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X-RAY COMPUTED TOMOGRAPHY FOR CHARACTERIZING CRACK-LIKE DEFECTS
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ABSTRACT

With the aging worldwide pipeline infrastructure, the need for accurate and precise inspection techniques has never been greater. X-ray Computed Tomography (XRCT) has been emerging as a technology that could address this need. This work evaluates the capabilities and limitations of XRCT technology from the perspective of detecting and sizing crack-like features in pipelines.

This paper combines the findings from two extensive bodies of works undertaken at PRCI through projects NDE-2-11 and NDE-2-12. Combined, these projects accomplished an XRCT technology state-of-the-art overview including a literature review, industry discussions, and trials with select providers. To facilitate this, sets of "truth data" based on synthetic (manufactured) and real-world crack-like features were scanned and destructively tested to determine crack geometries. The generation of future truth data samples would be a great benefit for the pipeline industry to advance both Non-Destructive Examination (NDE) and In-Line Inspection (ILI) technologies.

Details on samples used for the XRCT inspection, creation of synthetic features, sizing comparison with destructive and conventional NDE techniques, and the validation process will be discussed. Additionally, key parameters influencing the performance of the XRCT technology and their effect on the inspection results will be discussed as well as current industry capabilities and limitations. The paper will also include discussion of the current gaps in the technology and future direction in the context of practical applicability for use in pipeline inspections.

There are two assessment objectives in evaluating the XRCT technology. One is evaluating XRCT as an in-ditch NDE tool. The other objective is to evaluate XRCT as a tool for characterizing reference samples in lieu of destructive testing. The aim is to integrate XRCT as a resource for improving the capabilities of ILI and in-ditch NDE technologies.

The research associated with this work is an excellent example of a partnership involving researchers, regulators, pipeline operators, and technology companies in advancing technology for improving pipeline safety.

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INTRODUCTION

This paper documents the testing and inspection efforts undertaken to evaluate the capabilities and limitations of X-Ray Computed Tomography (XRCT) technology from the perspective of detection and quantification of flaws in pipelines. The fundamental motivation behind the work was to leverage the capabilities of the XRCT technology for accurate detection and characterization of crack-like features in pipelines. Accurate sizing and characterization of flaws/cracks in pipelines is of great consequence in providing effective and efficient operational and repair decisions in any integrity management program. Traditionally, conventional NDE techniques such as Phased Array Ultrasonic Testing (PAUT), Shear Wave Ultrasonic Testing (Shear Wave UT), and Eddy Current Testing (ET) have been used for characterization of crack-like flaws in pipelines. Although well established, these conventional methods lack the ability to replicate details and accuracy that can only be seen in images and measurements available after destructive sectioning. Emerging technologies such as XRCT have the potential to be superior to conventional NDE techniques in terms of quality of flaw imaging and measurements and can support the development of reference standards.

The objective of the effort was to evaluate the use of XRCT technology for accurate and precise detection and sizing of crack-like flaws in pipe toward the development of reference standards for in-line inspection (ILI) and in-the-ditch NDE technologies. As is the case with any emerging technology, comprehensive validation is needed before the technology can be considered mature enough to be effectively deployed by operators in the real world or be used in the development of reference standards. This report discusses a validation approach and compares the XRCT results with those obtained from conventional NDE, and sectioning and microscopy, for synthetic and real-world features. Results are discussed in the context of the development of reference standards using synthetic flaws. The discussion provided in this document will be valuable for operators in understanding the applicability, gaps, and future direction for XRCT technologies in the context of accurate flaw detection and characterization in pipelines.

Results discussed in the paper show that XRCT has the potential to enable the pipeline industry to establish a set of reference standards that can be used for a wide range of purposes, including development, optimization, and qualification of NDE and ILI technologies, personnel training, and competency testing for inspection of flaws in pipelines. Once established as a proxy for “truth,” XRCT will minimize the need for frequent destructive testing for the generation of validation data, further enabling the use in the development and retainment of reference standards.

XRCT TECHNOLOGY

XRCT is a radiographic imaging process. From a practical usage perspective, the concept was developed in the 1950s to the 1970s [1] and was primarily used in medical imaging applications. In the 1990s, industrial XRCT branched from the development of medical XRCT. Since then, XRCT has found extensive applications in medical and engineering fields; however, information on high-resolution crack detection and imaging has been limited.

In its basic form, XRCT is an X-ray based technique that scans an object of interest by transmitting and receiving X-rays through the object as it rotates, generating hundreds or thousands of projections and then reconstructing the projections using software to create a three-dimensional (3D) visualization. The "CT" (Computed Tomography) part of XRCT refers to the process in which the projections are reconstructed in such a way to get a volumetric representation from the 2D images. The 2D image formation relies on the attenuation of the X-rays after they leave the emitter and as they are received at a detector. In simplified terms, "attenuation" is the drop in the intensity of the X-rays as they pass through material. The higher the density of the material, the higher the attenuation. This attenuation is responsible for the contrast observed in typical X-ray images.

In the context of flaws in pipe, when X-rays pass through a pipe sample, any change in pipe density (e.g., presence of voids/delaminations, cracks, etc.) results in a change in the attenuation of the X-rays passing through the pipe and correspond to changes in contrast at the detector. The pipe body with high-density steel provides a high-attenuation path, whereas the voids and cracks in the pipe represent areas with low density (compared to the pipe) cause lower attenuation of the X-rays as compared to the rest of the pipe. The differences in the attenuation result in contrasting regions in the image on the detector (see Figure 1).

SPECIFIC XRCT TECHNOLOGY USED IN THIS STUDY

InspeCT's XRCT inspection system was used in this project. This system is comprised of a clam-shell type gantry, X-ray tube as an X-ray source, and a scintillating type X-ray detector. In the laboratory version of the setup, the gantry houses the X-ray source and the detector at diametrically opposite positions (12 O'clock and 6 O'clock, respectively) and stays fixed. The pipe is mounted in the gantry, centered, and rotated slowly during imaging. In the field version of this setup, moving/rotating gantry carries the x-ray tube and digital detector along the length and around the axis of the pipe, and the pipe stays stationary. See Figure 1 and Figure 2 for the general arrangement of the XRCT inspection setup.

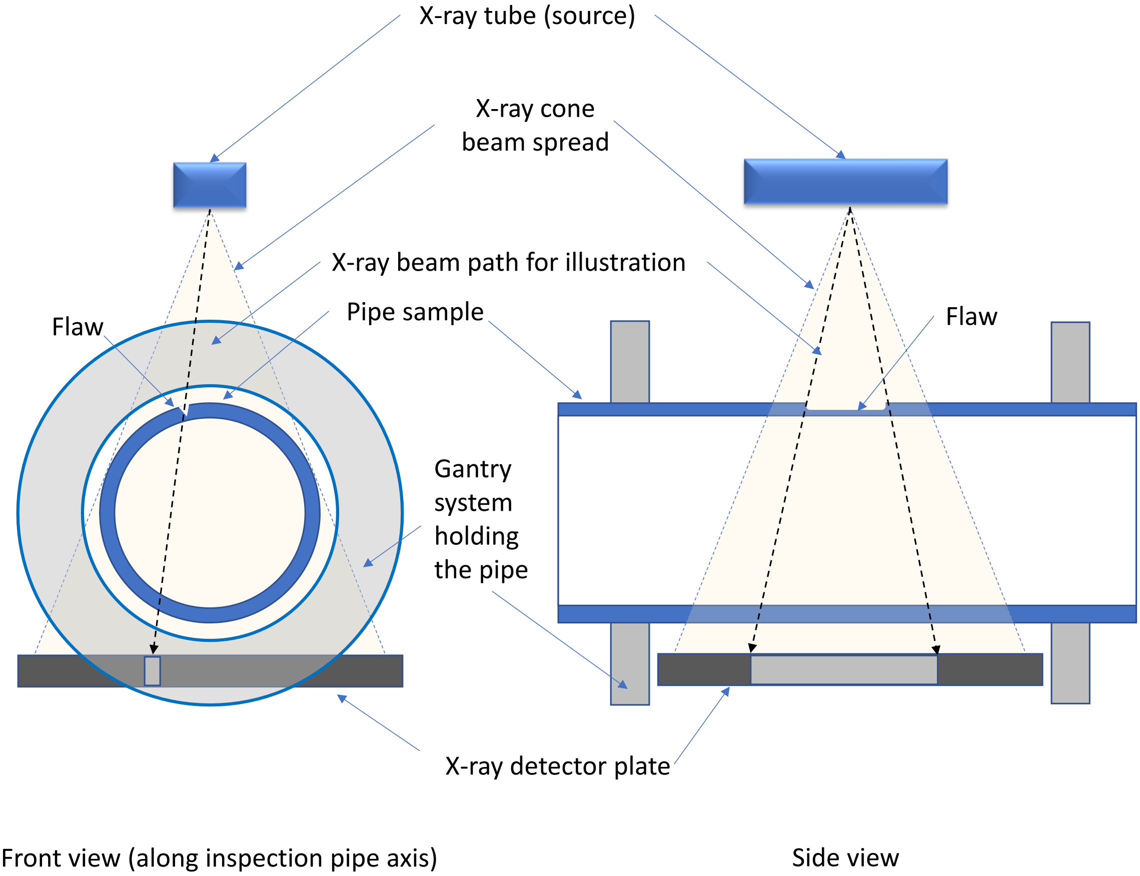


Figure 1: Schematic of the XRCT setup used for this work

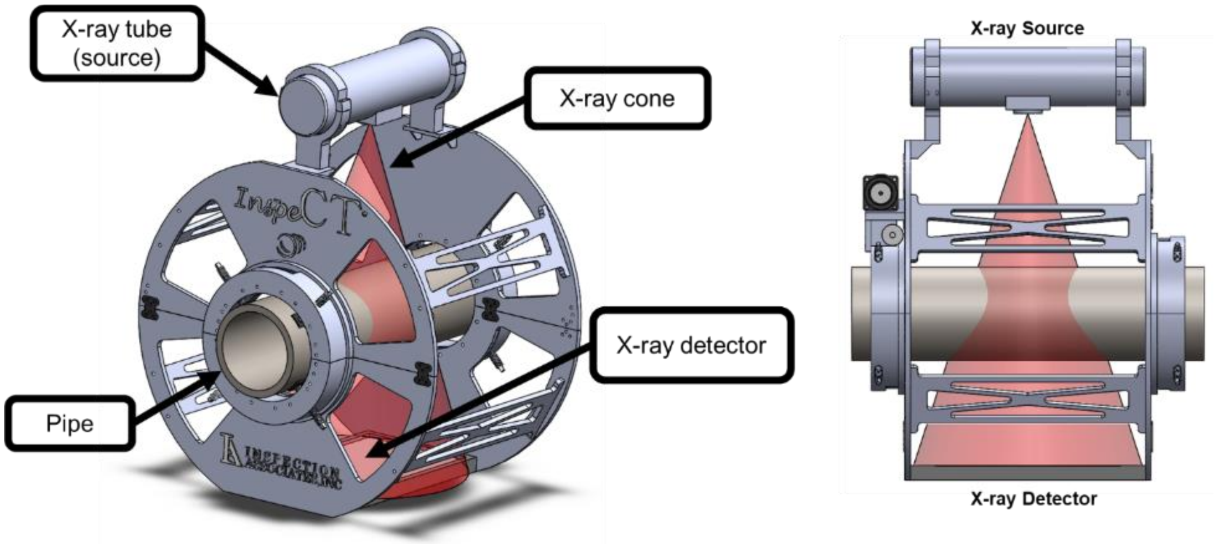


Figure 2: Isometric and side-view of the XRCT system used for this work

For a given position setting along the length, a circumferential scan projection on the pipe covers a length of approximately 304.8 mm (12 in) along the length of the pipe. A 1.524 m (5 ft) long sample will require five different scans for a 100% inspection. Each scan is comprised of thousands of 2D X-ray images taken as the pipe rotates slowly. These images are then reconstructed and analyzed for flaw characterization and visualization.

APPROACH AND METHODOLOGY

In the current scope of work the XRCT inspection technology was evaluated on two types of features: 1) synthetic features/cracks (notches fabricated from electrical discharge machining (EDM), followed by pressure cycling to generate microcracks at the base of the notches) and 2) "real-world" features gathered from pipe specimens donated by pipeline operators. For the synthetic features, the general workflow followed was to create the features, inspect using XRCT, evaluate using conventional NDE techniques to provide baseline reference data, and validate using either sectioning or freeze-breaking of the features for examination under a microscope. A similar approach was followed for the real-world features, except that the creation of features via pre-cycling was not required; moreover, with the real-world features an additional conventional NDE step was required before identifying features for XRCT inspection.

The results of the evaluation were organized into unity plots to provide comparisons between the measured flaw heights/depths (after sectioning and microscopy) and those that were quantified by XRCT and other conventional NDE methods.

The work scope consisted of three (3) primary tasks as listed below.

1. Generate synthetic features/cracks using EDM (Electrical Discharge Machining) to machine starter notches, followed by pressure cycling to generate cracking.
2. Use conventional NDE and XRCT to inspect pipe samples with manufactured (synthetic) and real-world crack-like features. Pipes containing real-world features were collected from operators who have removed previously inspected pipe materials from service having known crack-like features.
3. Verify accuracy of the XRCT inspection data by destructively sectioning or breaking open and measuring the synthetic and real-world features. Process the data and compare the XRCT results with those from conventional NDE methods as well as from sectioning. A few examples of micrographs from which the flaw depth data were measured for this work are shown in Figure 3.

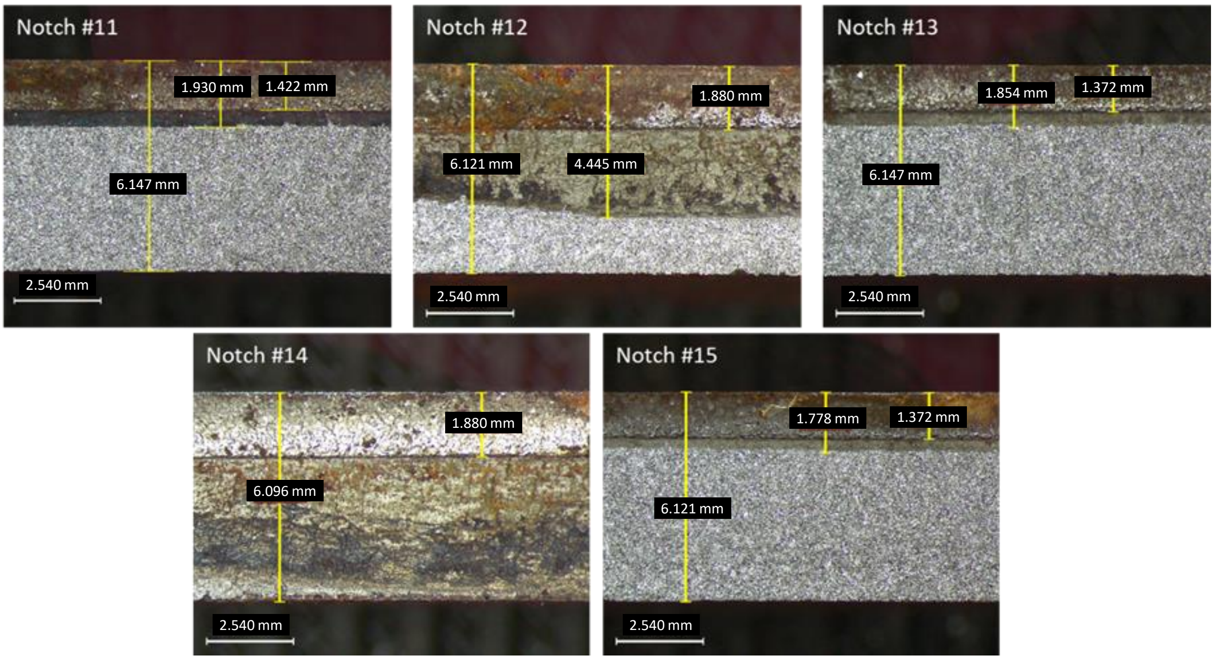


Figure 3: Examples of post-fracture (freeze-break) images for Notches #11 through #15 (synthetic features)

For the synthetic features tasks, four (4) pipe types were selected as listed below. Five (5) EDM notches were machined in each specimen for a total of 40 notches.

1. 508.0 mm OD (20 in, NPS 20) pipe material, Grade X60 (HF-ERW), 1 specimen, 5 notches
2. 558.8 mm OD (22 in, NPS 22) pipe material, Grade X52 (seamless), 1 specimen, 5 notches
3. 457.2 mm OD (18 in, NPS 18) pipe material, Grade X52 (LF-ERW), 3 specimens, 15 notches
4. 323.9 mm OD (12.75 in, NPS 12) pipe material, Grade X46 (LF-ERW), 3 specimens, 15 notches

After introducing the EDM notches, the pipe specimens were subjected to cyclic pressure loading to generate fatigue cracks at the base of the notches.

For the real-world features, additional pipes were donated from operators and included a mix of 323.9 mm OD (12.75 in, NPS 12), 355.6 mm OD (14 in, NPS 14), 457.2 mm OD (18 in, NPS 18), and 558.8 mm OD (22 in, NPS 22) pipes. These pipes were not subjected to any additional EDM processing but were inspected with conventional NDE techniques prior to identifying/isolating areas of interest for XRCT inspections. A total of 26 features were examined.

A summary of the workflow in evaluating the synthetic and real-world features is illustrated in Figure 4. With reference to Figure 4, the workflow for synthetic features was fairly straightforward. This is due to four significant characteristics of the synthetic features:

1. The precise location of each individual feature was known and could be ascertained by visual examination and conventional NDE techniques
2. Every synthetic feature was oriented axially making it readily detectable
3. The features were not clustered together – again, making conventional NDE techniques and XRCT easily applicable and less resource intensive
4. Because of the regular feature orientation and shape, freeze-breaking the sample for final verification could be easily implemented

Based on the aforementioned characteristics, the specimens containing synthetic features could be directly processed for XRCT inspection after pressure cycling. Also, these features could be readily sectioned for final validation by way of detailed examination and characterization under a microscope.

Figure 4 also shows that for the real-world features (most, but not all real-world features), the workflow included several additional steps. Reasons for these additional steps are listed below:

1. Due to the fact that some features were easier to see visually, and some were not even with Magnetic Particle Inspection (MPI), the precise location of each individual feature was not always readily known and could only be estimated using conventional NDE techniques. For example, most features on the 14-inch pipe were on the inside diameter (ID), and the location and sizing of the features varied over three different results from three different vendors.
2. Real-world features were not all straight or oriented axially – this necessitated additional rigor when using conventional NDE.
3. Most real-world features were clustered together, sometimes to an extent that locating and sizing every single feature in a cluster using NDE and/or XRCT was impractical.
4. Due to the wide range of distribution of sizes, shapes, and orientations of the flaws, not all flaws were easily broken open for detailed examination.

Due to the challenges described, additional conventional NDE inspection was necessary prior to XRCT inspection to ensure that the scope of the XRCT inspection was practical.

However, even with this additional NDE inspection, mapping between the conventional NDE results and XRCT results remains a challenge for real-world features – introducing the possibility that the destructive sectioning may miss the feature of interest, which in turn introduces the possibility of false positives or false negatives in validation process.

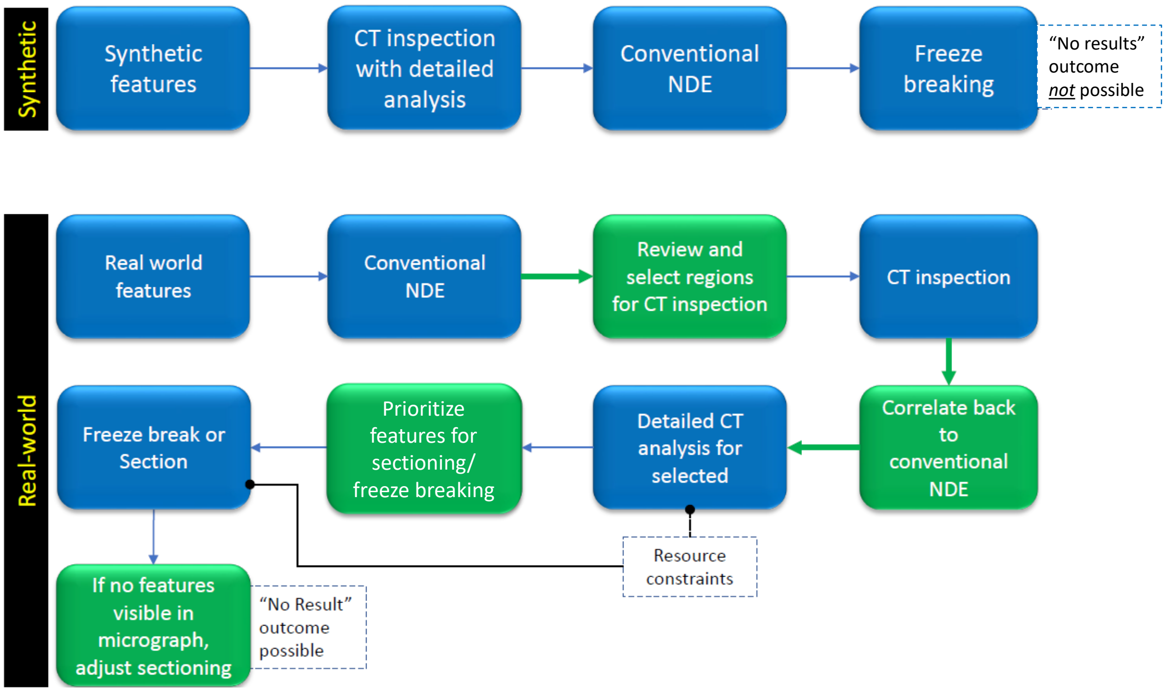


Figure 4: Workflows for synthetic and real-world flaws

Results for Synthetic Features

A summary of results for the XRCT, conventional NDE, and microscope measurements for the synthetic features are shown in Figure 5 through Figure 8. Figure 5 and Figure 6 show the unity plots for XRCT data and conventional NDE data, respectively. In these figures, the flaw depth measurements (or truth data) are shown on the X-axis. Data are shown to convey the observation that results from widely accepted, conventional NDE methods can carry large uncertainties in flaw sizing.

Figure 7 and Figure 8 show the residuals associated with the XRCT and conventional NDE data, respectively. A residual is defined as the difference between observed value and the expected value for the data to match the corresponding microscope observations. A positive residual signifies over-called inspection data compared to microscope measurements, and a negative residual signifies under-called inspection data compared to microscope measurements.

Figure 7 and Figure 8 also show the mean and the standard deviations calculated from the residuals for XRCT and conventional NDE data, respectively. The mean of the residual data signifies the accuracy of the data (the closer the mean is to zero, the higher the accuracy), and the standard deviation signifies the precision or variance of the data (the higher the standard deviation, the lower the precision). A high quality, consistent inspection process should ideally exhibit zero residual mean, and a low standard deviation.

With reference to Figure 7, the mean of the residual for the XRCT data is negative, indicating a marginal under-calling bias for the data set. Figure 8 illustrates the conventional NDE data has a positive residual mean, indicating a marginal over-calling bias for the data set. No specific trends are observed in either data set with increasing flaw depth/height.

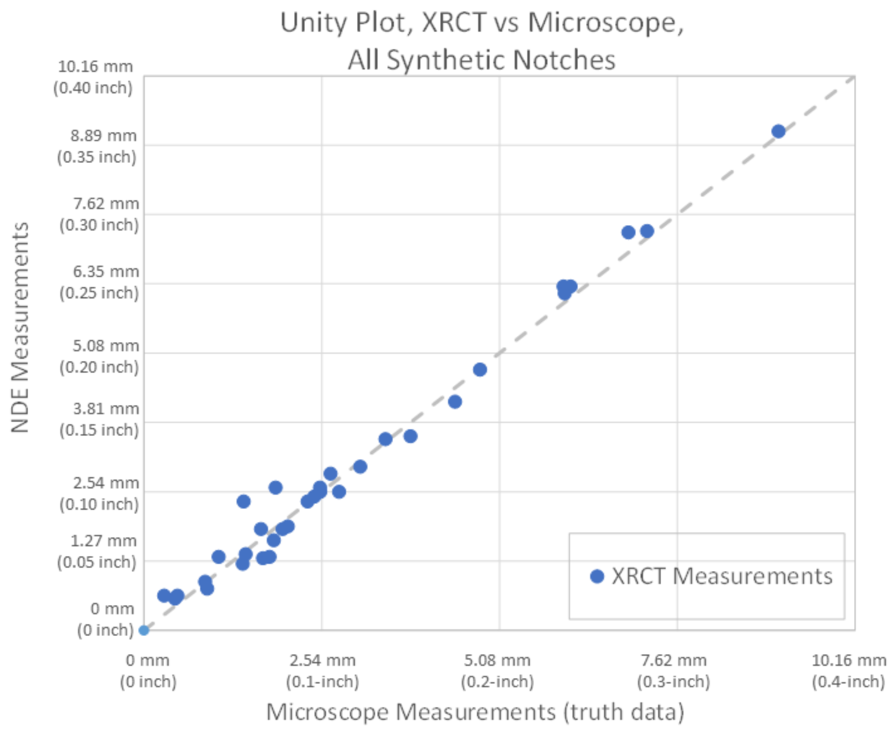


Figure 5: Unity plot for all pipe sizes and features, comparing initially reported data vs post-review flaw height data

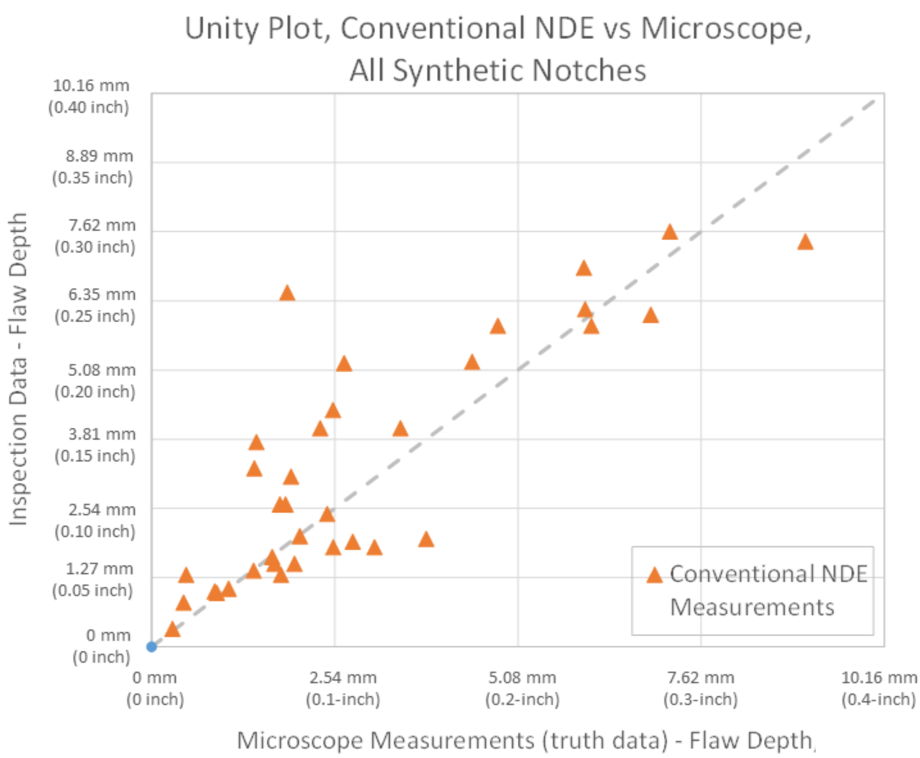


Figure 6: Residuals for all synthetic features, comparing initial XRCT data vs post-review XRCT flaw height data

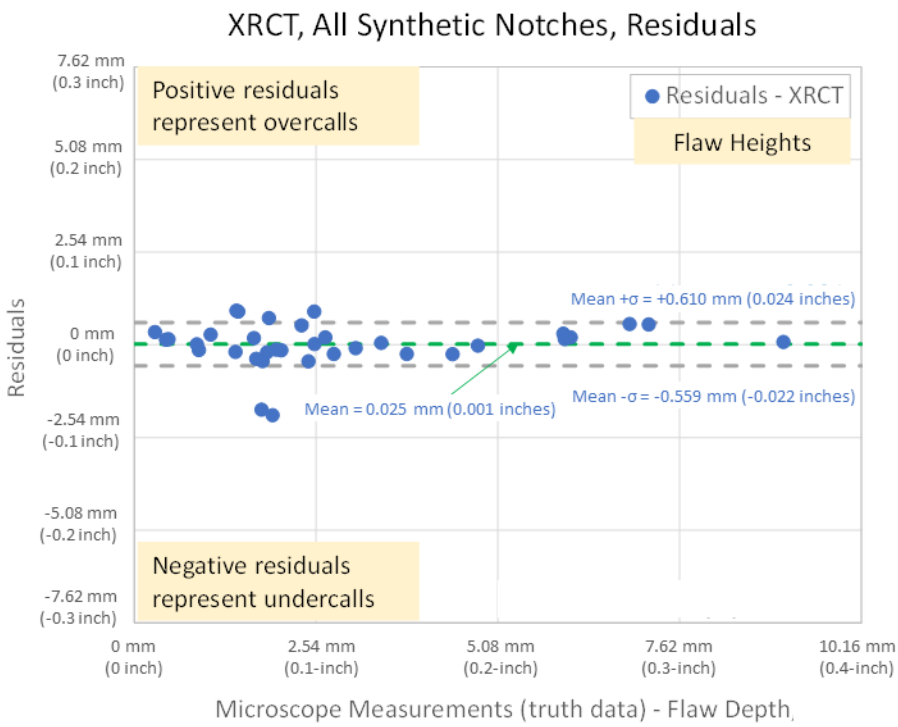


Figure 7: Residuals for all synthetic features, comparing XRCT data vs conventional NDE data

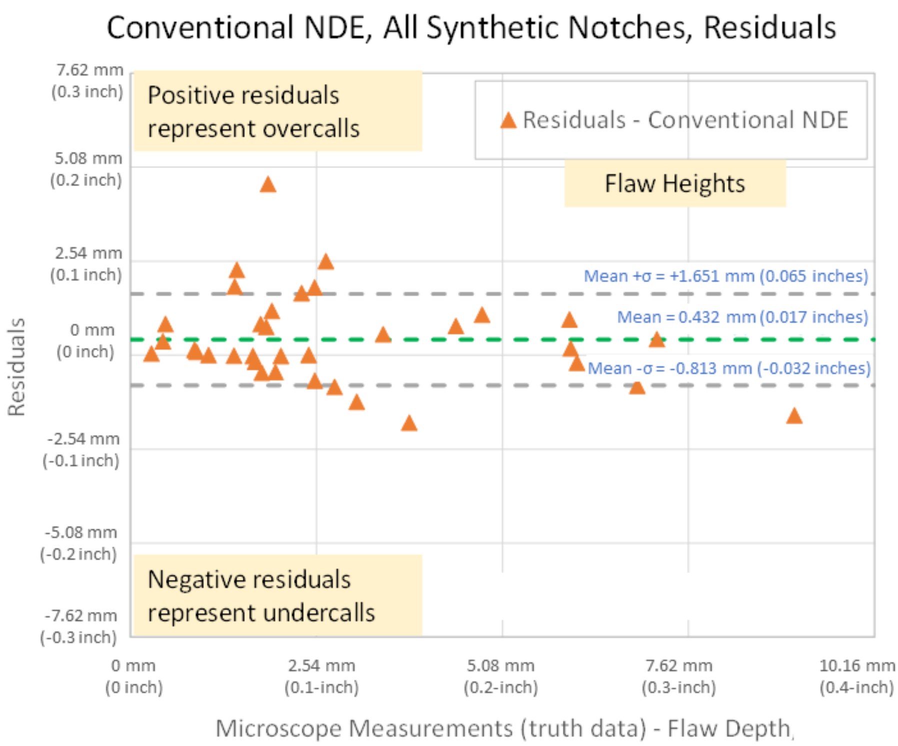


Figure 8: Residuals for all synthetic features, comparing XRCT data vs conventional NDE data

Results for Real-world Features

For the real-world features, the validation of the XRCT data with "truth data" from microscope measurements was challenging for the following reasons:

1. The flaws are rarely linear and mostly irregularly shaped. When these flaws are small, they cannot be broken open by freeze-breaking the entire flaw. Hence, the "truth" data needs to be generated by sectioning. However, when flaws are irregularly shaped, sectioning may not be able to cut across the deepest point of a flaw of interest – introducing uncertainty in the "truth" data itself. In this case, unlike synthetic flaws, the probability of the microscope observations from destructive testing being off-track is very high.
2. In real-world conditions, flaw generation is not controlled. As such, individual, isolated flaws that are easy to inspect are not readily available.

The complex geometries of real-world features make it challenging to generate a clean and true unity plot. However, for the sake of completeness of the discussion in this paper, a unity plot was generated by forcing a one-to-one mapping between XRCT and microscope measurements; this is shown in Figure 9. Cursory observation of Figure 9 indicate that the XRCT data tends to be biased toward being over-called. When compared to the unity plot for synthetic features shown in Figure 5, data in Figure 9 are relatively more scattered (less precise).

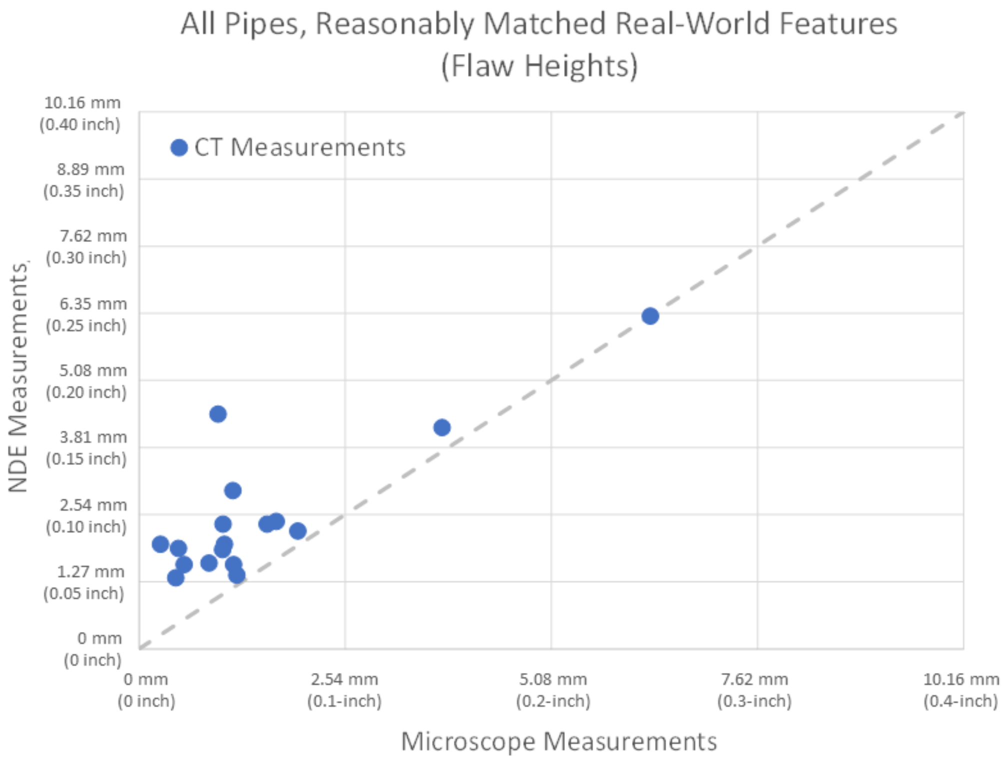


Figure 9: Unity plot for all real-world features (CT vs microscope measurement data)

General Outcomes – Characteristics of XRCT Inspection Results

The XRCT inspection results received by ADV included improved reporting information in terms of detailed dimensional characterization of the flaws as compared to conventional NDE techniques. A high-level comparison between XRCT and conventional NDE techniques is provided in

Table 1.

Table 1: Comparison of key characteristics between XRCT and conventional NDE

Characteristics	XRCT	Conventional NDE
Speed	Slower than conventional NDE when all aspects of inspection are included (actual inspection, data analysis, and reporting)	Faster than XRCT
Equipment size/portability	XRCT equipment currently in use is heavy, bulky, and requires specialized lifting equipment	The equipment for most of the conventional NDE techniques used in the study was light and maneuverable by a single technician.
Flaw reporting details	Significantly more information on flaw extent is provided, including depth profile, and visual, 3D representation of the extent of the flaws	Reporting for conventional NDE techniques typically only included numerical values for the deepest flaw height and length. Visual representation of the flaws was not provided (the techniques are not inherently capable of providing data visually)

The high level of detail provided by XRCT inspection is illustrated by way of the example results for a set of features identified in the 12-inch pipe sample as 12-inch-Sample-SCAN-002-B and 12-inch-Sample-SCAN-002-C, identified distinctly as two separate features on account of how they were called during the conventional NDE inspection. The conventional NDE reported data are shown in Figure 10. This region was identified for XRCT inspection. Prior to detailed 3D analysis of XRCT data, an initial comparison was made between the conventional NDE data and a 2D version of XRCT data (Figure 11).

Post-reconstruction XRCT results are shown in Figure 12, which shows a broader field view including the features of interest (12-inch-Sample-SCAN-002-B and 12-inch-Sample-SCAN-002-C) along with several other features that were identified in this field. In fact, XRCT identifies the set of features as one continuous feature with significant changes in the axial and depth profiles. Additional details provided in the XRCT report for this set of features are shown in Figure 13 (four different views of the features) and Figure 14 (showing a detailed isometric view). With the use of specialized imaging software, data can also be displayed as an interactive 3D map, allowing the user to traverse through the entire feature profile. Going from Figure 13 to Figure 14 is representative of the extent of details that can be achieved in going from conventional NDE to XRCT.

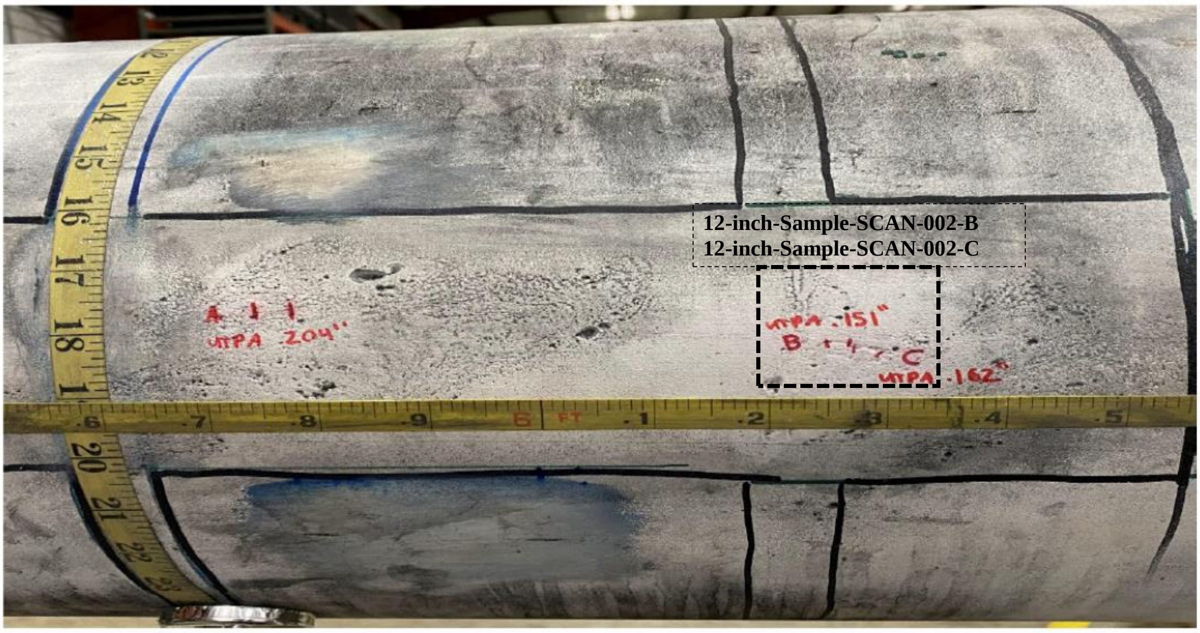


Figure 10: As-reported conventional NDE data for 12-inch-Sample-SCAN-002-B and 12-inch-Sample-SCAN-002-C

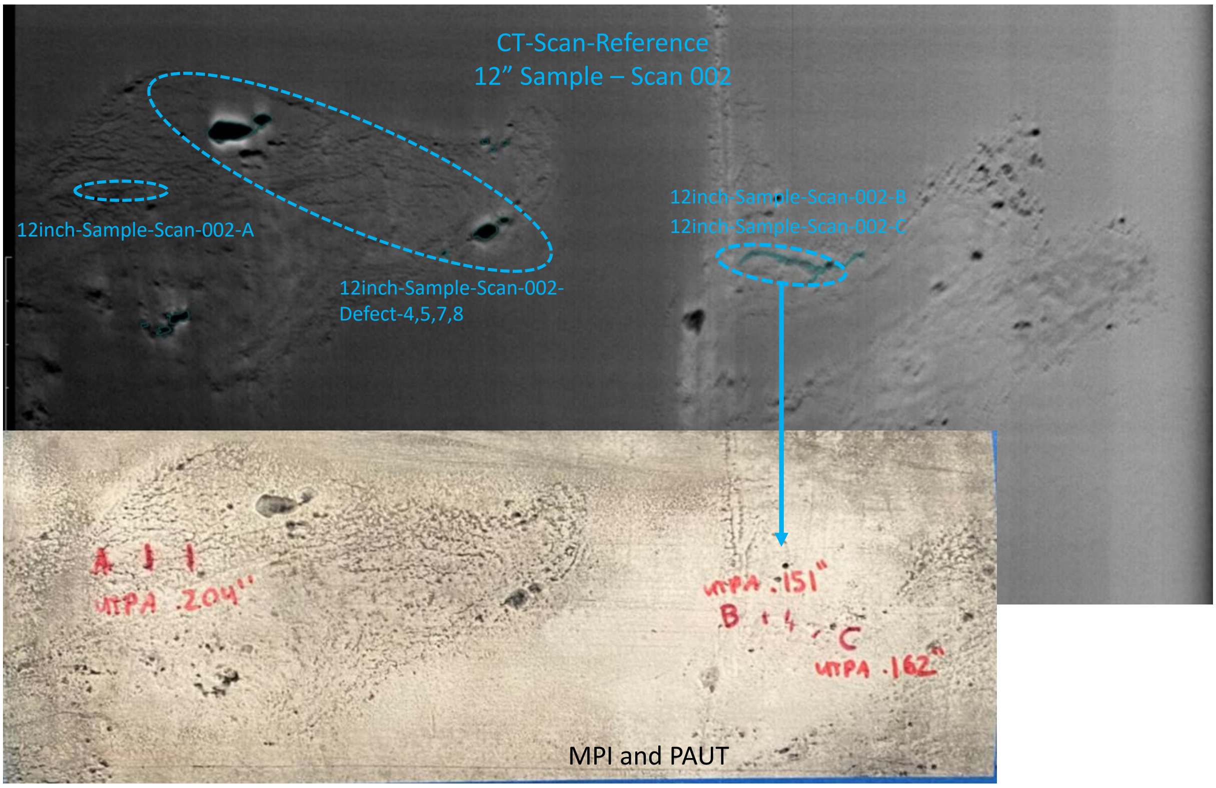
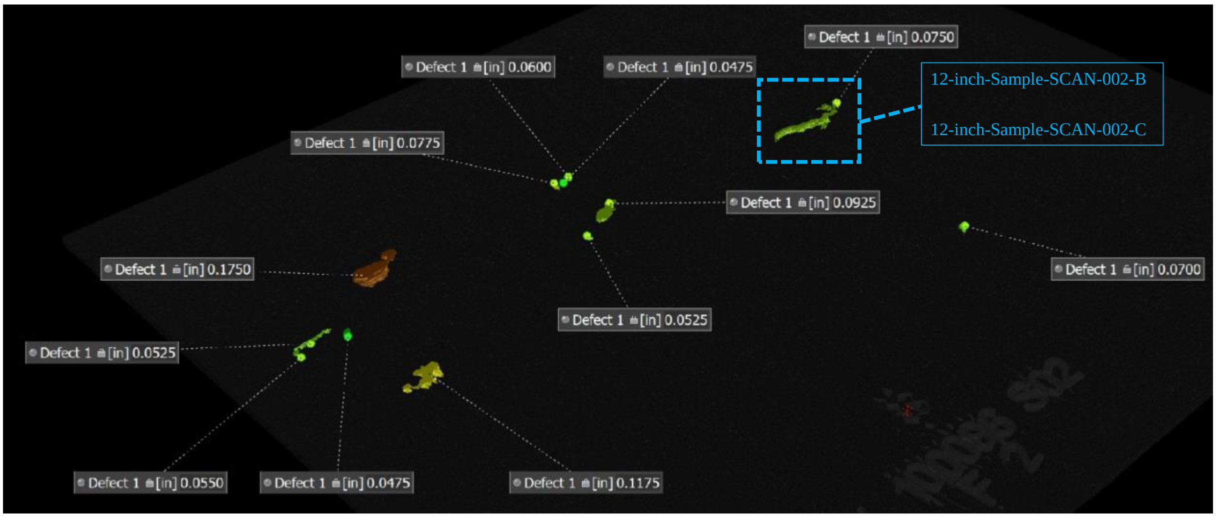


Figure 11: Comparison between 2D XRCT image (before full analysis) and conventional NDE information



Scale reference: the length of the feature marked in the blue box is approximately 1.17 inches

Figure 12: Broader field view of a section of the 12-inch pipe sample showing features of interest

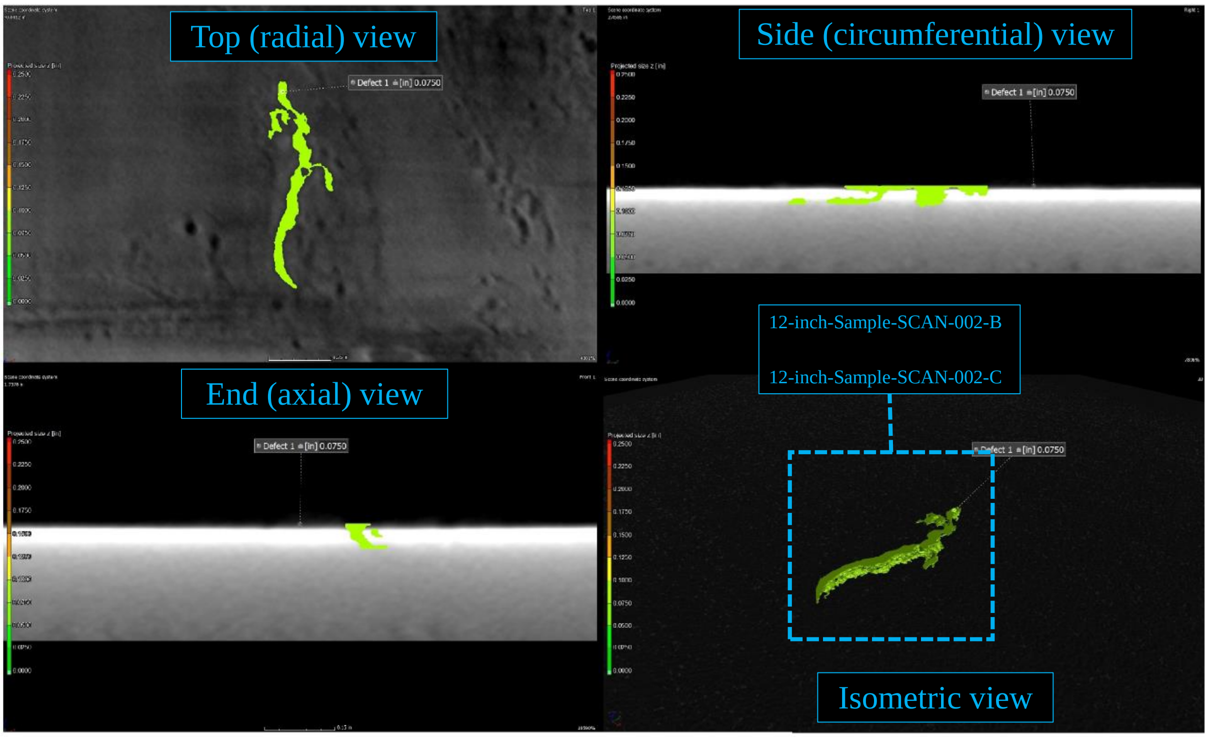


Figure 13: Four different views from XRCT inspection results for the features of interest

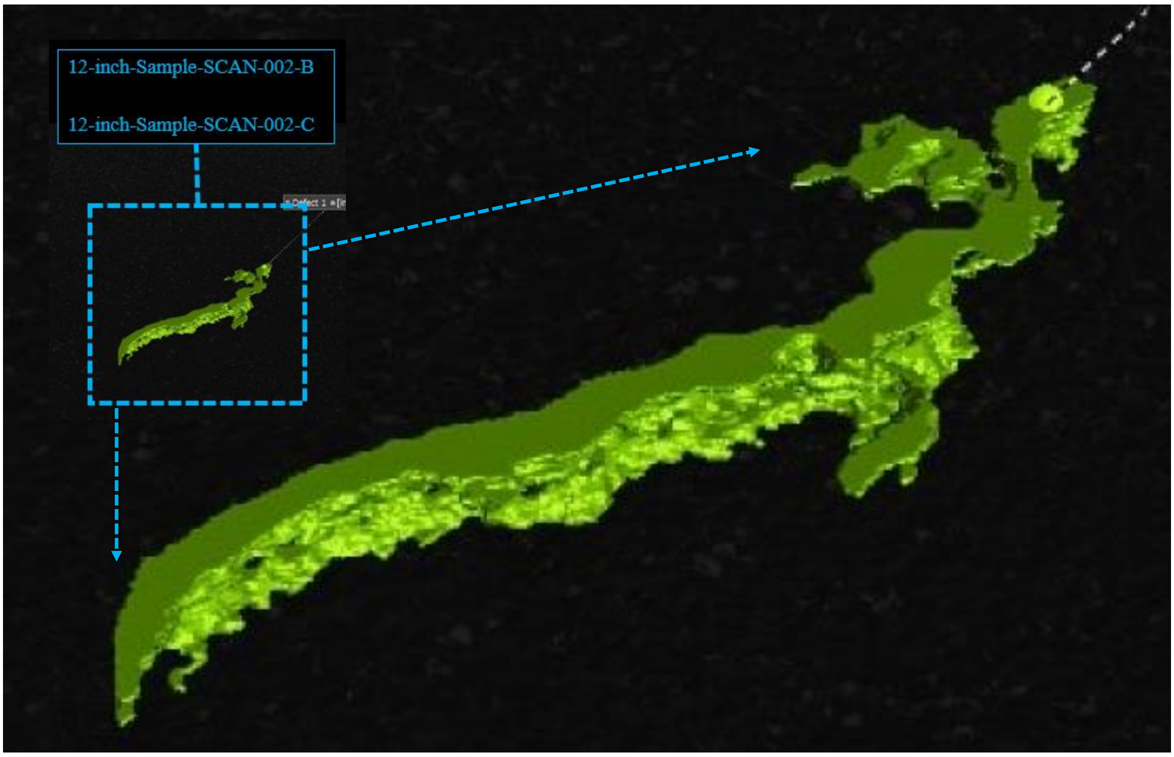


Figure 14: Detailed isometric view of the features of interest showing an extraordinary level of detail

Closing Thoughts, Gaps, and Recommendations

Since crack depth/height measurements cannot be validated using visual techniques and require destructive sectioning, XRCT can play a role as the most accurate non-destructive validation technique for flaw depth/heights. From the perspective of in-the-ditch validation, the common practice for crack assessments is to obtain length by using magnetic particle inspection (MPI), while phased-array-based techniques are used to obtain flaw depth/height. The MPI-based assessment of flaw lengths (including errors associated with the technique) are generally acceptable for technology validation and failure pressure calculations. Therefore, for XRCT validation, the project focused on flaw depth/height instead of flaw length.

Based on the performance of XRCT for validating the depths and nominal lengths of the manufactured flaws, XRCT is a viable option for validating *the depth* of synthetic reference standards. Rigorous length validation for synthetic reference standards will need additional confirmation beyond the validation efforts undertaken for this work; this is because the process (pressure cycling) used for creating crack-like flaws from EDM notches results in substantial growth in the crack depth/height direction, but significantly less growth in the flaw length direction. As a result, it could not be conclusively determined if the XRCT length measurements accurately tracked the tight crack tip of the crack-like flaw growth in the length direction (instead of the blunt EDM notch ends). Additionally, the research found that the information processed from this particular XRCT system was not sufficient to accurately validate reference standards made from real-world flaws. As such, additional validation work would be required to identify the equipment and process necessary to create reference standards from real-world defects.

For the synthetic flaws that were pressure-cycled to grow fatigue cracks, the XRCT data on flaw heights showed a good correlation with the measured data flaw heights. It should be noted that for this correlation, it was not just the heights of the (relatively blunt) EDM notches that were being measured, but also the finer fatigue cracks that grew from the base of the notch. These fine fatigue cracks growing from the EDM notches due to pressure cycling can be considered reasonably representative of the sharpness/tightness of real-world crack-like flaws. The industry standard uses notches when replicating cracking; using notches with fatigue cracking generated from the notch by pressure cycling is more representative of real-world cracks than those created through the current standard of notching alone.

For real-world crack-like flaws that are irregularly shaped (e.g., do not have uniform bottom profile, are at an angle to the pipe axis, or exist in a close cluster with other flaws), the difficultly in the precise determination of the length (and at times the associated height) increases, sometimes making validation of the flaw lengths by sectioning impractical or extremely resource intensive. Without such validation, the resulting data set cannot be used for reference standards purposes with high confidence.

A possible alternative for a more precise comparison of length data would be to perform progressive sectioning of the flaw and making measurements of height observed for each sectioning step and do a detailed "profile matching" between the sectioning data and the XRCT data. With this approach, flaw validation data will not be limited to a two-parameter definition of height and length, and serves as a better foundation for rigorous establishment of reference standards using real-world flaws. This activity was not addressed in the present scope of work, but is recommended for future validation efforts.

Other characteristics of the XRCT inspection technology – as evaluated in this work scope – are discussed in the following sections.

Strengths and weaknesses of the current XRCT inspection approach

1. In spite of the challenges encountered in verification of XRCT data for real-world features, the unique positive attributes of the XRCT system cannot be dismissed. With well-trained technicians and data processing software, the system can be deployed with high degree of reproducibility and can provide reliable results.
2. However, the manner in which the current syst5em was deployed in the present project (including hardware, software, data management, etc.), the XRCT approach presented itself as extremely resource-intensive, and cost-prohibitive for large-scale inspections.
    a. On the technological side, XRCT inspection data brings about the need for processing massive amounts of stored data and management of the data systems that support the activity.
    b. Certain subjective elements currently exist in the analysis of the XRCT data and the software adjustments that resulted in improved re-evaluation results. These elements further emphasize the need for technician and equipment/machine training of the XRCT process.
    c. Due to the use of an X-ray radiation source, XRCT equipment requires specialized operating licenses; requirements may vary regionally.

Development of reference standards

1. The correlation between the results obtained by XRCT and microscope observations for synthetic features was accurate and consistent, conveying the confidence that XRCT data can be used as proxy for truth data. These results when viewed in conjunction with process of creating the synthetic features using EDM notches followed by pressure cycling form the basis

of the development of reference standards that can be used to verify performance of other NDE techniques.

   a. The process of creation of EDM notches and subsequent fatigue crack growth under pressure cycling is extremely controlled, repeatable, and consistent. Therefore, fabrication of reference crack/notch samples (or calibration spools) can also be established on a repeatable basis.
   b. For any physical attribute to be used as a reference standard, the confidence in the “true” value of that attribute needs to be extremely high. In the present case, this confidence is demonstrated by the combination of consistent feature creation process and XRCT inspection performance in detecting/sizing these features.
   c. Results show that with appropriate analysis of XRCT inspection scans, the precision and accuracy of the inspection results can be improved over conventional NDE techniques. Furthermore, the ability to provide 3D visualization of the flaws would make it a preferred method for use in development of reference standards.
   d. A potential drawback of using synthetic flaws in reference standard development is that synthetic flaws may not be accurately representative of real-world flaws.

2. For real-world features, the mapping of XRCT data and microscope observations was difficult and challenging (as compared to that for synthetic features) because real-world features tended to be irregular in shape and could not be readily processed for destructive sectioning (for generating truth data). Therefore, although real-world features better represent other real-world features compared to synthetic features, the use of real-world features as precise reference standards may not be straightforward.

Portability and in-the-ditch application

1. The XRCT system used in this effort was laboratory-based and not portable. However, a field-deployable XRCT system has been built and used for in-the-ditch for inspection of pipeline cracks by the vendor. Studying the capabilities and limitations of a field-deployable XRCT system was not within the scope of this project, however, based on the observations of the laboratory-based system, the following challenges are expected for a portable, field-deployable system:
   a. Compared to the conventional NDE equipment (PAUT-based or Eddy current-based), the XRCT equipment is larger and bulkier to handle and cannot be carried around by a technician. Specialized handling equipment, fixtures and high-torque motors are required to allow the XRCT equipment to scan around the subject inspection pipe.
   b. With real-world pipe installation curvature and bends, the alignment of the X-ray source and detector with respect to the pipe is expected to be challenging.
   c. In laboratory settings, typically there is a greater flexibility/control with the resources (time and labor) which can be leveraged for better quality of results (more time can be spent on scanning and analyzing the XRCT data). Field-deployable XRCT systems may need to operate under more rigid time and labor constraints and may not be able to reproduce the similar quality of results as the laboratory-based systems.
   d. Also, in laboratory settings, the XRCT equipment is not calibrated for contents (liquid/oil or gas) inside the pipeline. Longer inspection/scanning times are expected for pipelines with liquid as compared to what can be achieved in laboratory settings due to the mass/density of the liquid. Pipelines with gas are expected to be easier to scan/inspect using XRCT.

It is expected that as the technology matures, research resources will be expended towards improving the portability aspects in future.

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