Final Report

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Research Topic No. 13.2-PH1

Titled

Structured Waveform, Magnetic Field (SWMF) PIG Development for Cracks and Corrosion

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Preface

This final report provides the results and recommendations of the Phase I SBIR titled "Structured Waveform, Magnetic Field (SWMF) PIG Development for Cracks and Corrosion". Based on these results, JENTEK strongly recommends that a Phase II program or an alternative follow-on contract is funded. This SBIR effort is critical to JENTEK's commercialization plans for an In-Line Inspection (ILI) tool for the detection and characterization of internal and external pipeline damage.

JENTEK has successfully completed the Phase I effort as described in the Executive Summary and in this final report. We appreciate this opportunity to contribute to the Department of Transportations' Pipeline and Hazardous Materials Safety Administration plans for improved safety of our nation's pipelines by exploring new technologies that can detect damage and imminent failure in pipelines.

1.0 Executive Summary

The primary objective of this Phase I program was to demonstrate feasibility for ERW weld crack detection, internal/external corrosion imaging, longitudinal stress mapping, and post weld heat treatment assessment using a next generation advanced MWM-Array or MR-MWM-Array integrated solution.

This program focused on through wall inspection of external defects. The MWM-Arrays that JENTEK has been using on existing ILI prototypes are limited to higher operating frequencies, which makes them suitable for inspecting ID defects at high tool speeds, but these arrays are not sensitive to mid-wall or OD defects. JENTEK's MR-MWM-Arrays can operate at lower frequencies and can detect ID, mid-wall, and OD defects, but the current technology is limited to low tool speeds that make it impractical for conventional ILI approaches. In this SBIR program, JENTEK investigated two different concepts that have the potential to produce an ILI tool that can break through these limitations and provide ID, mid-wall, and OD defect inspection (corrosion and cracks) under ILI operating conditions.

1. **SWMF.** [redacted]
2. **Low Frequency Eddy Current with Saturating Field.** [redacted]

Efforts during this Phase I program also included enhancing the high frequency Integrated Cleaning Tool to add the capability to characterize internally initiated cracks. This tool is currently being tested for internal corrosion and stress mapping using MWM-Arrays, under PRCI funding. It is also the basis for two new tool designs that are being developed under funding from a major oil company. The work under this SBIR program focused on detection of ID surface breaking cracks in ERW welds. Different sensor designs were evaluated and several showed the capability to successfully detect flaws in ERW welds. This information will provide a benchmark for future tool design.

The major accomplishments of this SBIR are summarized below:

1. As a result of substantial demand for enhanced ILI capability, JENTEK is now under contract with a major oil company, with funding of over $2.5 million, for development and testing of an ILI tool for internal corrosion and stress mapping. This same customer is also interested in both internal crack detection for girth welds and through wall inspection capability for corrosion and

cracks. Thus, we anticipate continuing funding for crack detection and through wall applications, as well as a continuation of the current funding through deployment.

2. Investigated the requirements for enhancement of the MR-MWM-Array methodology. Two major efforts were undertaken under this program. [redacted]

3. Investigated the requirements for detecting flaws in ERW welds using JENTEK's Integrated Cleaning Tool. Measurements were taken on EDM notches in an ERW weld to demonstrate the effect of sensor geometry on the ability of the Integrated Cleaning Tool to detect ERW defects. This effort showed the feasibility of using a modified 8200 electronics module to perform practical ILI runs for internal crack detection.

4. [redacted]

Although [redacted] is a promising method, it does not address the primary objective of enabling frequent, low cost inspections. One goal is to provide a small tool that is logistically less cumbersome and can use the same type of pig launchers as a cleaning tool. Thus, JENTEK will continue to pursue multiple avenues, to provide more options for operators. It is likely that there will be a market both for [redacted] MR-MWM-Array approach that can be run frequently with logistics demands similar to a cleaning tool.

2.0 Work Plan and Technical Objectives

2.1 Phase I Technical Objectives

1. Adapt MR-MWM-Array technology for ILI and enable sufficient data resolution at high transit speeds to keep up with production flow rates.
2. Demonstrate detection feasibility for external corrosion at transit speeds above 5m/s and develop a transition plan for the demonstrated capability.
3. Enhance the current JENTEK integrated cleaning tool with the capability to detect internally initiated cracks, to measure longitudinal stress, and assess post weld heat treatment.

2.2 Phase I Work Plan

Task 1: Problem definition

Task 2: Enhanced MR-MWM-Array Methodology Development

Task 3: Develop an Integrated Cleaning Tool for Internal ERW Flaw Detection

Task 4: Investigate the feasibility of a MWM-Array ILI tool with a saturating magnetic field

Task 5: Develop a Transition Plan for ILI Tools and Services

Task 6: Final Report

3.0 Summary of Phase I results

3.1 Problem Definition

The goal of this Phase I SBIR, as was stated in the solicitation, "is to encourage more repetitive ILI runs and wider use while ensuring safety of the hazardous liquid pipeline infrastructure." This goal is aligned with a substantial commercial opportunity for the delivery of next generation In-Line-Inspection (ILI) products and services that can enable more comprehensive inspection of critical pipeline infrastructure, thereby improving safety without adding costs and operational uncertainty.

This program addressed some pressing, high priority needs such as reliable detection of longitudinal cracks (including cracks at ERW welds). This program also encompassed a fundamental shift in ILI technology away from MFL and Ultrasonic solutions. The electromagnetic-based approach used in this Phase I effort can provide the needed sensitivity to defects relevant to pipeline safety in a tool that is able to keep up with production flow rates. Enabled by recent advances in key technological building blocks, the new approach relies on advanced parallel architecture electronics and rapid multivariate inverse methods (MIMs). In addition, the industry has recently become aware of deficiencies in existing ILI capability to address the most pressing safety concerns for pipelines. Taking these realizations into account, the Cost Benefit Analysis (CBA) of the JENTEK tool is expected to greatly surpass that of the current inspection while maintaining or improving reliability and detection requirements. The objectives include substantial cost reduction for initial tool production/procurement, data analysis/decision support, and logistics. More frequent inspections will enable continual trend mapping for damage (cracks, corrosion, mechanical) and strain, while also enabling monitoring and time stamping of damage incidences and tracking of damage evolution (e.g. mechanical damage caused by settling of a buried pipeline segment against a more rigid interference, such as a rock, growth of an SCC colony, evolution of external/internal corrosion, or growth of an ERW defect into a fatigue crack that might lead to pipeline failure). This time stamping provided by extremely reproducible, frequent inspection runs for pipelines that run through densely populated areas may be the only way to ensure pipeline safety, since some damage incidences are randomly tied to events such as incursions, land motion, flooding, or other events that are not necessarily well documented or observed. Also, for fatigue cracks, the time to initiation from a manufacturing defect can be very difficult to predict. After crack initiation, such a crack may grow to a critical size in only weeks or months. Thus, infrequent ILI runs every 3-5 years as currently performed, are likely to miss these defects. ***To constrain the proposed SBIR scope to a reasonable level of effort, in Phase I the primary focus was on mapping of internal and external corrosion and detection and sizing of longitudinal (axially oriented) cracks.***

3.2 Enhanced MR-MWM-Array Methodology Development

There were two major efforts in enhancing the MR-MWM-Array methodology. The first focused on a [redacted]

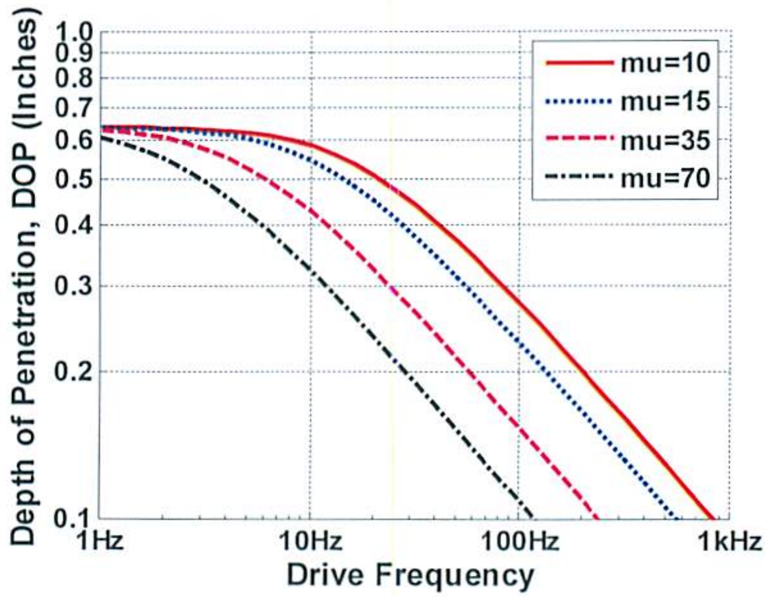
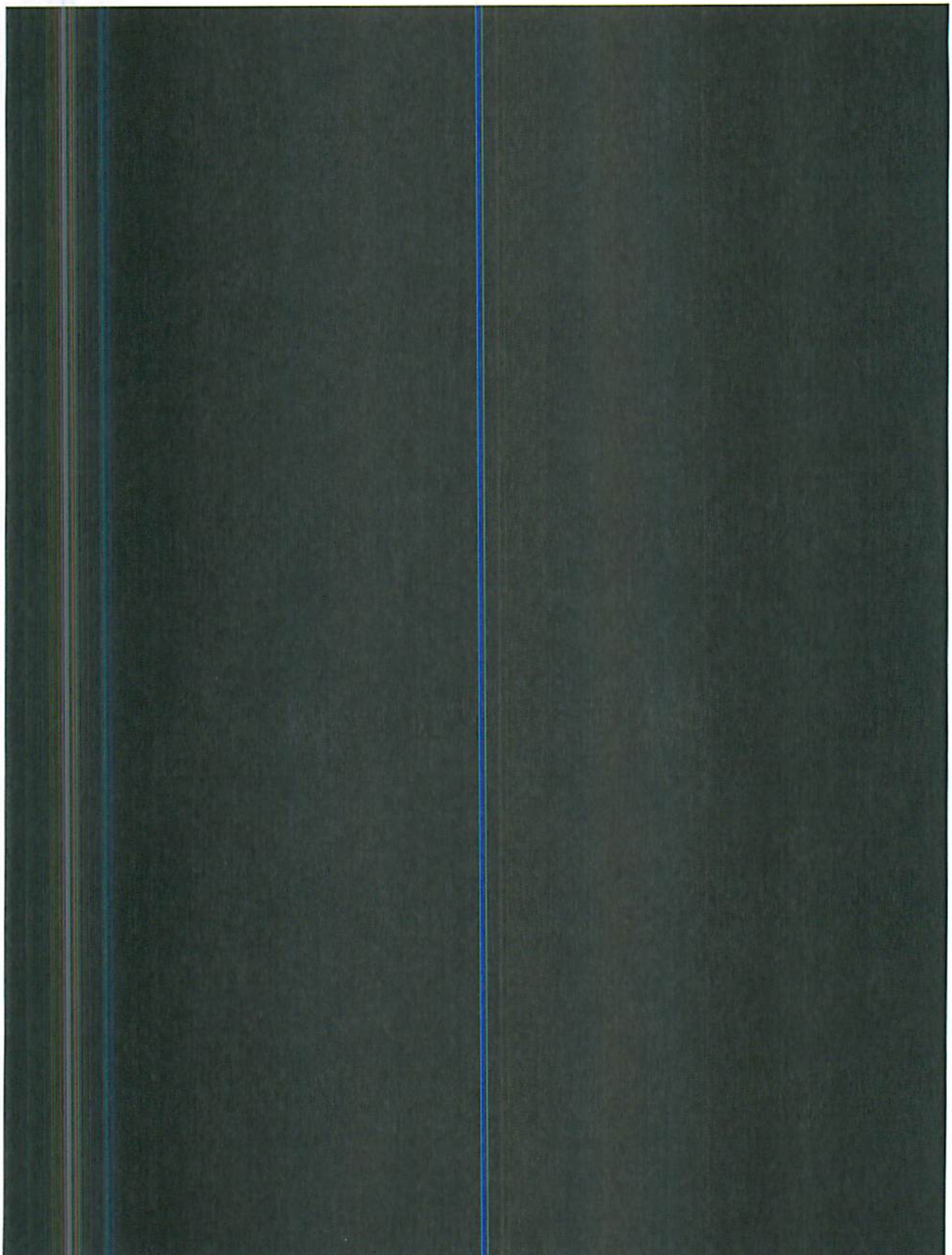
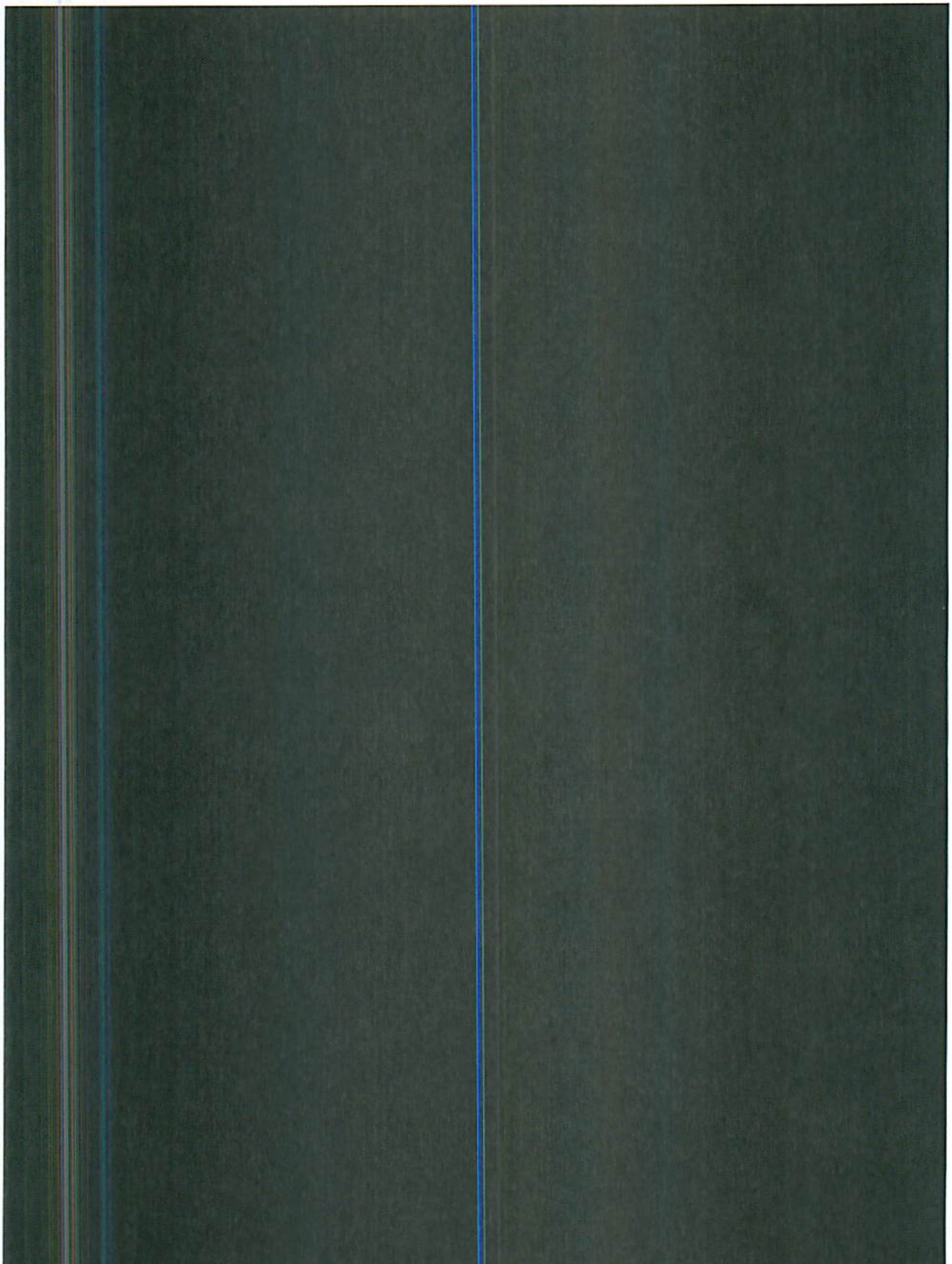
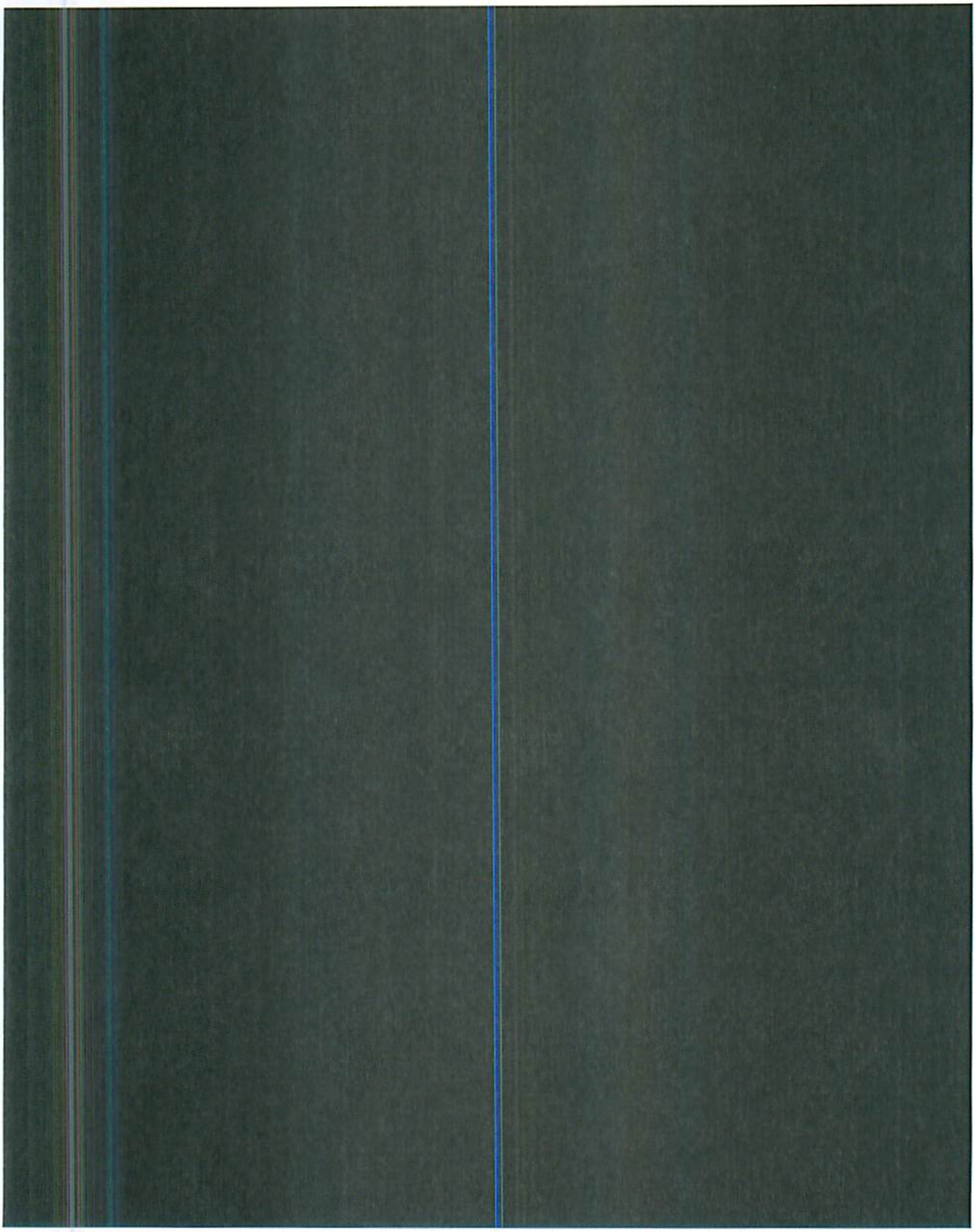


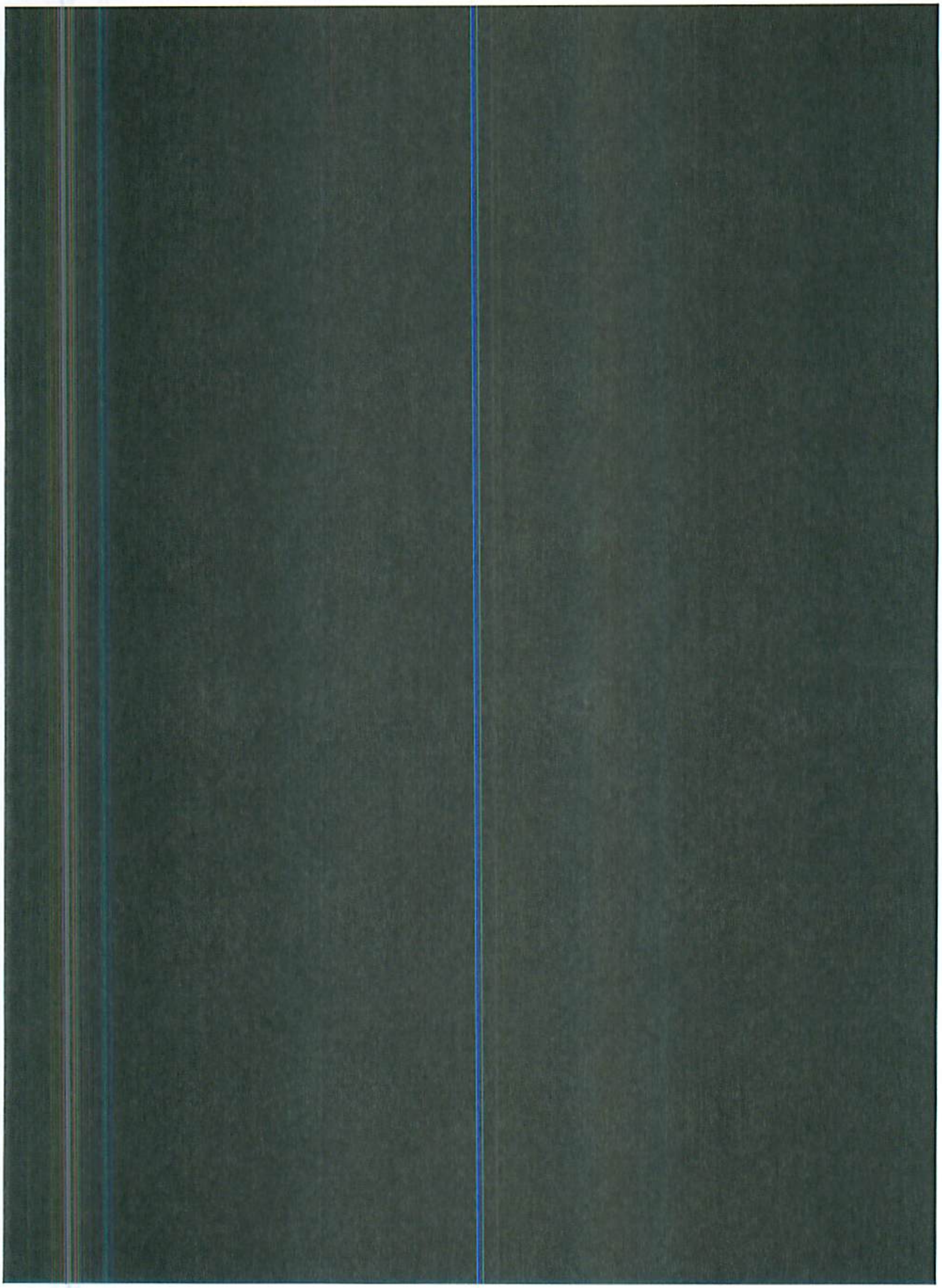
Figure 1. A typical Depth of Penetration (DOP) chart for steel. In order to be sensitive to external defects, the DOP needs to be similar to the pipe wall thickness. In practice, the drive frequency needs to be between 5Hz and 20Hz for typical pipeline materials.





[redacted]





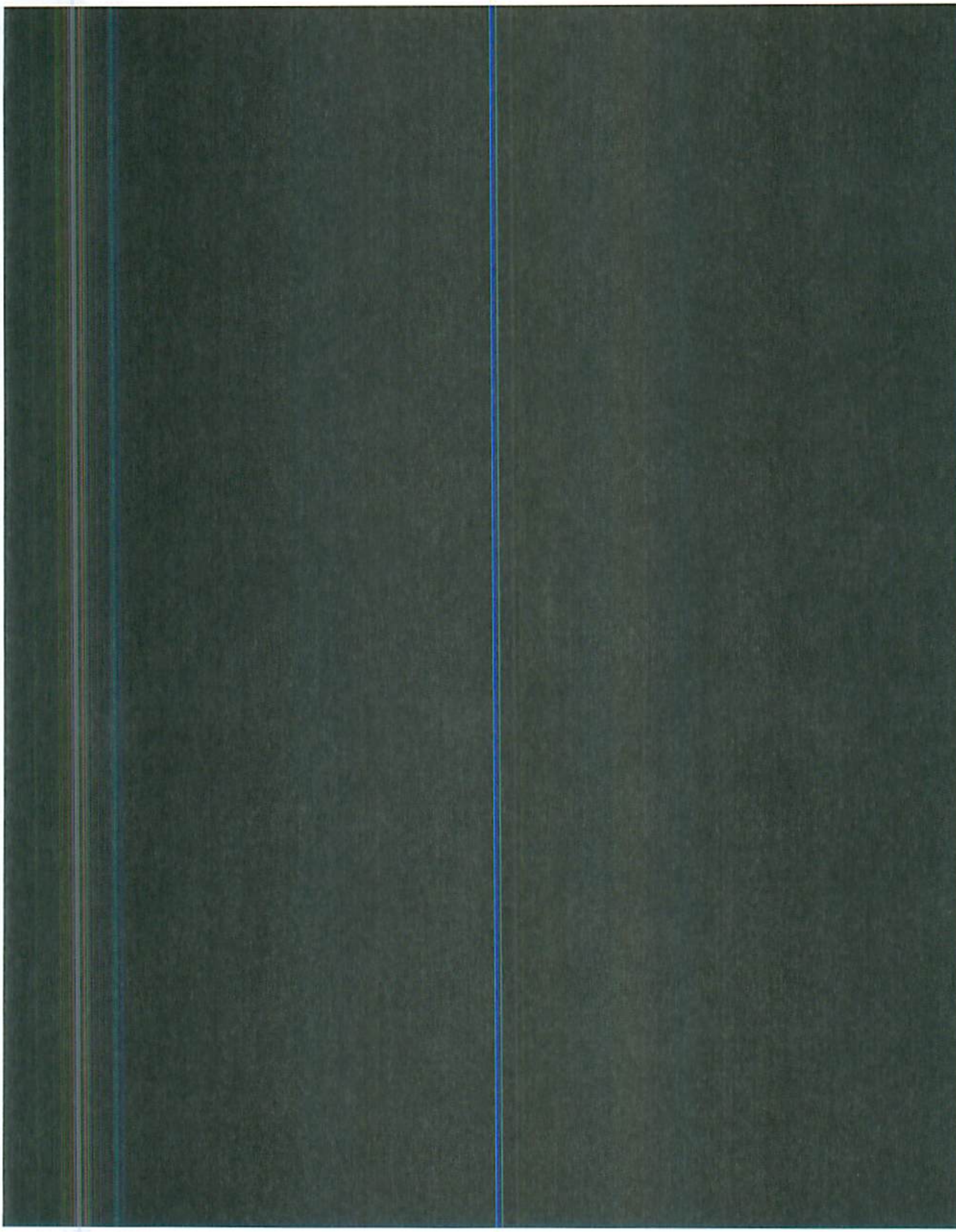
[redacted]

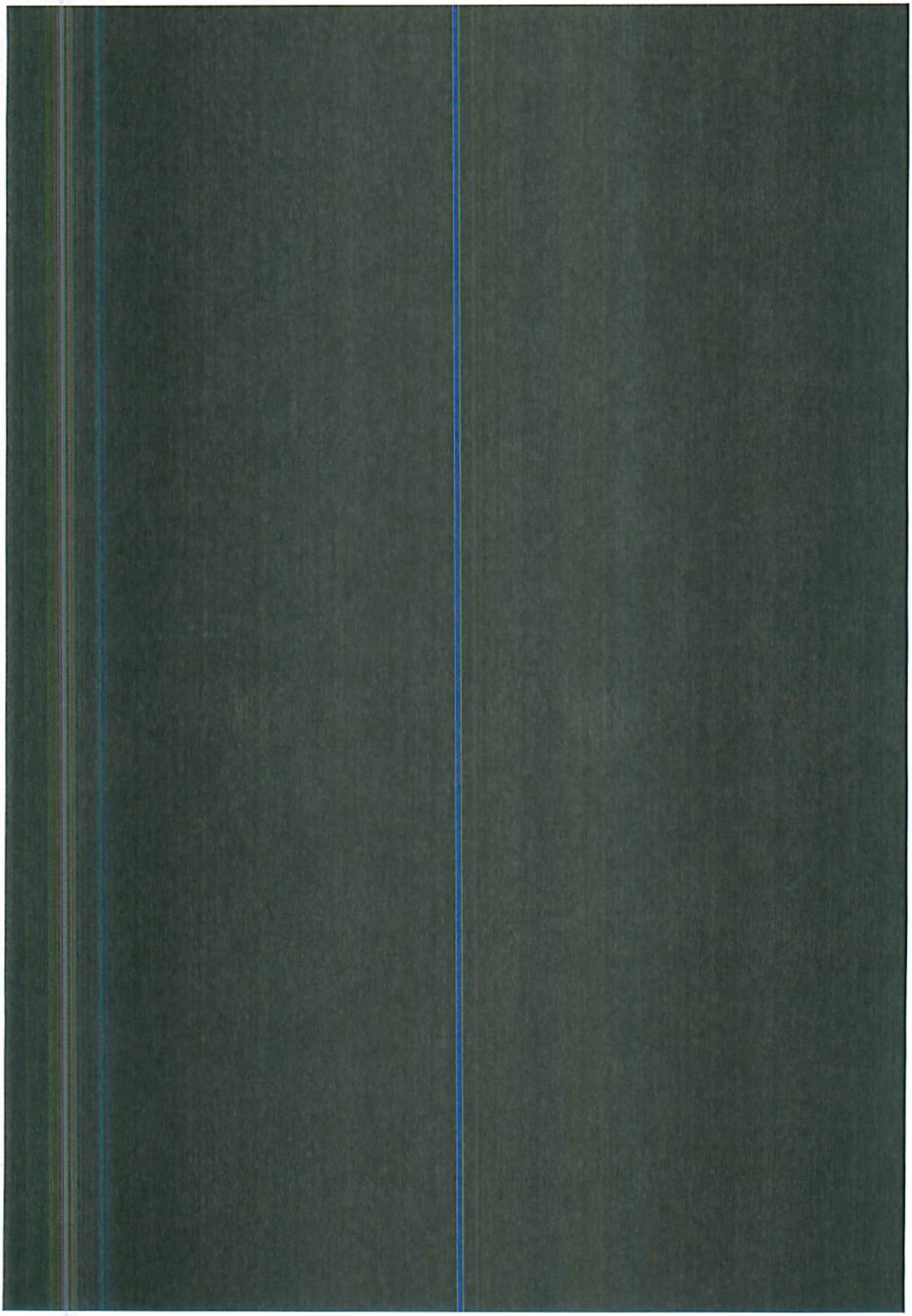
JENTEK is currently under contract with a major oil company to produce a high-frequency version of the Integrated Cleaning Tool for 12" and 20" lines. This project will include modifying the GridStation 8200 electronics based on the needs of the ILI tools. Specifically, changes will be made to reduce the complexity, power consumption, and cost of the electronics. These electronics will support storing data at 10kS/s to a hard drive (or other data storage device), which is consistent with this new data processing methodology. The stored data will then be available for post-processing by a computer after the ILI run to apply the new filtering and data rate improvement techniques.

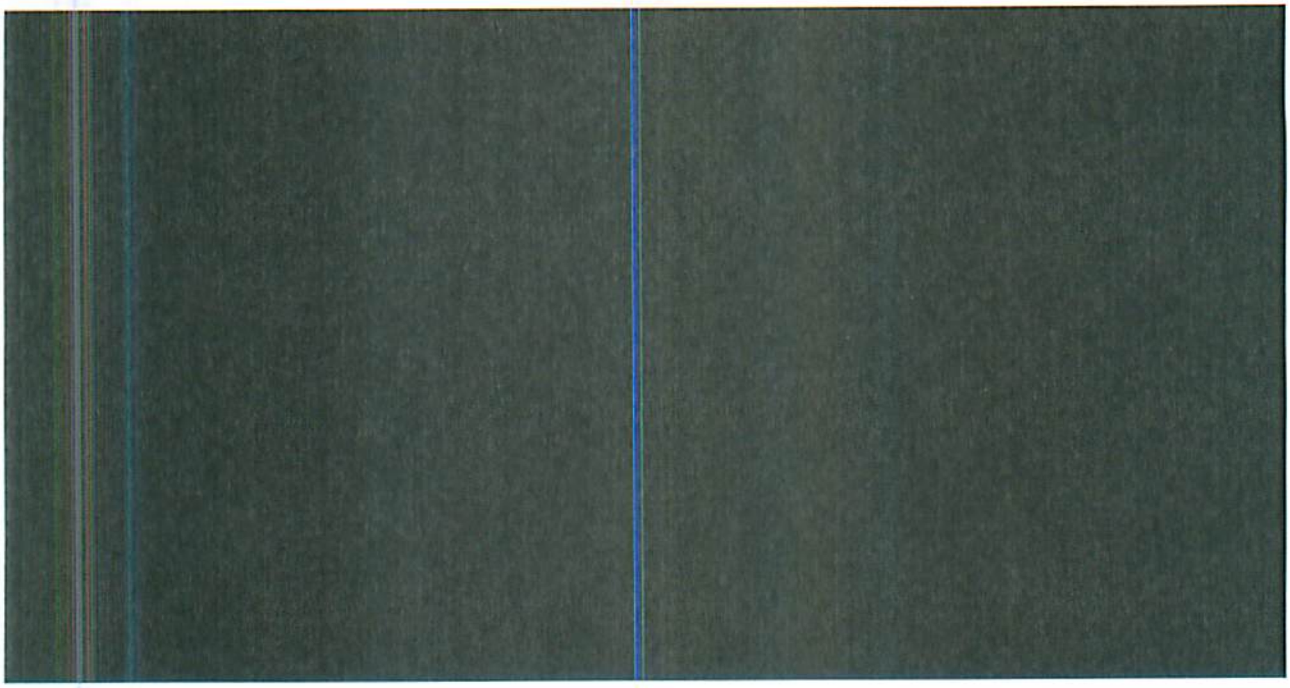
Figure 12 illustrates the value of very high data resolution for a low frequency MR-MWM-Array excitation. [redacted]

[redacted]

Another method for increasing the impedance measurement density is to increase the drive frequency. Since each impedance measurement requires one full period at the drive frequency, an increase in the drive frequency provides a direct increase in the data rate. However, the drive frequency is determined based on the properties of the pipe material, specifically the electrical conductivity, the magnetic permeability, and the wall thickness. [redacted]







3.3 Develop an Integrated Cleaning Tool for Internal ERW Flaw Detection

Under Task 3 and complimentary funding, JENTEK continued to develop the Integrated Cleaning Tool. The focus of this task was to provide a capability for characterizing internally initiated flaws in ERW welds. Figure 14 shows the FA218. The design of the sensor was adapted to provide complete coverage of a 16" pipe using 8 of the FA218 sensors and 72 instrumentation channels. The long, rectangular drive windings induce electrical current into the pipe wall in a circumferential direction, which is ideal for the detection of axially-oriented defects such as ERW flaws and cracks.

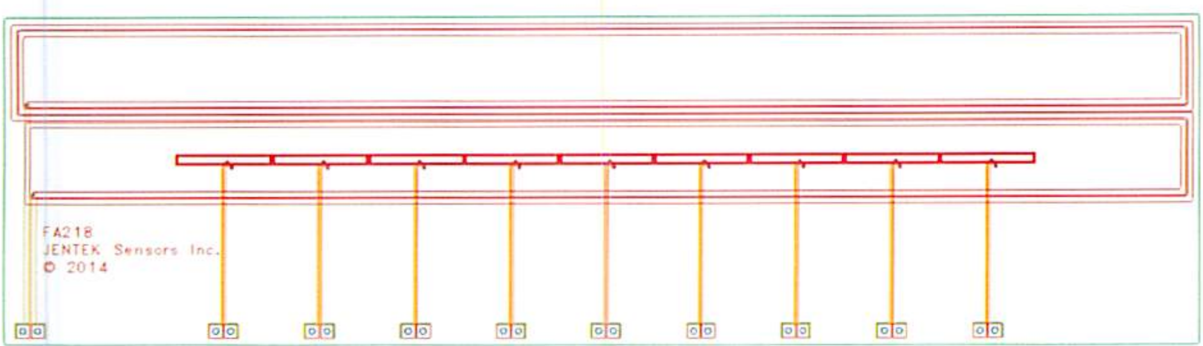


Figure 14. The FA218 MWM-Array. This design was adapted to allow for complete coverage of the ID of a 16" pipe using 8 of the FA218 sensors and 72 instrumentation channels.

Figure 15 shows where the sensors will be located on the Integrated Cleaning Tool. The current design has two modules – a front module and a rear module. The front module contains the batteries and the central computer. The rear module contains the GridStation 8200 impedance instrument. The sensors mount to the outside of the rear module. Note that future designs of large diameter tools will be consolidated into a single module to reduce weight, complexity, and cost.

Primary funding for the Integrated Cleaning Tool comes from JENTEK, PRCI (for testing on PRCI member parts only), and other commercial sources. The focus for this SBIR program is to ensure that the design and fabrication of the Integrated Cleaning Tool is performed in a manner that is consistent with the goal of characterizing axially-oriented cracks in ERW welds.

The initial build of the front module is complete (see Figure 16). The fabrication of the rear module body is also complete (see Figure 17). The GridStation 8200 impedance instrument, which has been fabricated and tested entirely under JENTEK funding, is now ready to be integrated into the tool (see Figure 18). The fabrication of the 8 sensor arms and the FA218 MWM-Arrays is ongoing.

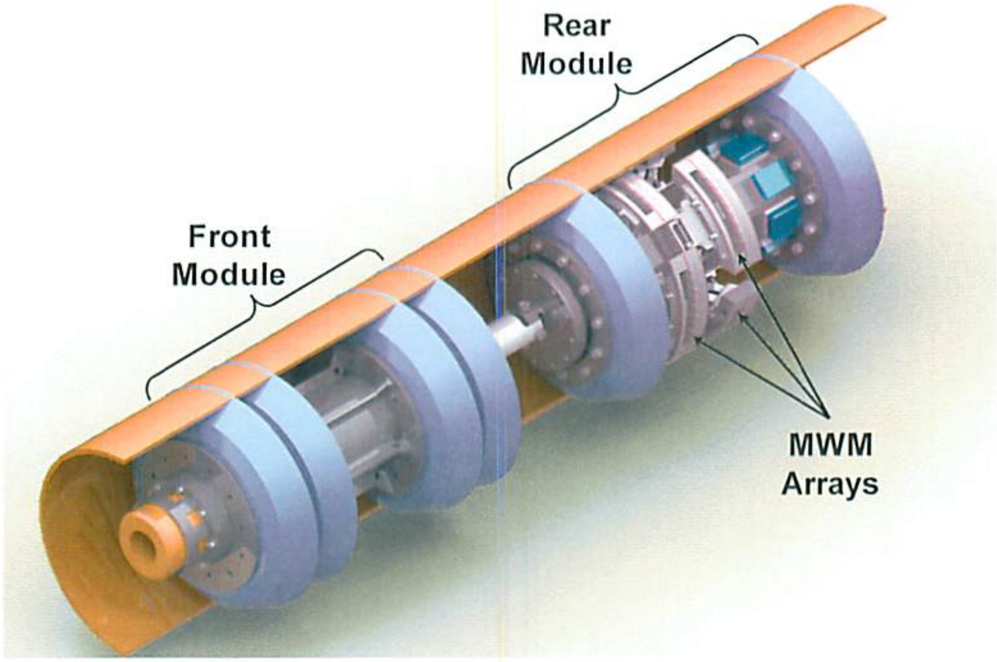


Figure 15. JENTEK's Integrated Cleaning Tool. The front module contains batteries and the central computer. The rear module contains JENTEK's 8200 impedance instrument. The MWM-Arrays mount to the rear module.

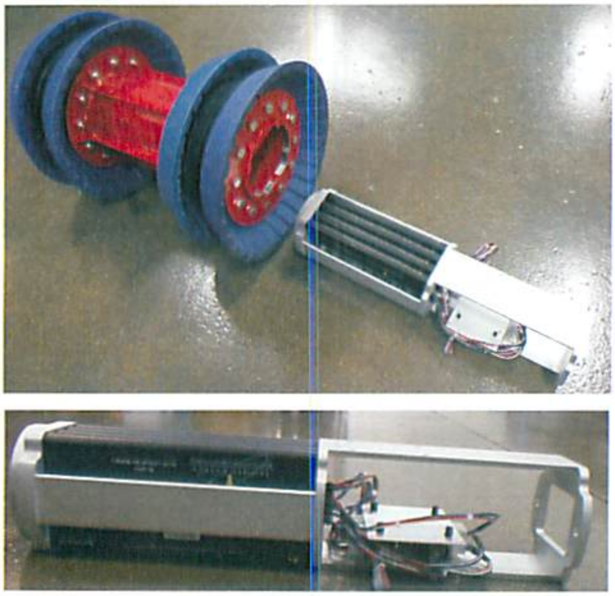


Figure 16. Front end module of the integrated cleaning tool. The cleaning tool body shown has been slightly modified to house the front module, which holds the batteries, power distribution electronics, hard drive for data storage, and an embedded computer.

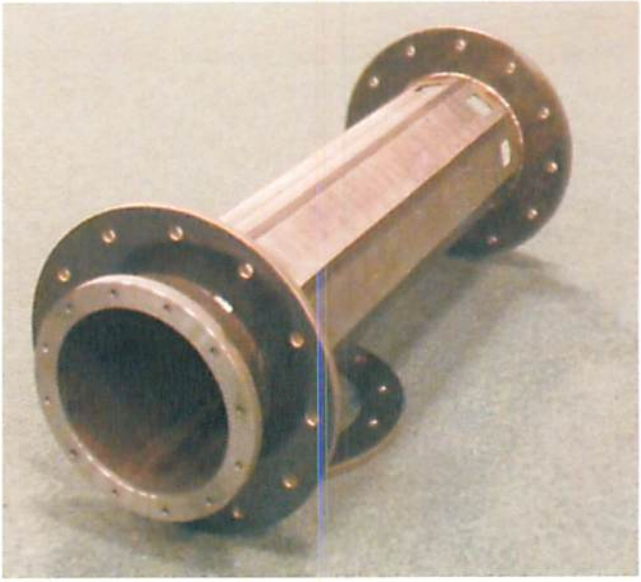


Figure 17. Rear module body. This body will house the GridStation 8200 impedance electronics and will be the mounting point for the sensor arms and FA218 MWM-Arrays.

Figure 18. GridStation 8200 impedance instrument. The internal electronics will be integrated into the rear module.

Testing was performed on an ERW weld sample that has two EDM notches (2" long and 0.050" deep). One notch is on the ID and one notch is on the OD. The goal of the testing was to assess the ability of the cleaning tool to detect EDM notches in ERW welds. Scans we performed with three different sensors: the FA28, the FA24, and the FA218. These sensors are each constructed to work for different applications. The FA28 has a small sense element spacing (0.040 inches) and is capable of high resolution scanning. The FA24 has moderate sense element spacing (0.100 inches) to produce a larger, lower resolution scan. The FA218 has a large sense element spacing (0.715 inches) and was designed specifically for the Integrated Cleaning Tool.

Figure 19 shows an image of data taken over the EDM notch on the OD of the sample using the FA28. This sensor is well suited for high resolution imaging of cracks, so the EDM notch is clearly detected. Figure 20 shows an image of data taken over the EDM notch on the OD of the sample using the FA24. For defects of this size, the FA24 still clearly detects the EDM notch. Figure 21 shows an image of data taken over the EDM notch on the ID of the sample using the FA24. While the EDM notch signal is equivalent, there is also significant property variation from the weld. This property variation would make it more difficult to detect smaller defects.

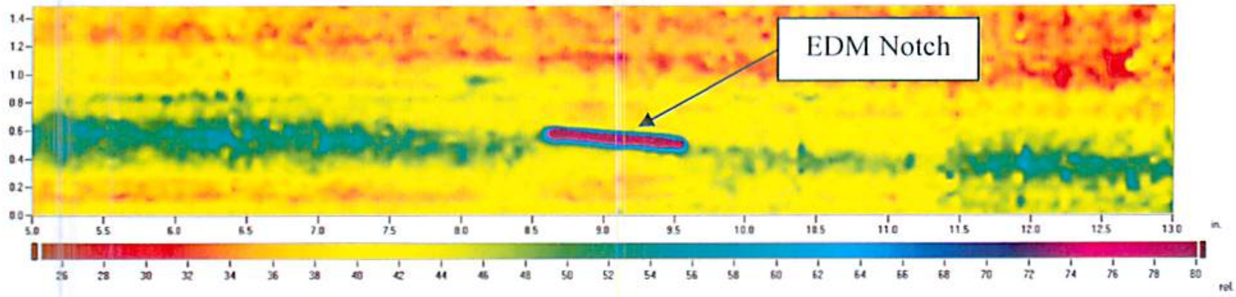


Figure 19. FA28 scan over an EDM notch in an ERW weld from the OD. There is little signature due to the material properties of the weld.

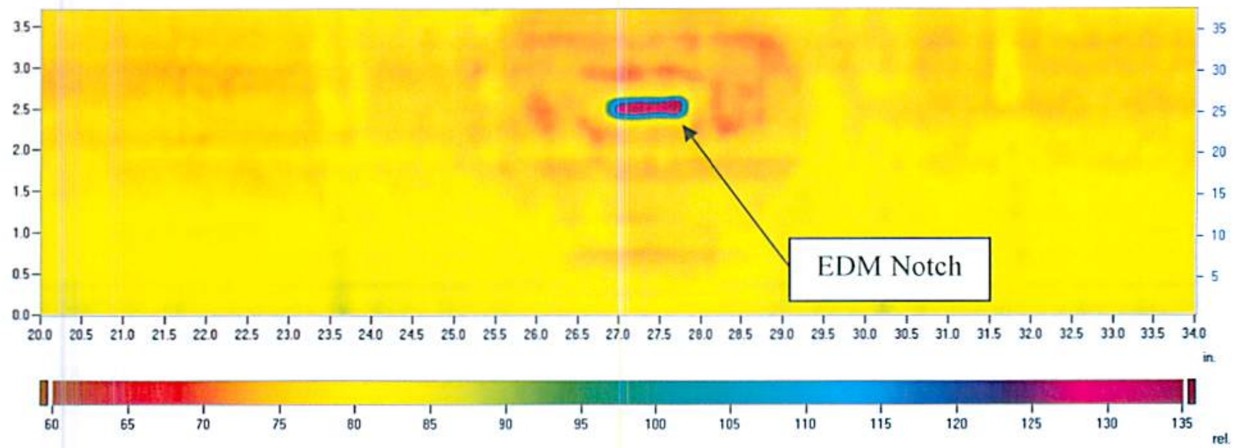


Figure 20. FA24 scan over an EDM notch in an ERW weld from the OD. There is little signature due to the material properties of the weld.

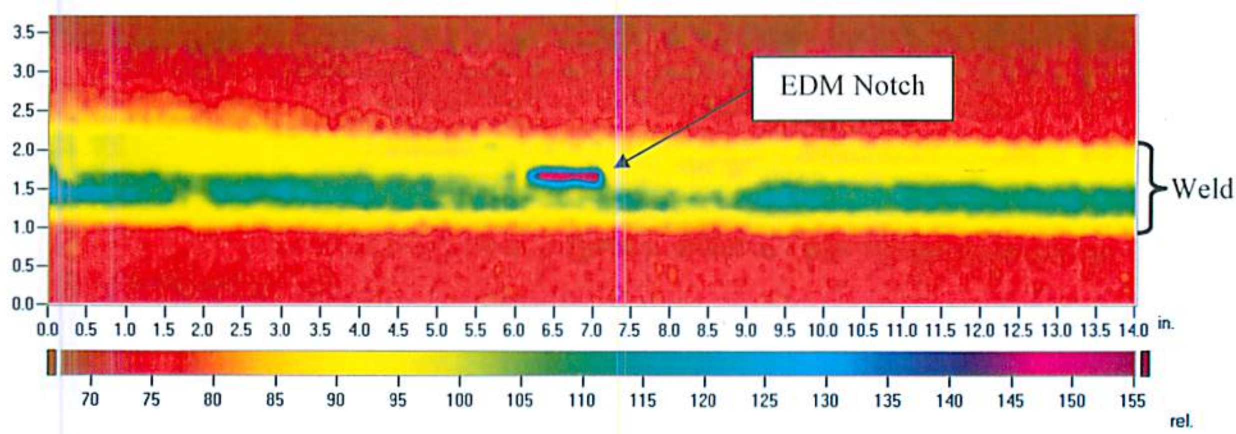


Figure 21. FA24 scan over an EDM notch in an ERW weld from the ID. There is a significant signature due to the material properties of the weld.

Figure 22 shows an image of data taken over the EDM notch on the ID of the sample using the FA218. This sensor produces a scan image similar to the FA24, but the EDM notch is no longer detectable in the image. Figure 23 shows a B-scan view of the same data. The EDM notch can be seen in this view, but it would be difficult to detect. This is due to the large size of the sense element for this sensor.

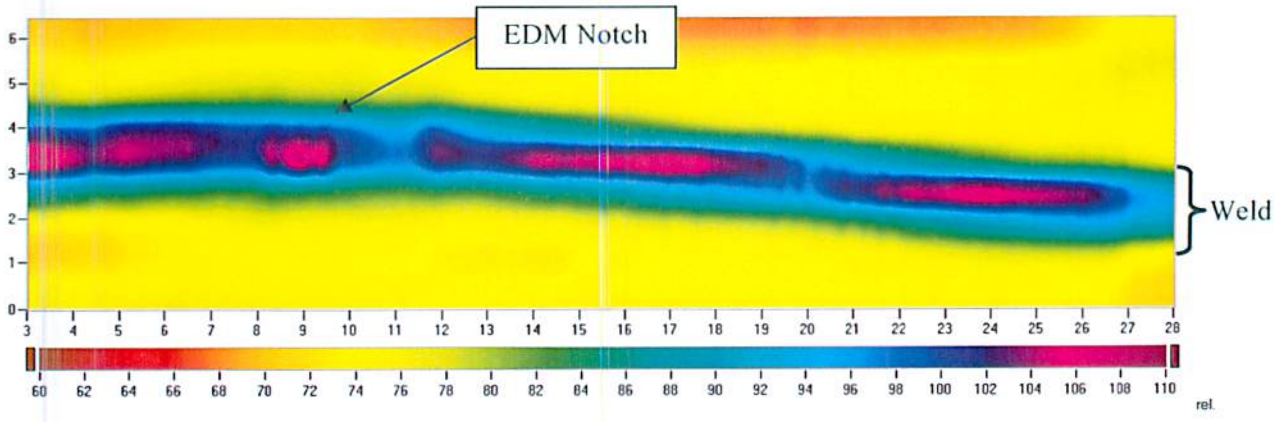


Figure 22. FA218 scan over an EDM notch in an ERW weld from the ID. There is a significant signature due to the material properties of the weld.

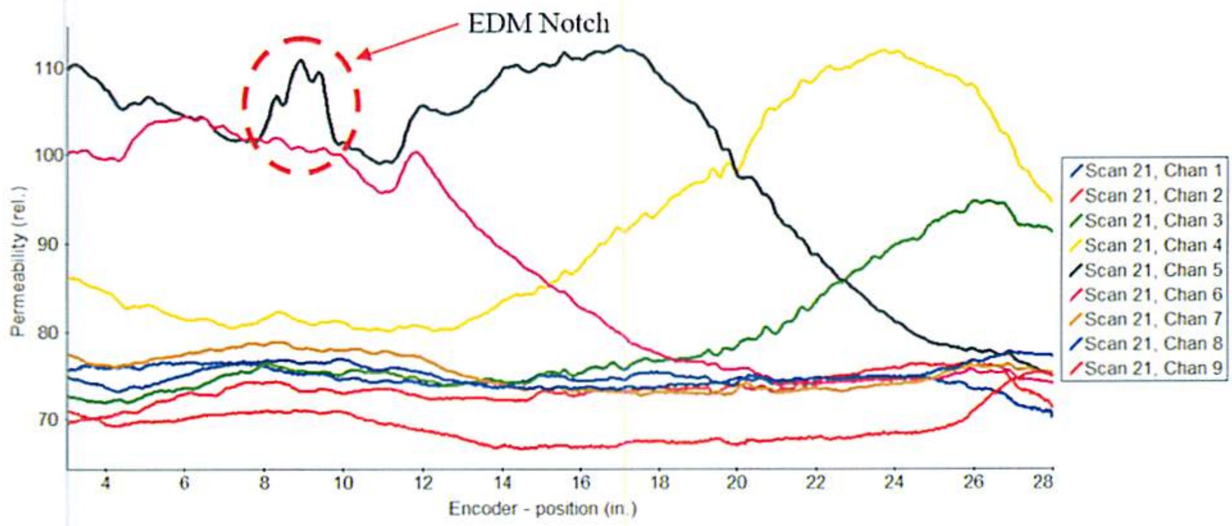


Figure 23. FA218 scan over an EDM notch in an ERW weld from the ID. Each line represents one of the channels in the array. Areas of high permeability are due to the variation in the weld properties. The EDM notch can be seen in this view, but is difficult to detect.

Figure 24 shows the velocity of the sensor during the scan in Figure 22 and Figure 23. The sensor was moved by hand as fast as possible and had a peak velocity of 1.7m/s. Testing was performed at a variety of speeds with no effect on the quality of the data. The data was taken at 1,280S/s, which produces a data density of 1.3mm per measurement at a scan speed of 1.7m/s. The 1,280S/s data rate is a limitation of the current instrument. The next generation ILI instrumentation (which is already being designed under commercial funding) will be able to support a data rate of 10,000S/s, which would produce a data point every 0.5mm at a tool speed of 10m/s.

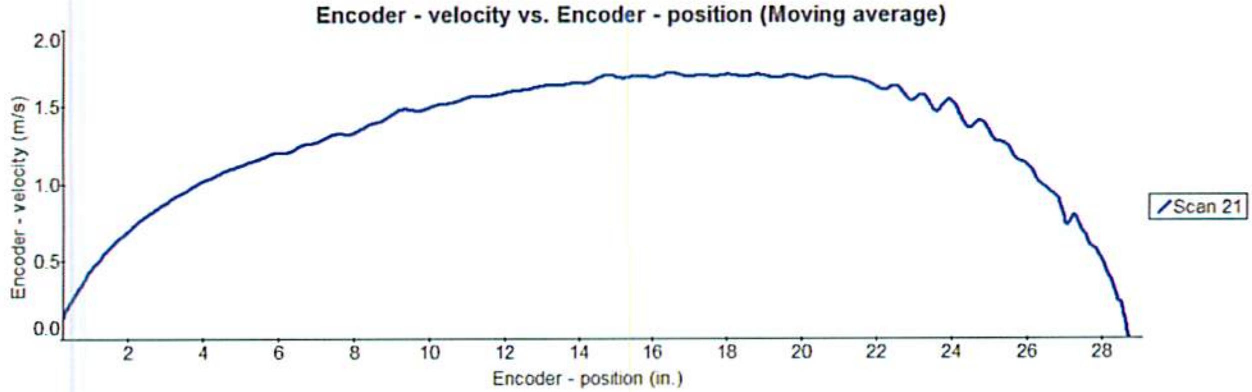
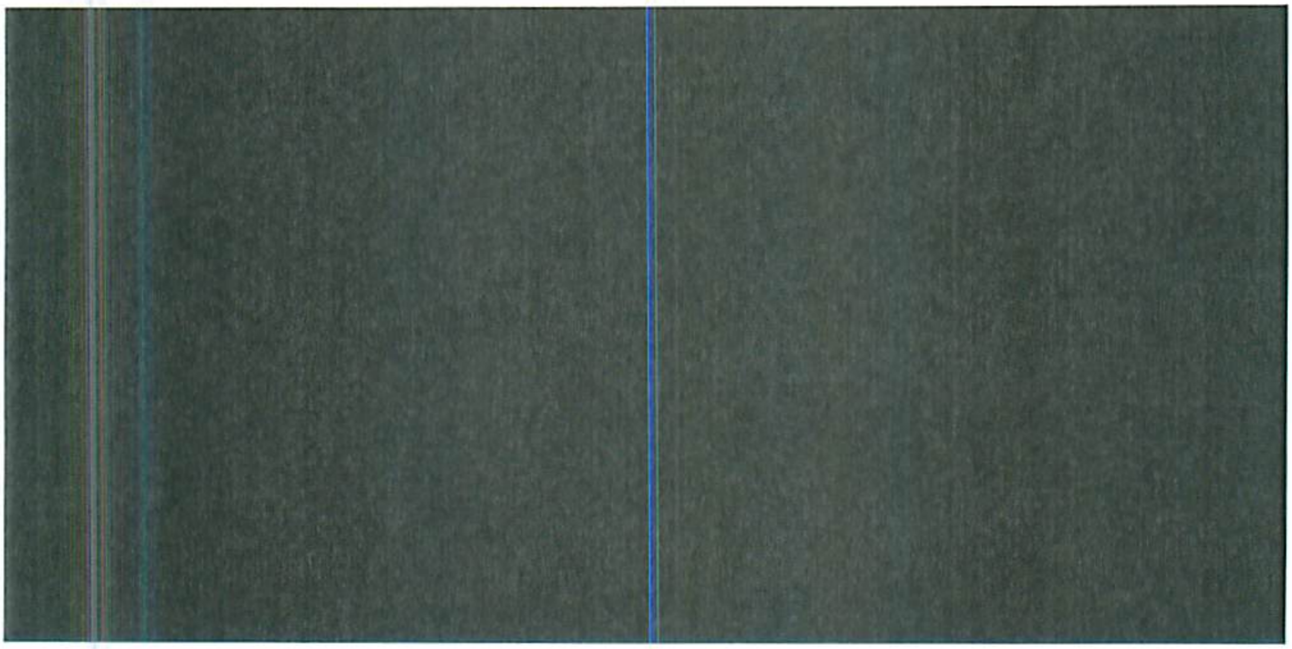
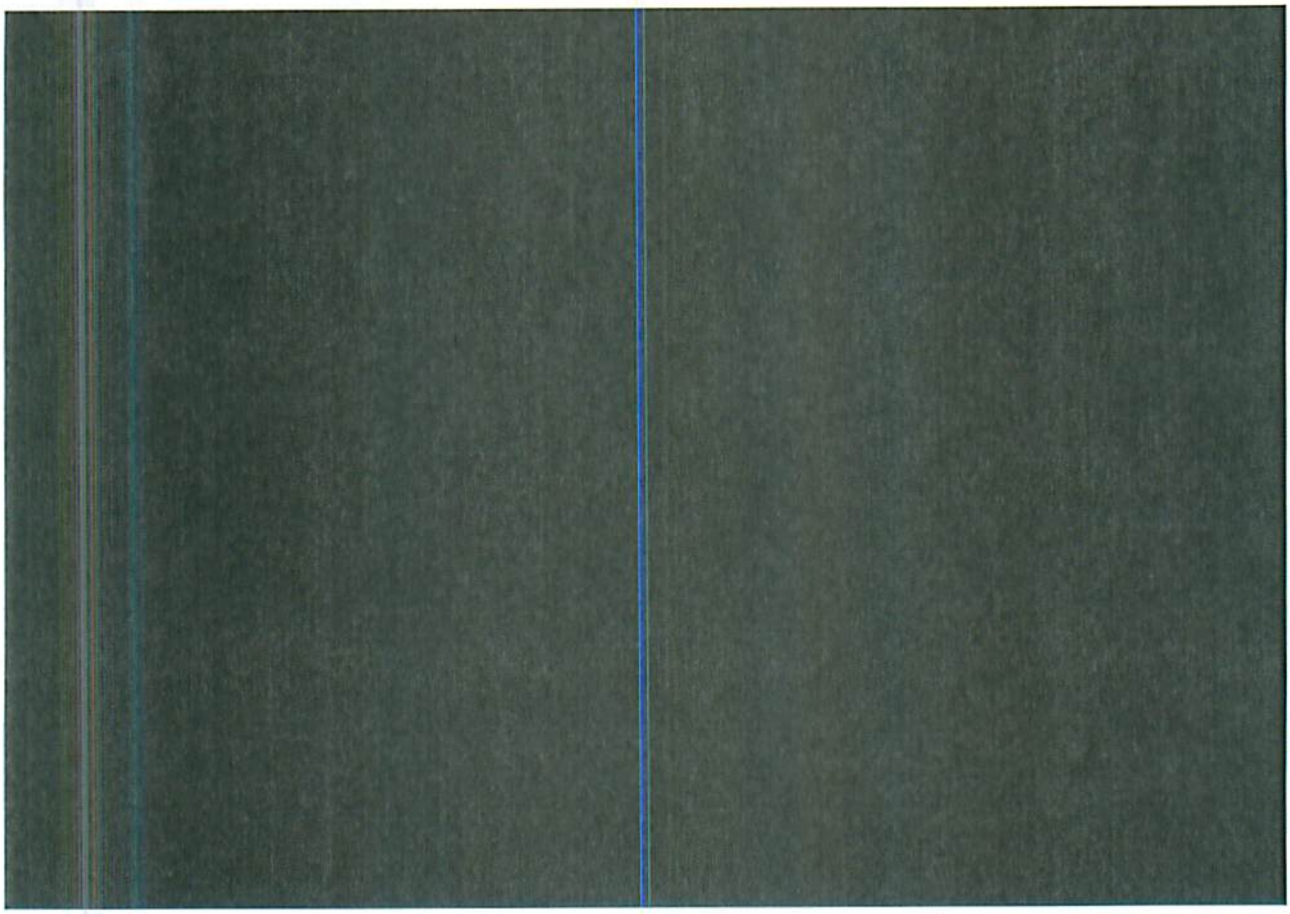


Figure 24. The velocity profile of the scan from Figure 22 and Figure 23. The peak velocity is 1.7m/s. Data was acquired at 1280 samples per second.

This data clearly shows that relevant EDM notches can be detected in ERW welds with the appropriate sensor. The sense elements for the current Integrated Cleaning Tool are too large to provide effective crack detection. The size of the sense element was dictated by the size of the pipe (16") and the number of instrument channels that could be installed into the tool given the existing GridStation 8200 electronics. JENTEK is currently designing a 12" tool and a 20" tool under commercial funding and the electronics is being redesigned to support those tools. The new electronics will allow more channels to be installed in the tool, which would permit smaller sense elements. JENTEK will use the data collected under this SBIR program to influence the design of future sensors and electronics to ensure that ERW crack detection can be supported.





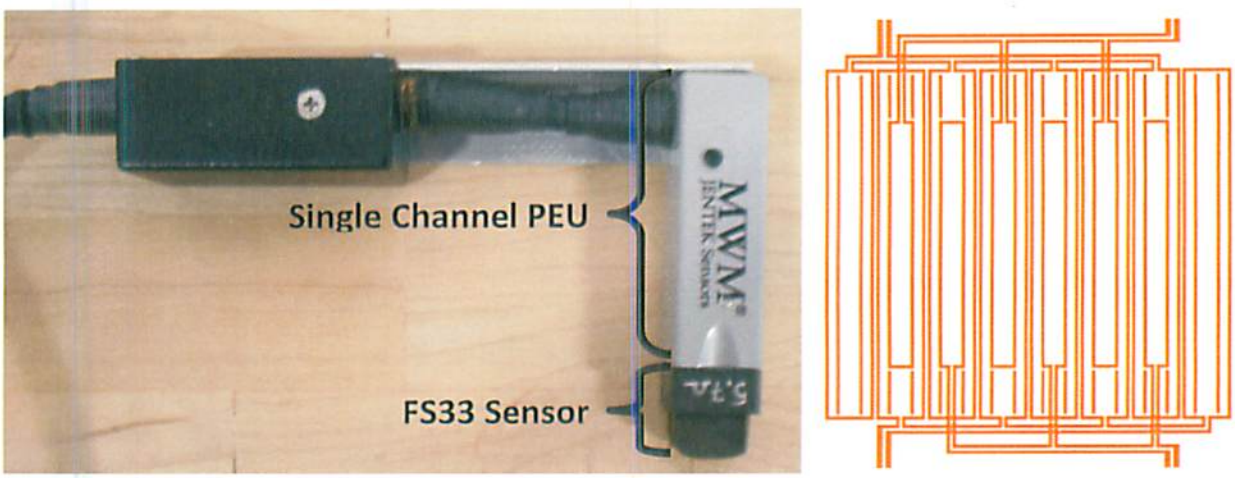


Figure 26. (left) Single channel probe electronics unit and FS33 MWM sensor used to take initial measurements on the saturation yoke. (right) FS33 Schematic: note the drive winding has longer conducting segments in the vertical direction, giving the sensor an orientation dependence.

[redacted]

The FA24 MWM-Array was used for this demonstration (Figure 28, left). The sensor was driven at 10kHz, 100kHz, and 1MHz. Since these are relatively high frequencies, the sensor was only sensitive to a thin layer of material on the OD surface of the steel, so only OD defects were detectable. The [redacted] This sensor was operated using the GridStation Durable 8000 impedance instrument (Figure 28, right).

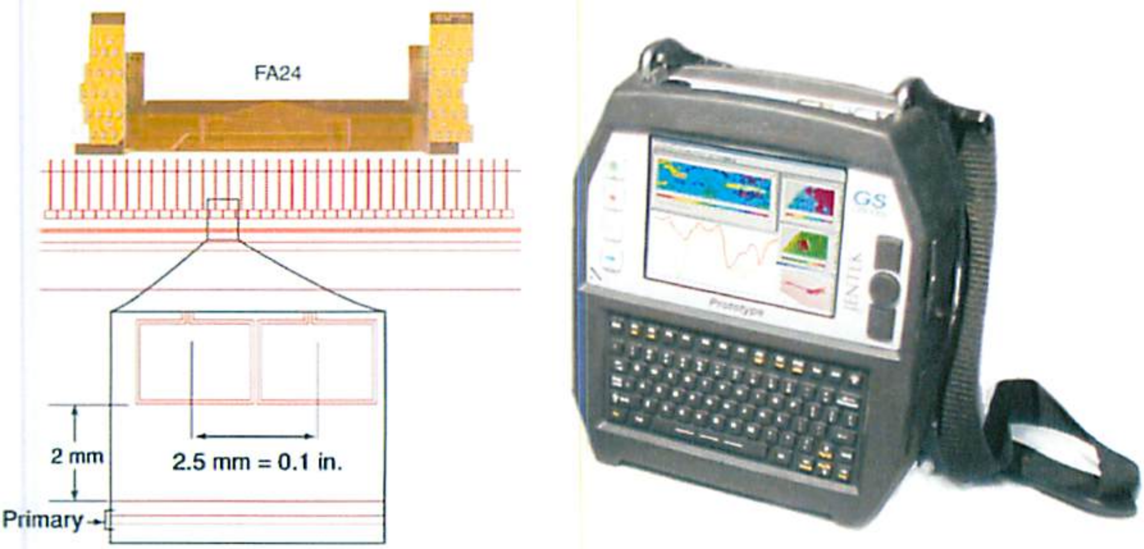


Figure 28. (Left) The FA24 MWM-Array. This array was used during this demonstration for high frequency measurements, so only OD defects were detectable. (Right) The GridStation Durable 8000.

JENTEK attempted to use the MR-MWM-Array and GridStation 8200α impedance instrument (Figure 29) during this demonstration for low frequency measurements. The advantage of this sensor is that it is sensitive to both ID and OD defects. [redacted]

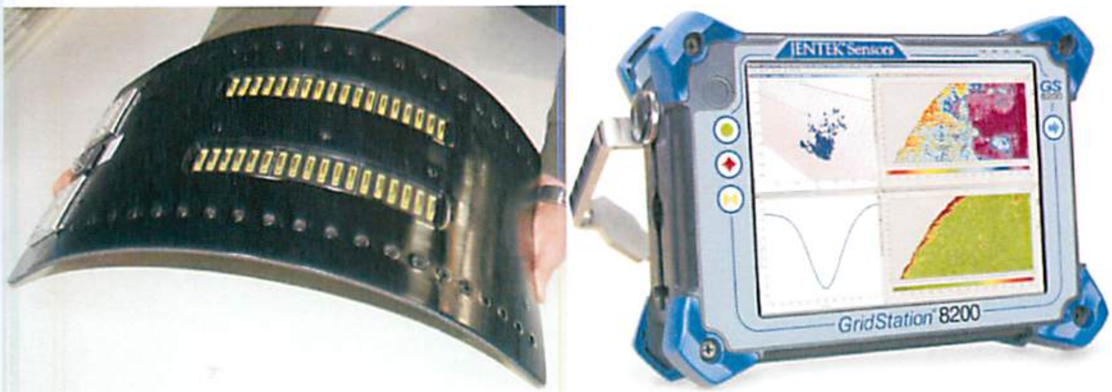
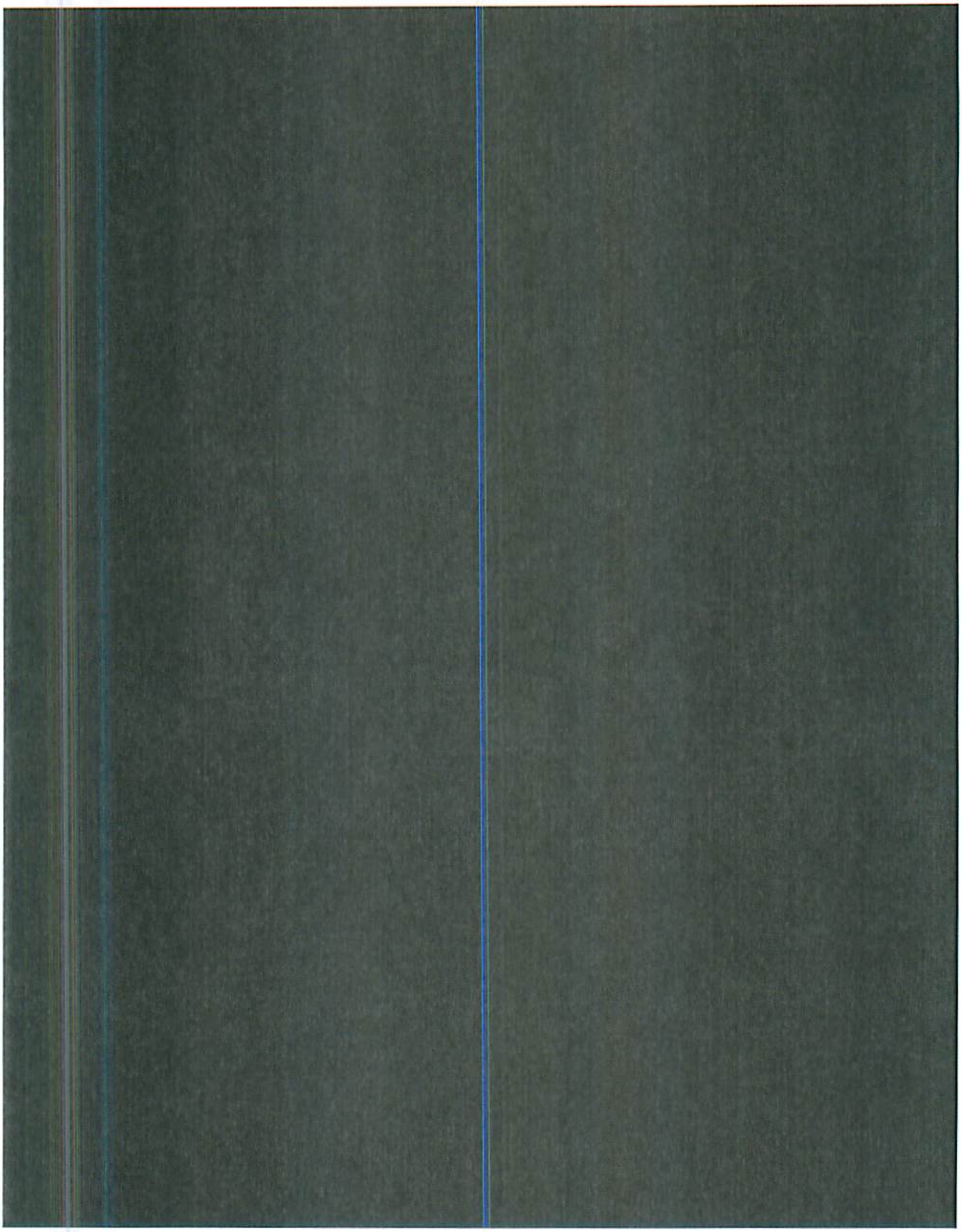
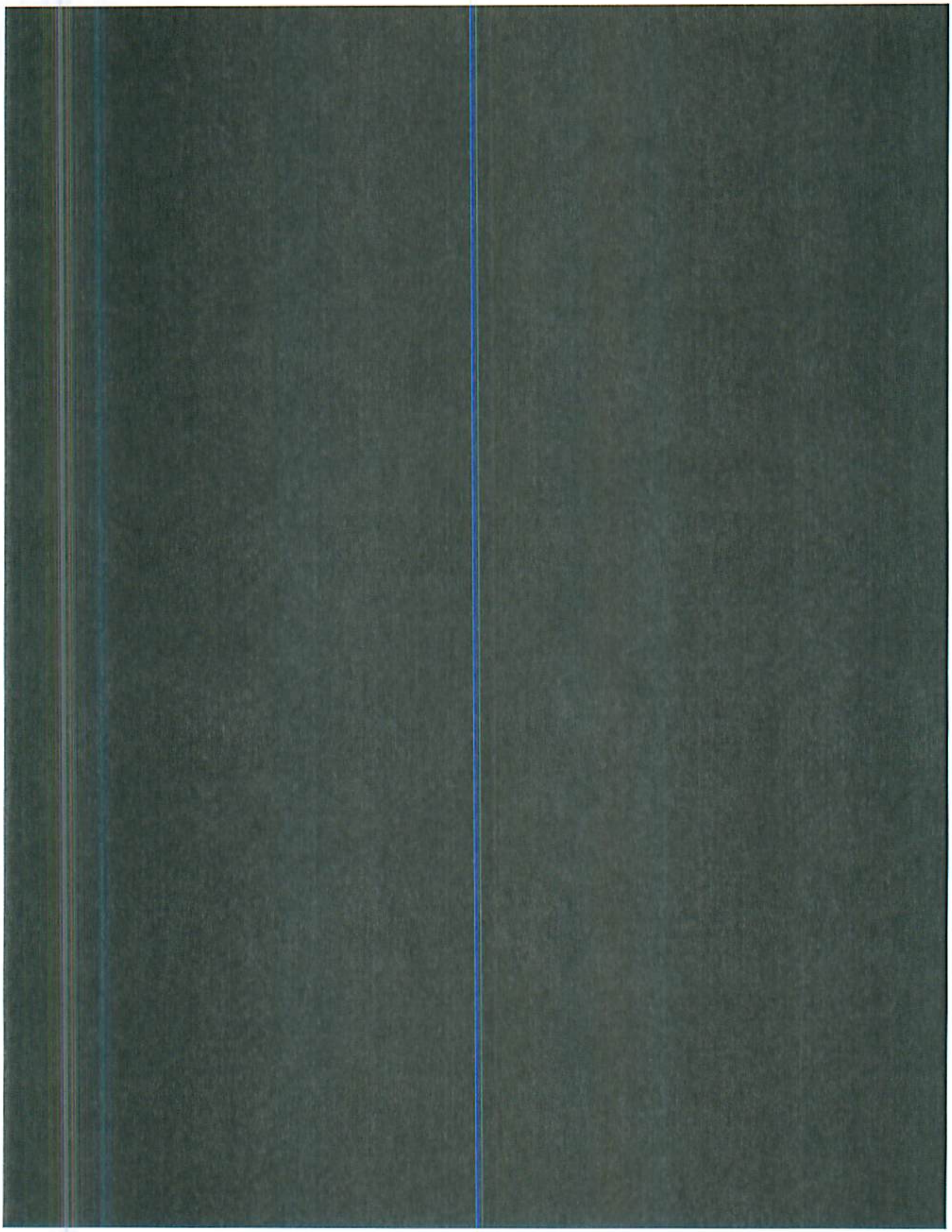
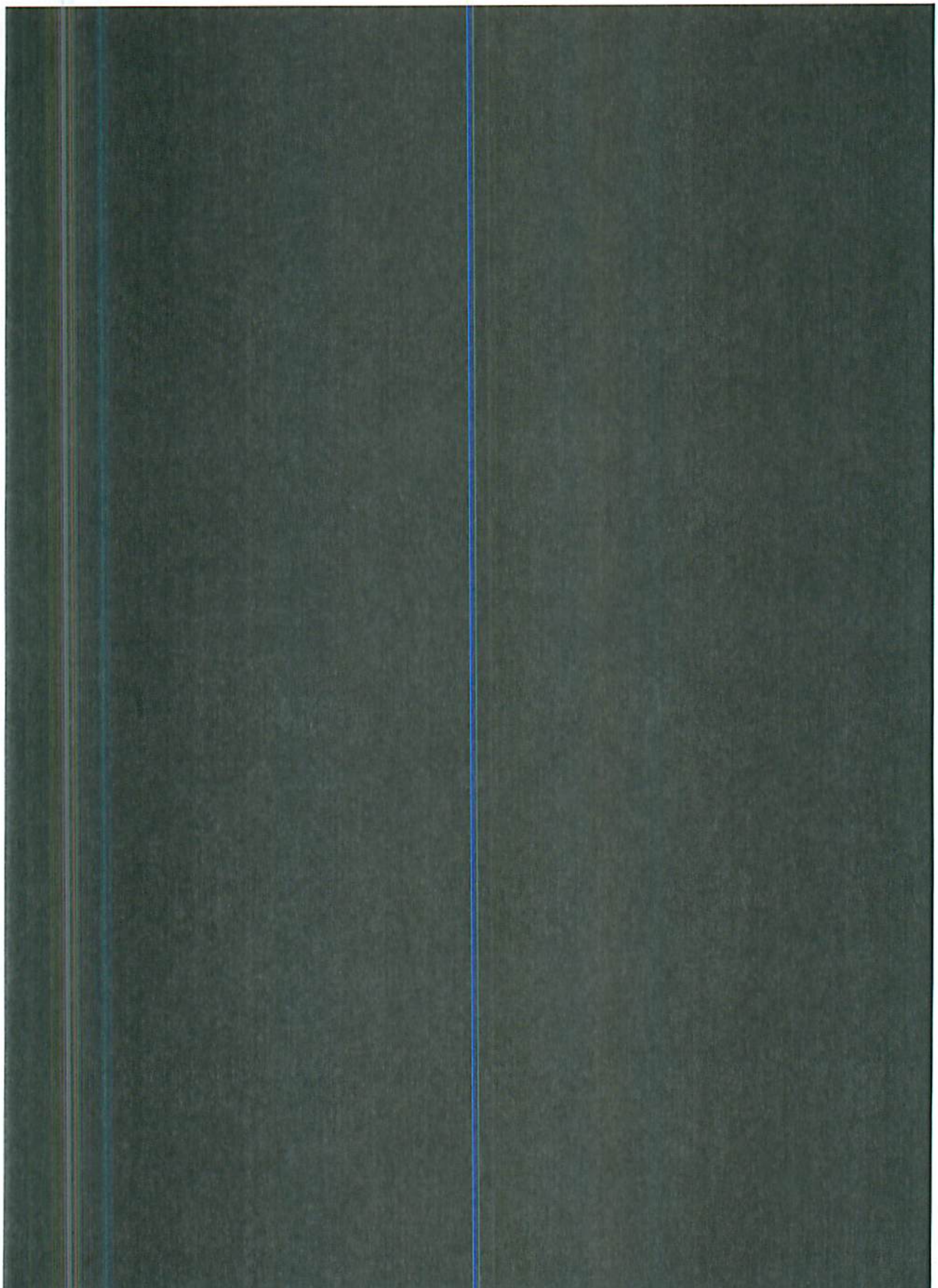


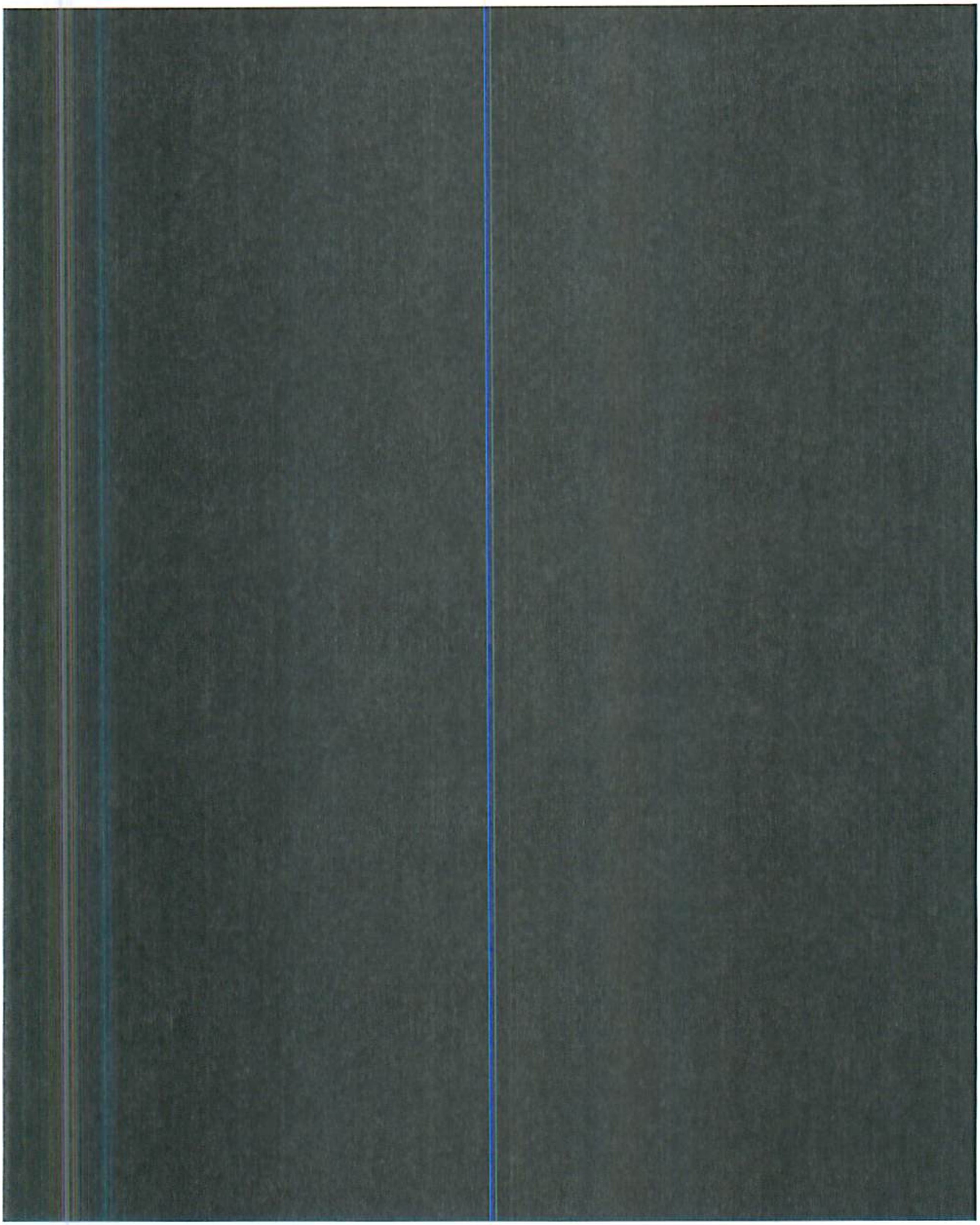
Figure 29. (Left) The MR-MWM-Array. This array was used during this demonstration for low frequency measurements, so both ID and OD defects were detectable. (Right) The GridStation 8200α. This is JENTEK's next-generation instrument and is required to operate the MR-MWM-Array.

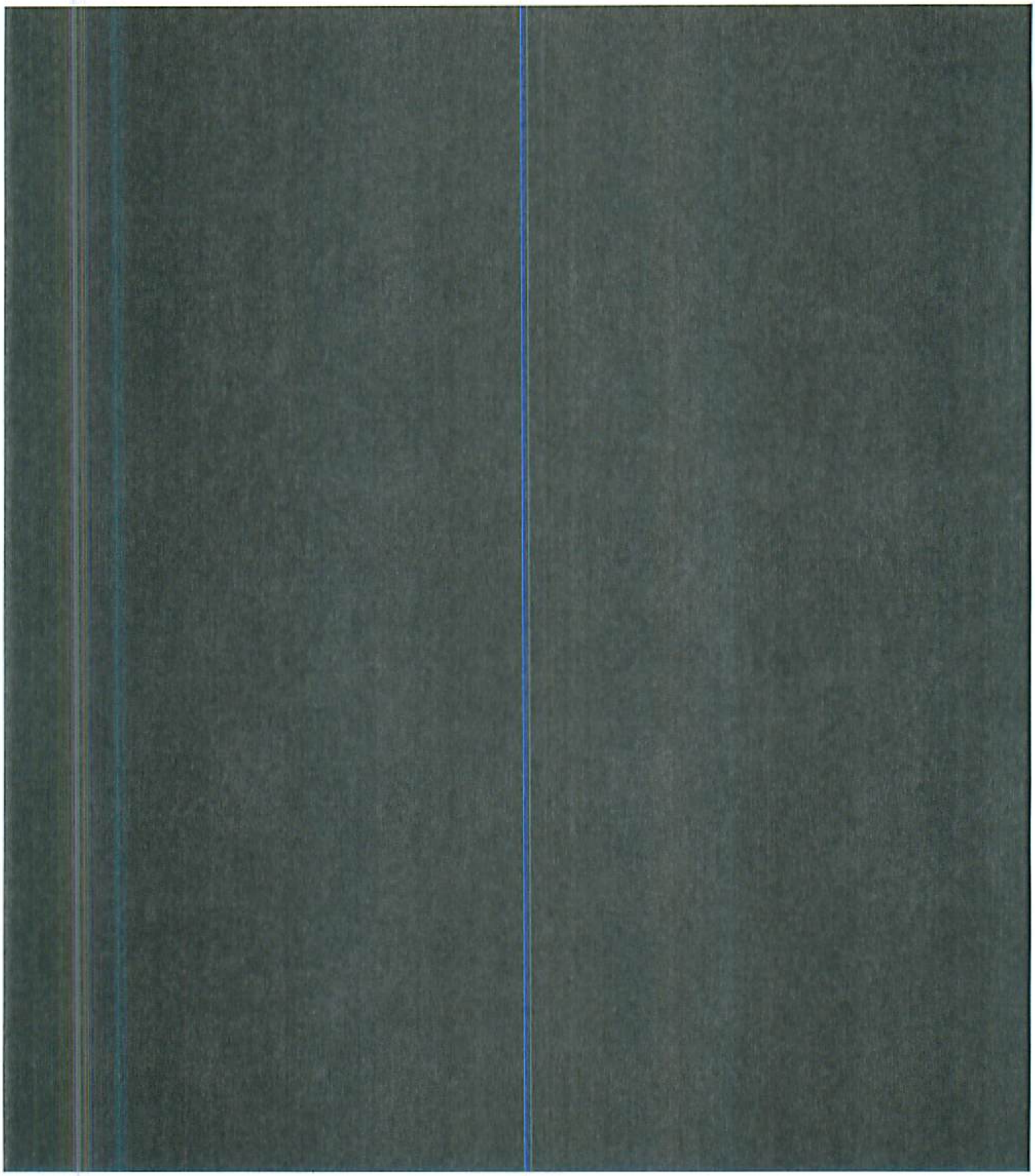
[redacted]

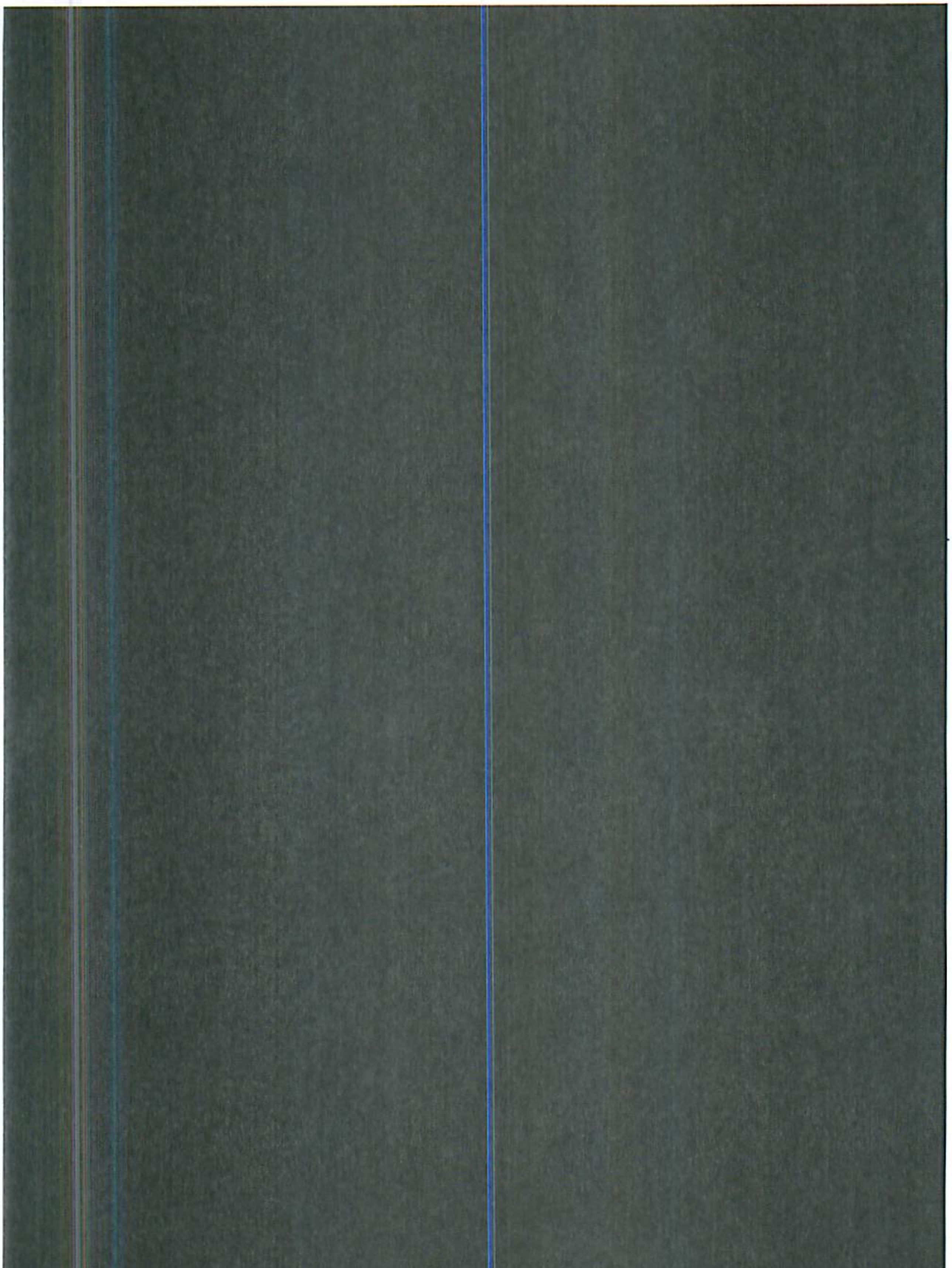


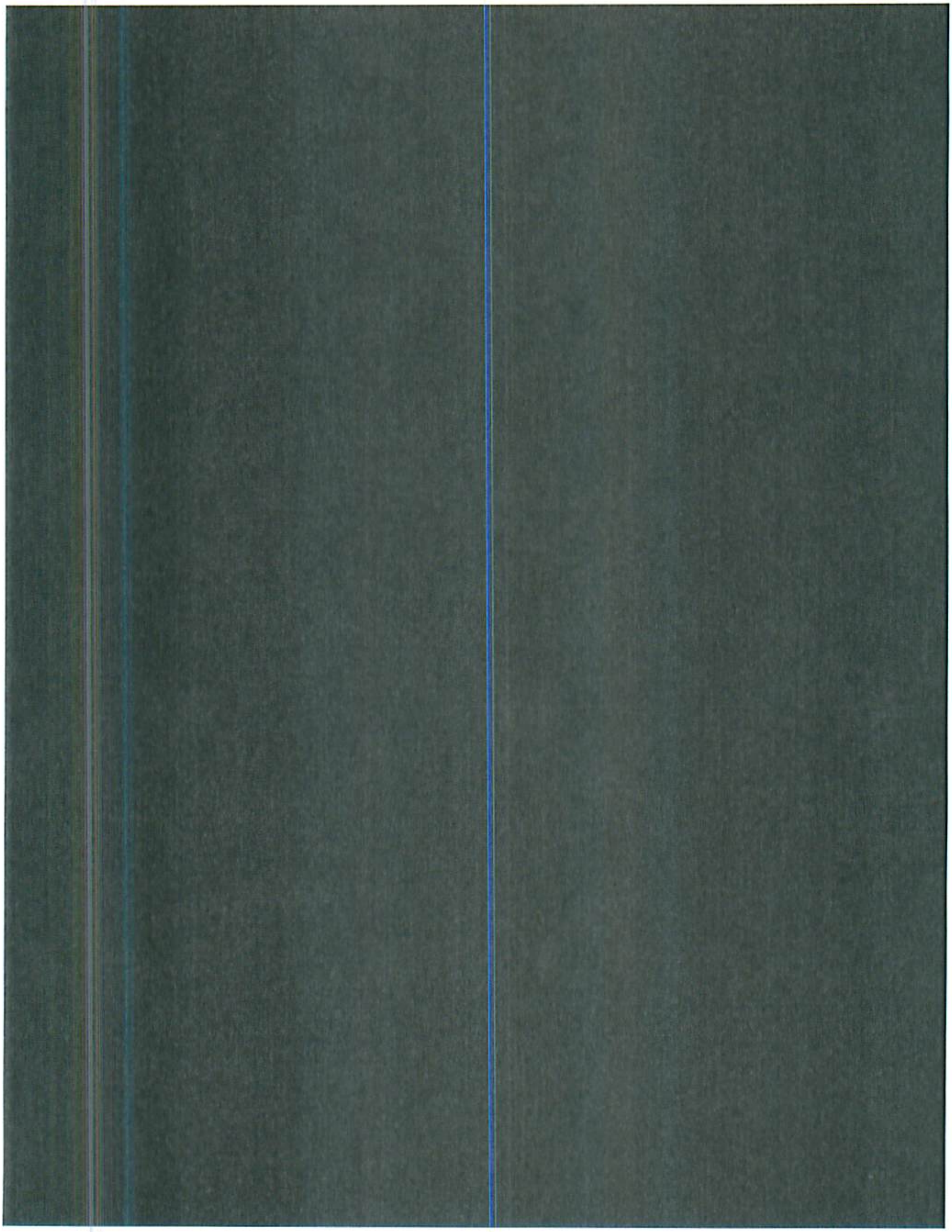


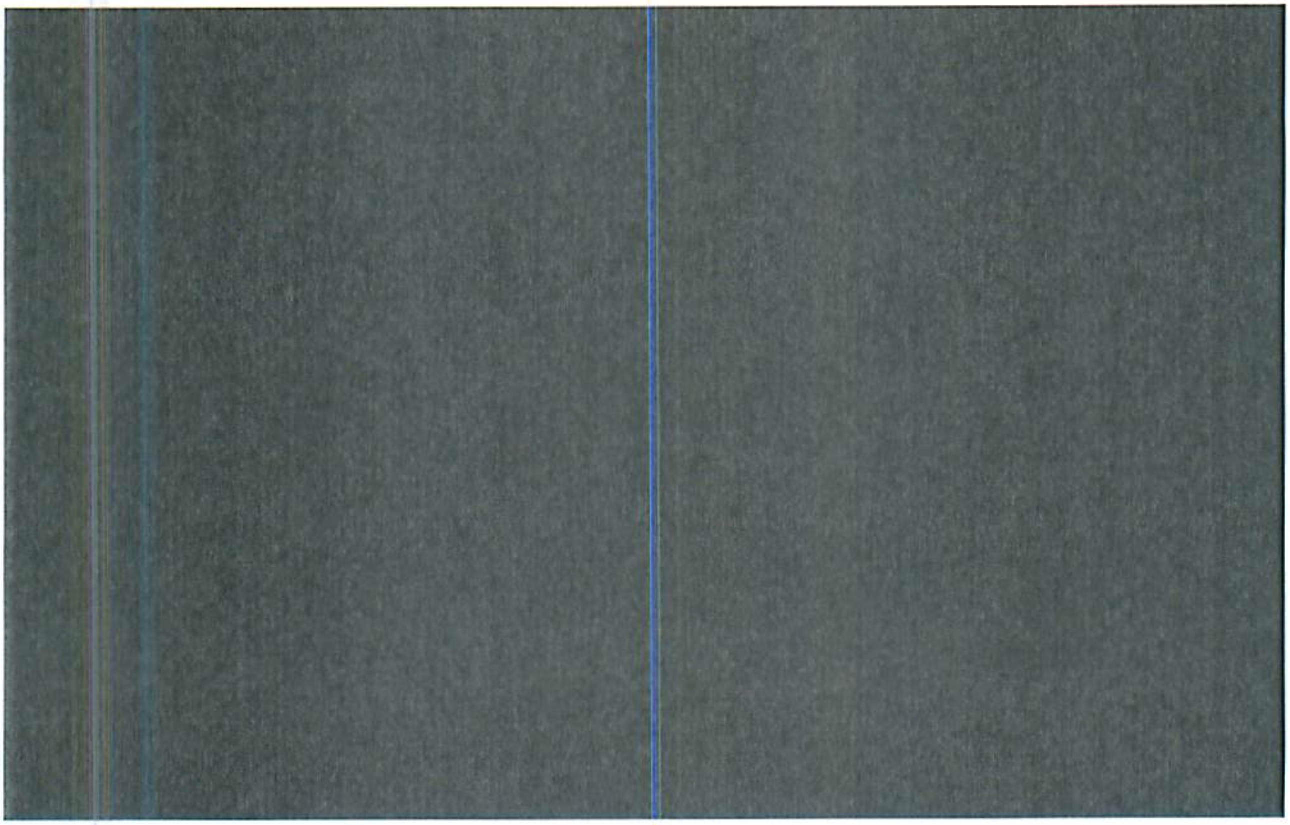












3.5 Develop a Transition Plan for ILI Tools and Services

JENTEK has recently received funding (over $2.5 million) from a major oil company for the development of a high frequency ILI tool capable of internal stress measurement and internal corrosion measurement. It is likely that this project will also be expanded to include detection of internal girth weld cracks. The same customer is also interested in long term tool capability enhancement, which will eventually include detection of external corrosion and external defects. Figure 41 outlines the development road map for the ILI tool and capability enhancements over the next five years pending funding from a major oil company, DOT, and PRCI.

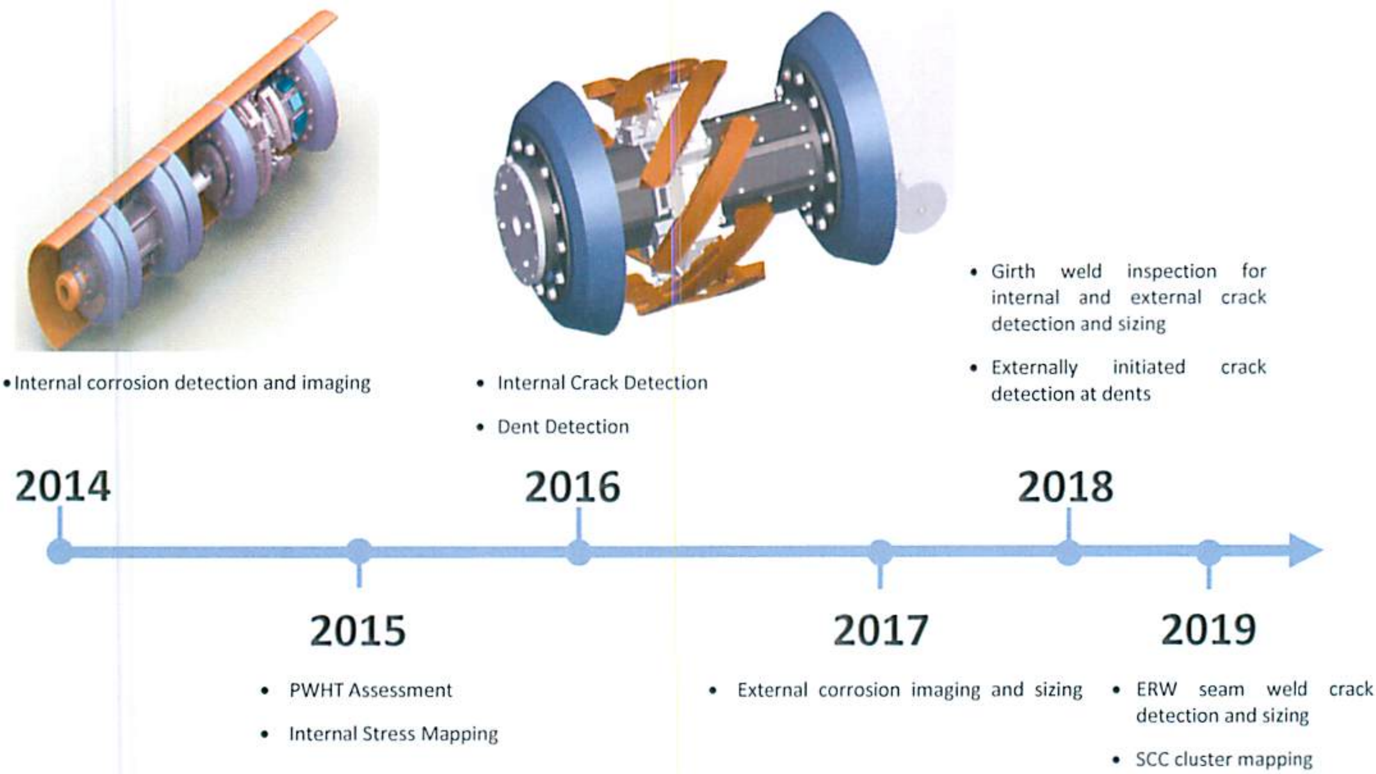


Figure 41. Five year roadmap for ILI tool development and capability enhancement.