
Name:						
Date:						
Company:						
Sensor Design:						
TEST DATA						
Pipe Sample:	1093					
Defect Set:	30" Diameter Pipe with Stress Corrosion Cracks - LINE 3					
	LINE 3					
Defect Number	Search Region (Distance from End A)	Start of Crack Region from Side A	End of Crack Region from Side A	Type of SCC		Comments
	inches	inches	inches			
SCC12 **(13,14,& 15)**	60" to 75"	**62"**	**71"**	☐	Isolated Crack	**Relatively small cracks in the same general vicinity**
				☑	**Colony of Cracks**	
				☐	None	
SCC13 **(9)**	75" to 90"	**78"**	**84"**	☐	Isolated Crack	
				☑	**Colony of Cracks**	
				☐	None	
SCC14 **(6)**	90" to 105"	**94"**	**94"**	☑	**Isolated Crack**	**1 crack; ~1/4" long**
				☐	Colony of Cracks	
				☐	None	
SCC15 **(3)**	105" to 120"	**114"**	**115.5"**	☑	**Isolated Crack**	**1 crack; ~1 1/2" long**
				☐	Colony of Cracks	
				☐	None	
SCC16 **(Blank 7)**	120" to 135"	*******	*******	☐	Isolated Crack	**Blank**
				☐	Colony of Cracks	
				☑	**None**	

Table 4-1 (cont). 30 inch SCC Inspection Technology Data Sheet "Answer Key"

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STRESS-CORROSION CRACKING SAMPLE COLLECTION AND STORAGE PROGRAM

PRC Pipe Sample Number: 1093 Company Designation: 3035

1. **Characteristics/material properties**

Manufacturer ____

Year of manufacture ____

Type of pipe (ERW, DSAW, SMLS, FW) ____

Diameter, in. 30 Wall thickness, in. 0.343 Length ~20' 5" Grade X52

Material properties:

Yield strength, psi	Tensile strength, psi	Elongation in 2 inches, percent

Chemistry (include all that apply):

C	Mn	P	S	Si	Al			

Charpy V-notch impact:

Temperature, F	Energy, percent	Shear Area, percent

2. **Operating History**

Year of installation ____

Operating pressure ____ psi Typical Pressure range in a year: ____ psi

Type of coating ____

Recoating date ____

Type of recoating ____

Initial test pressure level ____ psig Retest pressure level ____ psig

Time pressure held (hrs.) ____

Test medium (gas or liquid) ____

3. **General history of line in area of SCC**

Type of soil in the area of the sample ____

Cathodic protection level range (volts) ____

Range of the soil moisture level during the year ____

General terrain of the soil ____

Other information that might be significant about the location of the SCC pipe sample

____

1093.PDS(6/28/94)

Figure 4-1. SCC Pipe 1093 Data

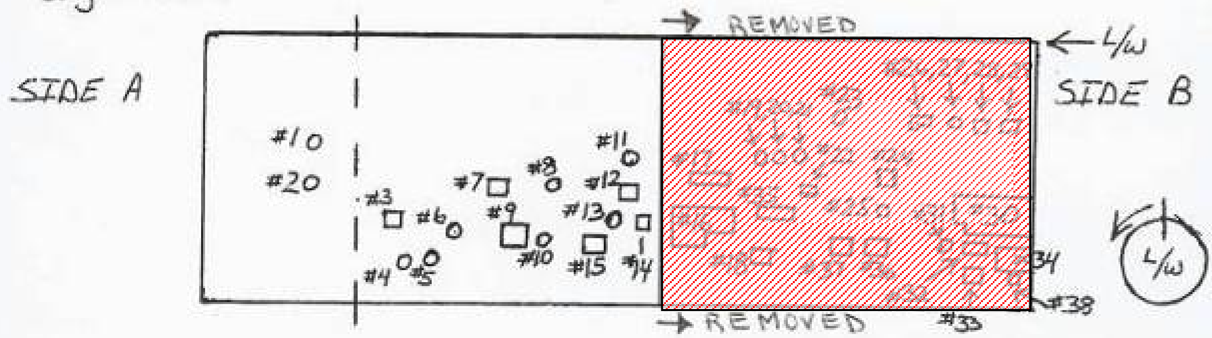
CONAM INSPECTION INC
A SUBSIDIARY OF STAVELEY NDT TECHNOLOGIES INC
4000 Lockbourne Road
Columbus, Ohio 43207
(614) 491-3000
FAX (614) 491-0677

JOB NO. 1783
DATE 5-9-94

LOCATIONS NATIONWIDE

Nondestructive Testing · QA/QC Services · Chemical & Environmental Testing · Mechanical Testing · Metallurgical Testing & Failure Analysis

Pipe Sample # 1093
dwg. # 1 of 1

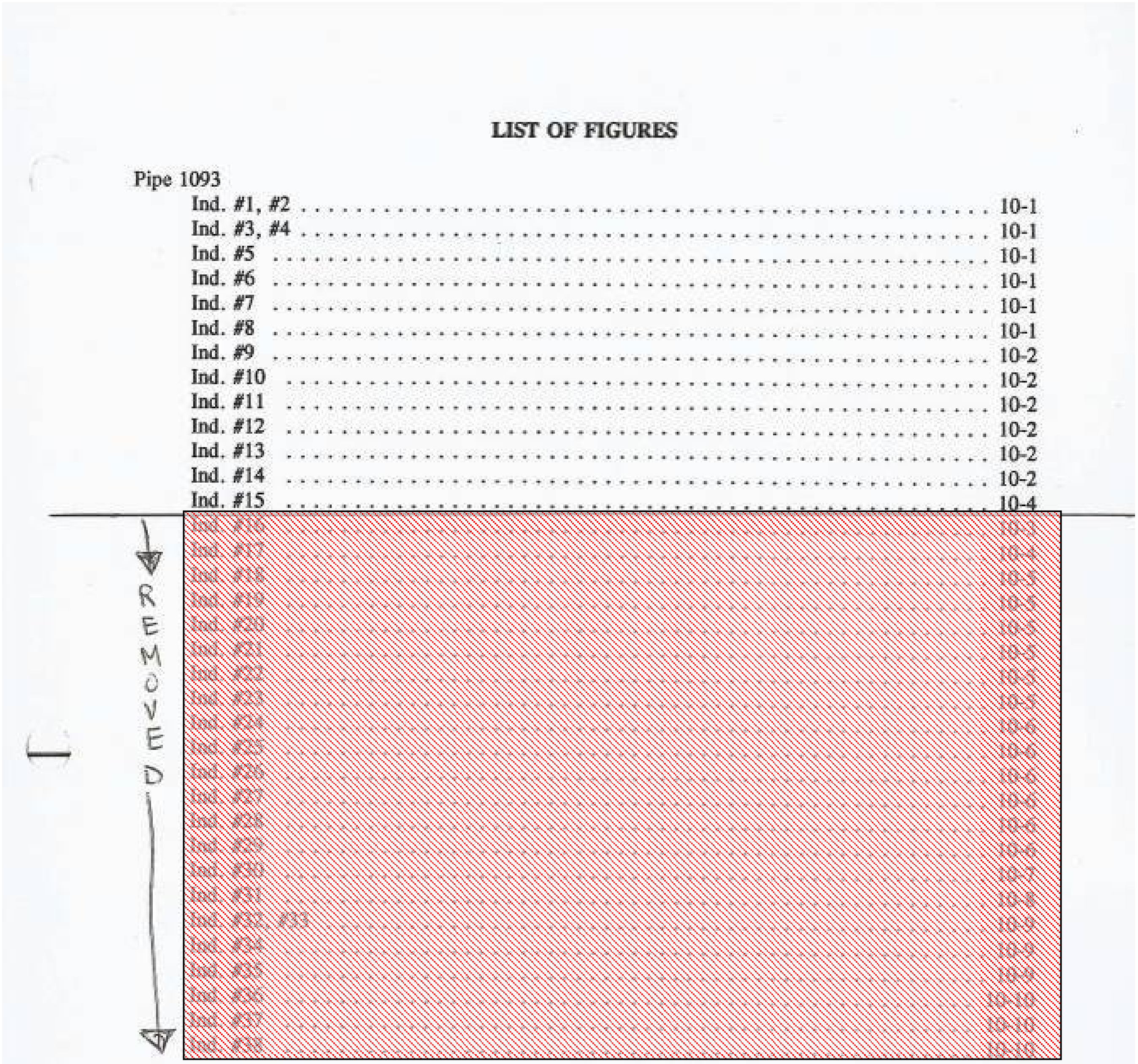


	IND. #	MAX SIZE CRACKS	AREA CRACKED	DISTANCE EOP	DISTANCE L/W
*	1	3/4"	.3/4"	B-196"	34"
*	2	1"	1"	B-196"	37"
*	3	mult 1/4"	1 1/2" x 1/4"	B 173"	45 1/2"
*	4	1/4"	1/4"	B 173"	49"
*	5.	1/4"	1/4"	B 167 1/2"	49"
*	6	1/4"	1/4"	B 153"	46"
*	7	mult 1/4"	2 1/2" x 1 1/2"	B 141"	36"
*	8	1/4"	1/4"	B 133 1/2"	36 3/4"
*	9	mult. 1"	6" x 5"	B 137"	44 1/2"
*	10	1/4"	1/4"	B 135"	49 1/4"
*	11	1/4"	1/4"	B 122"	36 1/2"
*	12	mult. 1/4"	6 1/4" x 4"	B 120"	38 1/2"
*	13	1/4"	1/4"	B 126"	46 1/4"
*	14	mult. - 1/2"	2" x 3"	B 121"	45 3/4"
*	15	mult. 1/2"	4" x 3 1/2"	B 125 1/2"	48"

[redacted]

[redacted]

Figure 4-1 (cont). SCC Pipe 1093 Data



LIST OF FIGURES

Pipe 1093

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Figure 4-1 (cont). SCC Pipe 1093 Data

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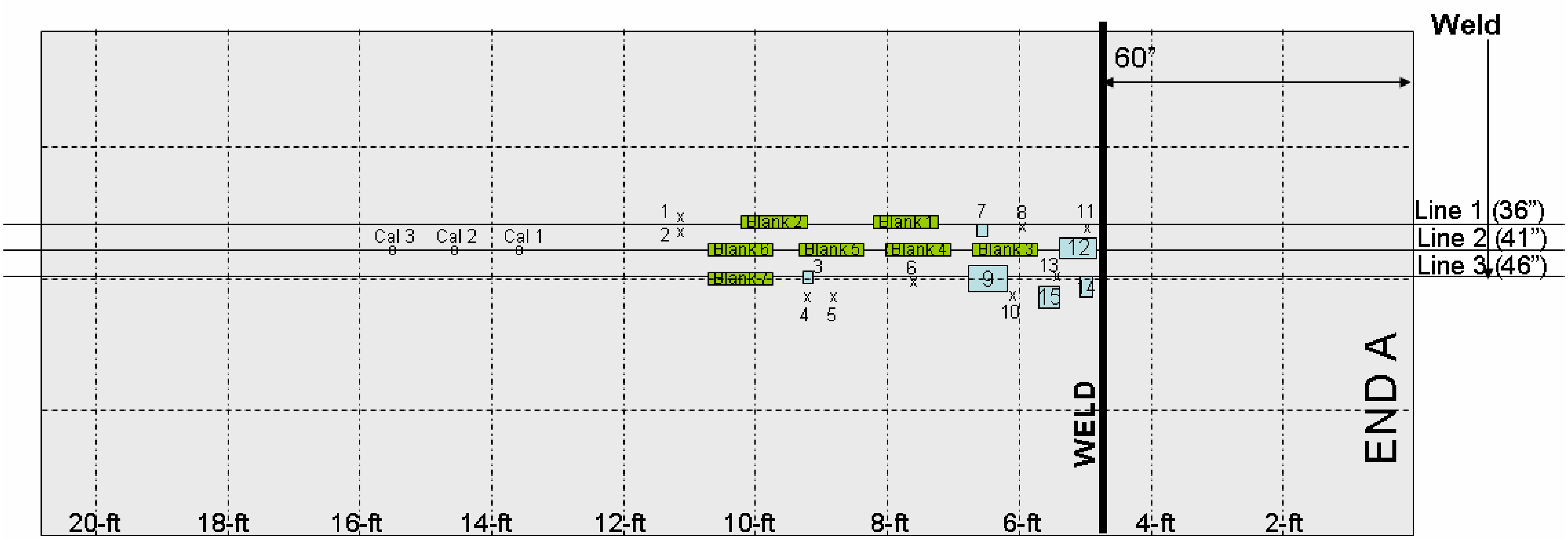

Crack #	Distance to Crack	Crack Length	Crack Depth
Cal 1		1"	25%
Cal 2		1"	50%
Cal 3		1"	75%

Figure 4-2. Diagram of SCC Pipe 1093

Data Sheet Code #	Indication #	Max Size Cracks	Area Cracked	Distance to Start of Crack Area (from End of Pipe – Side A)	Distance L/W (from weld to start of crack area)	Line #
SCC6	1	¾"	¾"	137"	34"	Line 1
SCC6	2	1"	1"	137"	37"	Line 1
SCC15	3	Mult. ¼"	1 ½" x 1 ¼"	114"	45.5"	Line 3
	4	¼"	¼"	114"	49"	NONE
	5	¼"	¼"	108.5	49"	NONE
SCC14	6	¼"	¼"	94"	46"	Line 3
SCC3	7	Mult. ¼"	2 ½" x 1 ½"	82"	36"	Line 1
SCC2	8	¼"	¼"	75"	36.75"	Line 1
SCC13	9	Mult. 1"	6" x 5"	78"	44.5"	Line 3
	10	¼"	¼"	76"	49.25"	NONE
SCC1	11	¼"	¼"	63"	36.5"	Line 1
SCC7	12	Mult. ¼"	6 ¼" x 4"	61"	38.5"	Line 2
SCC12	13	¼"	¼"	67"	46.25"	Line 3
SCC12	14	Mult. ½"	2" x 3"	62"	45.75"	Line 3
SCC12	15	Mult. ½"	4" x 3 ½"	67"	48"	Line 3
SCC4	Blank 1					
SCC5	Blank 2					
SCC8	Blank 3					
SCC9	Blank 4					
SCC10	Blank 5					
SCC11	Blank 6					
SCC16	Blank 7					

Table 4-2. SCC Pipe 1093 Data

Pipe 1093 SCC Defect Photos

Figure 4-3. Defect SCC 6 (1 & 2)

Figure 4-4. Defect SCC 15 (3)

Figure 4-5. Defect not used (5)

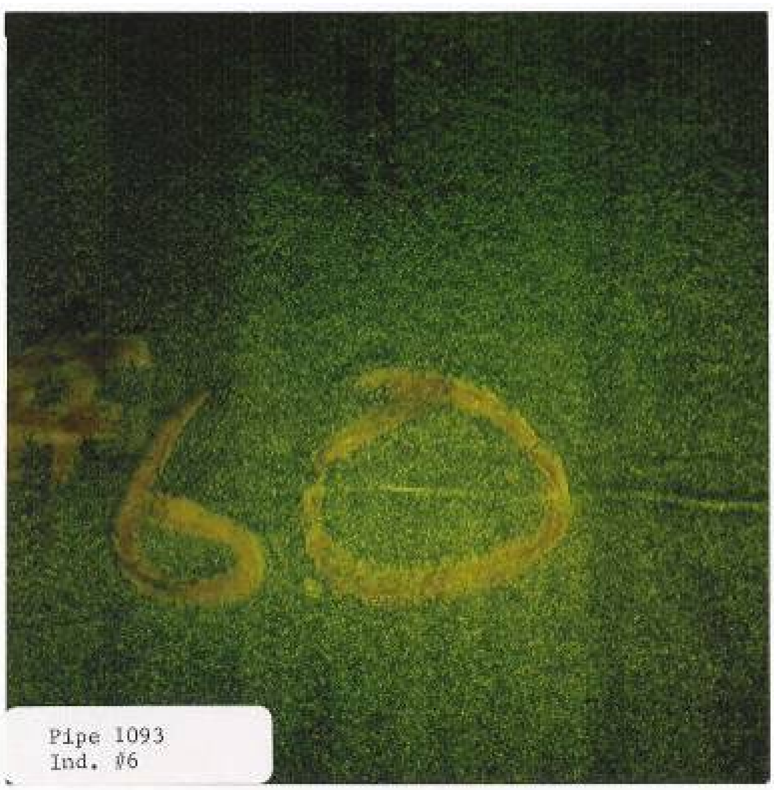

Figure 4-6. Defect SCC 14 (6)

Figure 4-7. Defect SCC 3 (7)

Figure 4-8. Defect SCC 2 (8)

Figure 4-9. Defect SCC 13 (9)

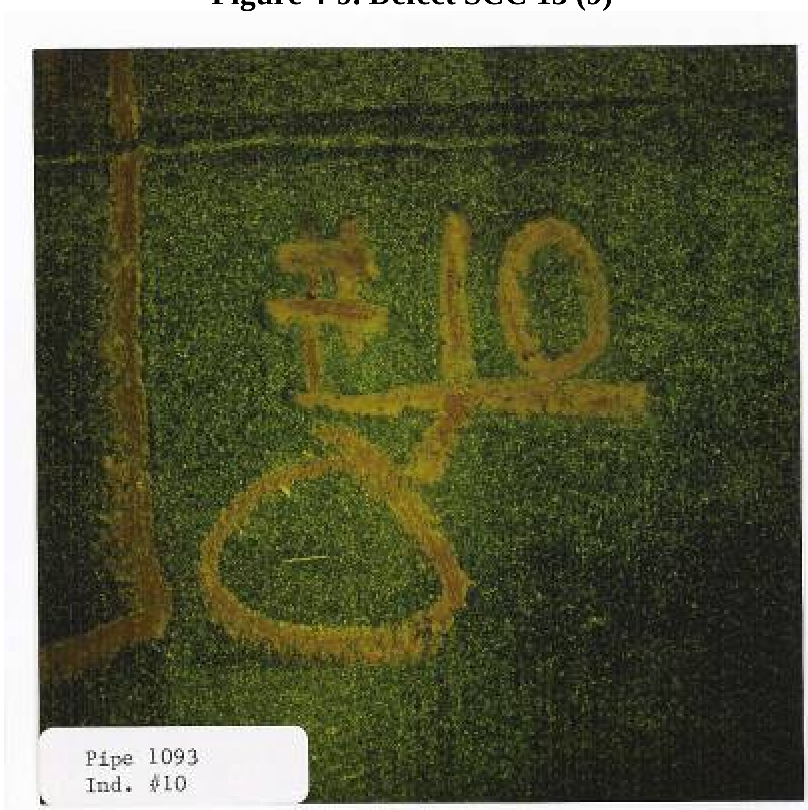

Figure 4-10. Defect not used (10)

Figure 4-11. Defect SCC 1 (11)

Figure 4-12. Defect SCC 1 (7)

Figure 4-13. Defect SCC 12 (13)

Figure 4-14. Defect SCC 12 (14)

Figure 4-15. Defect SCC 12 (15)