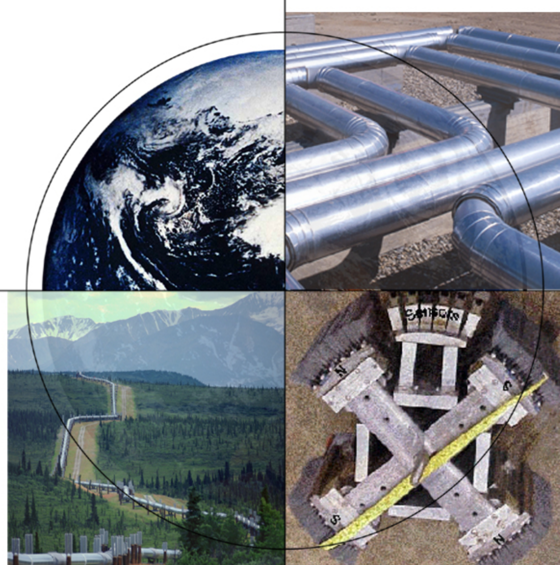
Natural Gas Delivery, Storage & LNG



Pipeline Inspection Technologies

Demonstration Report

Strategic Center for Natural Gas & Oil

EXECUTIVE SUMMARY

Assessing the integrity of natural gas transmission and distribution pipelines costs industry millions each year. With passage of the Pipeline Safety Improvement Act (PSIA) in 2002, industry will be required to invest significantly more capital to inspect and maintain their systems. The PSIA requires enhanced maintenance programs and continuing integrity inspection of all pipelines located within "high consequence areas" where a pipeline failure could threaten public safety, property and the environment. According to the Interstate Natural Gas Association of America (INGAA) the cost to industry to implement the PSIA in the first ten years will exceed $2 billion.

The Strategic Center for Natural Gas and Oil (SCNGO) is the Department of Energy's lead organization for research and technology development focused on assuring that sufficient quantities of affordable natural gas (and oil) are available to meet U.S. customer demands. Within the SCNGO, the Natural Gas Delivery Reliability Program has the responsibility to develop improved systems designed to improve the safety and reliability of the nation's transmission and distribution system.

> According to INGAA, "Operational costs will be dwarfed by the cost to the gas customer caused by supply constraints as many miles of pipeline are taken out of service during inspection and maintenance...This cost could be as high as $5.7 billion in higher gas costs [to consumers] over ten years"
>
> *Pipeline & Gas Journal*
> March 2003

For several years the Gas Delivery Reliability Program has funded the development of advanced in-line inspection (ILI) technologies to detect mechanical damage, corrosion and other threats to pipeline integrity. Many of these efforts have matured to a stage where demonstration of their detection capability is now warranted. During the week of September 13, 2004, the Gas Delivery Reliability Program and the U.S. Department of Transportation's Office of Pipeline Safety (OPS) co-sponsored a demonstration of eight innovative technologies; five technologies developed through SCNGO funding support and three technologies supported by OPS.

The demonstrations were conducted at Battelle's West Jefferson Pipeline Simulation Facility (PSF) near Columbus, Ohio. The pipes used in the demonstration were prepared by Battelle at the PSF and each was pre-calibrated to establish baseline defect measurements. Each technology performed a series of pipeline inspection runs to determine their capability to detect mechanical damage, corrosion, or stress corrosion cracking. Overall, each technology performed well in their assessment category. Further R&D will help to refine the precision and accuracy of these techniques with the goal of further testing in the coming fiscal year (FY2005).

This document provides a summary of the demonstration results. A brief assessment of the results is presented in order to give the reader a feel for how each technology performed relative to the benchmark data. It is not the intention of this document to provide a detailed analysis of each technology's performance or to rate one technology over the others.

BACKGROUND

> "... natural gas consumption will rise rapidly, as electric utilities make greater and greater use of this environmentally-friendly fuel. We will need newer, cleaner and safer pipes to move larger quantities of natural gas."
>
> George W. Bush
> *NEP* - May 2001

The Gas Delivery Reliability Program develops innovative sensor systems that provide enhanced assessments of the status of transmission and distribution pipelines. This includes sensors to detect corrosion defects, stress corrosion cracking, plastic pipe defects, physical damage areas, gas content, gas contamination, and 3rd party intrusion near gas line right-of-ways. A primary program goal is to develop ILI sensors that can be deployed remotely as part of an integrated robotic platform/sensor package. The sensor demonstrations conducted at Battelle's PSF were a key step toward achieving this goal.

Purpose

This document provides a brief summary assessment of the demonstration test results. The purpose of this assessment is to help identify promising inspection technologies best suited for further development as part of an integrated teaming effort between robotic platform and sensor developers. This document is not intended to provide a detailed analysis of each technology's performance or to rate their performance relative to one another.

The Technologies

Eight innovative sensor technologies were demonstrated at Battelle's PSF the week of September 13, 2004. The different technologies demonstrated their ability to detect pipeline corrosion, mechanical defects or stress corrosion cracking. The technologies were:

Shear Horizontal Electromagnetic Acoustic Transducer (EMAT) – Oak Ridge National Laboratory (ORNL) has developed an EMAT system that uses shear horizontal waves to detect flaws on natural gas pipelines. A wavelet-based analysis of ultrasonic sensor signals is used for detecting physical flaws (e.g., SCC, circumferential and axial flaws, and corrosion) in the walls of gas pipelines. Using an in-line non-contact EMAT transmitter-receiver pair, flaws can be detected on the walls of the pipe that the current magnetic flux leakage (MFL) technology has problems detecting. One EMAT is used as a transmitter, exciting an ultrasonic impulse into the pipe wall while the second EMAT located a few inches away from the first is used as a receiving transducer.

Remote Field Eddy Current (RFEC) – The Gas Technology Institute (GTI) has developed a RFEC inspection technique to inspect pipelines with multiple diameters, valve and bore restrictions, and tight or miter bends. This electromagnetic technique uses a simple exciter coil driven by a low-frequency sinusoidal current to generate an oscillating magnetic field that small sensor coils can detect. The oscillating field propagates along two paths; a direct axial path and an indirect path that propagates out through the pipe wall, along its exterior and then re-enters the pipe 2-3 pipe diameters from the exciter coil. Changes from nominal values of the amplitude and phase of the indirect field indicated defects in the pipe wall.

Collapsible Remote Field Eddy Current – Through funding support from OPS, the Southwest Research Institute (SwRI) has also developed a remote field eddy current technology to be used in unpiggable lines. The RFEC tool is expected to be able to detect corrosion and mechanical damage. Since a large percentage of pipelines cannot be inspected using "smart-pig" techniques because of diameter restrictions, pipe bends and valves, a concept for a collapsible excitation coil was developed. The SwRI technology utilizes a unique hinged coil that allows for inspection of various diameter pipes. The coil consists of six hinged segments that expand to create a full-diameter coil and then retract to accommodate smaller diameter restrictions. The collapsible coil can also be folded in half allowing passage through plug valves that have openings that are the same as the pipe diameter in one direction, but are narrow in the other direction.

Nondestructive Ultrasonic Measurement – Pacific Northwest National Laboratory (PNNL) has developed an ultrasonic sensor system capable of detecting pipeline stress and strain caused by mechanical damage i.e., dents and gouges. PNNL has established the relationship between residual strain and the change in ultrasonic response (shear wave birefringence) under a uniaxial load. Initial measurements on samples in both axial and biaxial states have shown excellent correlation between shear birefringence measurements. The demonstration focused on refining the methodology, particularly under circumstances when the damage is more complex than a simple uniaxial deformation.

Permanent Magnet Eddy Current – Battelle has developed an innovative electromagnetic sensor that incorporates high-strength permanent moving (rotating) magnets. This configuration is expected to reduce power consumption and improve energy coupling into the pipe wall compared to eddy current systems that use a fixed transmitter coil.

Multi-purpose Deformation Sensor – Los Alamos National Laboratory (LANL) has developed an ILI system capable of performing a number of inspection measurements. The LANL technology uses ultrasonic techniques to determine pipe ovality, structural defects, wall thickness, and the velocity/flow rate of gas flowing within the pipe.

Dual Magnetization MFL – Battelle has developed a magnetic flux leakage (MFL) inspection tool that detects and sizes both metal loss and mechanical damage. Theoretical work supported by OPS showed that two magnetic field levels improve mechanical damage detection and assessment capabilities. In addition to the high magnetic field employed on most inspection tools, this technology utilizes a lower field to detect the metallurgical changes caused by excavation equipment. This low field is needed because the high magnetic field level masks and erases important components of the signal that are due to mechanical damage.

Guided Wave Ultrasonics – The final technology was the only non-in-line inspection system demonstrated. This technology was developed by a research team comprised of PetroChem Inspection Services, Plant Integrity, Ltd., FBS, Inc., and The Pennsylvania State University with funding support from OPS. The technology uses guided wave ultrasonics (GWUT) to detect pipeline corrosion and other metal loss defects. Unlike conventional ultrasonics, which measures a single point on the pipe, the GWUT system can measure 100% of the pipe's circumference and has the advantage that long lengths (100 feet or more) in either direction may be measured from a single test point. The transducer collars can be assembled for pipes ranging in size from 2-inches up to 60-inches. The benefit of GWUT is ability to inspect inaccessible pipe including unpiggable lines, under sleeves and insulation, and buried pipes. This technology is also passed proof-of-concept stage and is commercially available.

Demonstration Configuration

The emerging inspection technologies were tested within a 40 by 100 foot high-bay area at Battelle's PSF. Pipes selected for these tests had various types of natural and machined defects. A black tarp covered the pipes to hide defect locations. Figures 1 and 2 show the configuration of the pipes during the demonstration. These pipes included:

Figure 1 (left) north end of the high-bay area looking south. 30-inch SCC pipe and 24-inch mechanical damage pipe in foreground. Figure 2 (above) high-bay looking north. 12-inch corrosion and 24-inch mechanical damage pipe with gouges in foreground. Dent and gouge machine in far background outside the high-bay area.

<u>Detection of Metal Loss</u>

- One 12-inch diameter seamless pipe measuring approximately 48 feet in length with natural corrosion defects.

- One 12-inch diameter seam welded pipe measuring 32 feet in length with manufactured corrosion defects.

<u>Detection of Mechanical Damage</u>

- One 24-inch pipe measuring 41.5 feet in length comprised of two separate pipes welded together with mechanical damage defects including gouges.

- One 24-inch diameter pipe measuring approximately 40 feet in length with plain (or smooth) dent defects.

Stress Corrosion Cracking

- One 30-inch diameter pipe measuring 20 and 1/3 feet in length with natural stress corrosion cracking.

Additional information on the pipe defect sets, pipe preparation, demonstration facility layout, and demonstration procedures can be found in the final benchmarking report, *Benchmarking Emerging Pipeline Inspection Technologies*, prepared by Battelle.[1]

DEMONSTRATION RESULTS

This section provides an assessment of the test data relative to the benchmark data developed at the Battelle PSF. The benchmark data is provided as Appendix A of this document and test results for the individual technologies, as prepared and submitted by the technology developers, can be found in Appendix B.

Metal Loss Corrosion Assessment

Two 12-inch diameter pipes were inspected by each technology for corrosion. The first pipe (Sample Pipe C1) was a seam-welded pipe measuring 32 feet in length. This sample consisted of three pipe sections welded together (two circumferential welds) and contained manufactured corrosion defects set along two test lines set 180^o apart. The second pipe (Sample Pipe C2) was a seamless pipe measuring approximately 48 feet in length containing natural corrosion defects. The benchmark data and test results for the four technologies that tested for metal loss on Sample Pipe C1 are shown in Table 1.

The Battelle *Rotating Permanent Magnet EC* technology did not detect any false positive signals, however, there were three defect sites on Sample Pipe C1 where no clear signal was detected. For example, site MC05 was not detected. This site contained a 1.2 x 2-inch metal loss region with a fairly significant 0.21-inch maximum metal loss depth. In areas where a clear signal was detected, the technology was able to identify the axial location of the corrosion region with good precision. Maximum depth of metal loss was qualitatively accessed as small, medium or deep. In this regard, there was some inconsistency in the reported values. On Line 1 for example, a 0.17-inch (47%) metal loss region (MC07) was defined as “medium” whereas on Line 2 a 0.18-inch (50%) metal loss region (MC12) was defined as “small.” Future efforts should include either quantifying metal loss or developing a standard qualitative scale (e.g., small < 25% loss, medium = 25% to 50%, and large >50%) that can be used for all pipes regardless of their nominal wall thickness. The rotating permanent magnet EC technology was unable to detect any clear defect signals on Sample Pipe C2.

[1] *Benchmarking Emerging Pipeline Inspection Technologies* is available on the SCNGO homepage at www.netl.doe.gov/scngo/Natural%20Gas/publications/t&d/Benchmark%20Emerging%20Technologies%20Final%20Report.pdf

Table 1. Benchmark Data vs. Test Results for Corrosion Testing Pipe Sample C1; Line 1

	Manufactured Corrosion Pipe Sample C1 - Line 1								
Defect Number	MC02	MC03	MC04	MC05	MC06	MC07[2]	MC08	MC09	MC10
Search Region	126" to 138"	144" to 156"	162" to 174"	186" to 198"	210" to 222"	234" to 246"	264" to 276"	282" to 294"	306" to 318"
	Length of Metal Loss Region								
Benchmark Data	3	blank	blank	1.2	blank	2.7	blank	2	blank
Battelle - Rotating EC	no signal			no signal		2.0		2.5	
GTI - RFEC	2.6			1.0		1.1 1.0		1.7	
SwRI - Collapsible RFEC	2.43			1.62		1.89		1.62	
	Width of Metal Loss Region								
Benchmark Data	1.2	blank	blank	2	blank	1.1	blank	1.5	blank
Battelle - Rotating EC	no signal			no signal		na		na	
GTI - RFEC	1.1			1.1		0.75 0.75		2.6	
SwRI - Collapsible RFEC	2.5			2.5		1.5		3.0	
	Depth of Metal Loss Region								
Benchmark Data	0.13	blank	blank	0.21	blank	0.17	blank	0.29	blank
Battelle - Rotating EC	no signal			no signal		medium		deep	
GTI - RFEC	0.243			0.258		0.211 0.229		0.279	
SwRI - Collapsible RFEC	0.06			0.16		0.12		0.22	
PetroChem - GWUT	small; all quads	(FP) small; Q1, Q2, Q3	(FP) very small @ 270^o	moderate @ 270^o	(FP) very small @ 90^o	moderate @ 270^o		small @ 270^o	

All measurements are in inches

FP = False Positive

[2] Defect MC07 was actually two axially separated defects. The GTI RFEC technology was able to detect the individual defects. For more information regarding this defect site, see GTI's test results comments in Appendix C.

Table 1 (continued). Benchmark Data vs. Test Results for Corrosion Testing Pipe Sample C1; Line 2

	Manufactured Corrosion Pipe Sample C1 - Line 2								
Defect Number	MC11	MC12	MC13	MC14	MC15	MC16	MC17	MC18	MC19
Search Region	78" to 90"	102" to 114"	138" to 150"	174" to 186"	198" to 210"	222" to 234"	246" to 258"	272" to 284"	288" to 300"
	Length of Metal Loss Region								
Benchmark Data	blank	3	blank	blank	1.5	blank	1.4	blank	1.4
Battelle - Rotating EC		1.0			1.5		1.0		no signal
GTI - RFEC		2.6			1.0		1.7		1.4
SwRI - Collapsible RFEC		2.69			1.08		1.62		1.08
	Width of Metal Loss Region								
Benchmark Data		1.4			1.5		3.3		3
Battelle - Rotating EC		na			na		na		no signal
GTI - RFEC		3.4			0.75		3.4		1.9
SwRI - Collapsible RFEC		2.5			2.0		3.0		1.5
	Depth of Metal Loss Region								
Benchmark Data		0.18			0.20		0.27		0.09
Battelle - Rotating EC		small			medium		deep		no signal
GTI - RFEC		0.118			0.143		0.226		0.1
SwRI - Collapsible RFEC		0.16			0.05		0.21		0.08
PetroChem - GWUT		small @ 90^o	(FP) small; Q1, Q2, Q3	(FP) very small @ 90^o	moderate @ 90^o		largest defect @ 90^o		small; all quads

All measurements are in inches
FP = False Positive

The GTI *RFEC* technology detected all defect sites on Pipe Sample C1 and there were no false positive signals. Defect lengths were estimated to ±15% of the actual length. The metal loss start location data clearly shows odometer slippage, which GTI had indicated was a problem during testing. GTI anticipated that the precision of their defect width estimates would be poorer than the length estimates, and in fact, these estimates are on average about ±35% of the actual defect widths. With respect to metal loss depth, the GTI technology typically overestimated on Line 1 and underestimated on Line 2 of Sample Pipe C1. Overall, the GTI technology performed very well with metal loss estimates of ±22% of the actual. Due to multiplexer failure, GTI was unable to scan Sample Pipe C2.

The SwRI *Collapsible RFEC* technology detected all defect sites on Pipe Sample C1 and there were no false positive signals. Defect lengths were estimated at ±20% of the actual length. Defect width estimates were on average about ±35% of the actual defect widths. For metal loss depth, the estimates for the SwRI technology were typically ±20%. However, estimates for defect sites MC02 and MC15 were significantly less than the actual metal loss depth. For example, the actual metal loss for MC15 (198 to 210 inches from side A) was 0.2 inches, whereas the Collapsible RFEC technology estimated 0.05 inches of metal loss.

The SwRI Collapsible RFEC technology was able to detect defects on the natural corrosion seamless Sample Pipe C2. With the exception of one false positive within the region of T02 (180 to 192 inches from side A) and one missed defect at T10, the results are very encouraging. The two defect sites T05 and T09 have only one region of corrosion and thus, they provide good points for data comparison. Table 2 shows good agreement between the benchmark data and SwRI's estimates (shaded) for these two sites. SwRI did detect separate signals at sites where two regions of corrosion existed, but only the maximum depth defect was reported due to confusion regarding reporting requirements. At site T01 however, it appears that the detected signal is a combination of both the benchmark sites T01a and T01b. For sites T12 and T13, the SwRI reported results show good correlation with benchmark sites T12a and T13b, respectively. Note, however, that T13b is shallower than defect 13a.

Table 2. Benchmark Data vs. Test Data for SwRI Collapsible RFEC; Sample Pipe C2

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
T01	144 to 156	T01a = 147.1 T01b = 153.4	T01a = 149.0 T01b = 156.6	T01a = 1.9 T01b = 3.25	T01a = 0.9 T01b = 0.8	T01a = 0.13 T01b = 0.15
SwRI		146.43	155.84	9.31	3.0	0.9
T05	272 to 284	273.7	284.3	10.6	1.1	0.12
SwRI		273.58	284.0	10.42	4.5	0.15
T09	360 to 372	363	367	4.0	1.3	0.20
SwRI		364.67	366.24	1.57	1.5	0.09
T12	474 to 486	**T12a** = 474.0 T12b = 482.6	T12a = 480.0 T12b = 485.4	T12a = 6.0 T12b = 2.75	T12a = 2.0 T12b =0.9	T12a = 0.18 T12b = N/A
SwRI		475.11	477.28	2.17	3.0	0.08
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
SwRI		492.32	493.22	0.9	0.5	0.29

All measurements are in inches

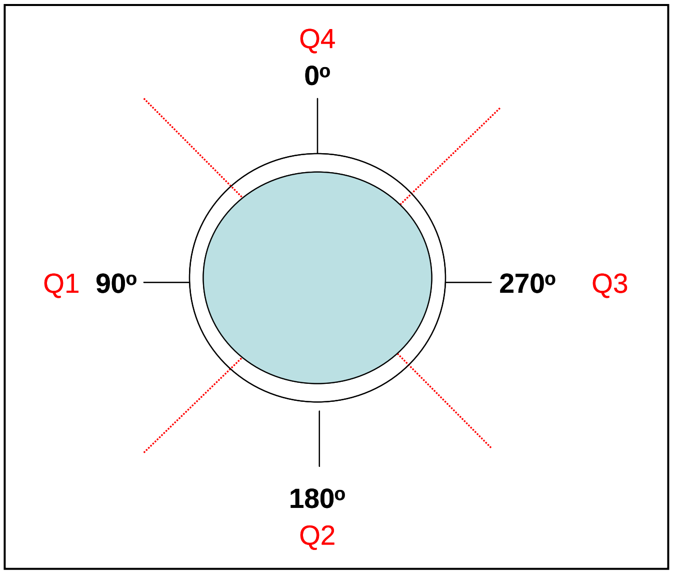


Figure 3. Guided Wave Ultrasonic grading quadrant configuration.

Figure 3 shows the grading quadrants used by the *Guided Wave Ultrasonic* system. For Pipe Sample C1, two scan lines were taken at approximately 90^{o} and 180^{o}. Because the guided wave technology detects a full 360^{o}, a number of small corrosion defects not included along the two manufactured defect lines were detected, resulting in a number of apparent false positive readings. Setting aside these data, the guided wave technology performed very well in determining the relative size—small, moderate, or large—of the corrosion defect for both scan lines. The only exception was defect site MC09 (Line 1). This site had the deepest metal loss defect of both lines and yet, it was detected as a small defect by the GWUT system. In comparison, site MC05 along the same line had slightly less surface area and nearly 30% less metal loss, but was defined as a moderate defect (refer back to Table 1).

For Sample Pipe C2, benchmark defect sites were generally within ±4 inches of the scan line at 0^{o} and thus, generally fell within the guided wave grading quadrant 4 (Q4). The guided wave technology performed adequately on the Sample Pipe C2 (see Table 3). Again, because of the full circumferential scanning of the system, a number of defects (albeit usually small) were detected outside the baseline testing region (i.e., Q1, Q2 and Q3). The guided wave did detected two large corrosion defects at sites T02 and T08 within Q4 that were not included as baseline defects. Moreover, the guided wave detected no visible corrosion in the area of T05 and only moderate corrosion in the area of T09. Unlike the other defect test sites on Sample Pipe C2, which consist of two separate defect regions, these two defect sites consist of a single large region of corrosion. The guided wave also detected small corrosion at the axial distance of T06, but within Q2. T06 contained two defect regions within the scanning area that were not detected; one fairly large and the other small. Baseline defect sites that appear to correlate well with detected signals from the GWUT system include T01, T10, T11 and T12.

As previously noted, the GWUT is an external inspection method. The corrosion anomalies planned for this benchmarking study were specifically selected to demonstrate the capability of internal inspection devices. As such, in some cases the test setup was less than optimal for the external inspection method.

Table 3. Benchmark vs. PetroChem GWUT Detection Results; Pipe Sample C2 (Natural Corrosion)

Manufactured Corrosion Pipe Sample C1 - Line 1							
		BENCHMARK DATA					
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 Guided Wave Ultrasonic Technology Demonstration Results
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**	Large (142 to 156) located in Q1 and Q4
T02	180 to 192	***	***	***	***	***	Large (188 to 197) located in Q3 and Q4
T03	216 to 228	***	***	***	***	***	Moderate (224 to 240) located in Q1
T04	260 to 272	***	***	***	***	***	Moderate (at 262) located in Q2
T05	272 to 284	**273.7**	**284.3**	**10.6**	**1.1**	**0.12**	no call
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**	Small (at 288) located in Q2
T07	296 to 308	***	***	***	***	***	Small (at 300) located in Q3 and Q4
T08	348 to 360	***	***	***	***	***	Large (at 350) located in Q2 and Q4
T09	360 to 372	**363**	**367**	**4**	**1.3**	**0.20**	Moderate (at 360) located in Q3 and Q4
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**	Moderate (at 448) located in all quadrants
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**	Large (at 470) located in Q1 and Q4
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**	Large (475 to 481) located in Q3 and Q4 (with T13)
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**	Large (475 to 481) located in Q3 and Q4 (with T12)
T14	500 to 512	***	***	***	***	***	Moderate (at 502) located in all quadrants

All measurements are in inches

Mechanical Damage Assessment

Two 24-inch diameter pipes were inspected by each technology for mechanical damage. The first pipe (Sample Pipe MD1) consisted of two separate pipes welded together. One of the two pipes had been cut and re-welded together thus, three welds were encountered along the scan lines. The pipe measured 41.5 feet in length with mechanical damage defects including gouges. The second pipe (Sample Pipe MD2) measured approximately 40 feet in length with plain (or smooth) dent defects. The benchmark data and test results for the three technologies that tested for mechanical damage are shown in Table 4.

Table 4. Benchmark vs. Test Results; Technologies Testing for Mechanical Damage

Defect Number	Search Region (distance from end A; inches)	Defect Length (inches)		Dent Depth (% of diameter)		Dent Severity*		
		Benchmark	LANL	Benchmark	LANL	Benchmark	PNNL	Battelle
Sample Pipe MD1								
Q1	406 to 430	0.25	6	6%	6.9%	1	3	1+
Q2	370 to 394	blank	11	blank	1.6%	--	--	--
Q3	334 to 358	6	9	3%	6.0%	3-	1	3
Q4	298 to 322	2	5.7	3%	7.0%	2	2	2
Q5	262 to 286	0.25	7	3%	7.0%	1-	1.5	1+
Q6	226 to 250	blank	blank	blank	blank	--	--	--
Sample Pipe MD2								
R03	96 to 120	4	2	1.21%	1.3%	1	1	1
R04	132 to 156	10	6	0.96%	1.6%	3	2	3
R05	168 to 192	8.5	6	0.83%	2.0%	2	3	2
R06	204 to 228	4	2	1.21%	2.1%	1	1	1
R07	240 to 264	8.5	6	0.83%	1.7%	2	2	2
R08	276 to 300	10	6	0.96%	2.0%	3	3	3
R09	312 to 336	8.5	6	0.83%	1.9%	2	2.5	2
R10	348 to 372	10	ND	0.96%	ND	3	3	3
R11	384 to 408	blank	--	blank	--	--	--	--

* 0 = No dent, 1 = Least severe, 2 = Moderate severity, 3 = Most severe. ND= no data

Both the Battelle *Dual Magnetization MFL* and the PNNL *EMAT Strain Measurement Tool* assess relative damage severity by measuring the stresses and strain surrounding the mechanical defect. As the results in Table 4 show, Battelle's MFL technology showed excellent results, identifying each defect and its severity on both pipe samples. PNNL's technology also performed well. At defect sites Q1 and Q3 on Sample Pipe 1 as well as R04 and R05 on Sample Pipe 2 there was discrepancy between the PNNL data and the benchmark.

LANL's *Acoustic Sensor* measures pipe deformation using ultrasonic methods. On Sample Pipe MD1, LANL used the opposite end of the pipe as a reference point and thus, their defect start and end data reflects measurement from pipe side B. LANL successfully identified all defect locations including the long shallow gouge at defect site Q2. The LANL system typically overestimated the defect length as well as the dent depth. For Sample Pipe MD2 (see Table 4), the technology generally identified the start location of a defect within 2 inches of its actual location. However, the measured defect lengths were on average 40% less than the actual defect. Dent depth was consistently overestimated on Sample Pipe MD2; also about 40%. Thus, for both pipes the LANL system overestimated defect depth, which is contrary to what the research team had expected.

Stress Corrosion Cracking

Only one technology, the ORNL *Shear Horizontal EMAT*, was tested for detection of stress corrosion cracking. As shown in Table 5 the technology ran three lines on a 30-inch diameter pipe with natural stress corrosion cracking. The EMAT technology detected several false positive signals; especially evident on Line 2. Because the EMAT configuration scans 9-inches of the pipe's circumference, some of the false positives could be the result of cracks lying along one of the neighboring scan lines. A number of defect sites (SCC1, SCC6 and SCC13) provided no discernable signal. The EMAT system had some difficulty distinguishing between isolated cracks and a group or "colony" of cracks.

Table 5. Benchmark vs. ORNL Test Results; SCC Testing

Defect Number	Search Region (Distance from End A)	Benchmark			ORNL		
		Start of Crack Region from Side A	End of Crack Region from Side A	Type of SCC	Start of Crack Region from Side A	End of Crack Region from Side A	Type of SCC
Line 1							
SCC1	60 to 70	63	63	isolated	no signal		none
SCC2	70 to 80	75	75	isolated	70	77	colony
SCC3	80 to 90	82	84.5	colony	82	90	colony
SCC4	90 to 100	blank		none	96	99	isolated
SCC5	110 to 120	blank		none	blank		none
SCC6	130 to 140	137	138	colony	no signal		none
Line 2							
SCC7	60 to 75	61	67	colony	69	72	isolated
SCC8	75 to 90	blank		none	80	90	colony & isolated 75" to 80"
SCC9	90 to 105	blank		none	94	104	colony
SCC10	105 to 120	blank		none	106	107.5	isolated
SCC11	120 to 135	blank		none	127	132	isolated
Line 3							
SCC12	60 to 75	62	71	colony	64	66	isolated
SCC13	75 to 90	78	84	colony	no signal		none
SCC14	90 to 105	94	94	isolated	90	93	isolated
SCC15	105 to 120	114	115.5	isolated	106	110	isolated & colony 113.5" to 120"
SCC16	120 to 135	blank		none	127	131	isolated

All measurements are in inches

SUMMARY

The corrosion detection techniques demonstrated hold significant promise for inspection of unpiggable pipes. Accurate detection of corrosion on seamless pipes appears somewhat more challenging. The two technologies—Collapsible RFEC and GWUT—that did detect metal loss in the seamless pipe performed well. This is particularly encouraging when one considers the 20% variation in nominal wall thickness of the seamless pipe (from 0.31 to 0.38 inches). Further development to target corrosion on seamless pipe must be balanced, however, with other critical technical challenges, as only a small percentage of existing distribution pipes are seamless.

The mechanical damage detection techniques also achieved good results. LANL was unfortunate that their system was damaged in transit and thus, could not be deployed to its full capability. Damaged components likely contributed to some of the measurement inaccuracies.

The ORNL EMAT system performed satisfactory but it did detect a significant number of false positives and had difficulty distinguishing between an isolated crack and a colony of cracks. In addition, as noted by the developer, the system typically overestimated the defect length.

Following the submittal of their test data, the technology developers were sent the benchmark data. They were given an opportunity to comment on their results and to provide their perspective on their technology's performance relative to the benchmark data. Appendix C contains the developer's comments. Overall, the Natural Gas Delivery Reliability Program believes each of the technologies performed well and the results are extremely encouraging. Table 6 provides a general assessment of the technologies. As the development of these technologies progresses and future testing takes place, it is envisioned that improvements in the technology and data analysis techniques will result in fewer false positives and greater precision and accuracy of defect signals.

Table 6. General Assessment of Demonstrated Technologies

Detection of Metal Loss	
Battelle – Rotating Permanent Magnet EC	Good correlation with baseline data on Sample Pipe 1; no detection on Sample Pipe 2
GTI – RFEC	Very good correlation with baseline data on Sample Pipe 1; no detection on Sample Pipe 2 due to apparatus failure
SwRI – Collapsible RFEC	Very good correlation with baseline data on both Sample Pipes 1 and 2
PetroChem – Guided Wave Ultrasonic	Very good correlation with baseline data on Sample Pipe 1 and Good correlation on Sample Pipe 2; some apparent false positives (see text)
Detection of Mechanical Damage	
PNNL – EMAT Strain Measurement Tool	Very good correlation with baseline data on both Sample Pipes 1 and 2
Battelle – Dual Magnetization MFL	Excellent correlation with baseline data on both Sample Pipes 1 and 2
LANL – Deformation Acoustic Sensor	Good correlation with baseline data on Sample Pipe 2; See text regarding Sample Pipe 1.
Stress Corrosion Cracking	
ORNL – Shear Horizontal EMAT	Good correlation with baseline data; many false positives

PATH FORWARD

As noted, a key Gas Delivery Reliability Program goal is to develop ILI sensors that can be deployed remotely as part of an integrated robotic platform/sensor package. The program has established an aggressive schedule to develop a prototype remote system that can traverse all pipes including unpiggable lines of various diameters while providing continuous and real-time detection of pipe anomalies or defects. This effort is driven in large part by new PSIA regulations that require inspection of gas transmission pipelines and distribution mains in high-consequence areas. A large percentage of these pipes cannot be inspected using "smart-pig" techniques because of diameter restrictions, pipe bends and valves. In addition, pressure differentials and flow can be too low to push a pig through some pipes.

Two teams have been established, each based on a unique remote platform system. The first team will base their system on the EXPLORER platform developed by the Robotics Institute at Carnegie Mellon University and the Northeast Gas Association. EXPLORER is an untethered, articulating platform comprised of a series of inter-connected modules that can be assembled as desired to achieve specific objectives. The core modules include a low-power locomotion system, an energy storage module, and a 190-degree field-of-view camera module. The second team will base their sensor system on a robotic platform designed by Foster-Miller and the Northeast Gas Association. This modular system utilizes a fiber-optic tether design to control operations. Tractor modules are incorporated between sensing modules to provide drive, steering, and clamping capabilities.

The teams also consist of sensor developers, many of which have been included in this demonstration. Each team will establish their own integration parameters and development schedules. Funding for the sensor development will be separate from that of the platform development efforts thereby providing DOE with greater flexibility to integrate sensors and platforms as development progresses. The goal is to develop an integrated prototype within two to three years.

The demonstrations conducted at Battelle's PSF were a fundamental step toward achieving the goal of a remote integrated sensor system. The test results will be used to guide future development efforts by identifying those technologies that hold the greatest promise.

APPENDIX A – BENCHMARK DATA

Benchmarking of Inspection Technologies
Detection of Metal Loss - Page 1

Name:	**BENCHMARK**
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**

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 2							
Name:	**BENCHMARK**						
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"**

Benchmarking of Inspection Technologies
Detection of Metal Loss - Page 3

Name:	**BENCHMARK**
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

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

Name:	**BENCHMARK**
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 ☑ **Gouged** ☐ None	**Gouge ~25% loss in wall thickness**
Q2	370" to 394"	***	***	***	***	☐ Smooth ☐ Gouged ☑ **None**	**Actually has only a gouge measuring 2" in length with ~5% loss in wall thickness**
Q3	334" to 358"	**343"**	**349"**	**6"**	**3%**	☐ Smooth ☑ **Gouged** ☐ None	**Gouge ~5% loss in wall thickness**
Q4	298" to 322"	**307"**	**309"**	**2"**	**3%**	☐ Smooth ☑ **Gouged** ☐ None	**Gouge ~5% loss in wall thickness**
Q5	262" to 286"	**270.9"**	**271.1"**	**0.25"**	**3%**	☐ Smooth ☑ **Gouged** ☐ None	**Gouge ~5% loss in wall thickness**
Q6	226" to 250"	***	***	***	***	☐ Smooth ☐ Gouged ☑ **None**	**Blank**

LANL Benchmarking of Inspection Technologies Detection of Mechanical Damage - Page 2	
Name:	**BENCHMARK**
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**

PNNL/Battelle Benchmarking of Inspection Technologies Detection of Mechanical Damage - Page 1					
Name:	**BENCHMARK**				
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**

PNNL/Battelle Benchmarking of Inspection Technologies
Detection of Mechanical Damage - Page 2

Name:	**BENCHMARK**
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**

Benchmarking of Inspection Technologies Detection of SCC - Page 1						
Name:	**BENCHMARK**					
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** ☐ Colony of Cracks ☐ None	**1 crack; ~1/4" long**
SCC2 **(8)**	70" to 80"	**75"**	**75"**	☑ **Isolated Crack** ☐ Colony of Cracks ☐ None	**1 crack; ~1/4" long**
SCC3 **(7)**	80" to 90"	**82"**	**84.5"**	☐ Isolated Crack ☑ **Colony of Cracks** ☐ None	**2 cracks; 1 crack ~ 2" long**
SCC4 **(Blank 1)**	90" to 100"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**
SCC5 **(Blank 2)**	110" to 120"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**
SCC6 **(1 & 2)**	130" to 140"	**137"**	**138"**	☐ Isolated Crack ☑ **Colony of Cracks** ☐ None	**2 cracks; 1 crack ~ 1" long**

Benchmarking of Inspection Technologies Detection of SCC - Page 2					
Name:	**BENCHMARK**				
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 ☑ **Colony of Cracks** ☐ None	**Large colony of cracks**
SCC8 **(Blank 3)**	75" to 90"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**
SCC9 **(Blank 4)**	90" to 105"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**
SCC10 **(Blank 5)**	105" to 120"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**
SCC11 **(Blank 6)**	120" to 135"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**

Benchmarking of Inspection Technologies Detection of SCC - Page 3					
Name:	**BENCHMARK**				
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 ☑ **Colony of Cracks** ☐ None	**Relatively small cracks in the same general vicinity**
SCC13 **(9)**	75" to 90"	**78"**	**84"**	☐ Isolated Crack ☑ **Colony of Cracks** ☐ None	
SCC14 **(6)**	90" to 105"	**94"**	**94"**	☑ **Isolated Crack** ☐ Colony of Cracks ☐ None	**1 crack; ~1/4" long**
SCC15 **(3)**	105" to 120"	**114"**	**115.5"**	☑ **Isolated Crack** ☐ Colony of Cracks ☐ None	**1 crack; ~1 1/2" long**
SCC16 **(Blank 7)**	120" to 135"	***	***	☐ Isolated Crack ☐ Colony of Cracks ☑ **None**	**Blank**

APPENDIX B – DEMONSTRATION TEST DATA

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 1							
Name:	Bruce Nestleroth						
Date:	8-Oct-04						
Company:	Battelle						
Sensor Design:	Rotating permanent magnet eddy current						

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"						No Clear Signal Detected
MC03	144" to 156"						No Clear Signal Detected
MC04	162" to 174"						No Clear Signal Detected
MC05	186" to 198"						No Clear Signal Detected
MC06	210" to 222"						No Clear Signal Detected
MC07	234" to 246"	Centered		2 inches		Meduim	
MC08	264" to 276"						No Clear Signal Detected
MC09	282" to 294"	Centered		2.5 inches		Deep	Largest Signal
MC10	306" to 318"						

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 2							
Name:	Bruce Nestleroth						
Date:	8-Oct						
Company:	Battelle						
Sensor Design:	Rotating Permanent Magnet Eddy Current						
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"						No Clear Signal Detected
MC12	102" to 114"	Centered		1 inch		small	
MC13	138" to 150"						No Clear Signal Detected
MC14	174" to 186"						No Clear Signal Detected
MC15	198" to 210"	Centered		1.5 inch		Medium	
MC16	222" to 234"						No Clear Signal Detected
MC17	246" to 258"	Centered		1 inch		Deep	
MC18	272" to 284"						No Clear Signal Detected
MC19	288" to 300"						No Clear Signal Detected

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 3	
Name:	Bruce Nestleroth
Date:	
Company:	Battelle
Sensor Design:	Rotating Permanent Magnet Eddy Current

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"						Technique was not sucessful at this time
T02	180" to 192"						No Clear Signal Detected
T03	216" to 228"						
T04	260" to 272"						
T05	272" to 284"						
T06	284" to 296"						
T07	296" to 308"						
T08	348" to 360"						
T09	360" to 372"						
T10	438" to 450"						
T11	462" to 474"						
T12	474" to 486"						
T13	486" to 498"						
T14	500" to 512"						

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 1							
Name:	Albert Teitsma						
Date:	6-Oct-04						
Company:	Gas Technology Insitute						
Sensor Design:	12" Remote Field Eddy Current Tool						
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			
Manuf. Metal Loss 1:	60"	1	0.3	0.557			
Manuf. Metal Loss 2:	96"	1.475	0.21	1.417			
Manuf. Metal Loss 3:	401"	1.475	0.21	1.417			
TEST DATA							
Pipe Sample:	Manufactured Corrosion Sample						
Defect Set:	12" Diameter, 0.375" 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		Maximum Depth of Metal Loss Region	Comments
	inches	inches	inches	inches	inches	inches	
MC01	66" to 78"						
MC02	84" to 96"						
MC03	126" to 138"	129	132.4	2.6	1.1	0.243 (68%)	Start of and end of signal are given here and below.
MC04	144" to 156"						No defect detected
MC05	162" to 174"						No defect detected
MC06	186" to 198"	190	191.8	1	1.1	0.258 (72%)	
MC07	210" to 222"	236.9	238.7	1.1	0.75	0.211 (59%)	Two axially aligned pitts closely spaced.
		238.2	240	1	0.75	0.229 (64%)	
MC08	234" to 246"						No defect detected
MC09	264" to 276"						No defect detected
MC10	282" to 294"	283	285.3	1.7	2.6	0.279 (78%)	
MC11	306" to 318"						No defect detected

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 2							
Name:	Albert Teitsma						
Date:	6-Oct-04						
Company:	GTI						
Sensor Design:	RFEC						
TEST DATA							
Pipe Sample:	Manufactured Corrosion Sample						
Defect Set:	12" Diameter, 0.375" 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	
MC12	78" to 90"						No defect detected
MC13	102" to 114"	105.6	109	2.6	3.4	0.118 (33%)	
MC14	138" to 150"						No defect detected
MC15	174" to 186"						No defect detected
MC16	198" to 210"	202.9	204.7	1	0.75	0.143 (40%)	
MC17	222" to 234"						No defect detected
MC18	246" to 258"	249	251.5	1.7	3.4	0.226 (63%)	
MC19	272" to 284"						No defect detected
MC20	288" to 300"	290	292.2	1.4	1.9	0.1 (28%)	

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 1	
Name:	Gary L. Burkhardt
Date:	9/14/2004
Company:	Southwest Research Institute
Sensor Design:	Collapsible RFEC

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"	130.83	133.26	2.43	2.5	0.06	
MC03	144" to 156"						
MC04	162" to 174"						
MC05	186" to 198"	191.31	192.93	1.62	2.5	0.16	
MC06	210" to 222"						
MC07	234" to 246"	239.10	240.99	1.89	1.5	0.12	
MC08	264" to 276"						
MC09	282" to 294"	286.08	287.70	1.62	3.0	0.22	
MC10	306" to 318"						

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 2							
Name:	Gary L. Burkhardt						
Date:	9/14/2004						
Company:	Southwest Research Institute						
Sensor Design:	Collapsible RFEC						
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"						
MC12	102" to 114"	107.05	109.74	2.69	2.5	0.16	
MC13	138" to 150"						
MC14	174" to 186"						
MC15	198" to 210"	203.49	204.57	1.08	2.0	0.05	
MC16	222" to 234"						
MC17	246" to 258"	251.45	253.07	1.62	3.0	0.21	
MC18	272" to 284"						
MC19	288" to 300"	292.67	293.75	1.08	1.5	0.08	

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 3	
Name:	Gary L. Burkhardt
Date:	9/15/2004
Company:	Southwest Research Institute
Sensor Design:	Collapsible RFEC

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	End of Metal Loss Region from	Total Length of Metal Loss	Width of Metal Loss Region	Maximum Depth of Metal Loss Region	Comments
	inches	inches	inches	inches	inches	inches	
T01	144" to 156"	146.53	155.84	9.31	3.0	0.09	
T02	180" to 192"	191.11	191.87	0.76	1.0	0.11	
T03	216" to 228"						
T04	260" to 272"						
T05	272" to 284"	273.58	284.00	10.42	4.5	0.15	T05 defect extends into T06.
T06	284" to 296"	284.00	288.66	4.66	2.0	0.15	T05 defect extends into T06.
T07	296" to 308"						
T08	348" to 360"						
T09	360" to 372"	364.67	366.24	1.57	1.5	0.09	
T10	438" to 450"						
T11a	462" to 474"	465.56	469.03	3.47	2.0	0.05	Two separate defects in T11 area.
T11b	462" to 474"	471.54	473.39	1.85	2.0	0.04	T11b may be part of T12.
T12	474" to 486"	475.11	477.28	2.17	3.0	0.08	
T13	486" to 498"	492.32	493.22	0.90	0.5	0.29	Signal only on one scan line; difficult to characterize.
T14	500" to 512"						

Benchmarking of Inspection Technologies
Detection of Metal Loss - Page 1

Name:	Li Zhang
Date:	28-Sep-04
Company:	FBS, Inc.
Sensor Design:	TeleTest

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"	133						Small and present in all quadrants
MC03	144" to 156"	144						Small and present in quadrants 1, 2, and 3
MC04	162" to 174"	174						Very small; May be located at 270 degrees
MC05	186" to 198"	193						Moderate size at 270 degrees
MC06	210" to 222"	215						Very small located at 90 degrees
MC07	234" to 246"	241						Moderate size at 270 degrees
MC08	264" to 276"							No call; too close to a weld
MC09	282" to 294"	286						Small located at 270 degrees
MC10	306" to 318"							No call;Overlapped with mode converted signals

Benchmarking of Inspection Technologies
Detection of Metal Loss - Page 2

Name:	Li Zhang
Date:	28-Sep-04
Company:	FBS, Inc.
Sensor Design:	TeleTest

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"							No Call
MC12	102" to 114"	108						Small located at 90 degrees
MC13	138" to 150"	144						Small and present in quadrants 1, 2, and 3
MC14	174" to 186"	184						Very small and possibly at 90 degrees
MC15	198" to 210"	204						Moderate located 90 degrees
MC16	222" to 234"							Possibly a very small defect at 229 inches at 270 degrees
MC17	246" to 258"	253						Largest defect noted and located at 90 degrees
MC18	272" to 284"							No call;Overlapped with mode converted signals
MC19	288" to 300"	295						Small and present in all quadrants

Benchmarking of Inspection Technologies Detection of Metal Loss - Page 3								
Name:	Li Zhang							
Date:								28-Sep-04
Company:	FBS, Inc.							
Sensor Design:	TeleTest							
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"	142	156					Large located in quadrants 1 and 4
T02	180" to 192"	188	197					Large located in quadrants 3 and 4
T03	216" to 228"	224	240					Moderate located in quadrant 1
T04	260" to 272"	262						Moderate located in quadrant 2
T05	272" to 284"	272	284					No call
T06	284" to 296"	288						Small located in quadrant 2
T07	296" to 308"	300						Small located in quadrants 3 & 4
T08	348" to 360"	350						Large located in quadrants 2 & 4
T09	360" to 372"	360						Moderate located in quadrants 3 & 4
T10	438" to 450"	448						Moderate located in all quadrants
T11	462" to 474"	470						Large located in quadrants 1 & 4
T12	474" to 486"	475	481					Large located in quadrants 3 & 4 (with T13)
T13	486" to 498"	475	481					Large located in quadrants 3 & 4 (with T12)
T14	500" to 512"	502						Moderate located in all quadrants

Benchmarking of Inspection Technologies
Detection of Mechanical Damage - Page 1

Name:	Paul D. Panetta and George Alers
Date:	October 8, 2004
Company:	Pacific Northwest National Laboratory and EMAT Consulting
Sensor Design:	Electromagnetic Acoustic Transducers (EMAT)

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	These calibration defects were in the portion of the pipe that burst, thus making
Calibration Dent Q02:	82"	2	3%	2	them unusable as calibration defects.
Calibration Dent Q03:	46"	0	6%	1	Further study is needed on these types of pipes.
Mechanical Damage Pipe SAMPLE 2 (40' 1.5")					
Calibration Dent R01:	42.25"	3.5	1.2%	1	Localized damage
Calibration Dent R02:	73.25"	8.5	0.8%	2	moderate damage over large area

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	Comments
	inches	0 = No dent 1 = Least Severe 2 = Moderate Severity 3 = Most Severe	
Q1	416.5"	3	Processing history (bursting, rerounding, rotating and welding) produced significant deviations in material properties from "normal"
Q3	347"	1	Processing history (bursting, rerounding, rotating and welding) produced significant deviations in material properties from "normal"
Q4	309.5"	2	Processing history (bursting, rerounding, rotating and welding) produced significant deviations in material properties from "normal"
Q5	272"	1.5	Processing history (bursting, rerounding, rotating and welding) produced significant deviations in material properties from "normal"
Q6	239.5"	nconclusive (burst pipe section	Processing history (bursting, rerounding, rotating and welding) produced significant deviations in material properties from "normal"

Benchmarking of Inspection Technologies Detection of Mechanical Damage - Page 2	
Name:	Paul D. Panetta and George Alers
Date:	October 8, 2004
Company:	Pacific Northwest National Laboratory and EMAT Consulting
Sensor Design:	Electromagnetic Acoustic Transducers (EMAT)

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	localized damage
R04	144"	2	moderate damage over large area, may be influenced by damage from R05
R05	183"	3	severe damage over large area
R06	217"	1	localized damage, may be influenced by damage from R05
R07	253"	2	moderate damage over large area, may be influenced by damage from R08
R08	289.5"	3	severe damage over large area
R09	325"	2.5	moderate damage over large area, may be influenced by neighboring dents
R10	360.5"	3	severe damage over large area
R11	397"	0	No dent - baseline material

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+	Cold worked length less than an inch Significant residual stress over scan area Similar to calibration dent Q03, but with more gouging and some reround
Q2	382"	0	3 inch removed metal region No significant reround or residual stress
Q3	347"	3	Cold worked length 6 inches Significant residual stress over scan area Similar to calibration dent Q01, but with less gouging and stresses. Still severe, but less than Q01
Q4	309.5"	2	Cold worked length 2 inches Reround halo indicates stress extend +/- 5inch Similar to Q02
Q5	272"	1+	Cold worked length less than an inch Significant residual stress over scan area Similar to calibration dent Q03, but smaller
Q6	239.5"	0	Dent Severity – 0 (No Dent) No significant cold work or stress signal

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	Relative to the other defects in this pipe.
R03	109.25"	1	Essentially similar to R01
R04	144"	3	R04 and R08 and R10 are essentially similar with slightly more stress than R02
R05	183"	2	Essentially similar to R02
R06	217"	1	Essentially similar to R01
R07	253"	2	Essentially similar to R02
R08	289.5"	3	R04 and R08 and R10 are essentially similar with slightly more stress than R02
R09	325"	2	Essentially similar to R02
R10	360.5"	3	R04 and R08 and R10 are essentially similar with slightly more stress than R02
R11	397"	0	No Dent

Benchmarking of Inspection Technologies
Detection of Mechanical Damage - Page 1

Name:	Dipen Sinha
Date:	8-Oct-04
Company:	Los Alamos National Laboratory
Sensor Design:	Acoustic

CALIBRATION DATA

	Calibration Dent Location	Length	Depth	Smooth or Gouged?	Measured Length	Measured Depth	Comments
	inches from end A to center of dent	inches	% Diameter		inches	% Diameter	
Manufactured Dent 1:	380.5"	6	6%	Gouged		5.5	Mexican hat shaped, center: 380.5, depth 5.5%
Manufactured Dent 2:	415.5"	2	3%	Gouged	4	2.5	
Manufactured Dent 3:	451.5"	0	6%	Smooth		5.8	

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	66" to 90"	82	88	6	6.9	☑ Smooth ☐ Gouged ☐ None	Incomplete data due to sensor transporter near edge Dent Center: 85 inch
Q2	102" to 126"	94	105	11	1.6	☐ Smooth ☑ Gouged ☐ None	A series of 3 small dents Dent center: 102
Q3	138" to 162"	147.4	156.5	9	6	☐ Smooth ☐ Gouged ☐ None	Double asymmetric dent Dent center: 152
Q4	174" to 198"	187.8	193.5	5.7	7	☑ Smooth ☐ Gouged ☐ None	Single clean dent Dent center: 191
Q5	210" to 234"	223.8	230.8	7	7	☐ Smooth ☑ Gouged ☐ None	Sharp deep dent Dent center: 227
Q6	246" to 270"					☐ Smooth ☐ Gouged ☐ None	Could not see anythin meaningful
Q7	346.5	344	348	4	2.3		Clearly see a dent + small gouge; Center - 346.5"

Benchmarking of Inspection Technologies
Detection of Mechanical Damage - Page 2

Name:	Dipen Sinha
Date:	8-Oct-04
Company:	Los Alamos National Laboratory
Sensor Design:	Acoustic

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	%		
R01	24" to 48"	38	40	2	2.2	☑ Smooth ☐ Gouged ☐ None	Nice single dent - well defined rounded Dent center: 39
R02	60" to 84"	67	73	6	1.4	☑ Smooth ☐ Gouged ☐ None	Peak of the dent looks flat instead of round Dent center: 70
R03	96" to 120"	105	107	2	1.3	☑ Smooth ☐ Gouged ☐ None	Nice rounded dent with slighter wider lip Dent center: 106
R04	132" to 156"	138	144	6	1.6	☑ Smooth ☐ Gouged ☐ None	Slightly asymmetric depth of dent - the top of peak slightly slanted Dent center: 142
R05	168" to 192"	176	183	6	2	☑ Smooth ☐ Gouged ☐ None	Wide peak with flat peak - nice smooth dent Dent center: 178
R06	204" to 228"	212	214	2	2.1	☑ Smooth ☐ Gouged ☐ None	Sharp peak - nice smooth dent Dent center: 213.5
R07	240" to 264"	247	253	6	1.7	☑ Smooth ☐ Gouged ☐ None	Broad peak with extra lipo and flat peak top Dent center: 250
R08	276" to 300"	283	289	6	2	☑ Smooth ☐ Gouged ☐ None	Same as above Dent center: 286
R09	312" to 336"	319	324	6	1.9	☑ Smooth ☐ Gouged ☐ None	Same as above except top of dent slightly tilted Dent center: 321.4
R10	348" to 372"					☐ Smooth ☐ Gouged ☐ None	Did not collect data Our transporter did not reach that far
R11	384" to 408"					☐ Smooth ☐ Gouged ☐ None	Did not collect data

Benchmarking of Inspection Technologies
Detection of SCC - Page 1

Name:	Venugopal K. Varma, Raymond Tucker, Austin Albright
Date:	10/1/2004
Company:	Oak Ridge National Laboratory
Sensor Design:	Shear Horzintal EMAT

CALIBRATION DATA

	Calibration Crack Location	Length	Depth	Measured Length	Measured Depth	Comments
	inches from end A	inches	% wall thickness			
Manufactured Crack 1:	146.75	0.88	25%			EMAT calculated position at 146.36
Manufactured Crack 2:	166.0625	1.212	48%			EMAT calculated position at 166.06
Manufactured Crack 3:	170.625	1.204	63%			EMAT calculated position at 170.69
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	60" to 70"			☐ Isolated Crack ☐ Colony of Cracks ☐ None	Interference from weld
SCC2	70" to 80"	70	77	☐ Isolated Crack ☑ Colony of Cracks ☐ None	
SCC3	80" to 90"	82	90	☐ Isolated Crack ☑ Colony of Cracks ☐ None	
SCC4	90" to 100"	96	99	☑ Isolated Crack ☐ Colony of Cracks ☐ None	
SCC5	110" to 120"			☐ Isolated Crack ☐ Colony of Cracks ☑ None	
SCC6	130" to 140"			☐ Isolated Crack ☐ Colony of Cracks ☑ None	

Benchmarking of Inspection Technologies
Detection of SCC - Page 2

Name:	Venugopal K. Varma, Raymond Tucker, Austin Albright
Date:	10/1/2004
Company:	Oak Ridge National Laboratory
Sensor Design:	Shear Horzintal EMAT

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	60" to 75"	69	72	☑ Isolated Crack ☐ Colony of Cracks ☐ None	
SCC8	75" to 90"	80	90	☐ Isolated Crack ☑ Colony of Cracks ☐ None	75-80 single crack
SCC9	90" to 105"	94	104	☐ Isolated Crack ☑ Colony of Cracks ☐ None	
SCC10	105" to 120"	106	107.5	☑ Isolated Crack ☐ Colony of Cracks ☐ None	109 to 112 isolated crack
SCC11	120" to 135"	127	132	☑ Isolated Crack ☐ Colony of Cracks ☐ None	

Benchmarking of Inspection Technologies Detection of SCC - Page 3	
Name:	Venugopal K. Varma, Raymond Tucker, Austin Albright
Date:	10/1/2004
Company:	Oak Ridge National Laboratory
Sensor Design:	Shear Horzintal EMAT

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	60" to 75"	64	66	☑ Isolated Crack ☐ Colony of Cracks ☐ None	Deep crack
SCC13	75" to 90"			☐ Isolated Crack ☐ Colony of Cracks ☑ None	
SCC14	90" to 105"	90	93	☑ Isolated Crack ☐ Colony of Cracks ☐ None	97-102 another isolated crack
SCC15	105" to 120"	106	110	☑ Isolated Crack ☑ Colony of Cracks ☐ None	113.5 -120 (Colony)
SCC16	120" to 135"	127	131	☑ Isolated Crack ☐ Colony of Cracks ☐ None	Deep Crack Crack/tar/corrosion from 133 to 143 on this line

APPENDIX C – DEVELOPER COMMENTS

505 King Avenue
Columbus OH 43201
Telephone (614) 424-6424
Facsimile (614) 424-5263

October 28, 2004

Via Federal Express and Email

Mr. Robert Vagnetti
Senior Scientist
Energetics, Inc
2414 Cranberry Square
Morgantown, WV 26508

RE: Benchmark Report

Dear Robert:

Battelle was pleased with the defect detection accuracy of our new and unique inspection method. In general, our inspection method found the larger defects and did not make any false calls. Also, the general characterization of size was encouraging. Specifically, we found defects:

- MC09, which was 77% deep and 2 inches long. We characterized this as deep and long.
- MC07, which was 45% deep and 2.7 inches long. We characterized this as medium and long
- MC12, which was 48% deep and 3 inches long. We characterized this as small.
- MC15, which was 53% deep and 1.5 inches long. We characterized this as medium and short.
- MC17, which was 72% deep and 1.4 inches long. We characterized this as deep and long.

Only one deep defect was not detected, MC05, which was 56% deep and 1.2 inches long. The technique appears to be more sensitive to longer defects. This is important since length directly affects failure pressure. This method would have advantages over inspection section technologies such as MFL which are more sensitive to corrosion width and depth, and narrow defects can go undetected.

Development of this unique approach to inspection energy generation began this year. The tool implementation tasks were accelerated to enable us to participate in the benchmarking study. As the tool used in the benchmarking was the initial design for this method, we feel optimization of both the rotating magnetizer and sensor will improve results. We are using these results and finite element modeling to increase signal to noise ratio to improve detection and sizing capability. With the benchmarking results, we are confident that a more robust system can be developed.

Sincerely

Bruce Nestleroth

J. Bruce Nestleroth
Senior Research Scientist
Advanced Energy Systems

JBN/cw

cc: Dr. Daniel Driscoll

Comments on the Comparison of Benchmarks and GTI Results

Albert Teitsma, Stephen F. Takach, Jennifer Fox,
Julie Maupin, Paul Seger, Paul Shuttleworth

Gas Technology Institute
25 October 2004

Introduction
During the week of 13 September 2004, GTI staff came to the West Jefferson facility of Battelle Labs in Columbus, OH to test a prototype RFEC inspection vehicle in 2 sections of 12" pipe. We reported on our test results in a previous document.[1] In this document we comment on the benchmarks reported in "Benchmarking Emerging Pipeline Inspection Technologies" by Stephanie A. Flamberg and Robert C. Gertler (hereafter, the "Answer Key").

Axial Lengths: Comparison of Benchmarks and GTI Results
Table 1 below compares GTI results to the axial length benchmarks contained in the pipe with manufactured corrosion.

	Search		Length of Metal Loss		% Diff from
	Region (in)	**Benchmark (in)**	**GTI Results (in)**	**Difference (in)**	**Benchmark**
Line 1	126-138	3.00	2.60	-0.40	-13.33
Line 1	186-198	1.20	1.00	-0.20	-16.67
Line 1	234-246(a)	1.00	1.10	0.10	10.00
	234-246(b)	1.00	1.00	0.00	0.00
Line 1	282-294	2.00	1.70	-0.30	-15.00
Line 2	102-114	3.00	2.60	-0.40	-13.33
Line 2	198-210	1.50	1.00	-0.50	-33.33
Line 2	246-258	1.40	1.70	0.30	21.43
Line 2	288-300	1.40	1.40	0.00	0.00

Table 1: Axial Length Comparison for Manufactured Defects

We note that the manufactured corrosion in the inspection segment 234"-246" (MC07 in the Answer Key) is designated as a single defect with 2.7" axial length. Figure 2-10 in the Answer Key shows (a photo of the MC07 defects) that this is really 2 distinct, axially-aligned defects, each about 1" in length and separated axially by about ½". In our original report[2], we actually claimed two distinct defects, which match the axial lengths in the photo very well. A raw comparison of the "single-pit" benchmark in Table 2-1 of the Answer Key and our "two-pit" result would be misleading. Our measurements of the axial lengths of the defects are probably no better than about ±20%; that uncertainty compares favorably with the percentage deviation from the benchmarks seen in Table 1.

Circumferential Widths: Comparison of Benchmarks and GTI Results
Table 2 below compares GTI results to the circumferential width benchmarks contained in the pipe with manufactured corrosion.

	Search		Width of Metal Loss		% Diff from
	Region (in)	**Benchmark (in)**	**GTI Results (in)**	**Difference (in)**	**Benchmark**
Line 1	126-138	1.20	1.10	-0.10	-8.33
Line 1	186-198	2.00	1.10	-0.90	-45.00
Line 1	234-246(a)	1.10	0.75	-0.35	-31.82
	234-246(b)	1.10	0.75	-0.35	-31.82
Line 1	282-294	1.50	2.60	1.10	73.33
Line 2	102-114	1.40	3.40	2.00	142.86
Line 2	198-210	1.50	0.75	-0.75	-50.00

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[1] "Report on Tests at Battelle Labs of Pipe Inspection by the Remote Field Eddy Current Technique, 13-16 September 2004", A. Teitsma, S.F. Takach, et al.
[2] Ibid.

Line 2	246-258	3.30	3.40	0.10	3.03
Line 2	288-300	3.00	1.90	-1.10	-36.67

Table 2: Circumferential Width Comparison for Manufactured Defects

The circumferential resolution of the remote field eddy current technique is about 2 times worse than the axial resolution. Thus, that the accuracies of the circumferential widths are generally worse than those for the axial lengths is not unexpected. Note that circumferential accuracy is not critical for determining the severity of pipeline flaws. Both B31G and RSTRENG use length and depth, but not circumferential extent, to determine metal loss severity.

We do make note of two cases. First, our result for the manufactured corrosion in inspection segment 102”-114” is very far off. We believe that this is some anomalous result from our apparatus or our analysis. Second, Figure 2-15 in the Answer Key shows defect MC19. The table of benchmark results states that the circumferential width of this defect is 3”. If we use the scale in the photo to measure the width, we get approximately, 2 3/8”. There are obviously corrections due to projecting a curved surface, on an angle, onto a flat photograph. However, similar comparisons of other photos and the benchmarks in Table 2-1 of the Answer Key do not yield such large discrepancies. We are wondering whether the benchmark is listed correctly in Table 2-1.

Maximum Depths: Comparison of Benchmarks and GTI Results

Table 3 below compares GTI results to the circumferential width benchmarks contained in the pipe with manufactured corrosion. We note that the values along defect line 1 are systematically high and those along defect line 2 are systematically low. This may be caused by changes in the pipe properties from one line of defects to the other.

	Search Region (in)	Benchmark (in)	Max Depth of Metal Loss GTI Results (in)	Difference (in)	Diff as a % of Wall Thickness
Line 1	126-138	0.13	0.24	0.11	32
Line 1	186-198	0.21	0.26	0.05	13
Line 1	234-246(a)	0.17	0.21	0.04	12
	234-246(b)	0.17	0.23	0.06	17
Line 1	282-294	0.29	0.28	-0.01	-3
Line 2	102-114	0.18	0.12	-0.06	-17
Line 2	198-210	0.20	0.14	-0.06	-16
Line 2	246-258	0.27	0.23	-0.04	-12
Line 2	288-300	0.09	0.10	0.01	3

Table 3: Maximum Depth Comparison for Manufactured Defects

The differences are greater than our estimated accuracy 10% of the wall thickness, and in this case only recalibration by separate defect lines would improve the accuracy, something that would not be done during a normal pipeline inspection.

Natural Corrosion Pipe

We reiterate what we stated in the original report --- that during our attempt to complete the scan of the pipe with natural corrosion our apparatus failed, and we were not able to repair it before the end of the test period. We were only able to obtain data from scanning the region from 144” to 154” and the visible region from 82” to 98”.

We did not find any indication of corrosion in the 144” to 154” area of the natural corrosion test pipe. We re-examined the data and again found no clear indication of metal loss. More extensive analysis may find it; however, our analysis methods have not advanced that far yet. We do note that we did report a good scan of the visible corroded area that was not on the Battelle list (82”-98”). We had planned to use it to calibrate any corrosion in the blind section of the pipe, rather than used machined defects. It is known that residual stresses in machined defects change the magnetic properties of the metal and can lead to mis-estimates of defects as large as 70% of the wall thickness, as repeatedly emphasized by the Queen’s University Applied Magnetics Group.

Comments on Benchmark Testing at Pipeline Simulation Facility
September 13–16, 2004

APPLICATION OF REMOTE-FIELD EDDY CURRENT (RFEC) TESTING TO INSPECTION OF UNPIGGABLE PIPELINES

OTHER TRANSACTION AGREEMENT DTRS56-02-T-0001
SwRI® PROJECT 14.06162
OFFICE OF PIPELINE SAFETY
U.S. DEPARTMENT OF TRANSPORTATION

SOUTHWEST RESEARCH INSTITUTE®

November 2004

The following are comments from Southwest Research Institute (SwRI®) related to the benchmark testing of the collapsible remote-field eddy current (RFEC) inspection system. These comments were generated based on comparison of blind test results with the answer keys provided later by the DOE.

Overall, the collapsible RFEC system performed well with few problems during the benchmark testing. Signals were obtained from known calibration flaws in both new and used pipe, and numerous signals were obtained from flaws in blind areas of the pipe.

The DOE requested analysis of the data in specified regions along the length of each pipe. The data requested in each region included start, end, total length, width, and maximum depth of metal loss. The intent of the original SwRI project was to show feasibility of flaw detection with the RFEC system; therefore, procedures for flaw characterization (primarily depth determination) were not included. Nevertheless, to support this benchmarking demonstration, cursory flaw characterization procedures were developed and used in the data analysis. It should be noted that more sophisticated analysis routines could produce more accurate results.

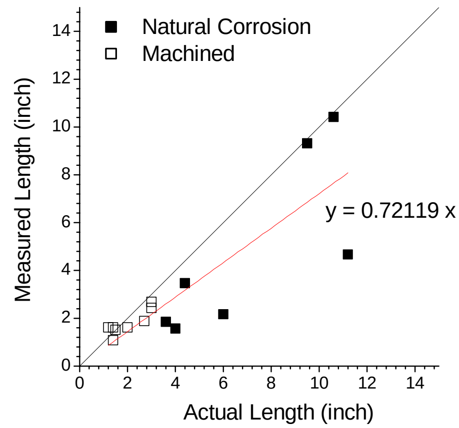
One of the samples was a seam-welded pipe containing manufactured defects; in this sample, all of the flaws were detected, and there were no false calls. The other sample was a seamless pipe with natural corrosion. Several factors made this pipe more difficult to inspect than the seam-welded pipe:

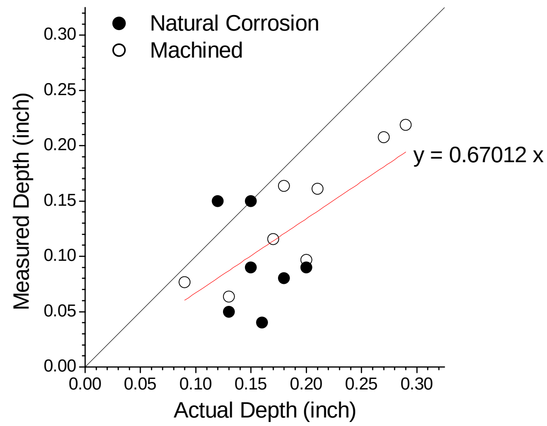
(1) The signal levels were much lower (about 20% of the amplitude of those in the seam-welded pipe—this is likely related to lower permeability);

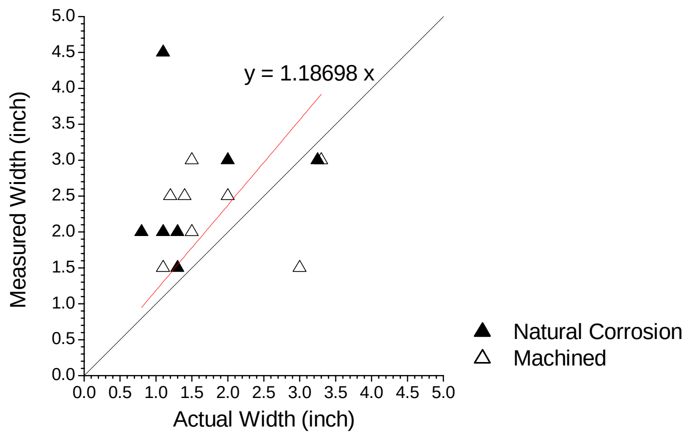
(2) There were significant background fluctuations (caused by the seamless manufacturing process—these are well known in the pipeline inspection industry); and

(3) The shapes of the natural corrosion defects were much more complex than the machined defects.

In spite of these difficulties, very good results were obtained. Overall, one defect was missed, and there was one false call. Comparisons of the measured flaw characteristics (length, width, and depth) based on those determined from the RFEC signals with the actual values provided in the answer key are shown in the following figures for both pipes. The black line (at 45 degrees) is the desired 1:1 relationship, and the red line is the best linear fit. In general, the trends were correct; but in the cases of length and depth, the values measured from the signals underpredicted the true values, and the width was overpredicted. If these data were used to refine the characterization routine, then more accurate results would be obtained, as shown by the red line. Some of the scatter in the width data results from the coarse scan increments used to determine these values. It should be noted that analysis of pipeline corrosion defects for determining maximum operating pressure only considers the depth and length, not the width.







The DOE report indicates that the collapsible RFEC system could not discern between two separate corrosion regions. This is due to a misunderstanding about the reporting requirements. It was not clear from the reporting form that multiple indications were to be reported separately since only maximum depth was requested. Therefore, multiple defect signals were not reported separately, even though the signals show separate defects.

SwRI believes that the results are very promising, given the level of development that went into the RFEC system, particularly the data analysis computations. These results show strong potential for development of a pipe inspection system that can collapse to pass through restrictions and then expand to full diameter to provide a reliable high-sensitivity inspection. SwRI is confident that this system can be readily adapted to a robotic pipe inspection vehicle.

Public Page

DOE National Energy Technology Laboratory Technology Demonstration Program

Report of Results: Blind Guided Wave Verification Exercise Conducted at the Battelle - West Jefferson Facility - September 13 – 17, 2004

The ***guided wave*** exercise describe below was conducted by a research team from PetroChem Inspection Services, Plant Integrity, Ltd., FBS Inc. and The Pennsylvania State University. The objective was to verify the effectiveness of a non-intrusive, nondestructive technology that has been used for pipeline inspections for over four years. This technique only requires access to the outside of the pipe. Refits and/or modifications are not necessary to assess the condition of a pipeline using ***guided wave ultrasonic inspection***. This verification test addressed two primary tasks:

1. To benchmark the test performance of the guided wave method on machined defects of known dimensions placed at measured intervals along a new piece of 12 inch O.D. pipe. The test was conducted "blind" to be graded later by an independent third party.

2. To benchmark the test performance of the guided wave method on actual corrosion defects of known dimensions and locations along a retired piece of 12 inch O.D. pipe. The test was conducted "blind" to be graded later by an independent third party.

Specific zones were selected for evaluation defects or the lack thereof on each of the two pipe samples. The team was to inspect the pipe and report the findings in the zones specified. The results of the exercise will be reported by DOE NETL and RSPA in a separate document. However, preliminary assessment of the pipe defect layouts supplied after the test confirms the viability of the ***guided wave*** technique for inspecting pipelines for corrosion. The test also validates the improvements to this technique that have been incorporated into the inspection equipment over the past two years as a result of research jointly funded by PetroChem Inspection Services, Plant Integrity Ltd. and RSPA.

A key deliverable in this program was the development a "*sound focusing technique*" that was utilized in this exercise. The evaluation of the results will show that this development has improved the sensitivity of the guided wave technique significantly. The "*sound focusing technique*" also added the ability to determine the position of a defect relative to the pipe circumference.

Guided wave inspections are currently utilized by pipeline operators on existing pipelines to assess them for corrosion.

Questions concerning this project should be directed to the Team Project Manager as follows:

Scott Lebsack
PetroChem Inspection Services
8211 La Porte Freeway
Houston, TX 77012
936-689-3554
aslebsack@houston.rr.com

Comments on the Pipeline Inspection Technologies Demonstration Report

Dual Magnetization Level MFL for Assessment of Mechanical Damage

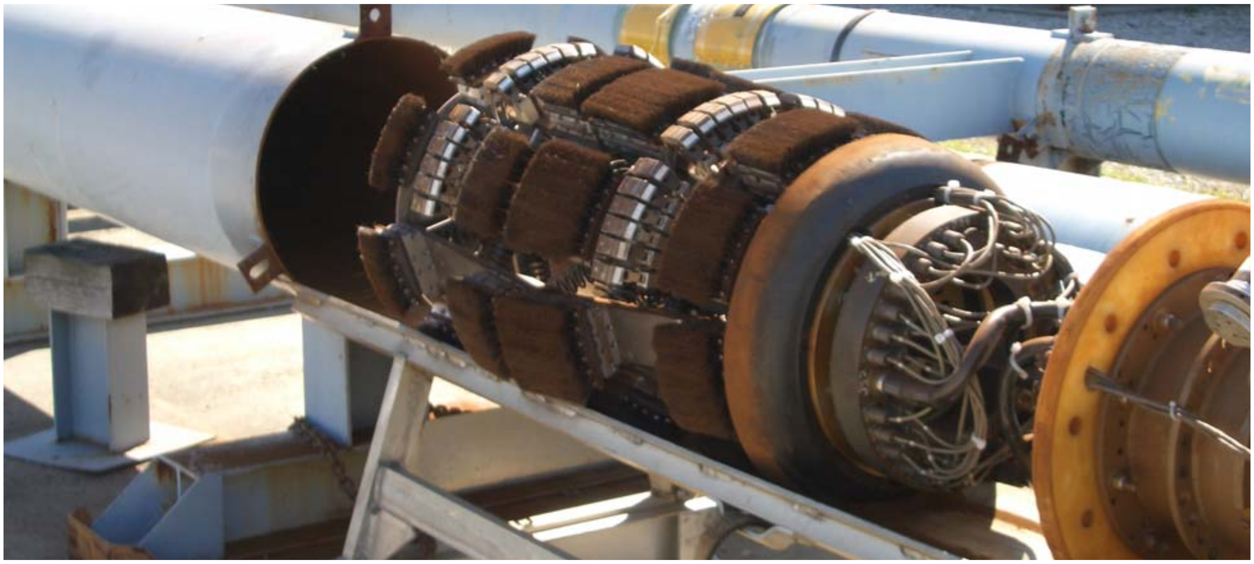
Agreement DOT RSPA DTRS56-02-T-0002

Bruce Nestleroth, Battelle

The dual magnetization magnetic flux leakage (MFL) technology is in the final stages of development. The initial concept was developed in the mid 1990's and subsequent projects have refined this technology. The goal of this technology is to develop a magnetic flux leakage (MFL) inspection tool that detects and sizes both metal loss and mechanical damage. An initial design concept for an MFL tool for mechanical damage employed two magnetizers, operating at both high and low field levels. However, it was not commercially accepted due to its extended length and complexity.

The design currently being developed involves a single magnetizer for detection of both corrosion and mechanical damage anomalies. The latest design includes features that minimize the effect of inspection variables such as velocity and the ability to pass tight bends. The magnetizer is simpler build and use, thus increasing the commercialization potential. In-line inspection for mechanical damage alone has limited commercial potential since an additional inspection would have to be conducted to detect corrosion defects. However coupling mechanical damage assessment with a routine corrosion inspection without adding complexity could change the inspection market. The newly developed inspection tool, shown below, has been run through a pull rig at speeds up to 6 mph and will be tested under pressurized conditions in November 2004.

The next step in the development of this technology is testing in an operational pipeline. We have begun discussions with a pipeline company and an inspection tool manufacturer to organize and conduct such a test.

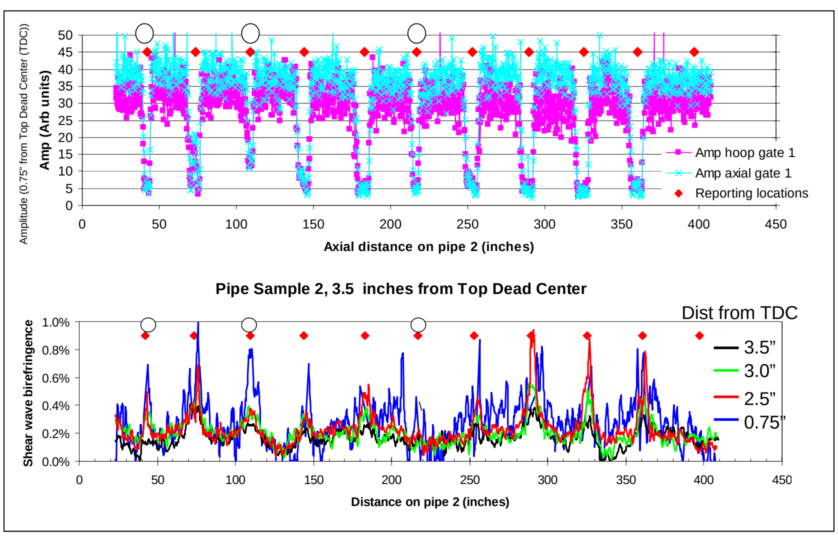


Dual magnetization inspection tool

Comments on NETL field test
Submitted by Paul D. Panetta from Pacific Northwest National Laboratory and George Alers from EMAT Ultrasonics

PNNL participated in the pipeline inspection demonstration held at Battelle on September 13-17, 2004. The focus of our work is to identify and classify third party damage based on ultrasonic measurements of changes in the material properties due dents and bends. The results were excellent for classifying the degree of deformation in the supplied pipes.

The results from pipe 2 are especially encouraging. The pipes were scanned along the axis from the interior utilizing a non-contact Electromagnetic Acoustic Transducer (EMAT). The EMAT generated a wave which traveled through the thickness of the pipe every 0.2" along the axis. The figure below shown the amplitude of the ultrasonic wave as a function of position along the axis of pipe 2 that was 0.75" along the hoop direction from top dead center. The bottom figure shows an ultrasonic parameters called the shear wave birefringence, which is independent of the thickness of the pipe. This aspect is important since the action of deforming the pipe causes the pipe to become thinner and our goal is to determine the degree of residual stress and plastic strain due to the mechanical damage not just the thickness of the pipe. Our classification or ranking of the dent severity is in the bottom figure below. We correctly assessed the degree of deformation on 8 out of the 9 reporting locations. Our assessment for locations R04 and R05 we reversed and our assessment for R09 should have been 2 rather than 2.5. The reason for the deviation for R09 was due to the fact the damage from the indenter at locations R08 and R10 was severe and extended over a large region, causing additional damage near location R09.

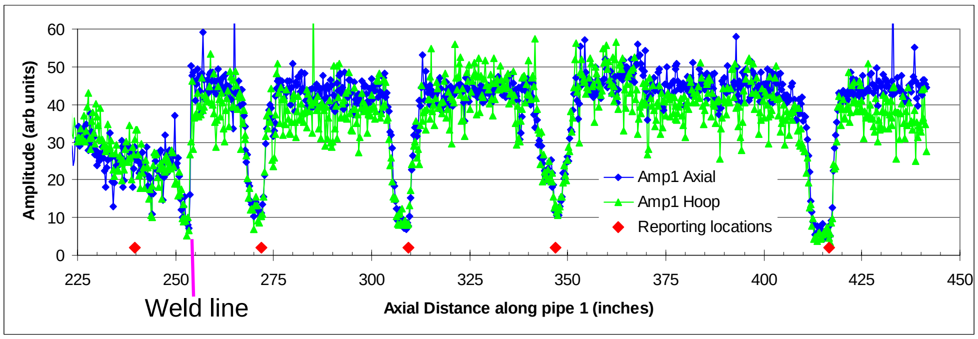


Reporting locations	R01 42.25"	R02 73.25"	R03 109.25"	R04 144"	R05 183"	R06 217"	R07 253"	R08 289.5"	R09 325"	R10 360.5"	R11 397"
Ranking	1	2	1	2	3	1	2	3	2.5	3	0

0 = No dent
1 = Least Severe
2 = Moderate Severity
3 = Most Severe

Figure 1. The amplitude of the ultrasonic signal as a function of axial distance on pipe 2 (top) and the shear wave birefringence as a function of axial distance on pipe 2. The red diamonds are the reporting locations.

Our assessment of pipe 1 was complicated due to the complex processing history of the pipe. After denting Pipe 1, it was ruptured during a pressure test, releasing some of the residual stress in the region of the calibration defects. In addition, the pipe was cut and a portion was rotated to align defects, then welded back together. The result was a set of calibration defects that existed in a section that was different than the reporting locations. Even with these complications our assessment was reasonably accurate, with our ranking for Q4 and Q5 correlating nicely with the degree of damage. Figure 2 shows the amplitude dot eh ultrasonic signal along the axis of pipe 2 for two different polarization of the shear wave. The location of the dents is clearly visible as is the difference in the material properties as the EMAT moved across the weld line of the pipes at ~250 inches.



Reporting locations	Q6 239.5"	Q5 272"	Q4 309.5"	Q3 347"	Q1 416.5
Ranking	**no ranking**	**1.5**	**2**	**1**	**3**

0 = No dent
1 = Least Severe
2 = Moderate Severity
3 = Most Severe

Figure 2. The amplitude of the ultrasonic signal as a function of axial distance on pipe 1 The red diamonds are the reporting locations.

These results are very encouraging and show that our ultrasonic measurements can accurately asses the damage in dented pipelines. The ultrasonic measurements are sensitive the degree of stress and strain in the specimens and can be applied to bent sections as well as dented regions. In addition, these EMAT sensors can be configured for small pipes (~4" diameter) and are conducive for attaching to PIGs and robots.

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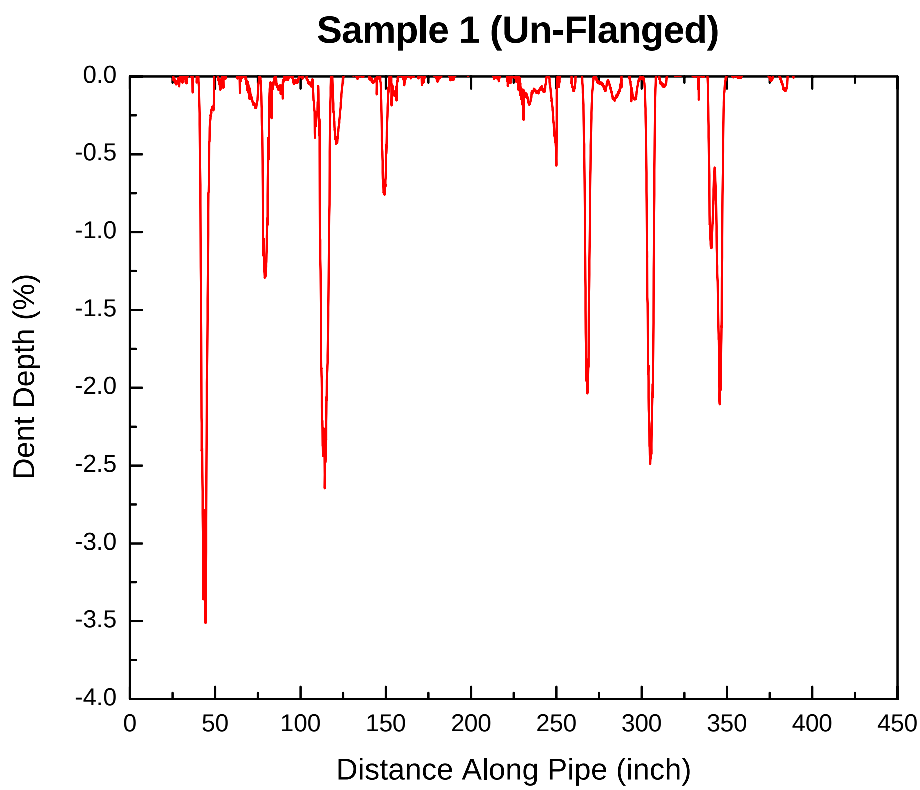
geoalers@charter.net

Multipurpose Deformation Sensor

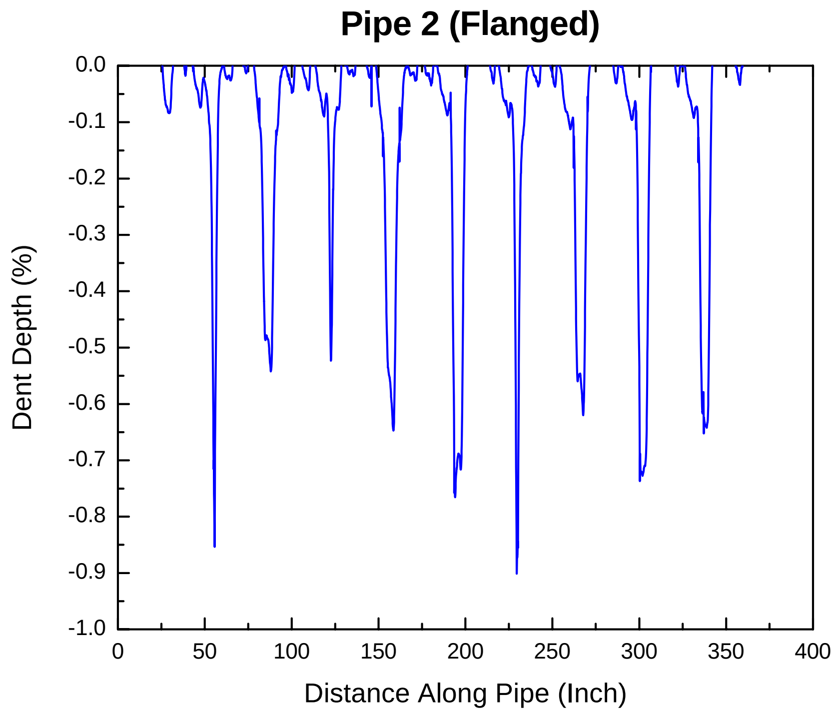
Dipen N. Sinha
Los Alamos National Laboratory

The multipurpose deformation Sensor designed by LANL included three separate types of measurements combined into one system. For deformation detection, it used an optical laser line imaging technique and also an acoustic phase detection technique. LANL had also designed an ultrasonic wall thickness measurement technique for this test but was not able to use it because of equipment failure.

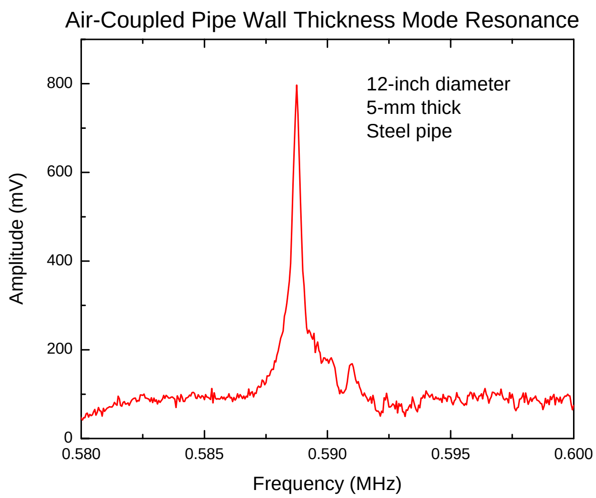
As regards to reporting erroneously higher dent depth, we found our mistake to be wrong calibration. In fact, all results got multiplied by a factor of 1.6. The raw data obtained from the tests on the two pipes are included below and these are closer to the benchmark values as it should have been.



The raw data above indicates that the measured dent depth for Sample 1 never exceeded 3.5% consistent with the benchmark information. The figure below shows the raw data from Sample 2.



For completeness, since several observers at the test facility had expressed an interest in our ultrasonic wall thickness measurement, an example data from laboratory test on a steel pipe at **ambient** pressure and from a stand-off distance of 2-cm (air coupled) is shown below. The resonance frequency is a direct measure of wall thickness.



ORNL Results and the Actual Flaw Locations

The discrepancy between the ORNL results and the actual results can be summarized into six distinct issues: Width of EMAT coverage, Weld Effect, Length of Crack Size, Depth of Crack, Presence of Tar or Corrosion, and Interpretation of Analytical Results.

1) EMAT Coverage: When the EMAT moves through the pipe it is covering a region of 9” along the circumference. The sensor centered on a scan line covers 4.5” on either sides of the line. Hence scans on line 1, 2, and 3 have intersecting regions that are also scanned during other scans as depicted in Figure 1.

2) Weld Effect: Welds create reflections of ultrasonic waves that make it difficult to detect cracks near it. The current EMATs are relatively big and one way to reduce the weld effect will be to reduce the size of the EMATs. Detecting SCCs near welds is something left to be accomplished later.

3) Length of Crack Size: The length of a crack has no bearing on the signal if it is not deep enough for the signal to interact with it. Hence, in detecting the location of the cracks, the detected length corresponds to the location in a particular crack where the depth has crossed a specific threshold. This may skew the crack location between measured and predicted results (see Figure 2). Also, the predicted crack length is always larger than the actual size due to the size of the EMAT. An EMAT going directly over a 0.5” hole will result in signal disruption for 2” (active area of the EMAT is 1.5” by 1.5”). Currently we are performing experiments to arrive at a compensating factor to correct for this.

4) Depth of Crack: The EMATs effectiveness in detecting a crack is directly proportional to the ***depth*** of the crack. The ***width*** of a crack does have an effect on the signal, but the system will not be able to detect differences between two cracks or one wide crack if all other parameters are held the same. If the depth of a crack changes in a particular flaw location, the EMAT’s greatest response will be centered around the deepest crack location and not the center of the gross size of the crack. Hence, the location of the predicted and measured crack (using liquid florescent magnetic particle inspection) may differ by the width of the EMAT or more as explained above. Since liquid florescent magnetic particle inspection does not predict the depth of the crack, a liquid penetrant X-ray is needed to correlate the results obtained. For cracks smaller than 15% of the pipe wall thickness – the current EMATs cannot detect the location of the defects.

5) Presence of tar or corrosion: EMAT signals are greatly attenuated by tar. There was tar present at the periphery of the covered regions of the pipe where these experiments were conducted. If there are locations on the black paper covered areas with tar patches, the sensors will record it as a flaw and give false results. The presence of corrosion also yields similar results. The projects aim is to have the ability to differentiate between the various types of defect.

6) Interpretation of analytical results: As can be seen in Figure 2, SCC6 is seen, but difficult to interpret as a flaw. An improved algorithm to detect flaws can hopefully extract the flaw information better. Also, while investigating the discrepancies on results obtained from Line 3, an error was discovered in the flaw decision algorithm. This error has since been corrected.

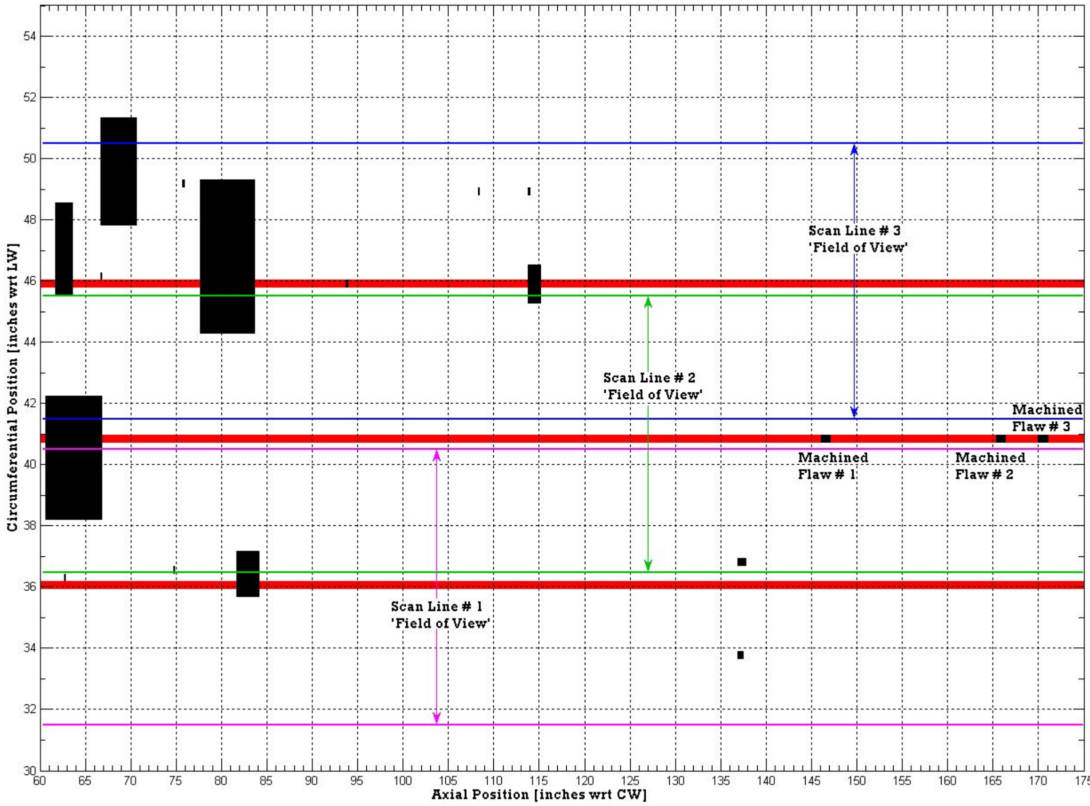


Figure 1. Flaw Location and the EMAT Scan Lines on test pipe at Battelle

Table 1 below gives an itemized summary of the discrepancies for the ORNL reported results.

Table 1. Resolution between predicted and measured results

Defect #	Measured	Predicted	Comments
SCC1	63” -1/4”	----	Reason 1
SCC2	75’ -1/4”	70”-77”	Predicted larger due to reason 3 & skewed due to 4 (flaw 8)
SCC3	82”-84.5”	82”-90”	Predicted larger due to reason 3 & skewed due to 4 (flaw 7)
SCC4	None	96”-99”	Probably reason 5
SCC5	None	None	
SCC6	137”-138”	None	Probably due to reason 4
SCC7	61”-67”	69”-72”	Predicted correct (reasons 1,2&3) (flaw 11,12,14)
SCC8	None	75”-80” &80”-90”	75”-Reasons 1 and 3 (flaw 8). 80”- Reason 3 (flaw 7)
SCC9	None	94”-104”	Probably reason 5
SCC10	None	106”-107.5” & 109”-112”	106”-probably reason 5 109” – Reasons 1& 3 (flaw 3)
SCC11	None	127”-132”	Probably reason 5
SCC12	62”-71”	64”-66”	Reason 6 –(flaw 14, 12, 13)
SCC13	78”-84”	None	Probably reason 4
SCC14	94”-1/4”	90”-93” & 97”-102”	Reason 6
SCC15	114-115.5”	106”-110” & 113.5”–120”	106” – reason 1(flaw 5) 113.5” – reasons 4 &6 (flaw 4&3)
SCC16	None	127”-131”	Reason 6

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