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Pacific Northwest
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Technical Letter Report

Preliminary Assessment of NDE Methods on Inspection of HDPE Butt Fusion Piping Joints for Lack of Fusion

JCN N6398, Task 2D

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May 2008

Prepared for the U.S. Nuclear Regulatory Commission
under U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The U.S. Nuclear Regulatory Commission (NRC) has a multi-year program at the Pacific Northwest National Laboratory (PNNL) to provide engineering studies and assessments of issues related to the use of nondestructive evaluation (NDE) methods for the reliable inspection of nuclear power plant components. As part of this program, there is a subtask 2D that was set up to address an assessment of issues related to the NDE of high density polyethylene (HDPE) butt fusion joints. This work is being driven by the nuclear industry wanting to employ HDPE materials in nuclear power plant systems. This being a new material for use in nuclear applications, there are a number of issues related to its use and potential problems that may evolve.

The industry is pursuing ASME Code Case N-755 entitled "Use of Polyethylene (PE) Plastic Pipe for Section III, Division 1, Construction and Section XI Repair/Replacement Activities" that contains the requirements for nuclear power plant applications of HDPE. This Code Case requires that inspections be performed after the fusion joint is made by visually examining the bead that is formed and conducting a pressure test of the joint. These tests are only effective in general if gross through-wall flaws exist in the fusion joint. The NRC wants to know whether a volumetric inspection can be conducted on the fusion joint that will reliably detect lack-of-fusion conditions that may be produced during joint fusing. The NRC has requested that the work that PNNL is conducting be provided to assist them in resolving this inspection issue of whether effective volumetric NDE can be conducted to detect lack of fusion (LOF) in the butt HDPE joints.

PNNL had 24 HDPE pipe specimens manufactured of 3408 material to contain LOF conditions that could be used to assess the effectiveness of NDE in detecting the LOF. Basic ultrasonic material properties were measured and used to guide the use of phased arrays and time-of-flight diffraction (TOFD) work that was conducted. Millimeter (mm) waves were also used to inspect these assemblies. Fluor and NDE Innovations, Inc. conducted TOFD inspections using their commercially available equipment on all 24 specimens. These NDE inspection results were reviewed and several of the specimens were selected for destructive evaluation using a microtome to slice small blocks of blank and fusion joint material. This interim report provides a status/summary of the work that has been conducted to date. In the areas selected for destructive testing where there were strong acoustic responses, LOF was verified. In areas where there were no NDE responses, no LOF was found. It needs to be noted that only a small amount of material has been destructively characterized at this point and further work is planned to determine if these trends hold up. Some of the material from three of the assemblies was sent off for mechanical testing but the results were not available to be included in this status report.

The initial work shows that at least some of the LOF is providing NDE responses that have been verified through destructive testing. Thus, there is promise that a volumetric examination can be conducted on HDPE butt fusion joints. The future work will lead to quantifying what various NDE methods can detect, what they miss, and what they incorrectly characterize as defective.

Glossary

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
DE	destructive evaluation
DIPS	ductile iron pipe size
DR	dimension ratio (pipe's average outside diameter divided by the minimum wall thickness)
Emc^2	Engineering Mechanics Corporation of Columbus
FMCW	frequency modulated continuous wave
HDPE	high density polyethylene
ID	inner diameter
IPS	iron pipe size
ISO	International Organization for Standards
LOF	lack of fusion
mm	millimeter
MWD	molecular weight distribution
NDE	nondestructive evaluation
NRC	Nuclear Regulatory Commission
OD	outer diameter
PA	phased array
PE	polyethylene
PENT	Pennsylvania Notch Test
PNNL	Pacific Northwest National Laboratory
PPI	Plastic Pipe Institute
PT	Liquid Penetrant Testing
TLR	technical letter report
TOFD	time-of-flight diffraction
UT	ultrasonic testing
VT	visual testing
YIG	yttrium-iron-garnet

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1.0 Background

The U.S. Nuclear Regulatory Commission (NRC) has a multi-year program at the Pacific Northwest National Laboratory (PNNL) to provide engineering studies and assessments of issues related to the use of nondestructive evaluation (NDE) methods for the reliable inspection of nuclear power plant components. As part of this program, there is a subtask 2D that was set up to address an assessment of issues related to the NDE of high density polyethylene (HDPE) butt fusion joints. This work is being driven by the nuclear industry wanting to employ HDPE materials in nuclear power plant systems. This being a new material for use in nuclear applications, there are a number of issues related to its use and potential problems that may evolve.

PNNL conducted work under a previous project, JCN-Y6604, with two major activities being pursued. One of these activities was to work with Dr. Prabhat Krishnaswamy of Engineering Mechanics Corporation of Columbus (Emc^2) to develop a technical letter report (TLR) entitled *Review of Literature on the Use of Polyethylene (PE) Piping in Nuclear Power Plant Safety-Related Class 3 Service Water Systems*, dated October 27, 2006. This TLR contained an extensive background on HDPE, its use in many applications along with the limited use in nuclear applications. PNNL provided input regarding the review of literature on NDE studies that had been conducted and reported in the open literature on the effectiveness of inspecting HDPE fusion joints.

The second major activity that PNNL also conducted was a literature review of published results on the effectiveness of NDE methods to detect flaws in polyethylene (PE) pipe joints. The letter report was submitted to the NRC on December 1, 2006. The significant item about this second TLR was that it spelled out the direction of research work that PNNL needed to pursue in order to try to fill in the gaps that were identified by the literature reviews. This current TLR is an update on the work that PNNL has been conducting to assess NDE methods and quantification of their effectiveness for the inspection of HDPE butt fusion joints.

The major industry driving force concerns ASME Code Case N-755 that is the basis for and contains requirements for nuclear power plant applications of HDPE. This Code Case requires that inspections be performed after the fusion joint is made by visually examining the bead that is formed and conducting a pressure test of the joint. These tests are only effective in general if gross through-wall flaws exist in the fusion joint. The NRC wants to know whether a volumetric inspection can be conducted on the fusion joint that will reliably detect lack-of-fusion conditions that may be produced during joint fusing. The NRC has requested that the work that PNNL is conducting be provided to assist them in resolving this inspection issue of whether effective volumetric NDE can be conducted to detect lack of fusion (LOF) in the butt HDPE joints.

This interim TLR presents the work that PNNL conducted and Section 2.0 covers the material properties of the fusion joints that PNNL had manufactured for the studies. Section 3.0 addresses the NDE methods that were evaluated in this initial assessment of NDE effectiveness to detect lack of fusion conditions and describes the mechanical testing planned for both NDE flawed areas and non-flawed areas. Section 4.0 then presents destructive testing results for some of the test samples that were used in these studies, and Section 5.0 provides a discussion of the results, and conclusions that can be drawn at this time. The work in progress and unresolved issues are discussed in Section 6.0.

2.0 HDPE Test Samples

2.1 Material Properties of HDPE

Polyethylene is a thermoplastic material meaning that it can be re-melted with heat to reform, recycle, or shape the material. It was invented in 1933 and at that time could only be formed under high pressures. In the 1950s a low pressure technique made it safer and more economical to produce. Polyethylene resins are characterized by their density, molecular weight, and molecular weight distribution (PPI). These three characteristics in turn determine behavior of the material which is discussed next.

The density of the material is determined by the amount of side branching (from the bonding of short polymer chains to the main long polymer chain). The more branching, the less dense the material is. Density or packing is also viewed in terms of the presence of a crystal structure which is tightly packed and ordered or the absence of such a structure which is an amorphous state. Polyethylene has both crystal and amorphous regions and is called a semicrystaline material. Resin density influences the physical properties of the material such as tensile yield strength and stiffness; both are directly proportional to density.

The molecular weight of polyethylene is an average value of all atomic weights of the atoms making up the molecule. This property directly influences the durability of the material. Long-term strength, toughness, ductility, and fatigue-endurance improve with increasing molecular weight. The molecular weight also affects the ability of the material to flow in the molten state, characterized by the melt index or melt flow rate. The melt index is inversely related to the molecular weight.

The molecular weight distribution (MWD) is generally Gaussian- or bell-shaped. A narrow distribution indicates a material with similar molecular weights. Such a material will crystallize at a faster and more uniform rate and will lead to less warpage. A broad distribution due to a wider range of chain lengths in the material is desirable for environmental stress crack resistance, impact resistance, and processability. More recently materials with bimodal distributions are formed by blending two different polymer populations to give both good physical properties and favorable processing characteristics.

The ASTM specification D3350-06, *Standard Specification for Polyethylene Plastics Pipe and Fittings Materials* (ASTM D3350-06), documents the identification of polyethylene materials according to a cell classification system. Based on this standard the density, melt index, flexural modulus, tensile strength at yield, slow crack growth (SCG) resistance, and hydrostatic strength are classified. The test method for determining SCG resistance is known as the Pennsylvania Notch Test (PENT) and is documented in ASTM F1473-07, *Standard Test Method for Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins* (ASTM F1473-07). University of Pennsylvania researchers found that one hour of PENT approximated 13 years of service life (Performance Pipe 2007). In referencing a pipe material the naming starts with PE for polyethylene, followed by 4 numbers. The first number designates the density and the second the slow crack growth resistance. The last two digits indicate the hydrostatic design stress divided by 100. Materials involved in the PNNL study thus far have been PE3408 and PE4710. By the classification system the PE3408 material has a density in the cell class 3, 0.941–0.947 gm/cm^3, a SCG cell class 4, PENT value > 10 hours, and an 800 psi hydrostatic design stress for water at 73 degrees Fahrenheit. The PE4710 material has a density in the cell class 4, 0.948–0.955 gm/cm^3, SCG cell class 7, PENT value > 500 hours, and a hydrostatic design stress of 1000 psi. In addition, the 4710 material is bimodal.

PE pipe is additionally classified based on outside diameter as specified in the ASTM specification F714-06a, *Standard Specification for Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Outside Diameter* (ASTM F714-06a). Three standard outside-diameter pipe sizing systems are discussed. These systems are the International Organization for Standards (ISO) metric system, the Iron Pipe System (IPS), and the Ductile Iron Pipe System (DIPS). A relationship between the pipe stress, pressure, pipe size, and wall thickness is given. The dimension ratio (DR) of a pipe is defined as the pipe's average outside diameter divided by the minimum wall thickness. This DR is inversely related to the internal pipe pressure. Tables of pipes listed by DR values are available and show pressure ratings for DR values and PE material types, i.e. 3408 or 4710.

HDPE pipe material obtained for nondestructive evaluation at PNNL included a series of 24 assemblies of 3408 butt-fusion joints and two pipe sections of 4710 material, one with a yellow stripe. Pipes are color-coded for use by the American Public Work Association standard and yellow indicates a gas, oil, and steam type of application. All pipe material was 12-inch (30.5-cm) IPS DR11. The 4710 black pipe material was made on October 8, 2007, and the 3408 material was made on April 7, 2005, as noted from the print line information on the pipe. Some fundamental acoustic material properties of the HDPE were thought to be needed to understand how to inspect these materials with ultrasound. In order to make these measurements, rectangular sections of material were cut from the base material in each pipe. Smooth and parallel sides were machined on the three pairs of faces. From such a test piece the acoustic velocity and attenuation were measured in the through-wall direction of the pipe (inner diameter, ID), from the radial (R) or circumferential direction and from the axial (A) direction of the pipe. The results are shown in Table 2.1. Both attenuation and velocity values are similar in these materials. They are also comparable in the three orthogonal directions: through-wall, radial/circumferential, and axial.

Table 2.1. HDPE Pipe Characteristics, 2.25-MHz, 0.375-inch (0.95-cm) Diameter Transducer, Longitudinal Wave

	Velocity (in./µsec) [mm/µsec]			**Attenuation (dB/in.) [dB/cm]**		
Pipe Material	**3408**	**4710**	**4710 Yellow Stripe**	**3408**	**4710**	**4710 Yellow Stripe**
Face[(a)]						
ID	0.092 [2.34]	0.091 [2.31]	0.092 [2.34]	21 [8.3]	18-21 [7.1–8.3]	16-20 [6.3–7.9]
R	0.088 [2.24]	0.090 [2.29]	0.092 [2.34]	14 [5.5]	15 [5.9]	14 [5.5]
A	0.088 [2.24]	0.090 [2.29]	0.091 [2.31]	15 [5.9]	15 [5.9]	16 [6.3]
(a) ID face – pipe thickness; R face – radial (circumferential) direction; A face – axial direction.						

Additionally in 3408 the frequency response evaluation showed that approximately 1.3–1.8 MHz was returned through 2 inches (5.08 cm) of material (round trip path) from a 2.25-MHz transducer. At 5 MHz incident, the return was 2.2 MHz, and at 10 MHz the return was 3.5 MHz showing the loss of the main excitation frequency of the probe. A shear wave velocity in the 3408 material was measured at

0.035 in./µsec (0.889 mm/µsec) in the through-wall direction (from the ID face). Only one echo was detected so the attenuation was not measured but it is assumed to be large.

2.2 Ultrasonic Transducer Wedge Materials

Various wedge materials were investigated for use in ultrasonic contact testing of the pipe. The measured velocity and attenuation values are listed in Table 2.2. Low-density PE was also considered and has a slower velocity than HDPE but its attenuation is large. The challenge is to find a material with a slower velocity in order to produce an ultrasonic beam over a range of angles as determined with Snell's Law but also having low attenuation. For both time-of-flight diffraction (TOFD) and phased-array (PA) inspection one would like to insonify the material at angles up to 60 degrees or greater. Dr. Mark Lozev at the Edison Welding Institute uses either Rexolite or Plexiglas. Rexolite with its lower attenuation was chosen for the wedge material in the TOFD examinations at PNNL. Plexiglas was not considered because of its higher velocity.

Table 2.2. Wedge Material Properties

Wedge Material	Velocity (in/µsec) [mm/µsec]	Attenuation (dB/inch) [dB/cm]
Rexolite	0.092 [2.34]	8 [3.2]
Teflon	0.051 [1.30]	21 [8.3]
Delrin	0.098 [2.49]	23 [9.1]
Wax	0.091 [2.31]	28 [11.0]
Indium	0.102 [2.59]	10 [3.9]
Plexiglas A	0.109 [2.76]	

2.3 Fused Pipes

James Craig at McElroy was contracted to heat fuse a series of butt welds in 3408 pipe containing a variety of kissing bond–LOF conditions. This kissing bond or LOF is characterized by contact in the joint between the two compressed surfaces, but there are no or a reduction in the number of molecular ties across the interface. This bond could also be defined as the perfect contact between two surfaces which transmit no shear stress so it is lacking in strength (Brotherhood et al. 2003). Six fusion conditions were selected with the parameters shown in Table 2.3. Four pipes at each condition were made. The sixth condition is the ideal or control condition and is fused according to the ASTM F2620 Procedure (ASTM F2620-06). The other five conditions are expected to produce LOF in the pipe welds. Several of the pipes are shown in Figure 2.1. Each welded section is approximately 2 feet (61 cm) long.

Table 2.3. HDPE 3408 Pipe Fusion Conditions to Produce Lack of Fusion

Fusion Condition	Description
1	Fusion pressure during heat cycle
2	Fusion pressure during heat cycle plus 20 sec open/close
3	Fusion pressure during heat cycle plus 10 sec open/close
4	Long open/close time only (20 sec)
5	Grease in joint area – print line area after heating
6	Good joint fused with 75 psi interfacial pressure and 425°F heater surface temperature

Figure 2.1. Several of the Butt Welded 3408 Pipes are Shown with 12-inch (30.5-cm) Scales on the Center Pipe, One in the Horizontal Direction and One in the Vertical. The pipe assemblies are approximately 2 feet (61 cm) long.

3.0 NDE Methods Studied in This Assessment

The NDE inspection methods evaluated for fusion butt weld assessment were visual testing (VT), millimeter wave, and ultrasonic testing (UT). The fusion zone groove between the weld beads was examined visually and suspect areas were photographed. The bead width and height were also measured. A preliminary evaluation with millimeter wave imaging was conducted. Most of the effort was directed towards evaluating the welds with ultrasonic TOFD and PA techniques. Preliminary results are presented.

3.1 Visual Testing

3.1.1 Weld Bead Profile

According to the ASTM standard F2620 (ASTM F2620-06) on heat fusion joining of PE pipe, the weld bead should be rounded and uniform in size and shape on both sides and roll back to the pipe surface. The width of the beads should be approximately 2 to 2½ times the bead height. The v-groove between the beads should not be deeper than half the bead height (see Figure 3.1).

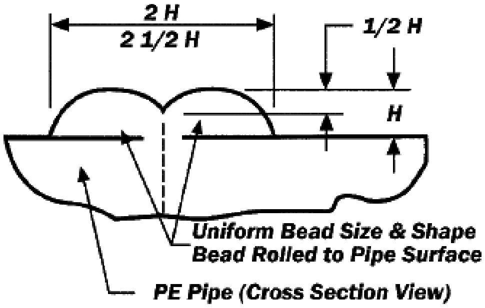

Figure 3.1. Butt Fusion Bead Dimensional Guideline (ASTM F2620-06)

The left and right weld bead widths, total width, and left and right bead heights were measured for the 24 fused pipes at eight positions around the pipe or approximately every 45 degrees. Figure 3.2 shows from left to right, two profiles taken from one pipe in each of the six fusion conditions. The top profile was taken at 0 degree, the print line of the pipe, and the lower profile at 135 degrees. Notice that the beads in conditions 1–3 are smaller than the beads fused with conditions 4–6. The average difference in left and right bead width and height was 0.67 and 0.34 mm, respectively, with no apparent correlation between the good four welds and the other welds expected to contain LOF. Also calculated was the average bead width-to-height ratio, which should be in the 2 to 2½ range. Figure 3.3 shows the results for this calculation for each of the 24 pipes. Joints fused with fusion pressure during the heat cycle, conditions 1–3, were out of bounds in the width-to-height ratio and the beads were smaller in these joints as already mentioned. With fusion pressure during the heat cycle, the weld bead width was approximately 15 percent smaller and the bead height 32 percent smaller than a bead with a normal heat cycle.

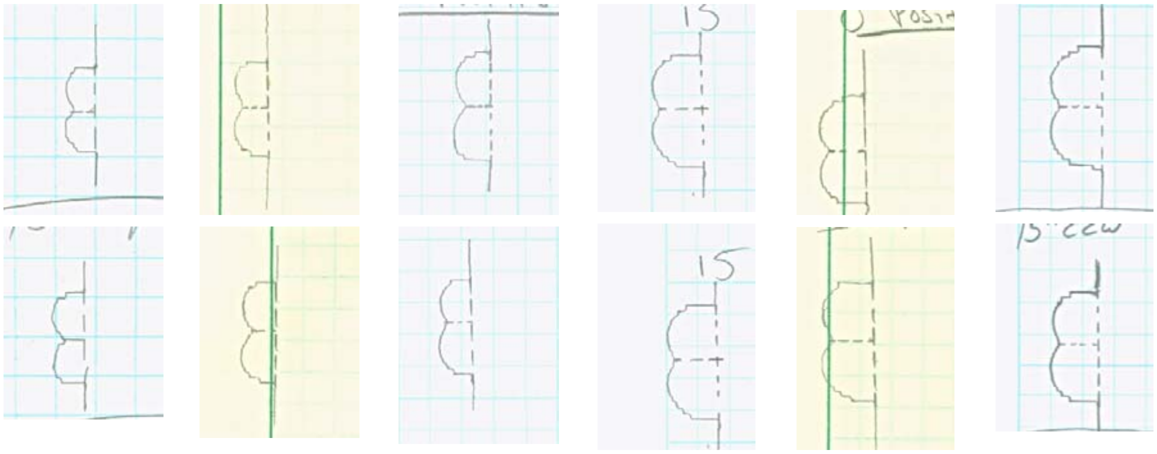

Figure 3.2. Weld Bead Profiles Taken Left to Right from a Pipe Fused at Conditions 1–6. The top profile was acquired at zero degrees and the bottom at 135 degrees. The grid spacing is 0.25 inch (0.64 cm).

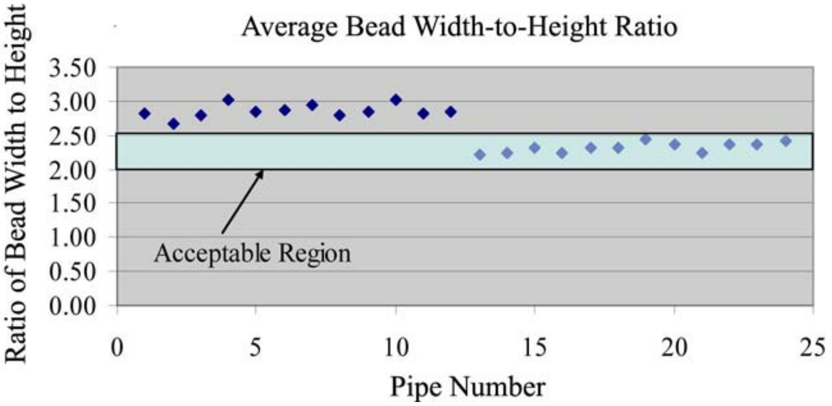

Figure 3.3. Bead Width-to-Height Ratio Comparison for the 24 Fused Pipes

3.1.2 Inspection of the Fusion Zone

The weld bead fusion zone from the outer diameter (OD) of each pipe was visually inspected and areas with anomalies were photographed. Typical anomalies were voids or dimples in the v-groove between the weld beads as shown in Figure 3.4. In general there was little or no correlation between the VT results and the ultrasonic TOFD data from the Fluor/NDT Innovations, Inc. workshop, which is discussed later. As an example, one pipe contained many TOFD indications with 70 percent of the pipe fusion zone showing flaw signals. From the VT results, only four small defective areas were noted in the fusion joint from an OD inspection.

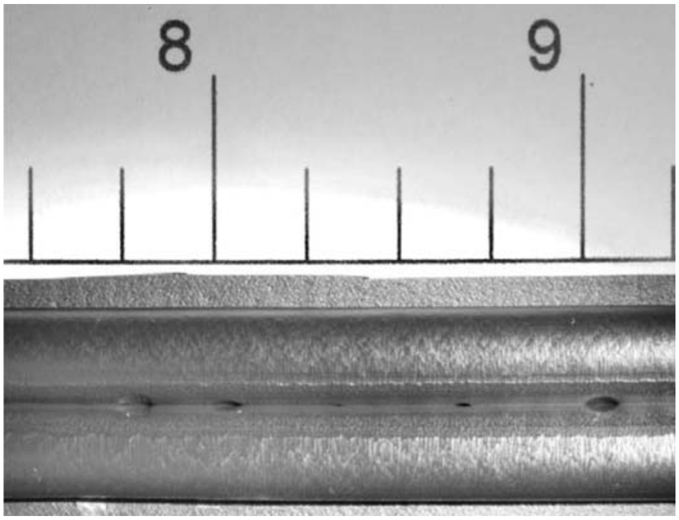

Figure 3.4. Fusion Zone Anomalies. The scale is in inches (1 inch = 2.54 cm).

3.2 Millimeter Wave

In November 2007 experiments were performed at PNNL to explore application of existing mmWave imaging technology at PNNL on HDPE pipe fusion joint inspection. The strategy was to implement PNNL's three-dimensional cylindrical imaging method that has been successfully deployed in other rapid inspection applications (Sheen et al. 1999; Sheen et al. 2000; Sheen et al. 2006). In order to efficiently use resources and personnel, this initial effort was limited to utilizing available transceivers and components in the mm-Wave laboratory. A scanner capable of performing cylindrical scans was available in the laboratory with two transceivers. The transceivers described in this test are Ku-Band (10–20 GHz) and U-Band (40–60GHz). Both use yttrium-iron-garnet (YIG) oscillators in a frequency modulated continuous wave (FMCW) mode.

3.2.1 Ku-Band Cylindrical Tests of HDPE Pipe Samples

The initial part of this test implemented the lower frequency transceiver. The Ku-Band illumination has a center frequency wavelength of 2 cm in free space. The measured wave speed in the HDPE samples was 1.8×10^8 m/sec (7.09×10^9 in./sec) (60% free space). Therefore, the wavelength in the material is about 1.2 cm (0.47 in.) in the HDPE material. The wavelength and effective aperture (F-number) determine the lateral resolution. In this case 1.2-cm (0.47-in.) lateral resolution can be expected. The transceiver bandwidth determines the down-range (depth) resolution. The 10-GHz bandwidth calculates to about 1.8-cm (0.71-in.) depth resolution.

A sub-set of the pipe samples was chosen to provide a diverse set of joint conditions. Also it was determined the samples would not be modified in these tests. For example, the outside bead would not be removed.

Figure 3.5 shows a picture of this initial setup. A number of configurations were employed in this lower frequency test. Polarization tests with co-Pol and cross-Pol Circular and co-Pol and cross-Pol linear were tried. A cylindrical reflector was placed in the center to act as a mirror.

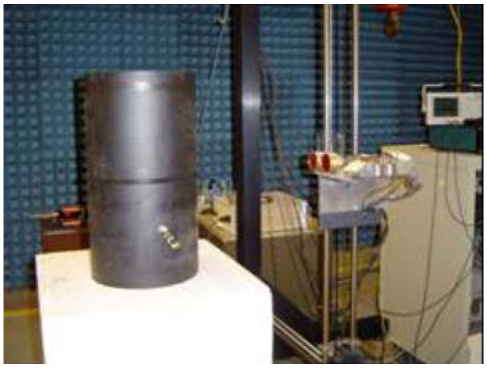

Figure 3.5. Ku-Band mmWave Laboratory System Setup

The conclusion of this effort was that linear co-polarization provided the best results, but that higher frequency would be necessary to achieve sufficient lateral resolution to see defects in this material. The HDPE material was quite transparent, but the ID and OD surfaces provided very good reflectivity.

3.2.2 U-Band Cylindrical Tests of HDPE Pipe Samples

A U-Band transceiver (40–60 GHz) was implemented because of the need for higher lateral imaging resolution. This system provided for a more promising scenario due to the much higher illumination frequency and higher bandwidth. Figure 3.6 shows a characteristic image slice of one of the pipe samples. The fusion joint is readily seen. However, any defect features are obscured by the outside bead and the geometry of the illumination.

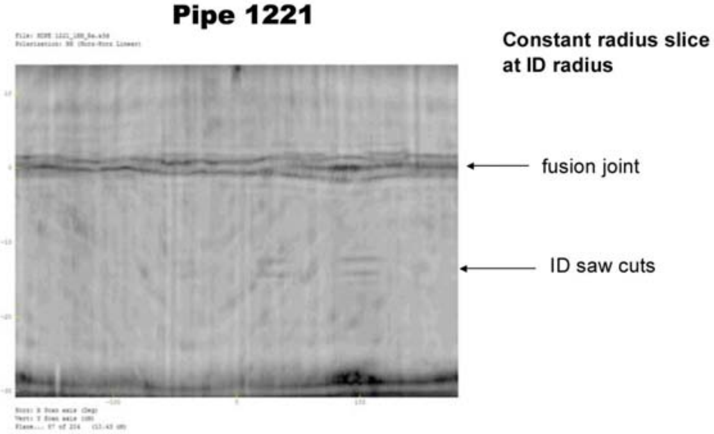

Figure 3.6. Typical U-Band Image Slice at the ID Surface

The method of displaying the image of the ID surface showed promise as it shows the shadow of the material variations.

3.3 Ultrasonic Time-of-Flight Diffraction (TOFD)

The TOFD technique applied to the fusion joint inspection has the advantage over standard pulse-echo or pitch-catch inspection in that it is a volumetric inspection method without raster scanning. Data is acquired as a single-line scan with the transmitter on one side of the fusion weld and the receiver on the other side. The pair of transducers is moved circumferentially around the pipe, collecting information on the material in between. Typically longitudinal waves are used because the diffraction is stronger than with shear waves (in steel) (Baby et al. 2002). The technique is generally not amplitude-dependent. The schematic in Figure 3.7 shows the response from an embedded flaw. A lateral wave, which is a wave that travels just below the surface, is received first. The upper and lower crack tip signals are received next in time and are from the forward-scattered diffracted signals originating at the crack or flaw tips. Finally the bounce off the back wall or pipe ID is received. As a flaw tip extends upward or downward close to the OD or ID, it starts to interfere with the lateral wave or back wall echo, respectively. Similarly, an OD- or ID-connected flaw response would also ideally show a disruption of the lateral or back wall signals, respectively. In all of the TOFD data presented in this report both the lateral wave and back wall echo are evident in the B-scan images. Diffracted signals that indicate the presence of a flaw will fall between these two signals and are typically parabolic in shape.

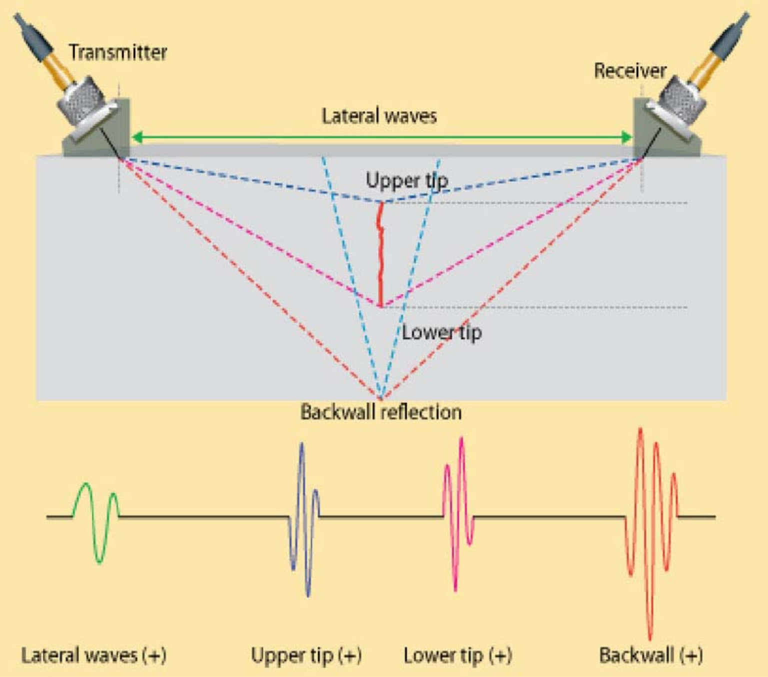

Figure 3.7. Schematic of the TOFD Signals Received from an Embedded Flaw (Panametrics 2006)

3.3.1 Fluor/NDT Innovations, Inc. TOFD

Arrangements were made for Fluor and NDT Innovations, Inc. personnel to visit and inspect the fusion zone of all 24 PNNL test pipes. Fluor in partnership with NDT Innovations has a patented (Messer and Yarmuch 2007) ultrasonic time-of-flight diffraction inspection system based on Olympus (RTD) Omniscan equipment. This system has been used extensively in the mining and gas pipeline industry for more than four years with reported good success. NDT Innovations personnel inspected all 24 PNNL pipes with the patented system at the Fluor Hanford building and presented the results at a workshop. The pipe inspection was conducted as a blind test with PNNL staff invigilating the process.

The NDT Innovations' findings were summarized in a flaw table and are listed in Appendix A. An indication was classified as planar, longitudinal, incomplete fusion, porosity, or multiple-porosity. The majority of the calls were porosity or multiple-porosity. Because of the patented system, an open discussion of the inspection technique did not occur.

A screen capture for a 10-inch (25.4-cm) section of pipe, one quadrant, is shown in Figure 3.8. The upper portion of the image shows the A-scan, amplitude–time trace. The lower portion shows the B-scan gray-scale image of the inspected 10 inches (25.4 cm) of fusion zone. An OD surface signal (lateral wave) runs across the top of the B-scan image and towards the bottom is the ID surface signal (back wall echo). Embedded flaw signals occur between these two signals. An OD-connected flaw typically disrupts the OD surface signal and an ID surface-connected flaw typically disrupts the ID surface signal. Several flaw signals are noted in the left portion of the image and are representative of the hyperbolic diffracted signals seen in a TOFD inspection. The technique relies on a disturbance of the base material signals caused by flaw tip diffracted signals.

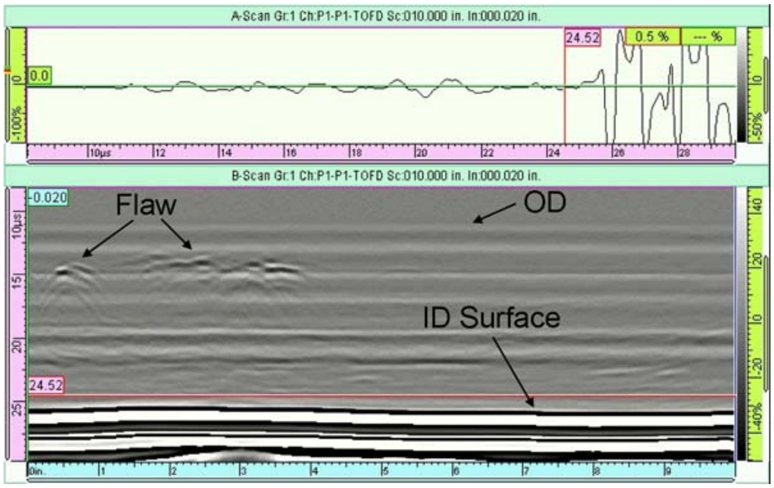

Figure 3.8. TOFD Image Showing the OD and ID Surface Signals and a Flawed Area

In general the technique appeared to detect acoustical anomalies in the pipes. Figure 3.9 shows an area that was identified as having incomplete fusion. Figure 3.10 shows an area called flawed in one of the good pipes, fusion condition 6. Images of all the data are shown in Appendix B. Destructive analysis is needed to verify these results. These calls, as noted on the images, were made by NDT Innovations personnel during their two-day inspection of all 24 joints. Some of the calls are obvious as in Figure 3.8 and others are less obvious as in Figure 3.9. It also needs to be noted that the original data had high resolution and contrast, which unfortunately is reduced in these figures.

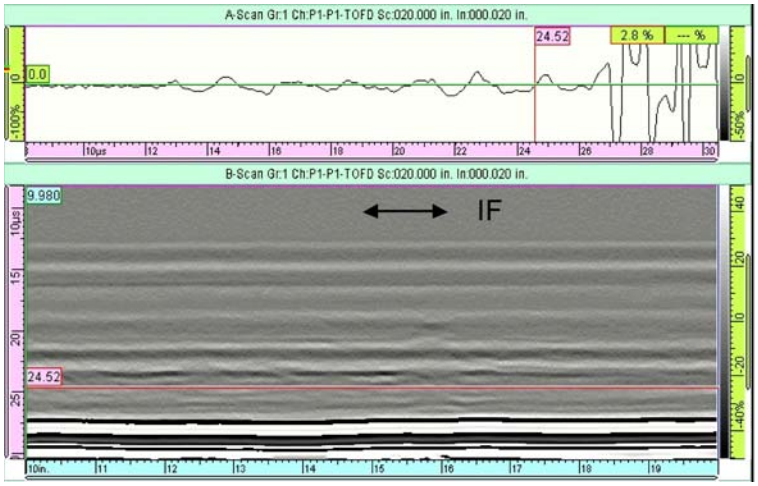

Figure 3.9. Area Identified as Incomplete Fusion

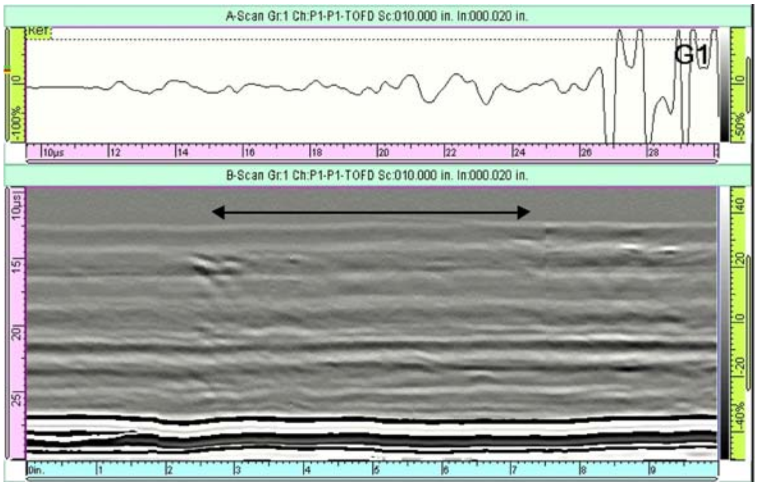

Figure 3.10. Possible Flaw Indications in One of the “Good” Pipes

3.3.2 PNNL TOFD

Initially the TOFD technique was applied in the immersion mode to avoid wedge material velocity and attenuation issues and the possible need for damping of signals bouncing in the wedge. A water velocity of 0.0584 in./µsec (1.48 mm/µsec) is slower than the HDPE pipe material thus allowing insonification at high angles. Sawcuts were placed in the base material of two pipes and most of these were detected in the immersion mode.

After these initial and encouraging immersion tests, contact testing was attempted with wedges made out of Rexolite and a pair of 1.5-MHz composite transducers. Sawcuts machined from the OD at through-wall depths of 75, 50, and 25 percent were detected. The 10 and 5 percent deep sawcuts were not detected. ID sawcuts were detected at all but the 5 percent depth. The weld fusion zone on one pipe from each of the six fusion conditions was examined with a mechanical scanner controlling the probe motion. Running water was applied at the base of the probes for coupling. With this inspection setup the data collection was very inconsistent. It was difficult to repeat the results and the flowing water introduced signals that interfered with the signals from the material. At this point manual scanning was determined to be more effective with a water-wetted surface so the mechanical scanning was abandoned. A small amount of dish soap was added to the water to act as a surfactant. The manual operator needs to apply a firm and consistent pressure on the transducer wedges to ensure uniform contact of the wedge bottom with the pipe surface as the pair is moved circumferentially around the pipe. This takes some practice and attention to acquire data that is repeatable. The wedges were also machined to fit the pipe curvature.

A pair of 2.25-MHz, 0.5-inch (1.27-cm) diameter, TOFD-style probes was acquired from Olympus/Panametrics. These composite probes are highly damped and highly sensitive. With the increase in sensitivity over the 1.5-MHz pair of probes, defect signals in the fusion zone were detected. A manual probe fixture with an attached encoder wheel was designed and assembled and is shown in Figure 3.11. This allowed circumferential positional information to be recorded with the ultrasonic signal as the probe was moved around the pipe. A ZETEC Tomoscan III system was used in the TOFD mode for data acquisition.

Responses from the ID sawcuts acquired at 52 dB of hard gain and no additional soft gain are shown in Figure 3.12 for the 75, 50, 25, and 10 percent through-wall deep flaws. These sawcuts were placed in the base material. The 5 percent deep notch was not detected. Note that the deeper two flaws are saturated and greater in response than the lateral wave. The 25 percent deep sawcut is 5 dB lower in amplitude and the 10 percent deep notch is 18 dB lower than full scale at the base gain level of 52 dB. The time or depth (vertical direction) window shown in these sawcut images extends beyond the ID or back wall echo. This allows viewing of mode-converted signals (longitudinal to shear) that can add additional information to the material inspection. This is an area for further investigation.

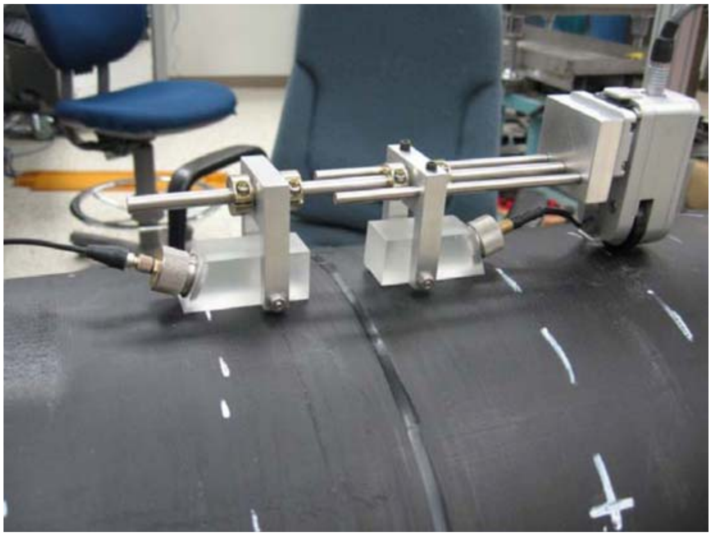

Figure 3.11. TOFD Probe Assembly

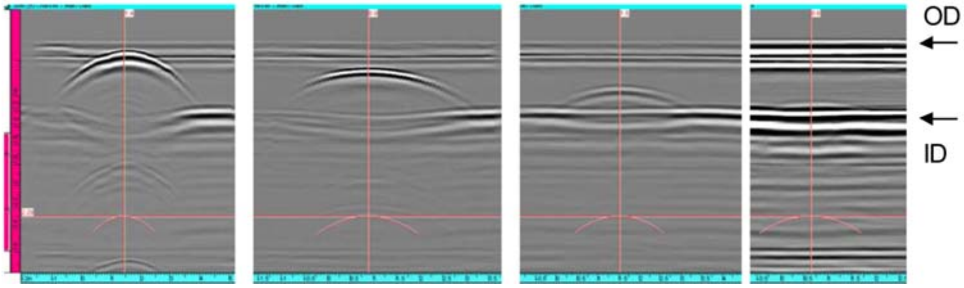

Figure 3.12. PNNL TOFD Results from Four ID-Connected Sawcuts. From left to right the through-wall depths are 75, 50, 25, and 10%.

The worst-case condition for pipe fusion, out of the McElroy batch of 24 test assemblies, and the one most likely to produce LOF was condition 2 with fusion pressure during the heat cycle and a 20-second open/close time. One of these pipes was examined with TOFD by PNNL showing results comparable to those presented by Fluor/NDT Innovations, Inc. The data are shown in Figure 3.13 and Figure 3.14 for the four pipe quadrants, with the PNNL data shown in the top of each figure and the Fluor/NDT Innovations, Inc. data at the bottom of each figure. Notice that the PNNL data show the mode-converted signals beyond the longitudinal-wave back wall (ID) echo. The time window was extended to include the slower mode-converted signals with the thought that this additional data would enhance the detection of defects. The Fluor/NDT Innovations, Inc. data images are cropped at the ID and additionally do not have the saturated OD lateral wave signal seen in most TOFD images and in the PNNL data. This results in a cleaner looking image and should provide better near-surface sensitivity to flaws. Fluor/NDT Innovations, Inc. data is also much more sensitive, due most likely to their patented processing of the raw data. Regardless, in this data comparison flaw indications are identified at similar locations by both PNNL and Fluor/NDT Innovations, Inc. Each quadrant represents approximately 10 inches (25.4 cm) of pipe circumference.

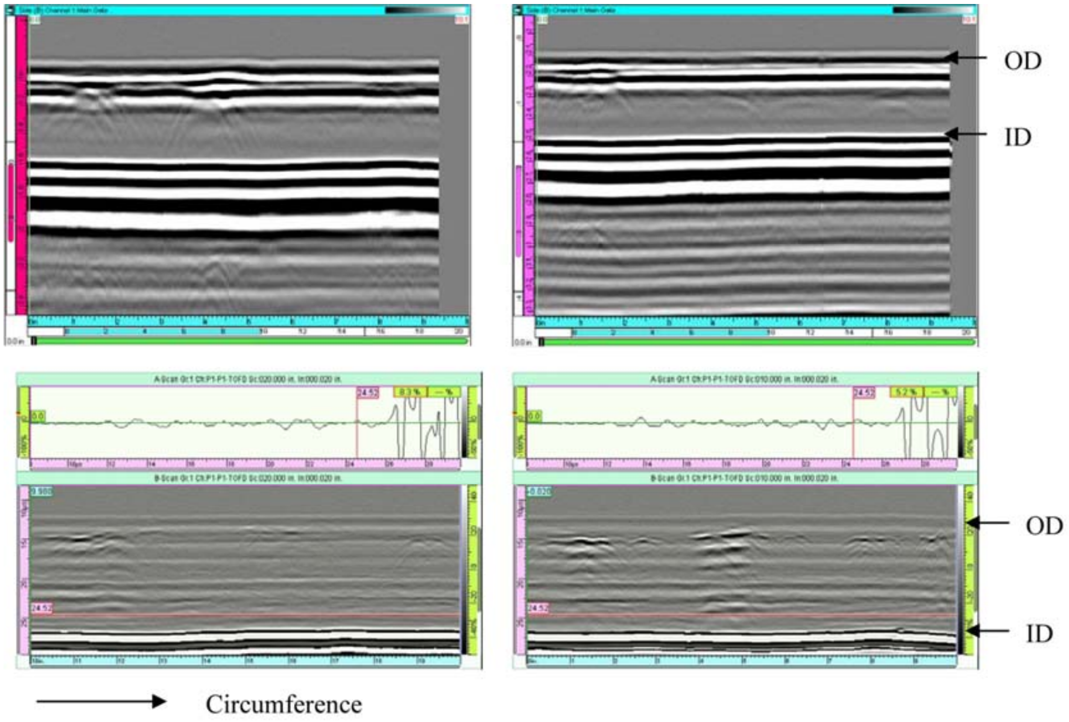

Figure 3.13. TOFD Data Acquired on Pipe 125, First and Second Quadrants (left and right), by PNNL in the Top and by Fluor/NDT Innovations, Inc. in the Bottom

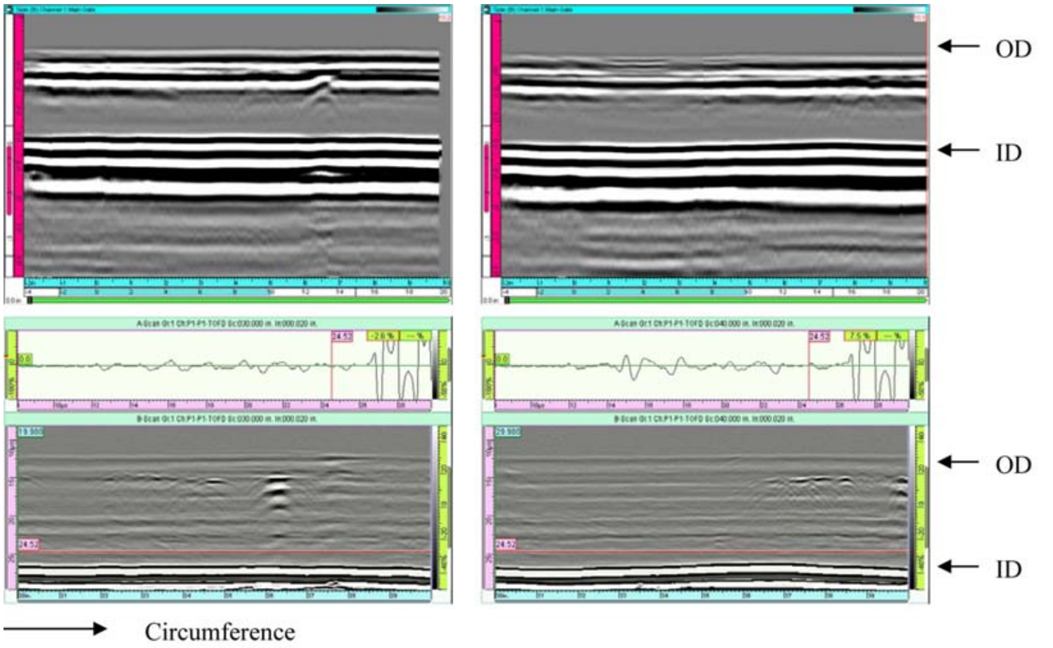

Figure 3.14. TOFD Data Acquired on Pipe 125, Third and Fourth Quadrants (left and right), by PNNL in the Top and by Fluor/NDT Innovations, Inc. in the Bottom

3.4 Ultrasonic Phased Array

A phased array probe was specifically designed for inspecting the HDPE pipe but has not been ordered. A problem to still address is in selecting a wedge material. This will be discussed in Section 6.0, Unresolved Issues and Work in Progress. As a result the PE pipes were evaluated with existing PA probes, specifically probes designed for the inspection of steel components. The best results were obtained with a 4-MHz probe composed of two one-dimensional linear arrays operating in the pitch-catch mode. The probe was designed to produce shear waves in steel but focal laws were developed for inspecting the HDPE pipe, and beam modeling based on these focal laws showed a good longitudinal response in the HDPE material over approximately 30 to 60 degrees of insonification. The simulated beams produced at 40 and 58 degrees are shown in Figure 3.15. An evaluation on the pipe sawcuts showed that OD notches at depths of 25, 50, and 75 percent through-wall were detected while the shallow 5 and 10 percent notches were not detected. All of the ID notches were detected.

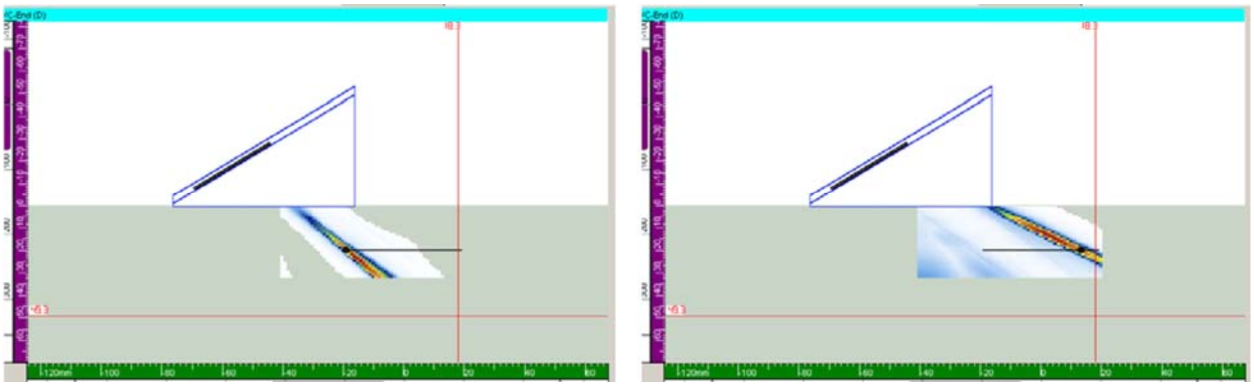

Figure 3.15. Phase Array Beam Modeling Results at 40 Degrees on the Left and 58 Degrees on the Right

As with the TOFD data collection, the PA data were acquired with manual scanning. The same probe assembly as used in the PNNL TOFD inspection was used with a new yoke for the PA probe. This probe assembly is shown in Figure 3.16. Constant and firm pressure on the wedges was also necessary for acquisition of repeatable data.

PA data was acquired on the fusion joint from pipe 125, a worst-case condition for joint integrity, and is displayed in Figure 3.17. The side view on the left shows the ID signal at the angle sweep start of 30 degrees. Data is acquired from 30 to 60 degrees at 1-degree increments. The highlighted flaw indication was centered at approximately 55 degrees as shown by the black line at the flaw indication in the side view. The associated end view at 55 degrees is shown on the top right with the flaw signal noted. Its circumferential extent is approximately from 7 to 9 inches (17.8–22.9 cm) in quadrant 4. The bottom right shows the A-scan trace from the position marked by the red horizontal line in the end view image.

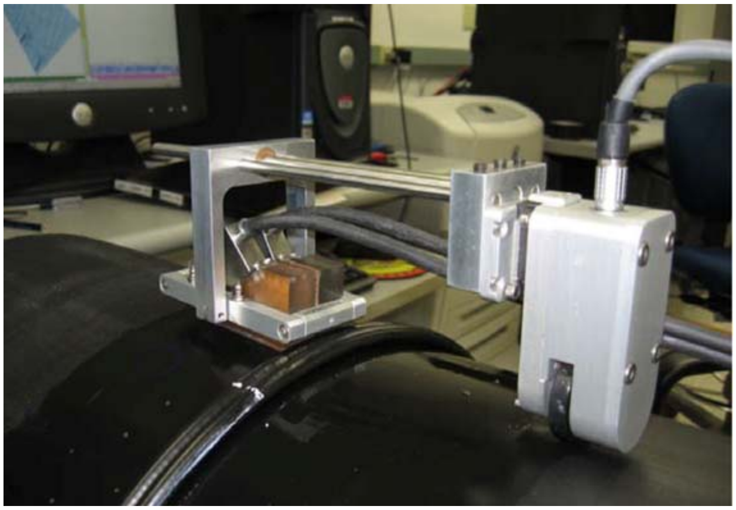

Figure 3.16. Manual Phased Array Probe Assembly in Position to Inspect a Fusion Joint

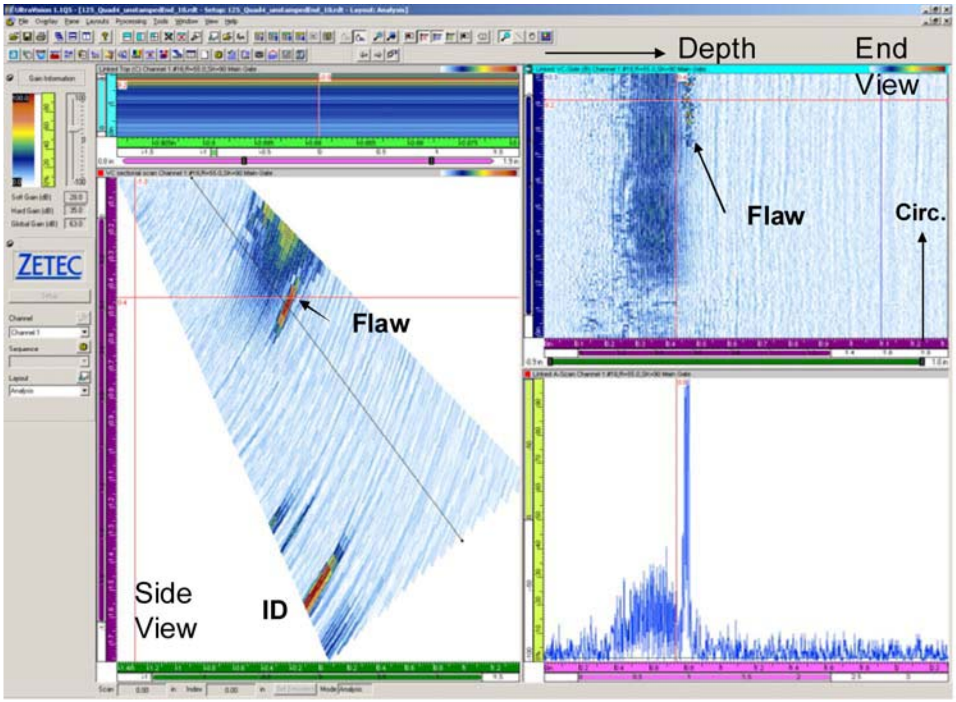

Figure 3.17. Phased Array Results on HDPE Pipe 125, Quadrant 4 Showing a Possible Lack of Fusion in the Noted Flaw Area

4.0 Destructive Test Results

Various destructive evaluation (DE) methods have been applied to the evaluation of HDPE material and the fusion joints. Mechanical tests include the bend back test and the high speed tensile impact test (ASTM F2634-07 2007). The tensile test is the industry standard and selected samples will undergo this test in the future. Another DE technique reported by others, including Fluor personnel and Frank Schaaf, Sterling Refrigeration Corp., is to slice the fusion zone or base material, looking for porosity, lack of fusion, or other anomalies in the thin slices of material. A photo from Frank Schaaf, showing a good joint and LOF, is shown in Figure 4.1. He used a microtome to slice the pipe perpendicular to the joint, axial direction, thus showing a cross section of the joint.

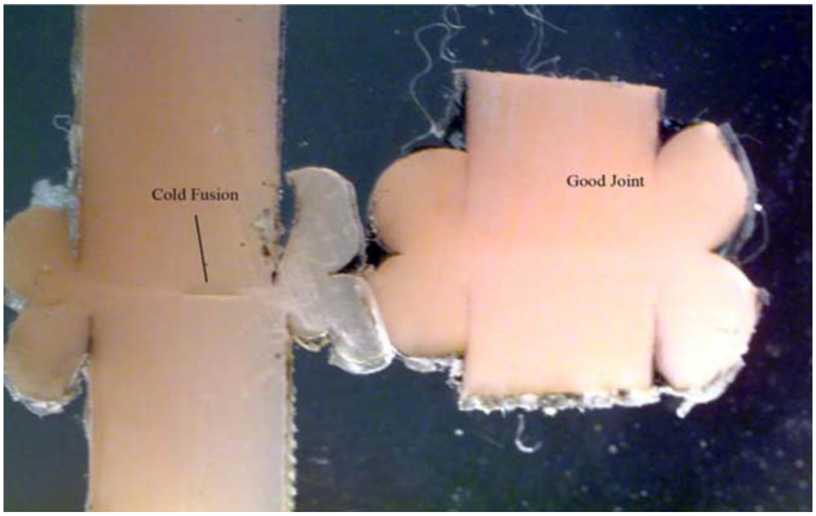

Figure 4.1. Cold Fusion and Good Joint in PE Material. Photo courtesy of Frank Schaaf.

4.1 Slicing

PNNL was able to temporarily borrow a Leica microtome from Bartels and Stout, Inc. for slicing the HDPE material. Figure 4.2 shows the rotary manual slice (model RM 2245) unit with a weld section cut-out and positioned in the vise. As the wheel on the right and out of the photo is turned, the specimen moves down and past the razor knife blade that is behind the red knife guard. A thin slice of material is peeled off the specimen and the specimen is advanced in position ready for the next slice. Slices in the 25–35 micron thick range were ideal for allowing sufficient light through the slice to view the material details. Thinner slices tended to fall apart.

The slices of material were viewed with a light table or light source behind or under the slice. The bulk specimen was viewed with a microscope or magnifying glass and the light source on top or to the side. A diffuse light box was also helpful. Both the slice and the bulk specimen were photographed using a camera stand and light table or light source. A bulk specimen and the camera setup are shown in Figure 4.3 with a light source off to the right side.

Figure 4.2. Rotary Manual Microtome Used to Slice HDPE Pipe Sections. The unit was on loan from Bartels and Stout, Inc.

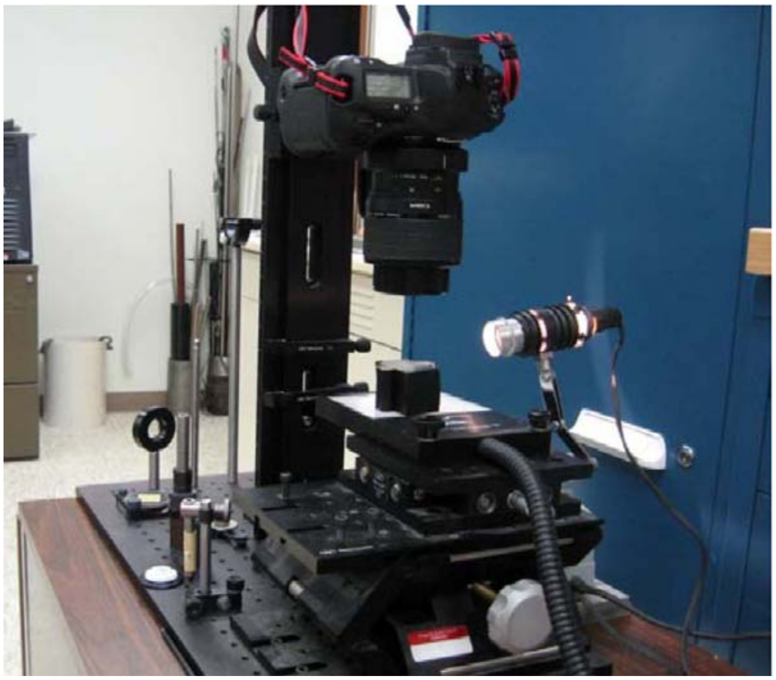

Figure 4.3. Setup for Photographing the Bulk Specimen

4.1.1 Fusion Joint Evaluation

A weld area from pipe 125 containing a flaw indication at approximately 7–9 inches (17.8–22.9 cm) was cut out of the pipe. Slices were made in the axial direction, perpendicular to the weld. These slices were in the 25–35 micron thick range and were thin enough to see through yet thick enough to still hold together. A slice at approximately 8.6 inch (21.8 cm) in the pipe circumference is shown in Figure 4.4. Because of uneven mixing of carbon black in the base material of this 3408 pipe there are light and dark swirls in the pipe. In the joining of the two pipe sections, this swirl pattern changes direction due to the melting and fusing and runs along the fusion line. These light and dark lines in the fusion zone camouflage lack of fusion in this region. Evidence of lack of fusion is, however, seen on the cut (or sectioned) pipe surface as shown in Figure 4.5. The microtome cut is made from the bottom of the piece in Figure 4.5 to the top, leaving cut marks that run perpendicular to the fusion line. Sufficient and appropriate lighting or tilting of the pipe section highlights the lack-of-fusion lines in the fusion zone. A liquid penetrant test (PT) or evaluation of this surface was also performed in attempts to enhance the LOF indication. A red dye was applied to the cut surface and allowed to soak for at least one hour. Normally during this dwell time the liquid penetrant is absorbed into surface discontinuities by capillary action. After the dwell time the surface was wiped clean of the dye and a white developer applied. The developer typically draws dye out of discontinuities and maps out the flaw shape/opening on the surface of the specimen. No flaw was seen on this specimen face with the PT. It is assumed that these LOF areas are so tight that the dye did not seep into the discontinuity.

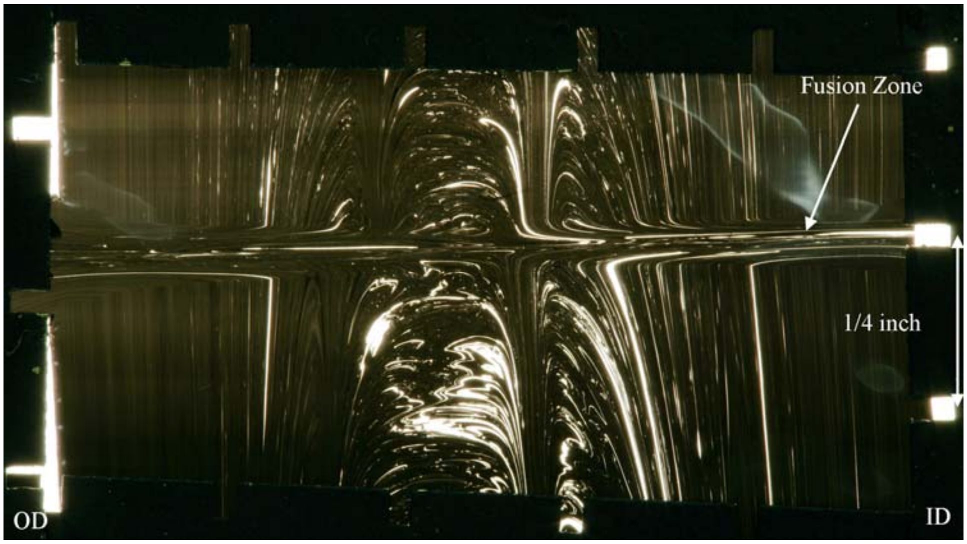

Figure 4.4. A Slice from HDPE Pipe 125, Quadrant 4 at Approximately 8.6 Inches (21.8 cm). Lack of fusion in the fusion zone is not evident due to light colored material streaks and swirls from uneven base material mixing.

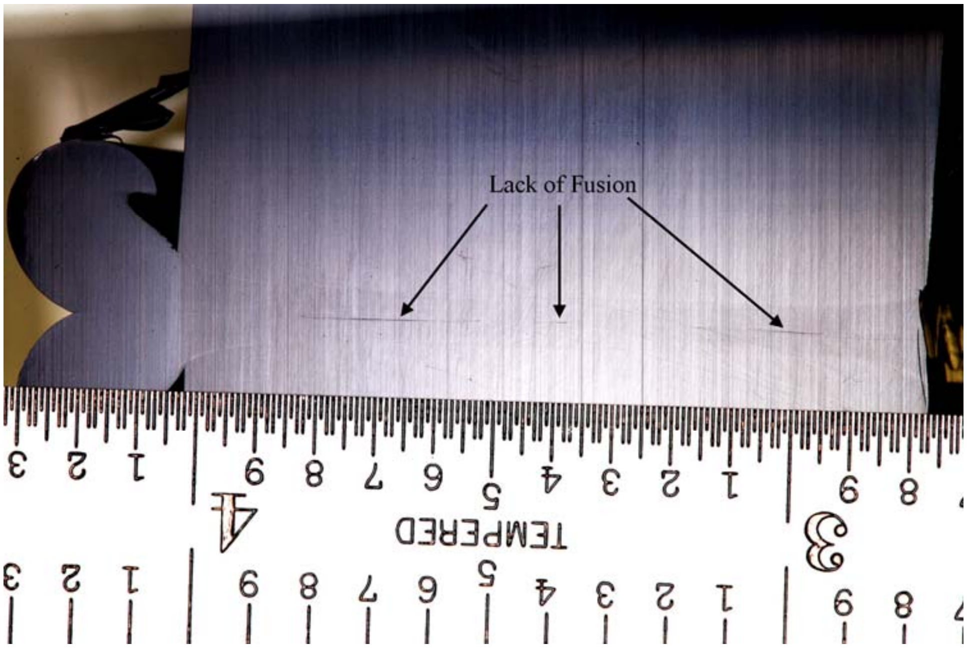

Figure 4.5. Surface of HDPE Pipe 125, Quadrant 4 at Approximately 8.6 Inches (21.8 cm). Areas of lack of fusion are noted.

The TOFD and PA results from the fourth quadrant of pipe 125 are shown in Figure 4.6. The approximate area of the slice and surface shown above in Figure 4.4 and Figure 4.5 is noted in each of the ultrasonic images. Both the PNNL TOFD (left) and Fluor/NDT Innovations, Inc. TOFD (right) data show a flaw indication in the end of the B-scan image. The PA data, below center, is a rotated-in-orientation B-scan image and also contains a flaw indication at the end of the circumferential scan line. This is confirmation that the ultrasonic techniques were able to detect this LOF.

For comparison a piece of a reportedly good weld was also evaluated. TOFD and PA ultrasonic examinations showed no indications in quadrant four of pipe 1224 at 3 to 4 inches (7.6–10.2 cm). This area was cut out and sectioned. Figure 4.7 shows a slice from this weld at approximately 3.4 inch (8.6 cm). As in pipe 125, streaks of light material due to uneven mixing with the dark carbon black pipe material are evident and make a lack-of-fusion detection from the slice difficult or impossible. The pipe surface after slicing appears to be a better indicator of the weld condition. Figure 4.8 shows the cut surface with no evidence of lack of fusion in the fusion zone.

The ultrasonic responses from quadrant two in the fusion joint in this good pipe, 1224, are shown in Figure 4.9. The area marked with a double-ended arrow has been sent out for tensile testing.

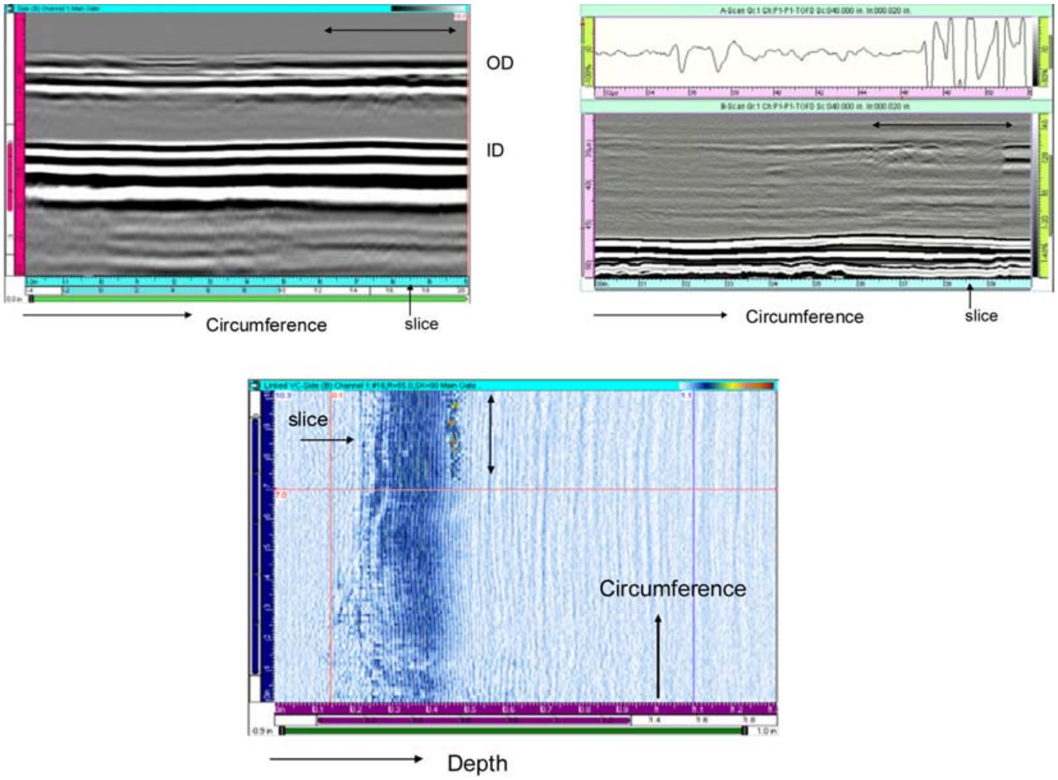

Figure 4.6. PNNL TOFD (upper left), Fluor/NDT Innovations, Inc. TOFD (upper right), and PNNL PA Data from the Fourth Quadrant of Pipe 125 All Show a Flaw Indication in the Approximately 7–9 Inch (17.8–22.9 cm) Circumferential Position

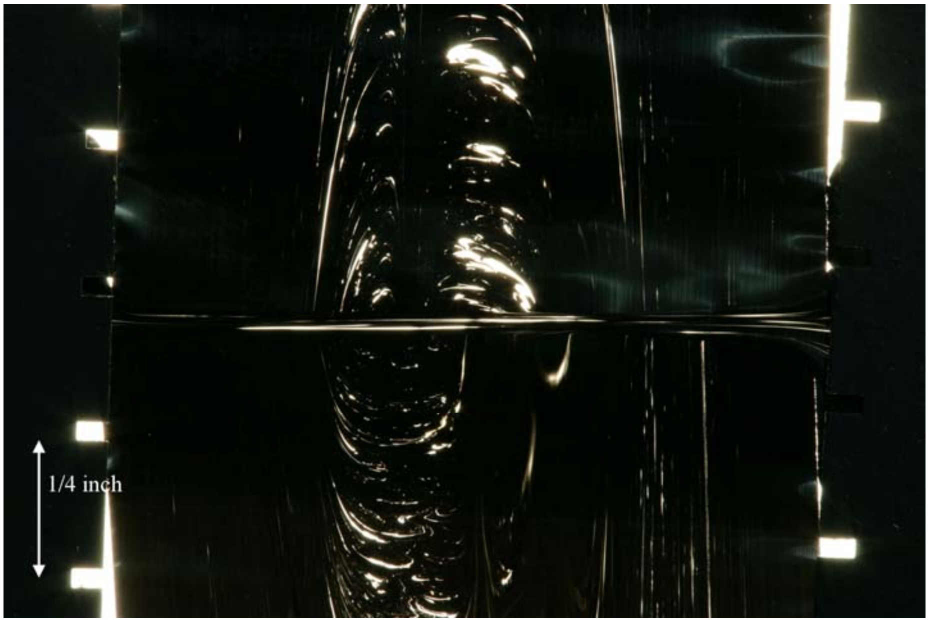

Figure 4.7. Slice from HDPE Pipe 1224, Quadrant 4 at Approximately 3.4 Inches (8.6 cm)

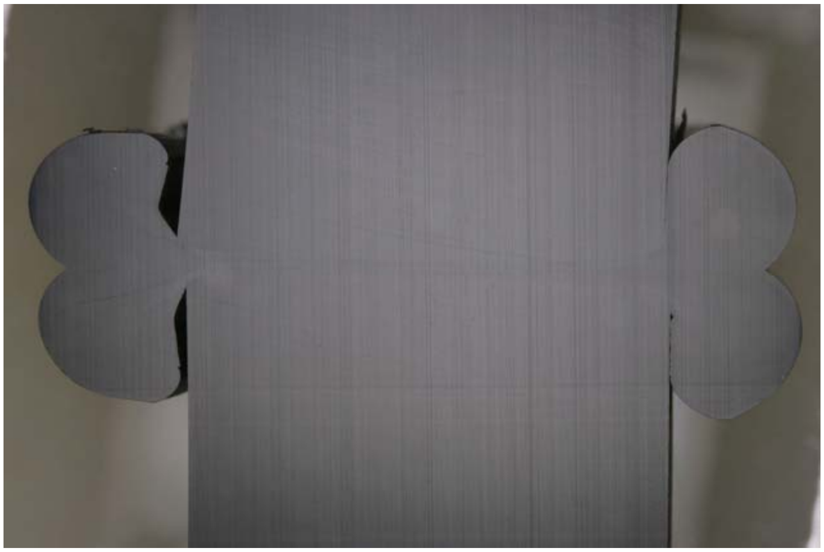

Figure 4.8. Surface of HDPE Pipe 1224, Quadrant 4 at Approximately 3.4 Inches (8.6 cm). No lack of fusion is seen.

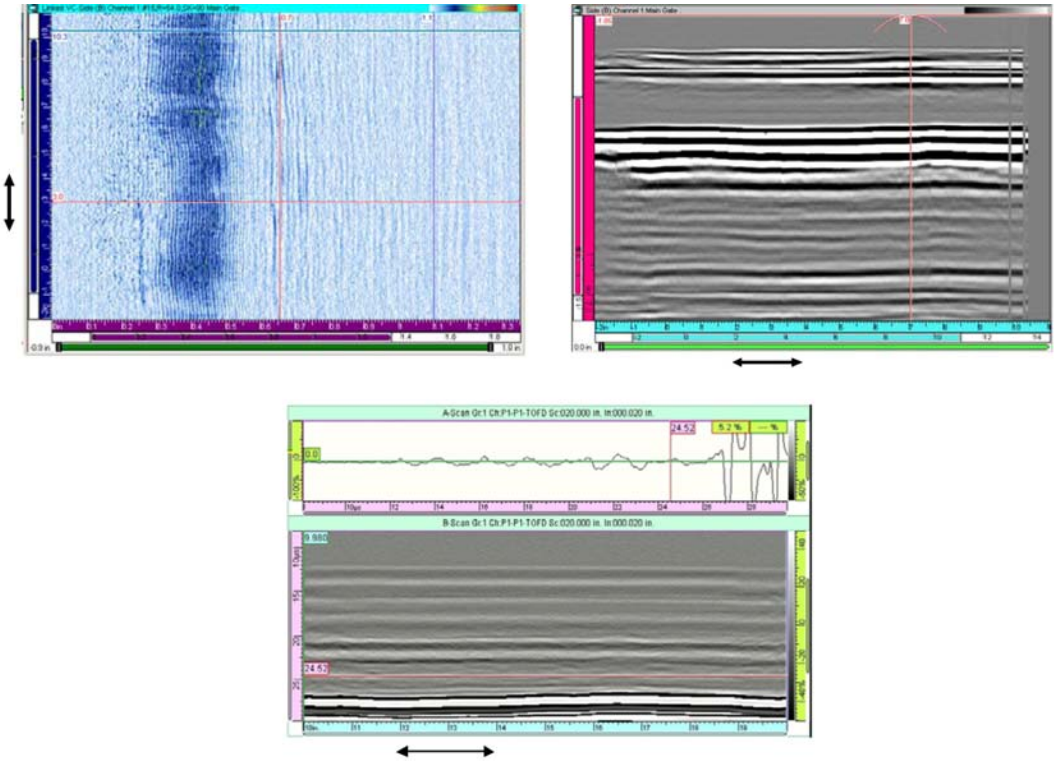

Figure 4.9. Ultrasonic Responses from Quadrant Two of Pipe 1224 All Show No Flaw Indication. The PNNL PA data is in the upper left, PNNL TOFD data in the upper right, and Fluor/NDT Innovations, Inc. TOFD data in the bottom.

4.1.2 Base Material Evaluation

A preliminary evaluation of base material showed no ultrasonic indications in one 3408 pipe and one 4710 pipe. Slices from the 3408 and 4710 base material are shown in Figure 4.10, left and right, respectively. The spacing between the fiducial notch marks on the edges of each image is 0.25 inch (0.64 cm). The 3408 material is less uniformly mixed. The 4710 material still shows some nonuniformity but to a lesser extent. Even with this amount of swirling it would likely still be difficult to examine a thin slice through a 4710 fusion joint for LOF. No porosity was found in the few slices through base material. Only one or two areas were found with a single pin hole or porosity in or near a fusion joint in the numerous fusion joint slices evaluated. This could approximately represent a 1 percent or less rate of porosity in a slice.

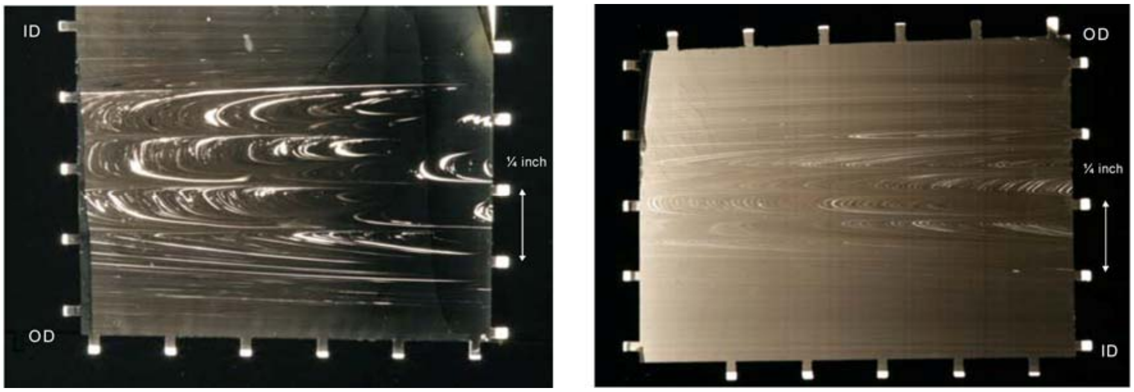

Figure 4.10. Base Material Slices from 3408 on the Left and 4710 on the Right Show Swirls from Nonuniform Mixing. The spacing between edge notches is 0.25 inch (0.64 cm).

4.2 Mechanical Testing

Several sections of pipe fusion zone were identified for mechanical testing. These specimens were sent to James Craig at McElroy who will perform the high-speed tensile testing. Two areas from pipe 126, which was fused under a condition (condition 2) most likely to produce LOF, were identified. One area produced ultrasonic indications and the other did not. Two areas from pipe 1215, fused under a less severe condition, were selected. One area produced a TOFD indication noted by Fluor/NDT Innovations, Inc. but not by PNNL TOFD or PA. The other area produced no detected ultrasonic indications. One area from pipe 1224, a good pipe, was also selected. James Craig also offered to do a test on the base material. This material was cut out and shipped on April 15, 2008, and results were received on April 25, 2008, but have not been reviewed and there was no time to get these results into this interim report so that it could be submitted to the NRC by April 30, 2008.

5.0 Summary and Conclusions

Assessment studies of the capabilities of NDE techniques to detect lack of fusion in HDPE butt fusion joints have begun at PNNL. These studies are underway involving several NDE methods and are not complete. Thus, only limited conclusions can be drawn at this point.

In summary mmWave technology shows promise in the inspection of HDPE fusion welds. Higher frequencies are probably needed in order to reliably detect the tight LOF conditions. The parent HDPE material is homogeneous and the dielectric properties are quite conducive to electromagnetic techniques.

Visual testing does not seem to reveal a subtle condition like lack of fusion in a butt fusion joint. It is a surface evaluation technique and does not represent the volumetric condition of a fusion joint. Research conducted to date shows that VT only detects certain unacceptable butt fusion joint conditions. The research indicates that VT will not detect many of the conditions that should not go into service.

Ultrasonic TOFD and PA evaluations have differentiated between a LOF condition and a “good’ joint as verified by slicing through a flaw indication area and visually observing LOF. Similarly, a slice through an ultrasonically good area showed no LOF. Work on less obvious LOF conditions is underway at PNNL. The PA probe that was used in these studies is not optimized for inspecting HDPE and future work should include the design and procurement of optimized PA probe(s). The TOFD and PA results provided confirmation of acoustical anomalies in specific areas of several specimens that provides confidence that these complimentary NDE responses are detecting some type of condition(s) that need to be carefully evaluated. The TOFD results by Fluor/NDE Innovations provided better near-surface resolution and sensitivity performance than the results of PNNL’s TOFD measurements. At this time only qualitative conclusions can be drawn because limited DE and no mechanical testing has been conducted to date. However, these qualitative results based on limited validation indicate that volumetric inspection of the fusion joint is possible but its effectiveness is not quantified.

6.0 Unresolved Issues and Work in Progress

PNNL plans to complete these studies on quantifying the effectiveness of NDE techniques for detecting LOF conditions in HDPE butt fusion joints per the NRC Statement of Work. The near-term work will focus on the current studies that are already underway. This includes conducting mechanical tests of zones within each of the five different LOF conditions that were contained in the test specimens along with DE slicing of similar zones to identify the type(s) of flaw conditions and their properties. The research to be conducted includes the mmWave, PA, pitch-catch UT, tandem UT and TOFD methods. It is planned to assess the capabilities of several commercially available methods such as Evisive's microwave method which may be used for the NDE of HDPE.

It will also be necessary to fabricate some new LOF samples made with 4710 material. Initial studies show that there is a difference in the homogeneity of this material versus the 3408 that has been used to date.

6.1 PNNL Millimeter Wave

The cylindrical method employed in the millimeter wave test utilizes a divergent beam illumination method with numerical focusing of the information after the data collection. Because the region of interest is fairly small in this application, a physically focused antenna configuration on the transceiver would more directly address the fusion joint area. This system configuration would have the ability to perform angular imaging in order to evaluate the fusion joint without having to go through the surface bead or to require the removal of the OD surface bead.

Higher frequency imaging will also be investigated. The favorable characteristics of HDPE material lends itself to imaging as high as 350 GHz. This would be an important step to improve lateral imaging resolution. This frequency range is commonly known as the Terahertz region. The recent popularity of Terahertz imaging in security applications is beginning to lower the cost of components at these frequencies, which will greatly improve the field-ability of a Terahertz HDPE inspection system.

6.2 Ultrasonic and DE

Planned work will include the fabrication of an optimized phased array probe specifically designed for HDPE inspection. The evaluation of wedge materials will be necessary to achieve optimum performance. Possible wedge materials include ballistic gel or some type of water column.

Ultrasonic evaluation of the less severe fusion joints, that is, conditions 1, 3, 4, and 5, will continue with thoughts towards improving the TOFD sensitivity. This might include a mode-converted or shear-wave TOFD analysis. Based on these results, further mechanical testing and DE slicing is needed to confirm and characterize the ultrasonic findings. Samples for slow crack growth rate testing will also be identified and included in such testing. These samples will be sent to Dr. Prabhat Krishnaswamy at Emc^2. Dr. Krishnaswamy is under contract to the NRC to, among other things, investigate and quantify HDPE slow crack growth rate. This is considered to be the primary mode of failure in HDPE pipe in the long term.

Industry sources have indicated that the electro-fusion process is currently the only method available for repairing damaged pipe. Work is being planned to assess this process and Code Case N-755 will be revised to include provisions for the application of this joining method. Edison Welding Institute is conducting extensive studies on assessing the effectiveness of inspecting electro-fusion joints so this work will be followed closely to take advantage of their work to ensure that PNNL is leveraging and not duplicating any research.

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Appendix A

TOFD Inspection Results on 24 Fusion Joints in 3408 HDPE Pipe as Determined by Fluor/NDT Innovations, Inc.

Appendix A

TOFD Inspection Results on 24 Fusion Joints in 3408 HDPE Pipe as Determined by Fluor/NDT Innovations, Inc.

Inspection Matrix - Blind Samples					
Sample No	Diameter	Dimension Ratio	Actual Thickness	Defect Location	Defect Type
121	IPS 12	DR11	1.16”	13.25	PL
				14.5	IF
				20	IF
				25	IF
				32.5	L
				35	P
				39	IF
122	IPS 12	DR11	1.16”	3	MP
				8.7	PL
				13.5	PL
				14.5	PL
				23.5	IF
				28	MP
123	IPS 12	DR11	1.16”	2	MP
				8	MP
				11	MP
				13	L
				16	L
124	IPS 12	DR11	1.16”	3.5	L
				11.4	L
				26.5	L
				32.2	P
				38	L
125	IPS 12	DR11	1.16”	0.5	MP
				7.5	MP
				18	MP
				20.5	MP
				25.5	L
				35.5	P
				36	MP

Inspection Matrix - Blind Samples					
Sample No	**Diameter**	**Dimension Ratio**	**Actual Thickness**	**Defect Location**	**Defect Type**
126	IPS 12	DR11	1.16”	5.5	MP
				8.5	MP
				12.5	L
				15	PL
				20	MP
				37.5	MP
127	IPS 12	DR11	1.16”	0.5	P
				1.5	MP
				10.5	P
				10.8	P
				12.4	P
				12.8	MP
				17	MP
				19.5	MP
				28	MP
				39.5	P
128	IPS 12	DR11	1.16”	0	MP
				21.5	MP
				26.4	P
				32.5	MP
129	IPS 12	DR11	1.16”	2.4	P
				34	PL
				38.7	P
1210	IPS 12	DR11	1.16”	3	IF
				10	IF
				16.5	P
				21	IF
				28.5	PL
				32	MP
				39	L
1211	IPS 12	DR11	1.16”	4	L
				6.2	L
				9.1	PL
				16	MP
				26.5	PL

Inspection Matrix - Blind Samples					
Sample No	**Diameter**	**Dimension Ratio**	**Actual Thickness**	**Defect Location**	**Defect Type**
1212	IPS 12	DR11	1.16”	3.2	MP
				9.1	P
				12.2	PL
				17.3	PL
				22	P
				22.5	P
				24.5	L
				31.5	MP
1213	IPS 12	DR11	1.16”	15	IF
				23.5	P
				27	L
				30	PL
				36	PL
1214	IPS 12	DR11	1.16”	12	L
				14.5	MP
				19	IF
				35	MP
1215	IPS 12	DR11	1.16”	4	MP
				11.5	MP
				23.5	MP
1216	IPS 12	DR11	1.16”	3	L
				5.2	L
				34	MP
1217	IPS 12	DR11	1.16”	1	PL
				9.5	MP
				27.5	P
1218	IPS 12	DR11	1.16”	20.5	MP
				25.5	L
				27.3	PL
				37.3	P
1219	IPS 12	DR11	1.16”		
1220	IPS 12	DR11	1.16”	2.5	L
				22	MP
1221	IPS 12	DR11	1.16”	17.7	PL

Inspection Matrix - Blind Samples

Sample No	Diameter	Dimension Ratio	Actual Thickness	Defect Location	Defect Type
1222	IPS 12	DR11	1.16”	1.5	P
				5	P
				7	P
				15	P
				20	PL
				25.5	P
				27	P
				32	P
				37	P
1223	IPS 12	DR11	1.16”	2.5	MP
				23.5	MP
1224	IPS 12	DR11	1.16”	9.5	P
				25.5	PL

C – Crack
PL – Planar
IF – Incomplete Fusion
L – Longitudinal
P – Porosity
O – Other

ED – Embedded
PR – Point Reflector
BSB – Bottom Surface Breaking
TW – Through Wall
TSB – Top Surface Breaking

Appendix B

TOFD Inspection Results on 24 Fusion Joints in 3408 HDPE as Acquired by Fluor/NDT Innovations, Inc.

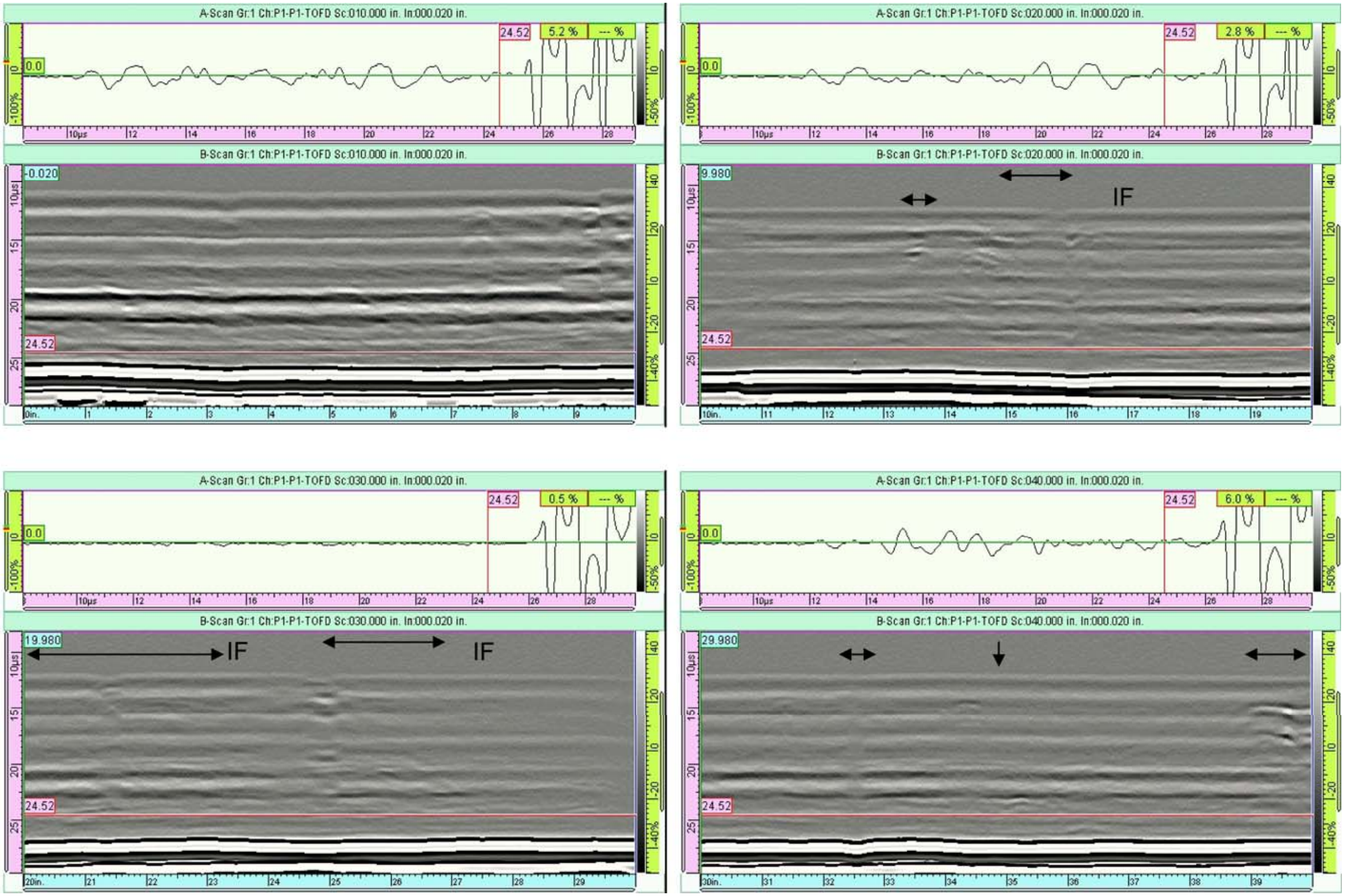

Figure B.1. HDPE Pipe 121, Condition 1

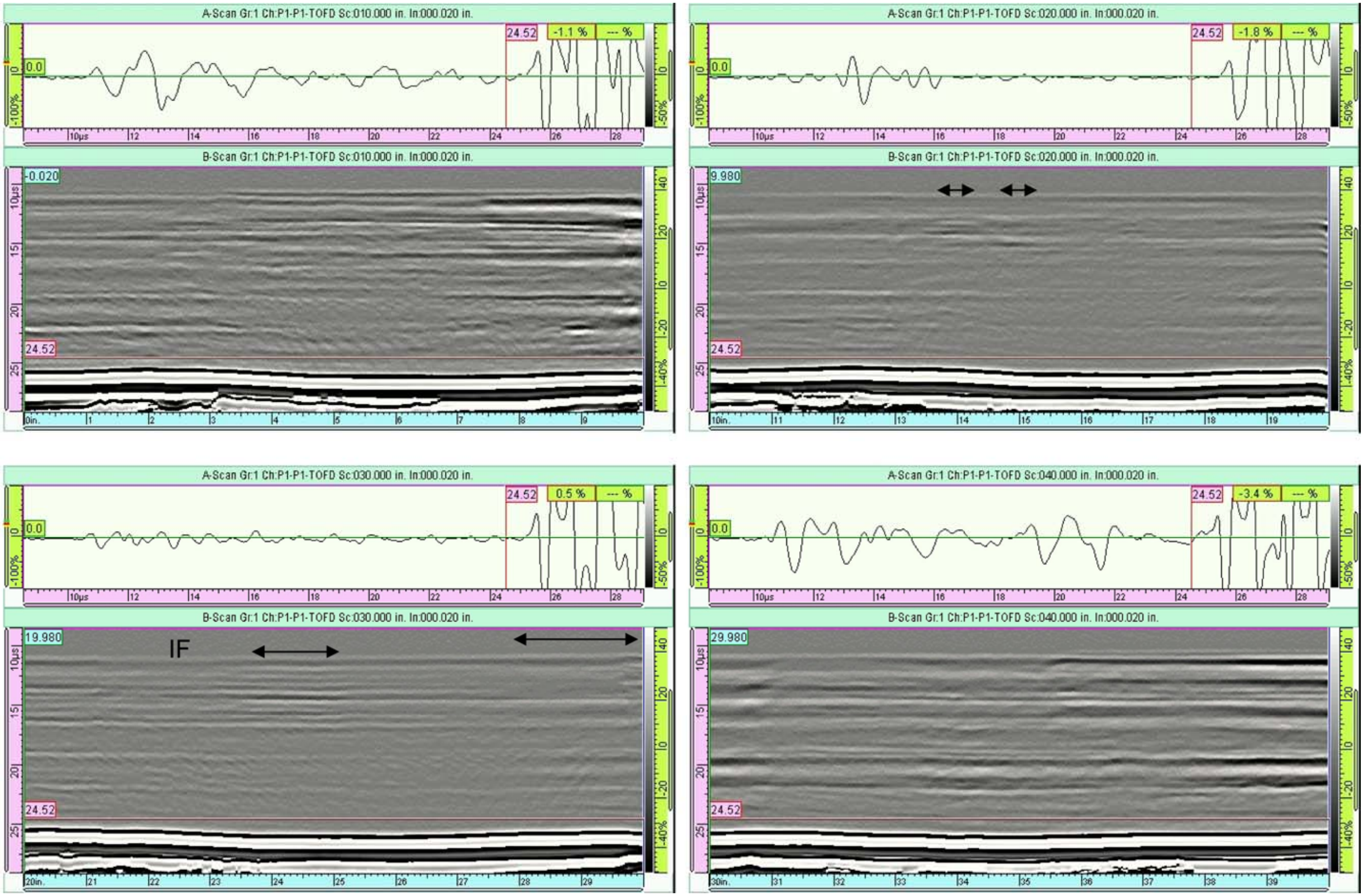

Figure B.2. HDPE Pipe 122, Condition 1

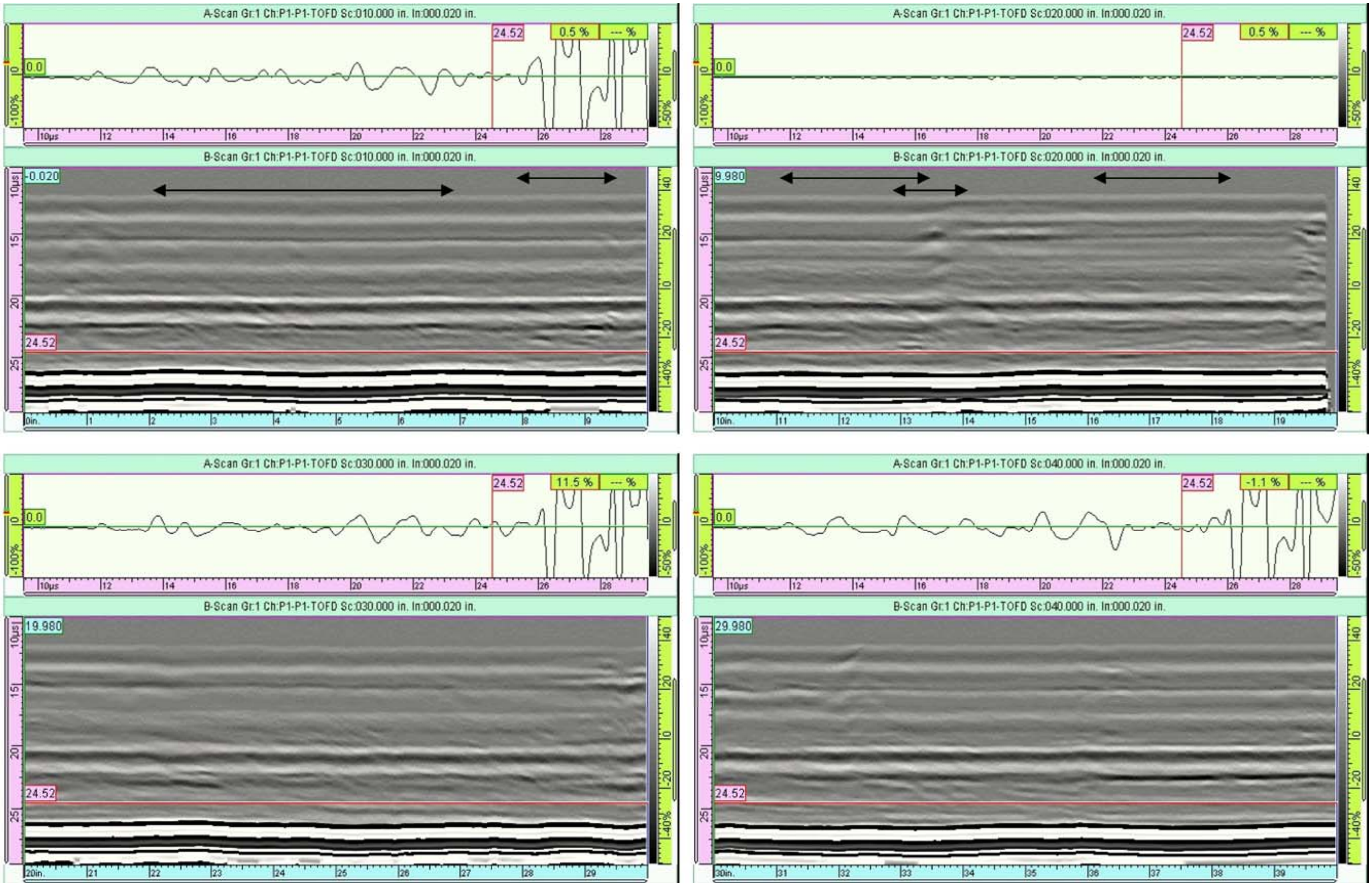

Figure B.3. HDPE Pipe 123, Condition 1

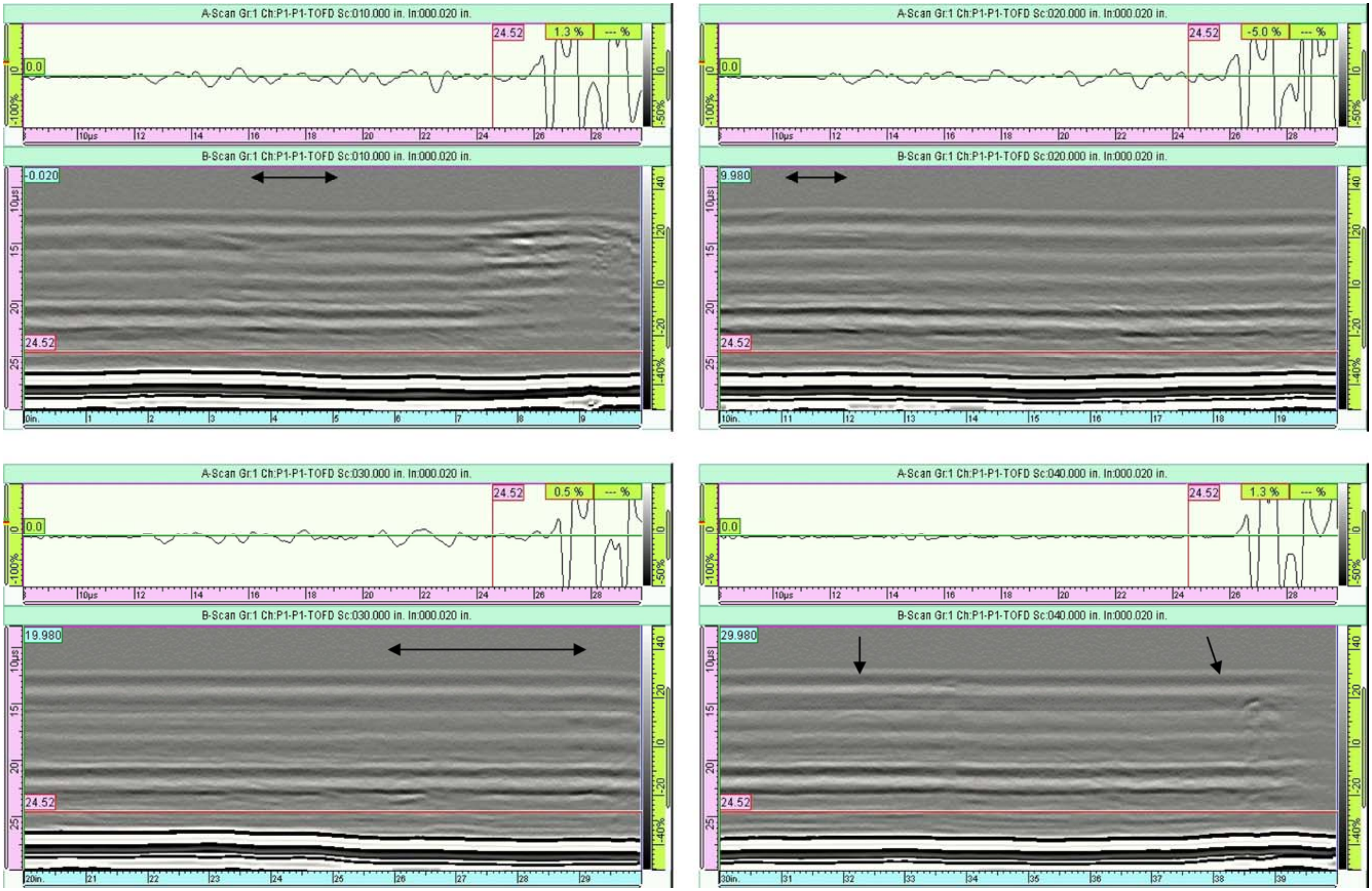

Figure B.4. HDPE Pipe 124, Condition 1

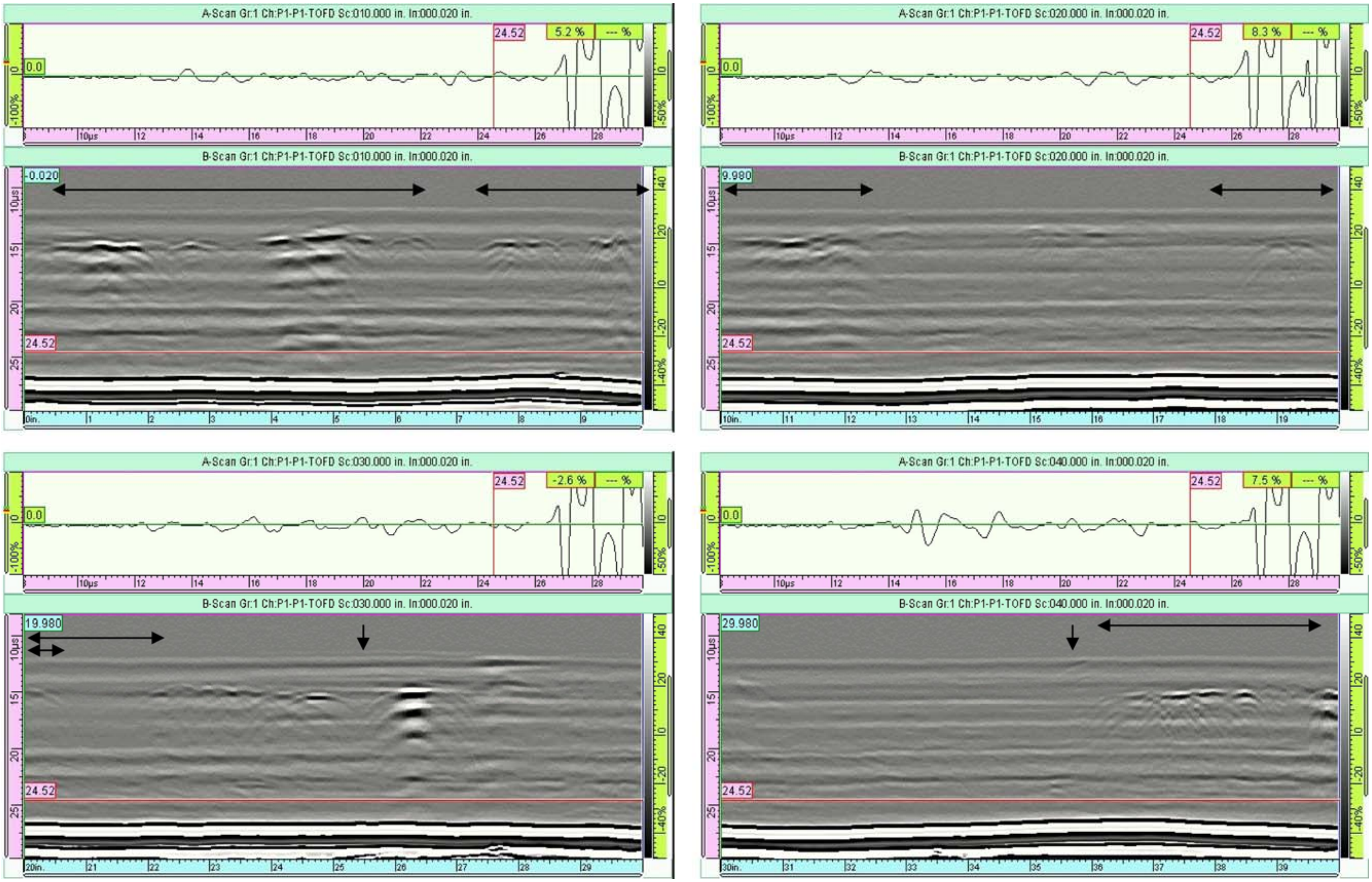

Figure B.5. HDPE Pipe 125, Condition 2

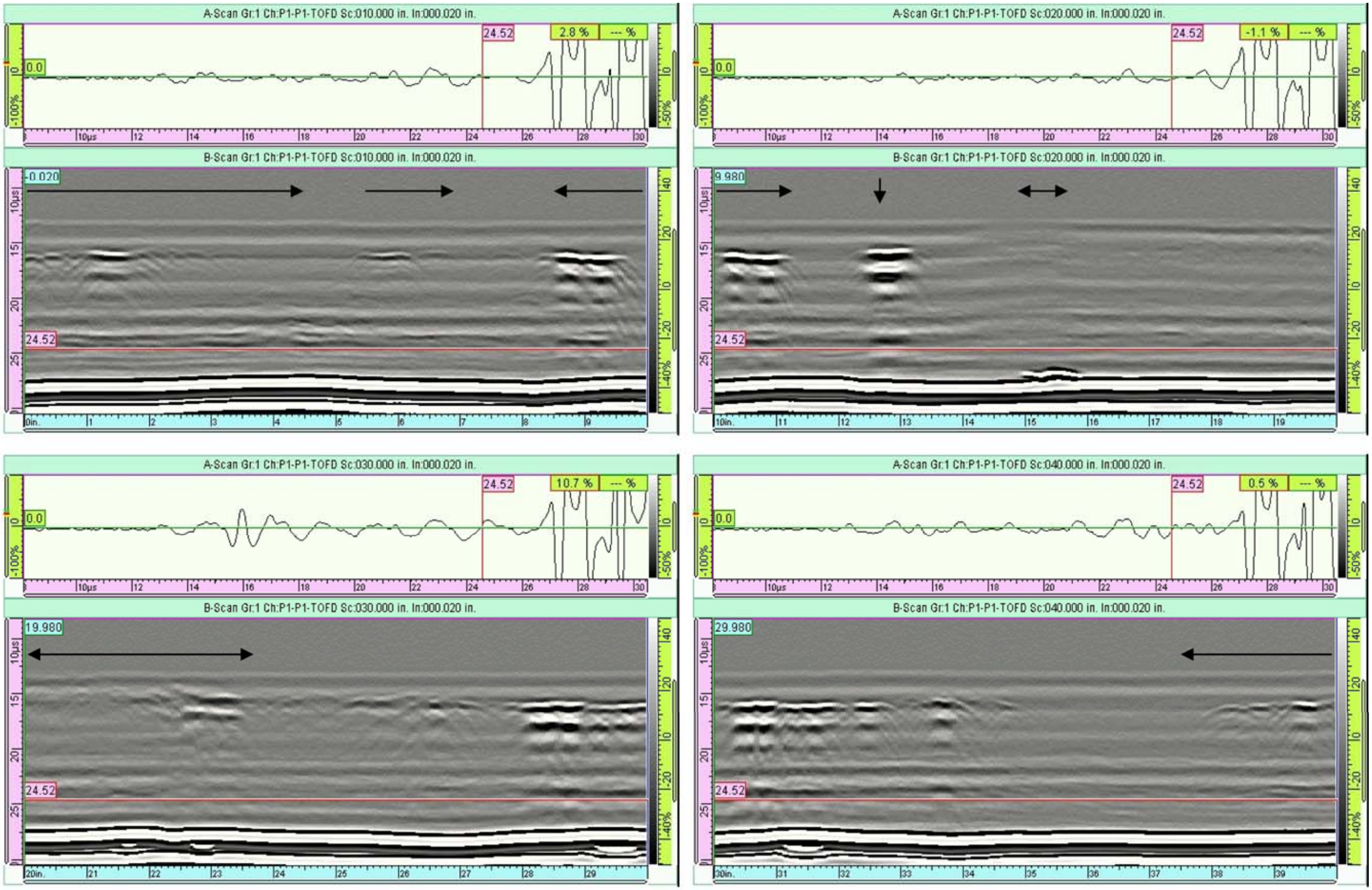

Figure B.6. HDPE Pipe 126, Condition 2

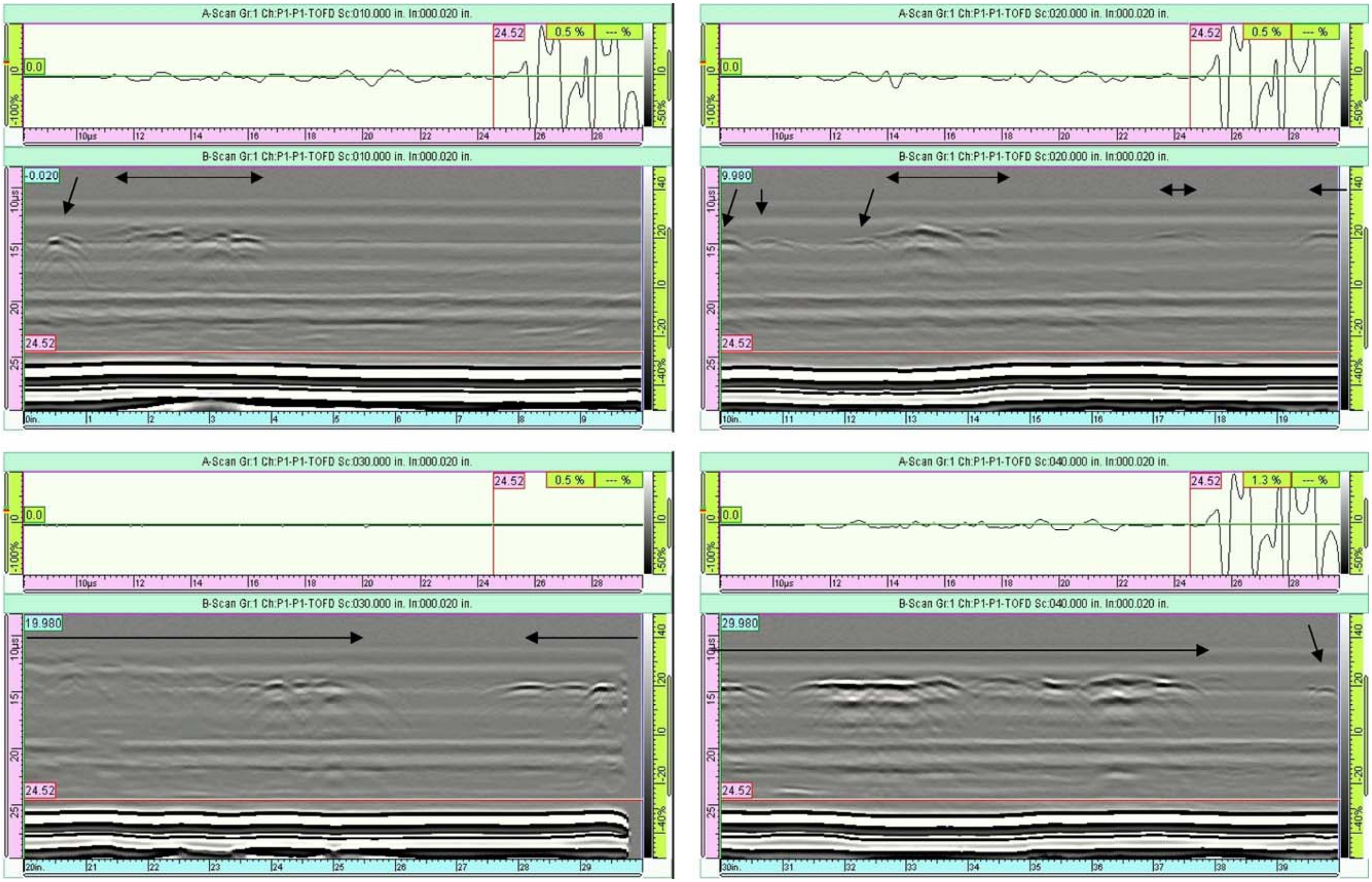

Figure B.7. HDPE Pipe 127, Condition 2

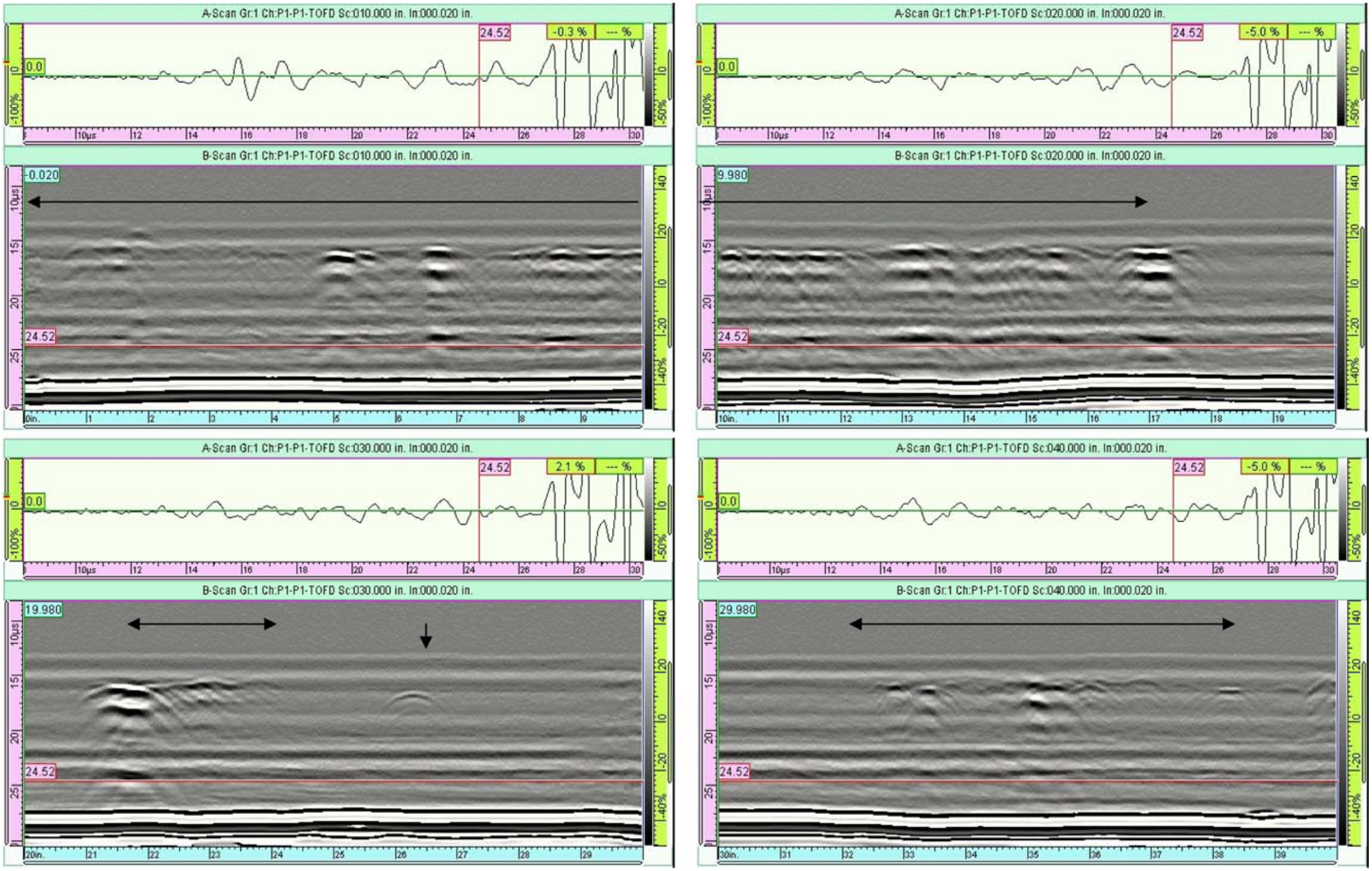

Figure B.8. HDPE Pipe 128, Condition 2

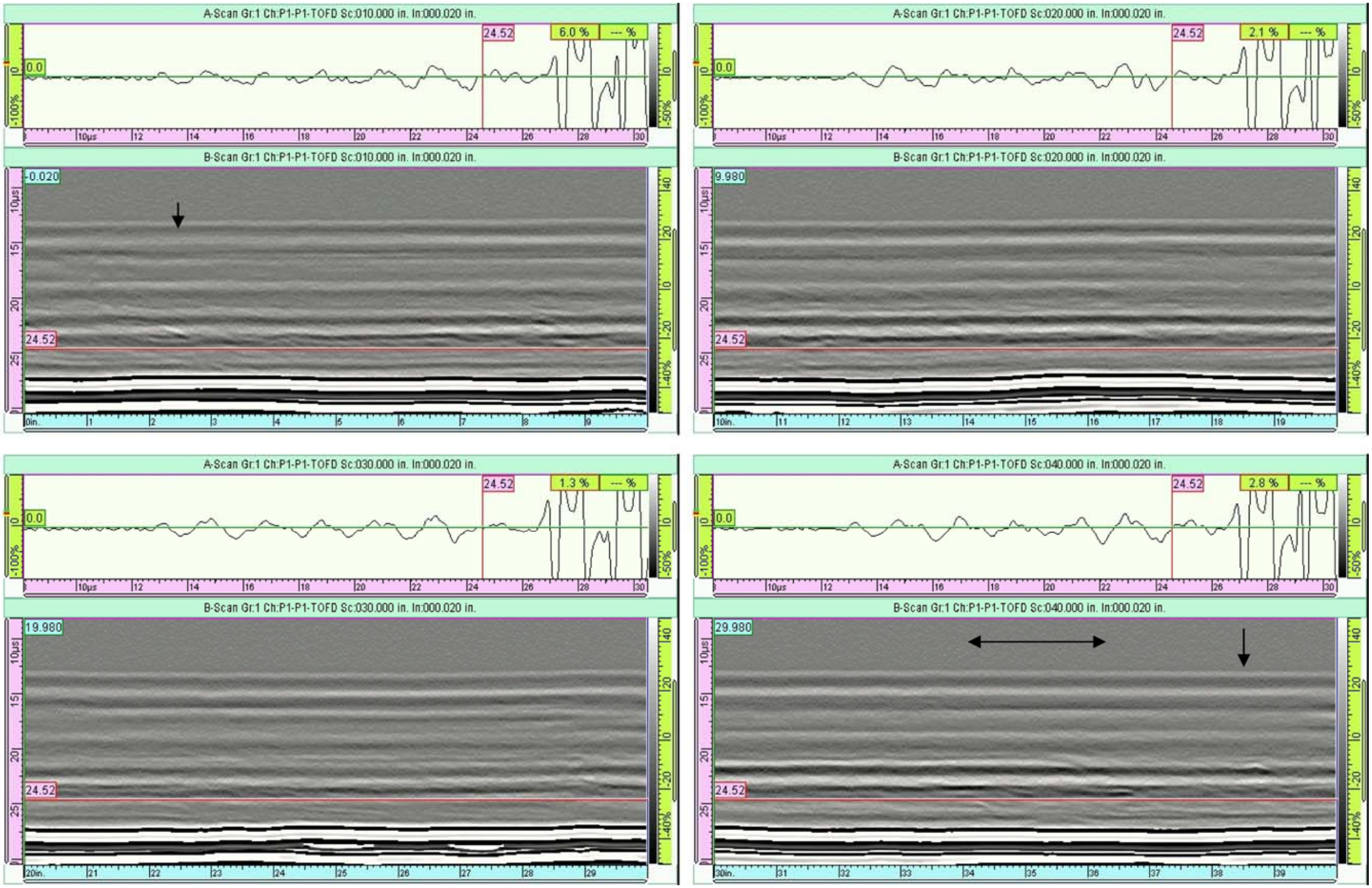

Figure B.9. HDPE Pipe 129, Condition 3

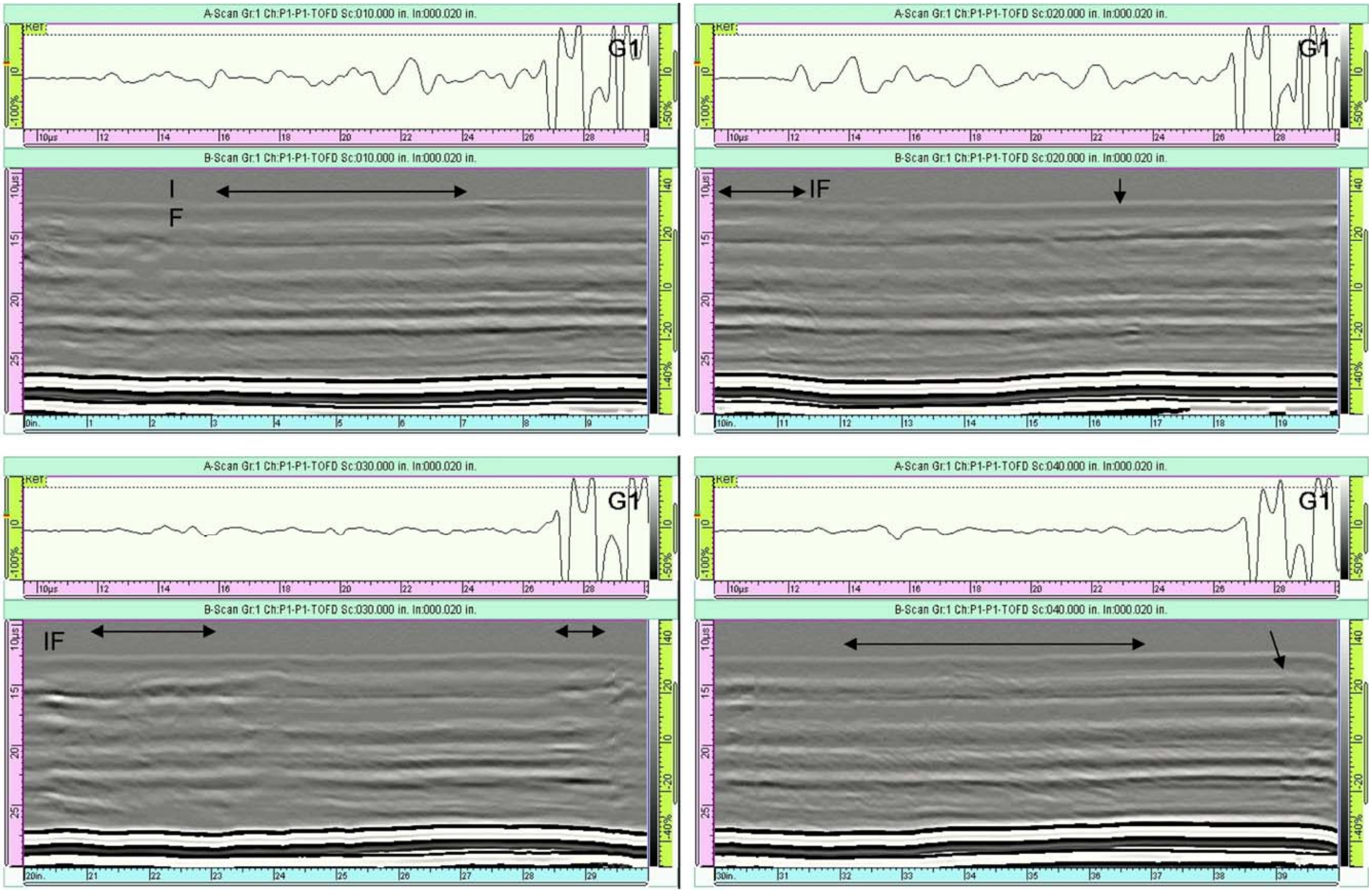

Figure B.10. HDPE Pipe 1210, Condition 3

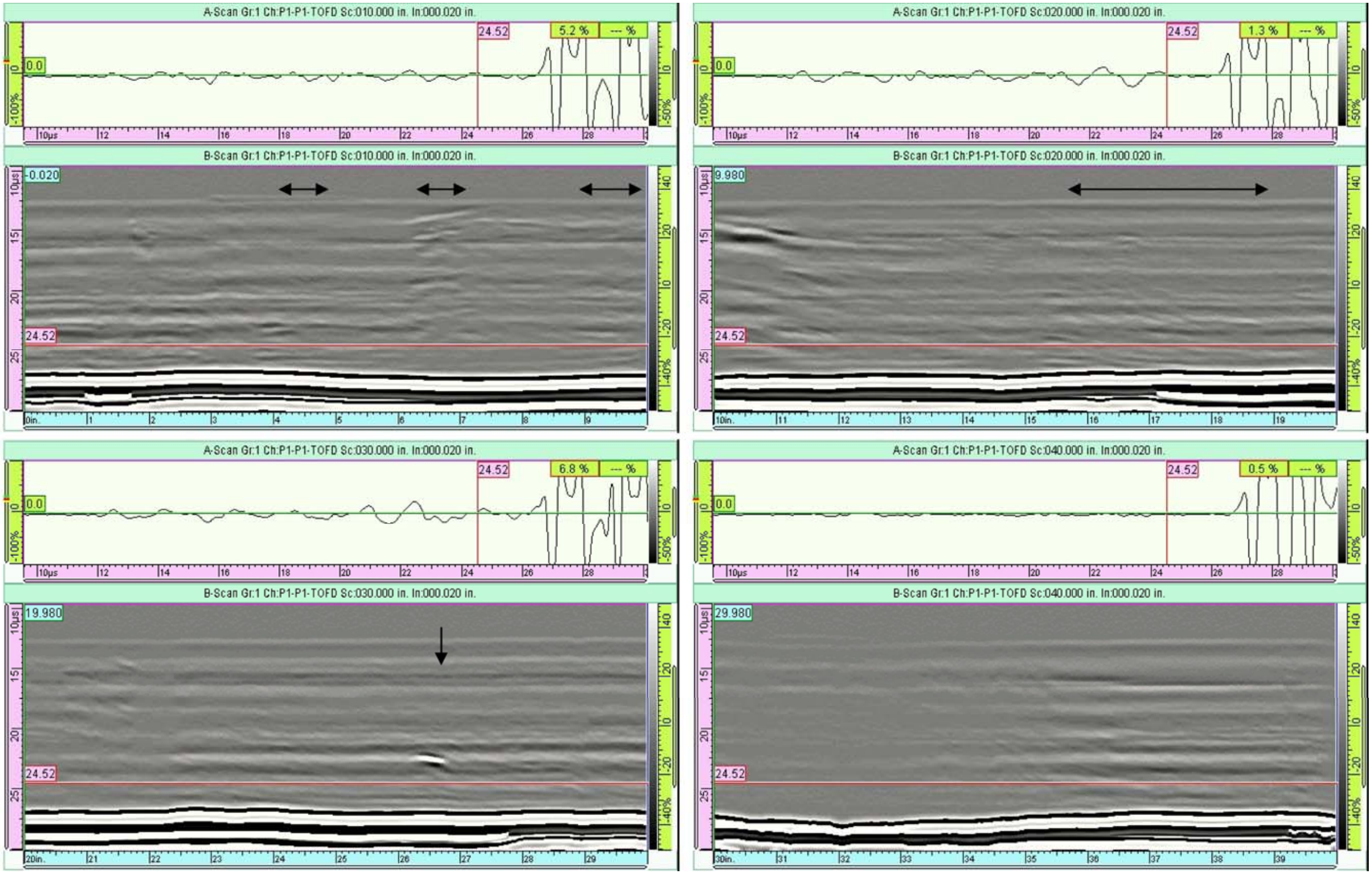

Figure B.11. HDPE Pipe 1211, Condition 3

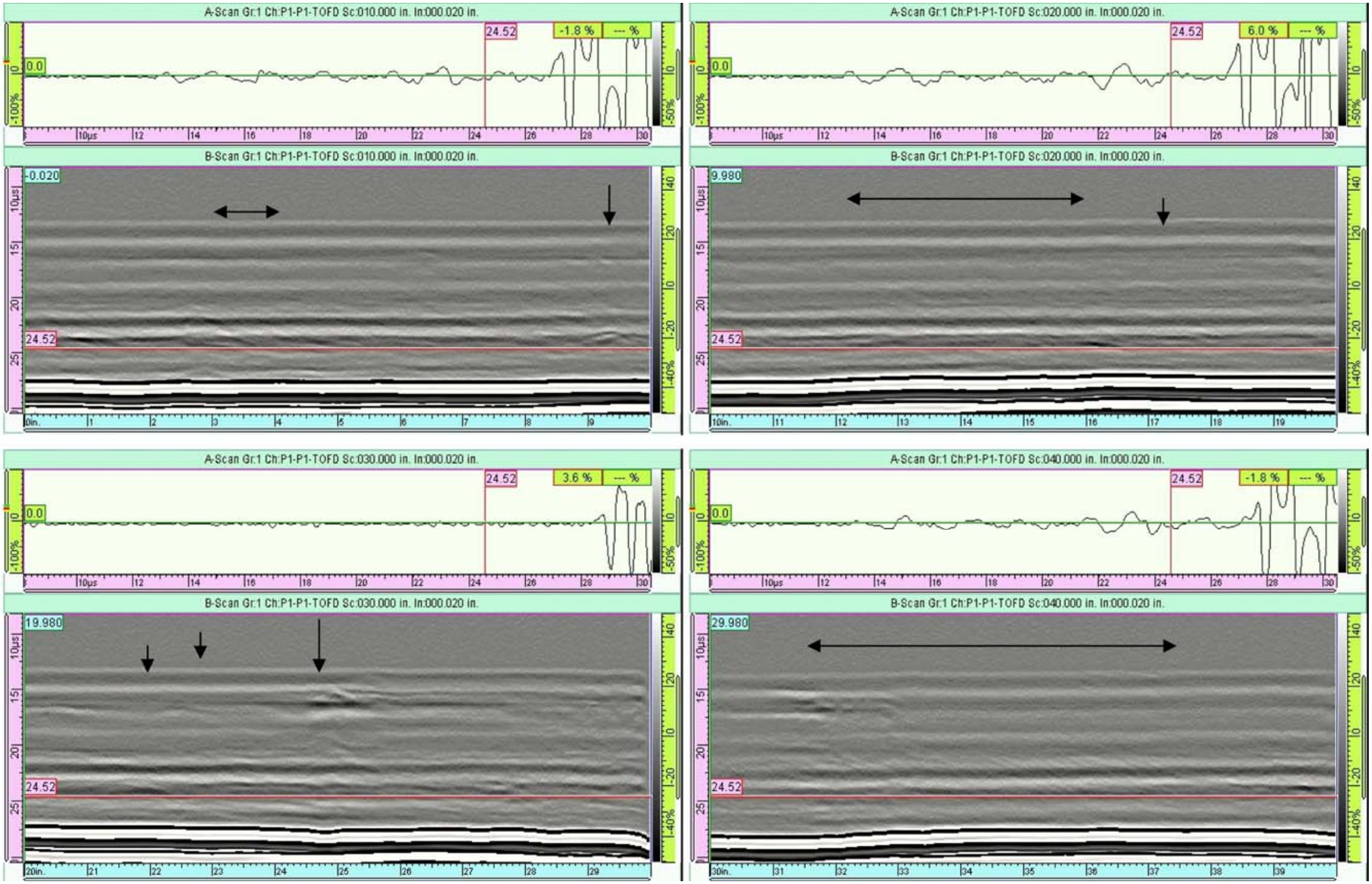

Figure B.12. HDPE Pipe 1212, Condition 3

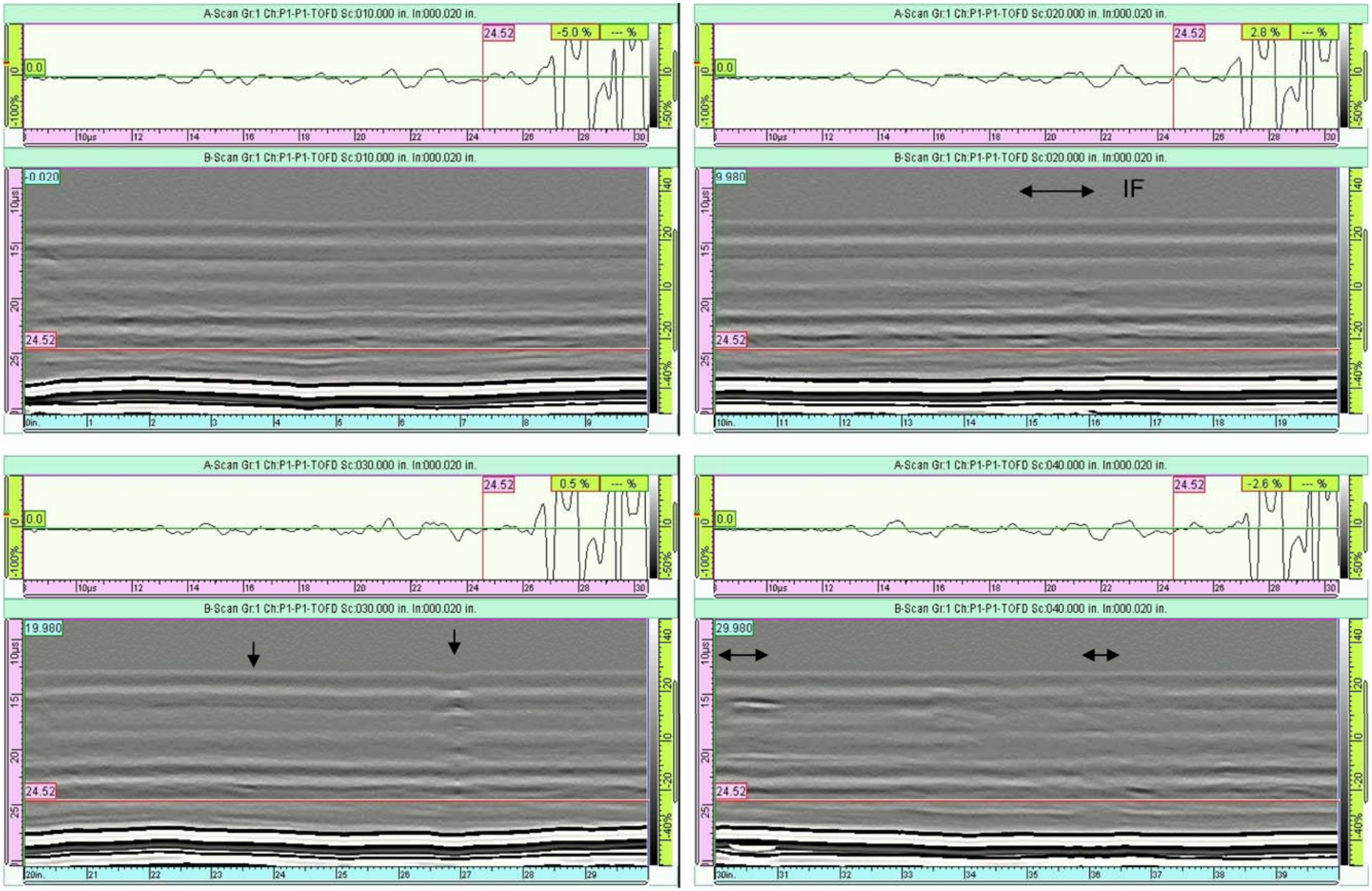

Figure B.13. HDPE Pipe 1213, Condition 4

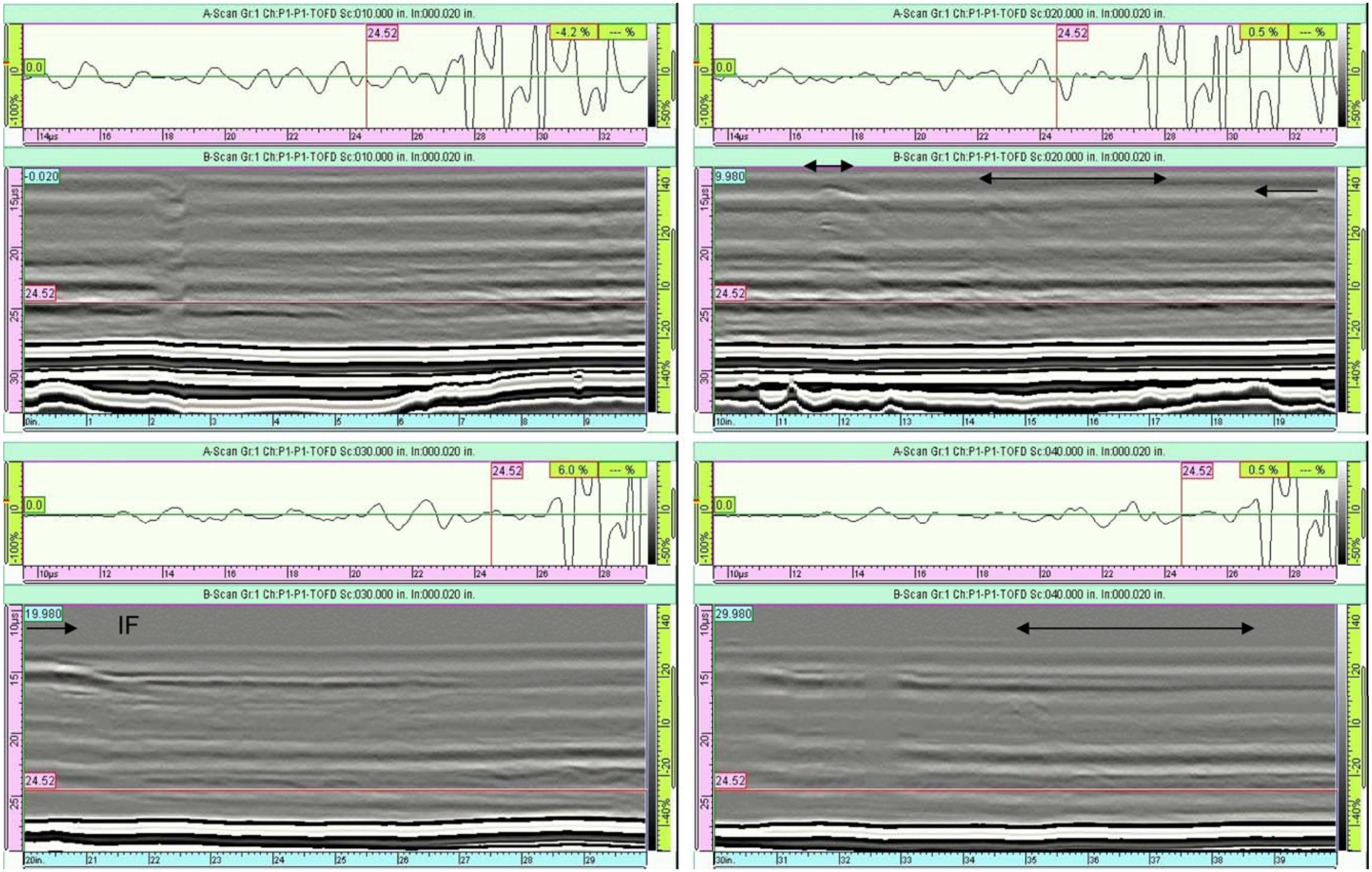

Figure B.14. HDPE Pipe 1214, Condition 4

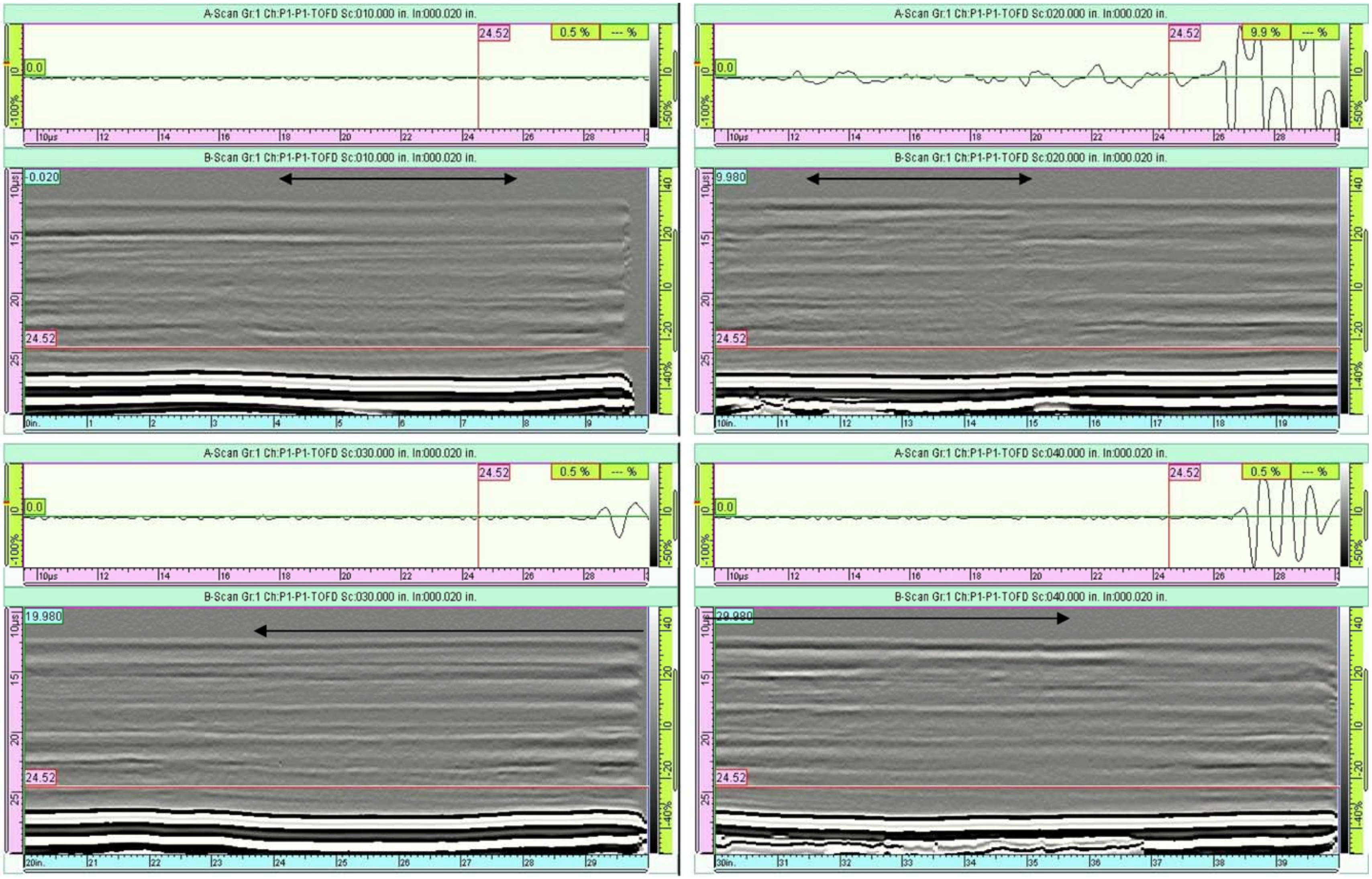

Figure B.15. HDPE Pipe 1215, Condition 4

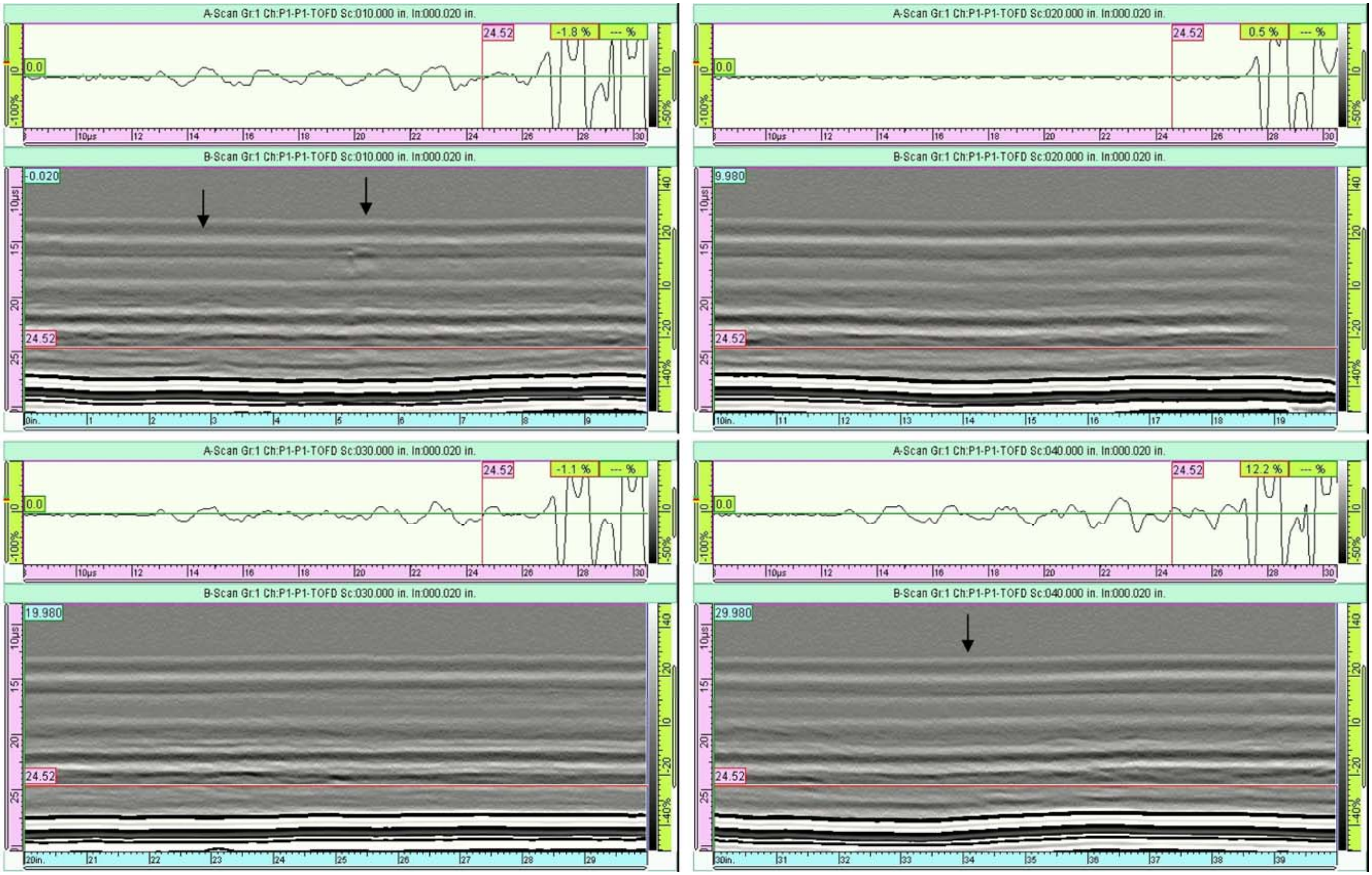

Figure B.16. HDPE Pipe 1216, Condition 4

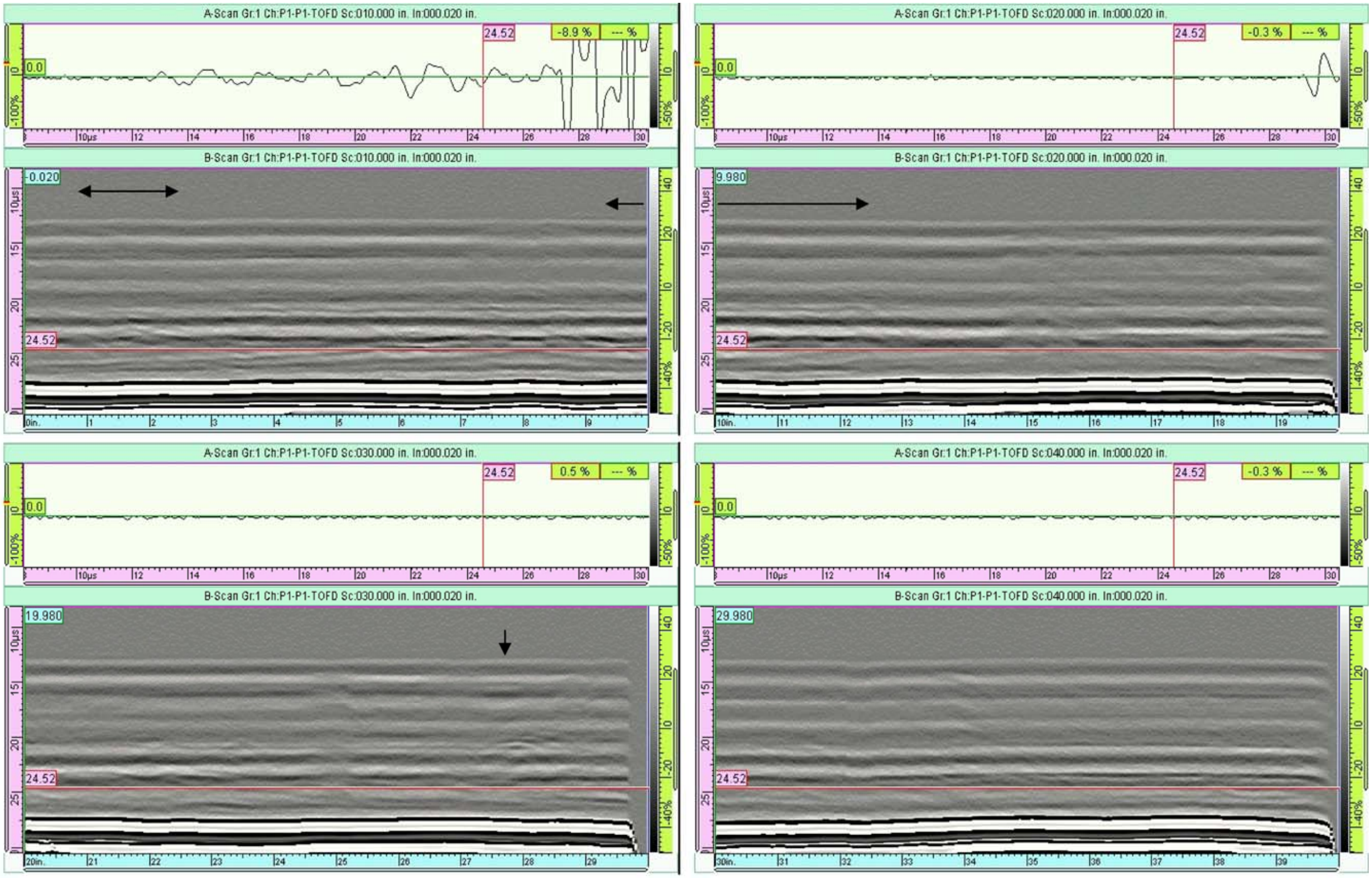

Figure B.17. HDPE Pipe 1217, Condition 5

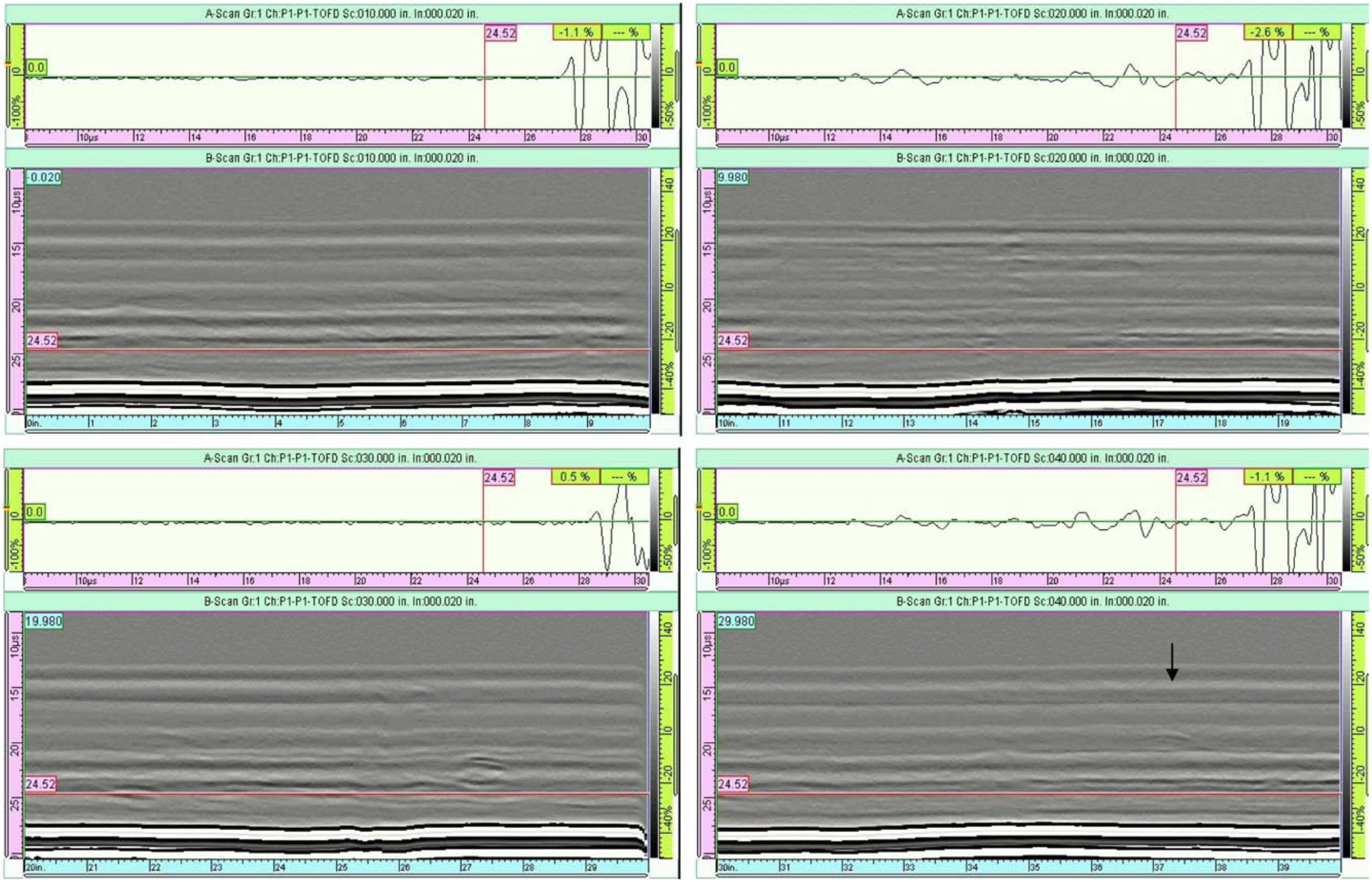

Figure B.18. HDPE Pipe 1218, Condition 5

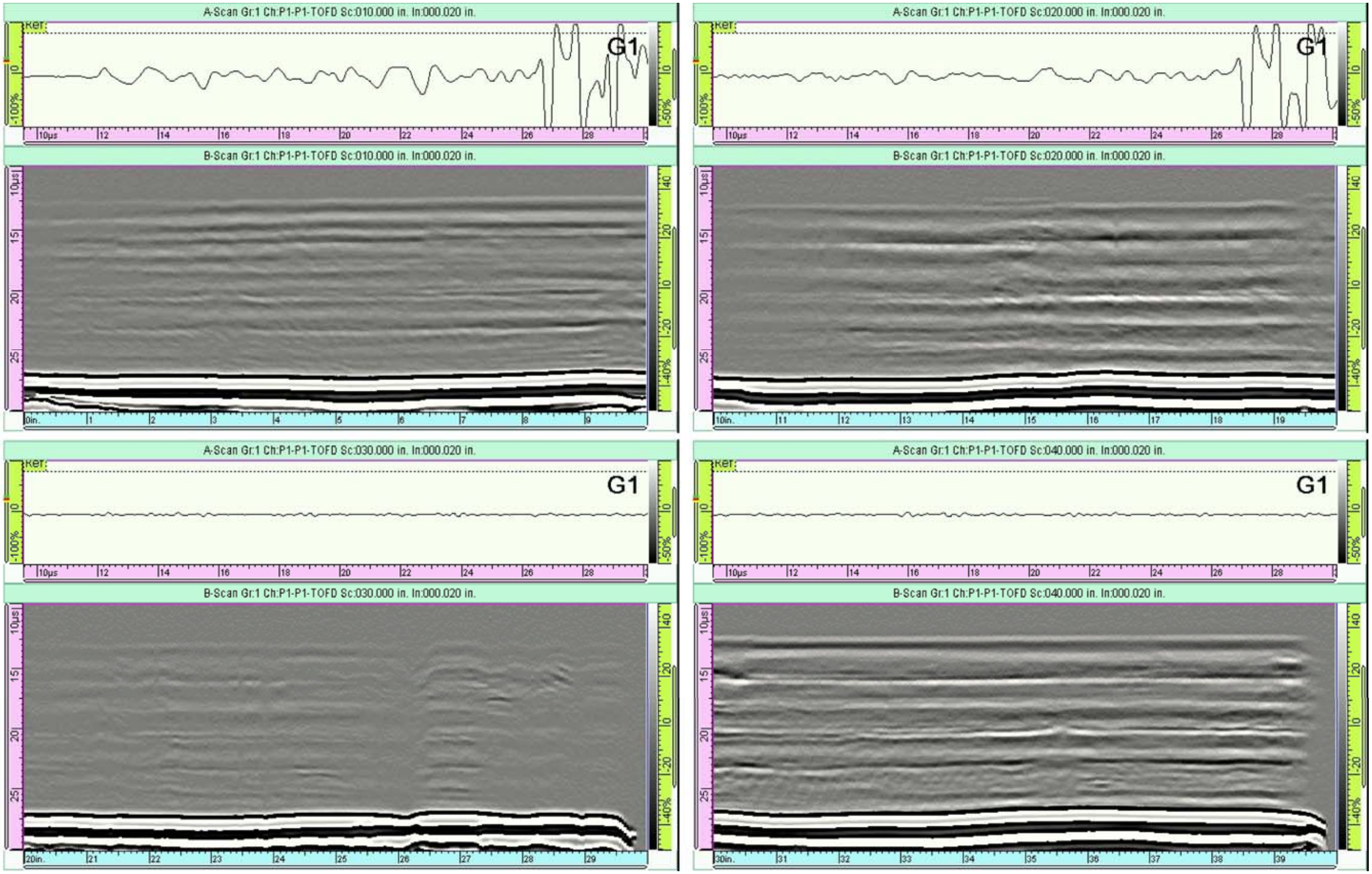

Figure B.19. HDPE Pipe 1219, Condition 5

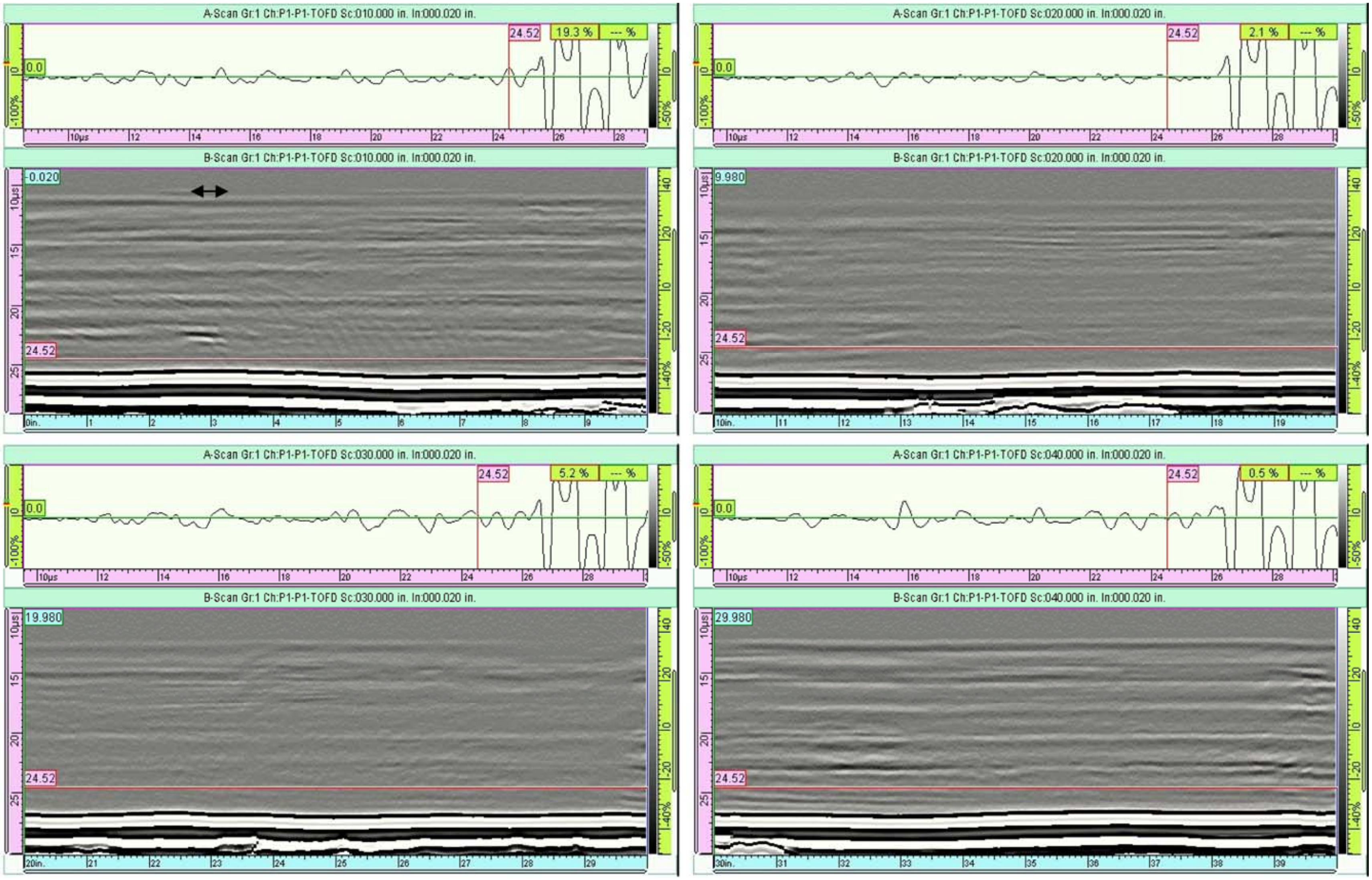

Figure B.20. HDPE Pipe 1220, Condition 5

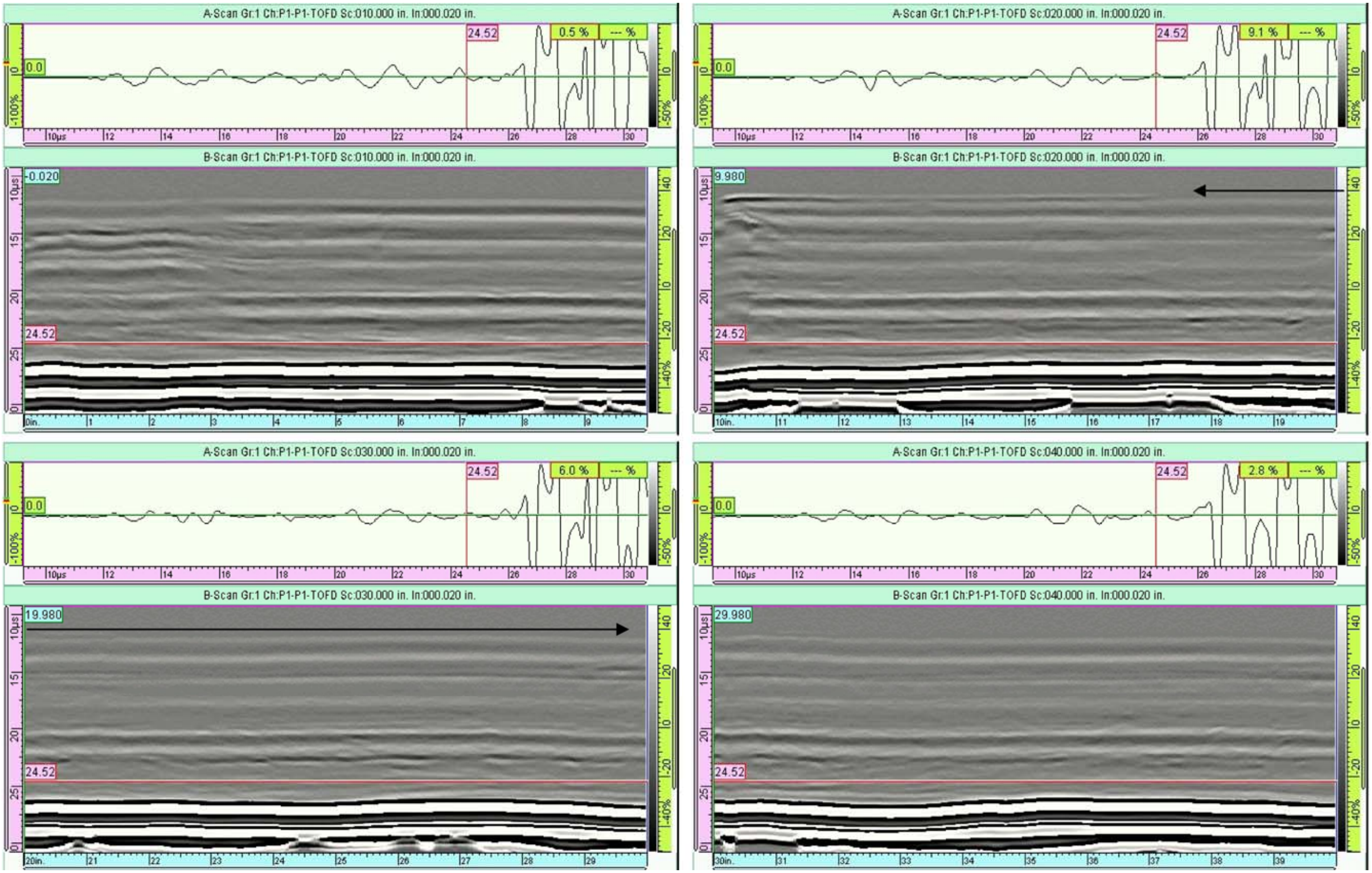

Figure B.21. HDPE Pipe 1221, Condition 6

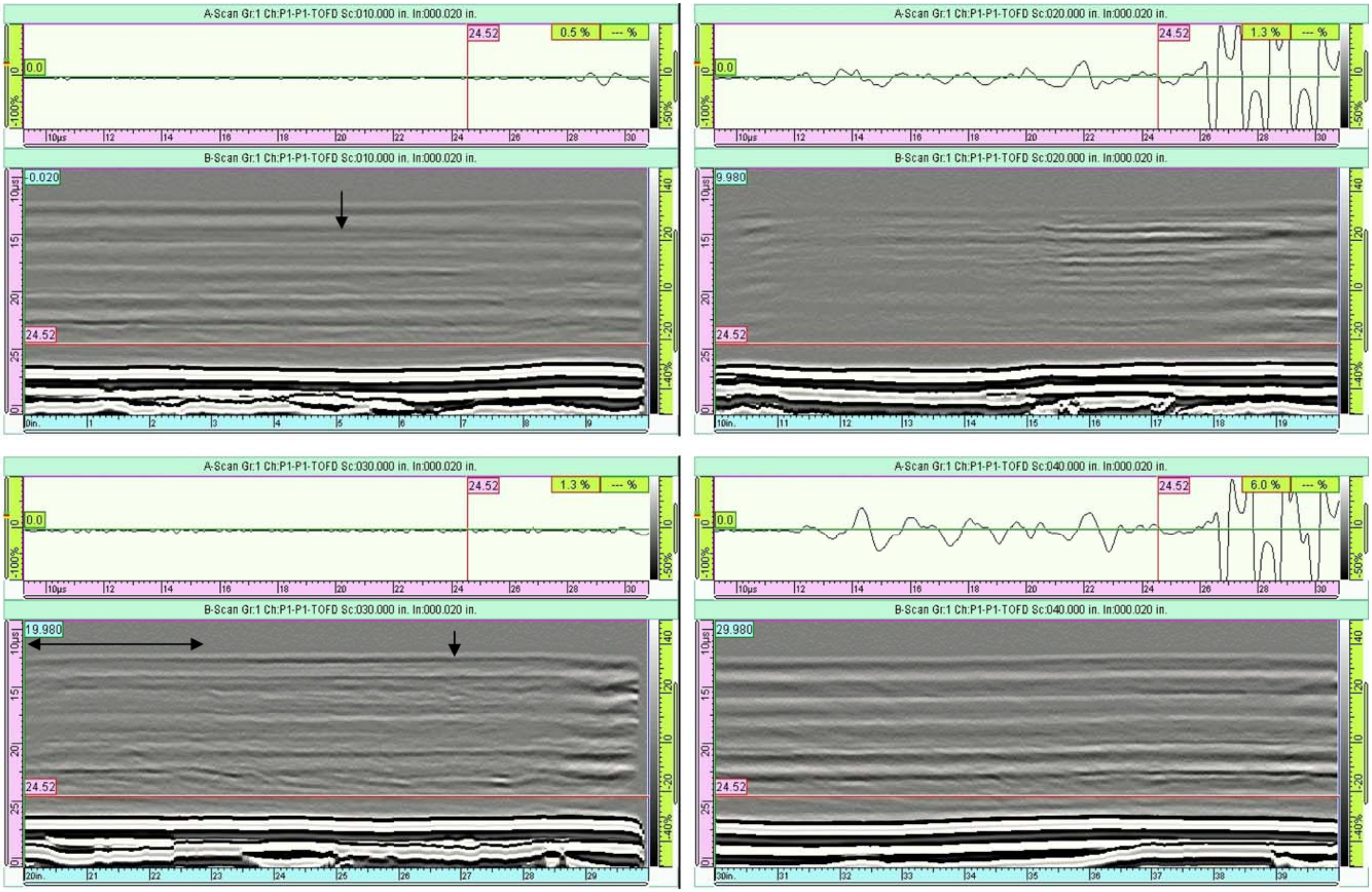

Figure B.22. HDPE Pipe 1222, Condition 6

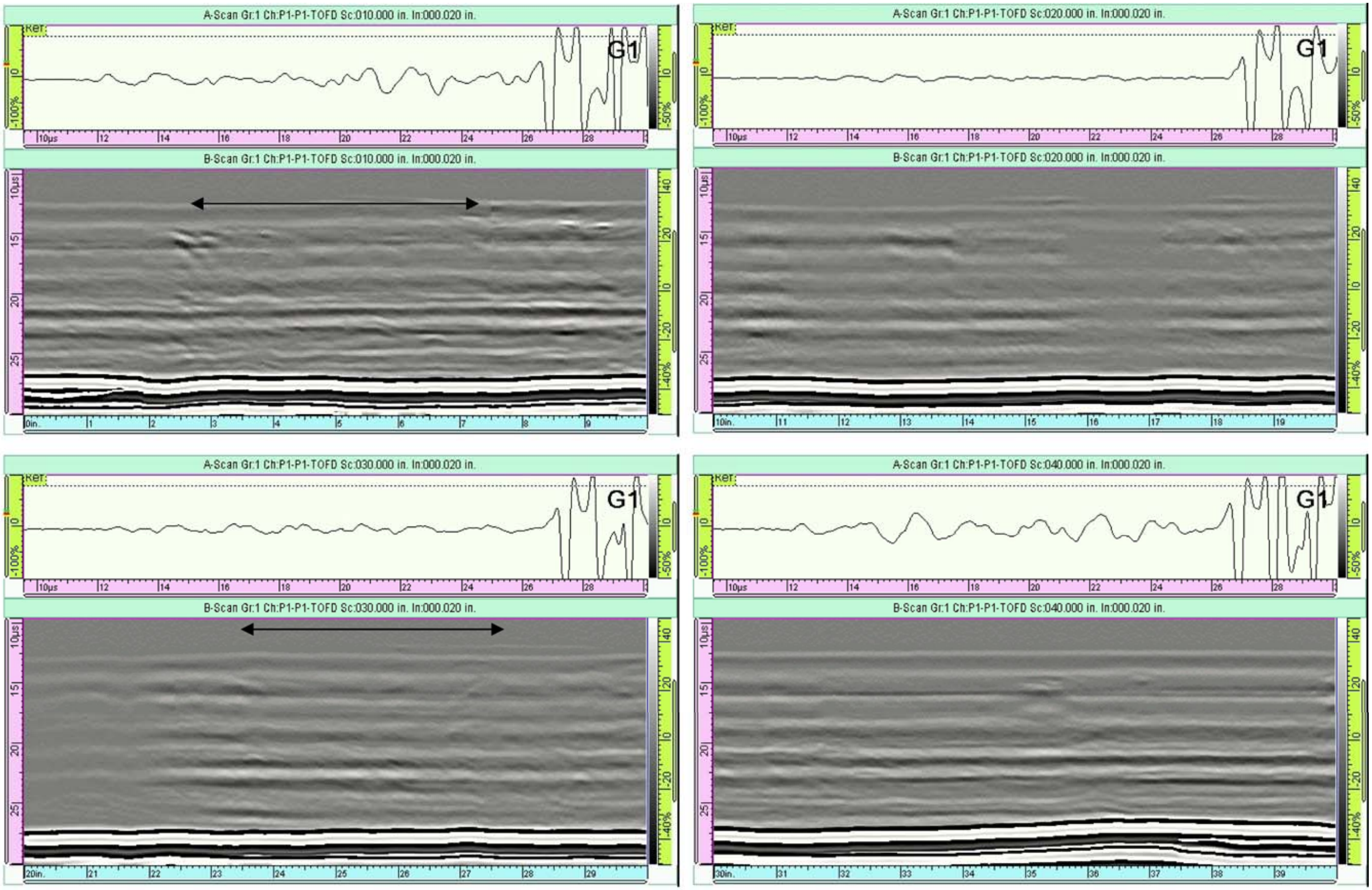

Figure B.23. HDPE Pipe 1223, Condition 6

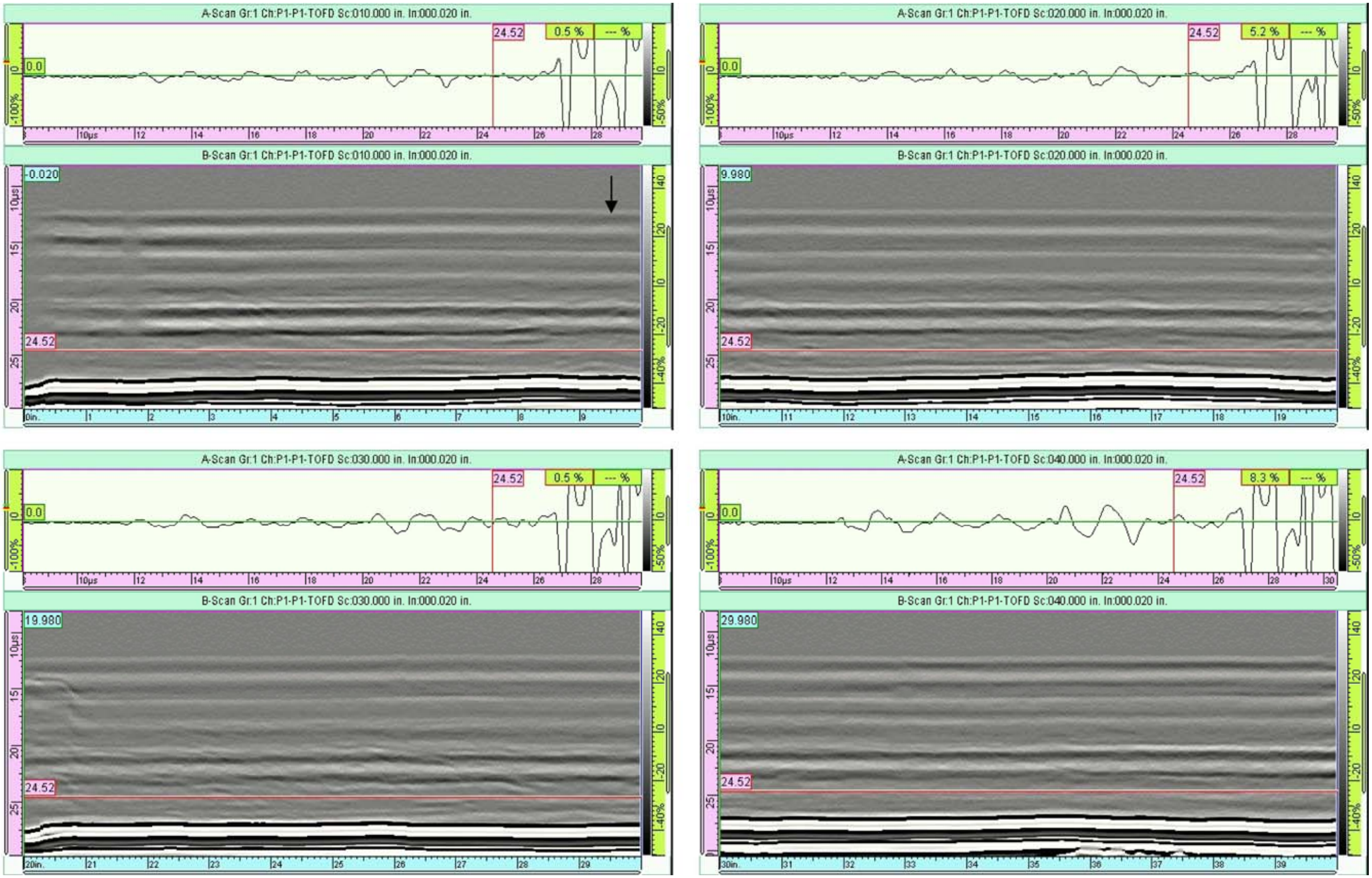

Figure B.24. HDPE Pipe 1224, Condition 6