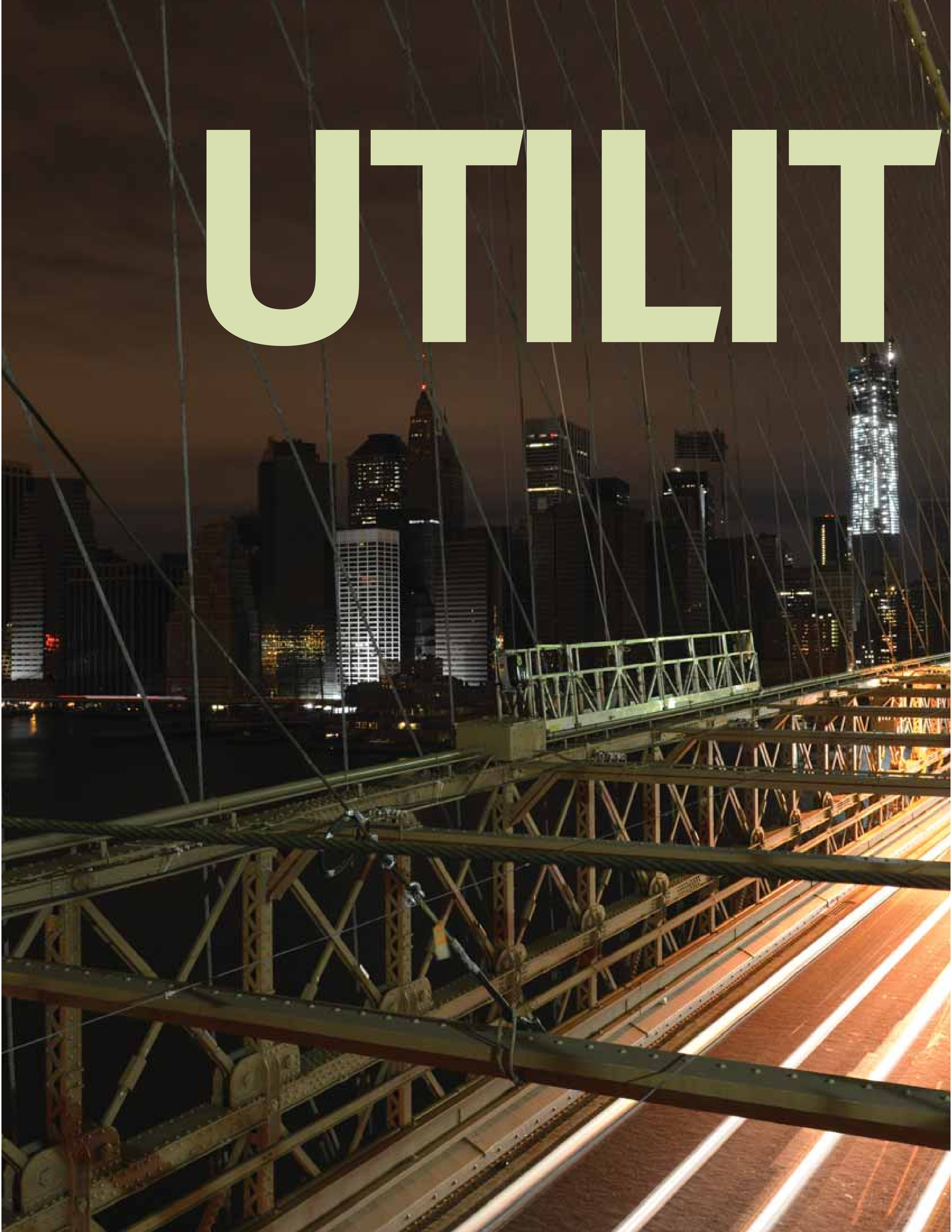
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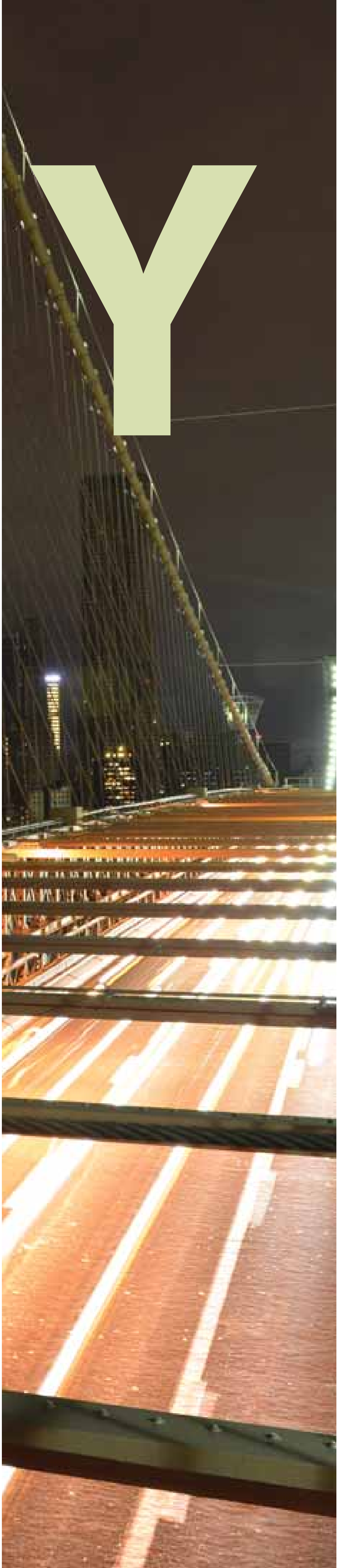

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An Innovative Application of Computed Tomography: The Next Dimension of Safety for Critical Infrastructure

by A. Makovoz and R. Maziuk

Given the growing demands currently placed on existing infrastructure, keeping public utility systems fully functional is more challenging than ever before. This is especially evident in major cities where millions of individuals and businesses are heavily reliant on the installed electrical grid. The reliable delivery of energy to businesses, medical facilities, communication systems, and residential locations is critical, and failures can, and do, create disastrous consequences.

Today, the power industry continues to provide safe uninterrupted service to its customers by diligently assessing critical infrastructure challenges. New York City, with a population of more than 8 million people, has been looking for the next dimension of safety for critical infrastructure. To this end, innovative inspection techniques are being developed for detailed diagnosis and to drive preventive maintenance going forward.

Over time, high-pressure, fluid-filled underground power transmission feeders move back and forth in a predominantly linear fashion from a few inches to as much as several feet. This motion is caused by several different factors, including variations in the electrical power load placed on the transmission feeders, which has a direct impact on the thermal expansion and contraction of the feeders. A transmission feeder installed in the winter, for example, will see a significant variation in stress when summertime temperatures arrive, prompting air conditioning use that places a greater power load on feeders than during the colder months.

Other factors can cause motion or stress on pipe-type transmission feeders, such as gravity's effect on elevation variations: a transmission feeder's weight, ~45 to 70 kg/m (~30 to 47 lb/ft), will place an increasingly physical load in its descent over a distance, pulling the feeder downhill. Also contributing to these issues is seismic stress, the impact of traffic-roadway vibration above underground transmission feeders as well as effects from adjacent subway lines.

All of these motion variables can affect the quality and reliability of the feeder joints over time, potentially compromising their integrity and effectiveness, which could ultimately result in catastrophic failure if undetected. These mechanical stresses, caused by either thermal expansion and contraction, or movement, will disturb the joint's metallic shielding and lead to high electrical stresses at these points. The result will compromise the insulation's integrity around the conductors, particularly near the joint, causing the joint's eventual failure.

When detected early enough, the joint can be repaired, saving time and money, and minimizing collateral damage due to an actual cable failure. Otherwise, the need to replace a substantial length of cable between two existing joints could result in much greater cost and down time, as opposed to just a localized joint repair.

The challenge was to find a way to conduct the most accurate inspection possible, without shutting down power or risking further damage or outages once potential problems were identified.

With this in mind a local digital X-ray inspection service company was chosen. A pilot program was initiated for the application of limited angle, 3D computed tomography technology to rapidly inspect selected areas of the power grid in 3D to determine where preventive action was warranted or recommended (Schneberk et al., 2015).

The Theory

The goal was to develop a transportable field solution combining high-energy X-ray generation, digital imaging detectors, and specialized imaging software to detect discontinuities and possible flaws. The result was an innovative gantry system that made it possible to obtain limited angle, 3D volumetric computed tomography images of underground utility cables and joints in high-pressure, fluid-filled cable systems (Schneberk et al., 2015).

Field inspection activities would be in situ, while the transmission feeder was energized and in full operation, minimizing the necessity of any service shutdowns or interruptions.

Preliminary results demonstrated that this technology enables a better analysis of conductors, insulation, and splice joints than historic 2D imaging, all while under load. Once the inspection is complete, the utility company is able to plan a shutdown to repair potential failure conditions, avoiding expensive, unplanned, and prolonged power interruption that may extend beyond the localized joint.

For years, 2D inspection of underground piping has been utilized, but with limitations. First, using X-ray film and an isotope gamma sources, and then later using portable high-energy X-ray generators, digital X-ray detection systems and highly specialized image processing algorithms were used for near real-time results (ASNT, 2002).

The X-ray film technique required exceptionally long exposure times and film processing that made it a very inefficient process. The advent of the portable high-energy X-ray sources, coupled with digital detectors, made the process far more effective and efficient, but the results were still only 2D.

Critical failure indications (that is, flaws, discontinuities that would need replacement or other attention) may not be visible in 2D images due to the masking effect of materials in front of or behind the failure indication. Whether or not a visible discontinuity or indication in the image represents a potential critical failure condition is often undetermined in a 2D image, since the precise location cannot be confirmed. Location of a potential flaw with respect to the other components in 3D within the feeder is often required to determine whether the indication is benign or critical.

The Innovation: Limited Angle Computed Tomography

Computed tomography scanning techniques provide a 3D inspection of an object or assembly's internal structures (Martz et al., 2016). The computed tomography voxel-wise reconstructed image produces an

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image of an object's internals with the value of each voxel proportional to product of chemical formula and density. As such, these inspection data are a rich source of information on any object or assembly. Multiple viewing options include the ability to move through the reconstructed volume via a series of axial slices, longitudinal slices, and to rotate and articulate the volume. The result achieves a view of potential flaws from many angles to better identify the discontinuity and to accurately determine its location with respect to conductors, ground wires, insulating materials, and layers.

This innovative imaging system provides a perspective view previously only available after destructively cutting and sectioning a portion of the transmission feeder.

Traditional tomographic scanning includes the acquisition of a series of 2D images, known as projections, to be taken of the object at discrete angular steps around a complete 360° rotation of the object. This is achieved by either rotating the object or by rotating the imaging system around the object (Martz et al., 2016). Clearly, an installed, high-pressure, fluid-filled pipe cannot be rotated, so the inspection system instead must rotate the X-ray generator and the digital detector around the pipe to get an image of the transmission feeder within.

One major problem existed. The underground access points to transmission feeder joints do not typically have sufficient space between the high-pressure, fluid-filled pipes and the floor, ceiling, and walls to enable a full 360° rotation by the high-energy X-ray equipment and digital detector. Consequently, the team focused on adapting 180° two fan-angle techniques for reconstructing volumetric images from a limited number of 2D projections over less than 360° of rotation (Feldkamp et al., 1984; Parker, 1982; Yang et al., 2004). The work started with proving the concept in the laboratory, and then to field test the concept on selected underground transmission feeders.

The Proof of Concept in the Laboratory

The first phase of work included an application study commissioned to investigate and demonstrate usefulness of computed tomography for feeder cable inspections. For this part of the project, a prototype gantry style computed tomography scanning system was developed, and a sample section of an actual high-pressure, fluid-filled pipe containing a splice joint was brought into the laboratory. The equipment featured a rotating gantry capable of a full 360° rotation around the pipe; it was configured for offset scanning techniques (Schneberk et al., 2015). The gantry system was of a modular design, capable of

Figure 1. Prototype gantry scanning system in high-energy laboratory for the proof in concept phase.

accommodating horizontal sections of pipe, as well as vertical sections, and the entire length of the pipe could be scanned, as in Figure 1.

Figure 2 is an example of the 2D digital radiographic image collected as the gantry rotates around the pipe through 360° of rotation showing the conductors (1), insulation (2), ground ropes (3), and cable support spacer (4).

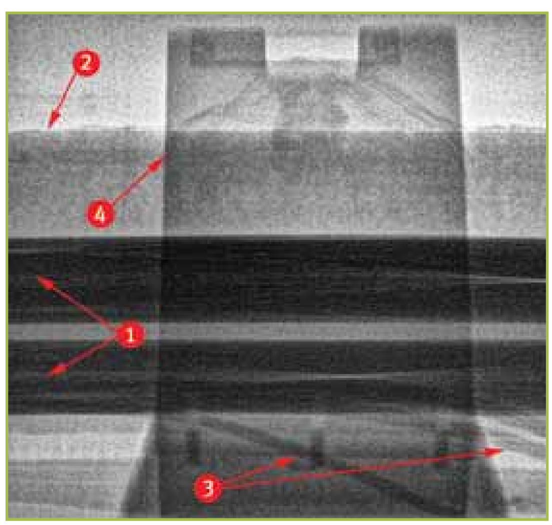

Figure 2. Two-dimensional X-ray image of a high-pressure, fluid-filled pipe and feeder joint in the lab showing: (1) conductors, (2) insulation, (3) ground ropes, and (4) cable support spacer.

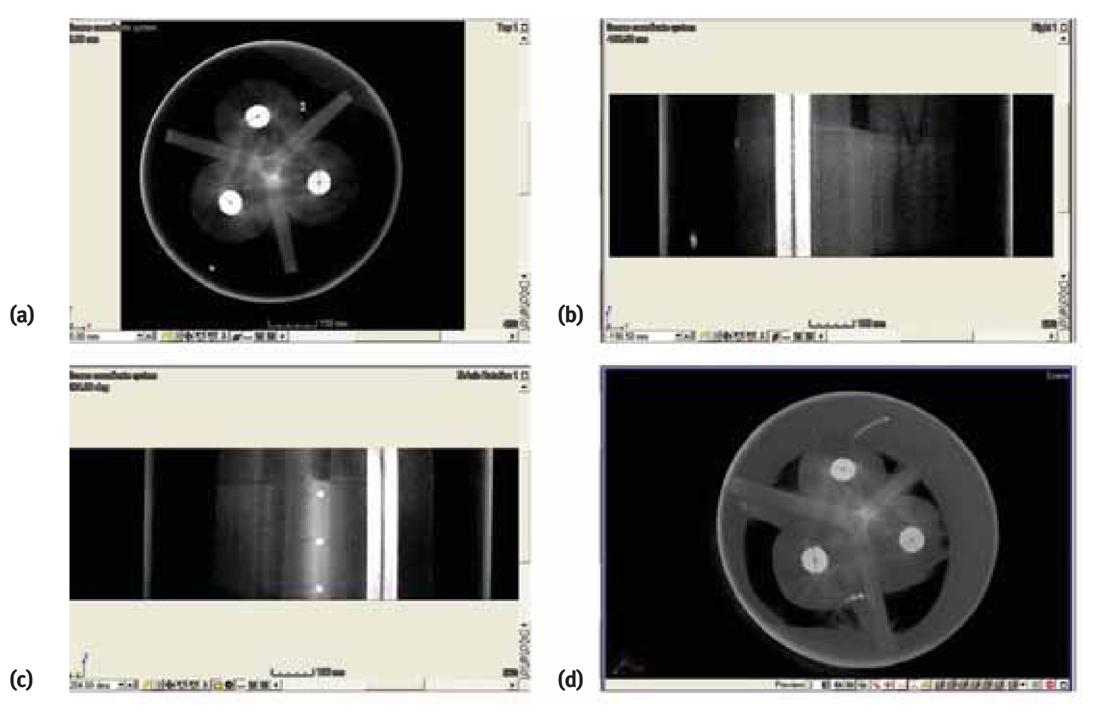

Figure 3. Computed tomography volume visualization screen: (a) "top" slice view; (b) longitudinal slice from the right; (c) longitudinal slice from the left; and (d) 3D volume visualization.

Figure 3 illustrates the main visualization screen of the volume viewing software. The 3D volume visualization is shown in the lower right hand corner, while the other three windows show slice views from different perspectives. The upper left hand quadrant represents the "top" slice view of the reconstructed volume or the "axial" view. The other two windows represent the longitudinal slice views from two opposing sides of the pipe.

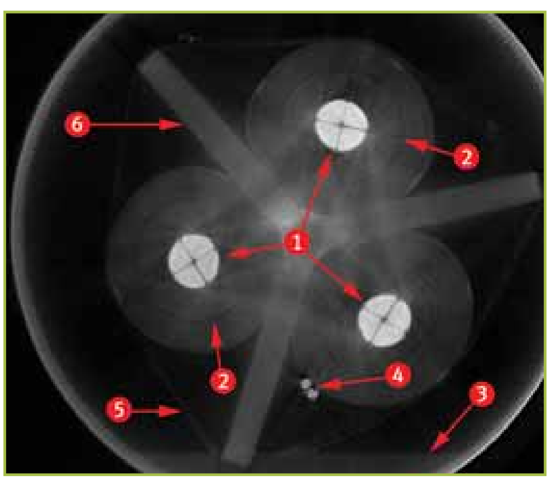

Figure 4. Axial slice view of a reconstructed feeder in a high-pressure, fluid-filled pipe showing: (1) conductors, (2) gaps in insulation, (3) oil in the bottom of the pipe, (4) ground ropes, (5) tape, and (6) joint support.

In Figure 4, the conductors are highlighted (1) as well as the gaps in the layers of insulation (2). Also visible in this image is the oil level in the bottom of the pipe (3) and the ground ropes (4). The layer of tape (5) that goes around the entire outer diameter of the joint support (6) is also visible.

Conclusions from the Lab Study

The study confirmed that a portable high-energy digital inspection system using X-ray energies of 7.5 MeV and a digital detector array would produce robust inspection results, yielding computed tomography slice and volumetric images of the sample feeder cable joint under ideal conditions in a laboratory setting. The concept for a system for inspection of feeder cables in the field was thus identified.

Field Deployment of the Prototype and Results

In the laboratory trials, the computed tomography system was able to execute a complete, unimpeded 360° rotation around the sample feeder cable. Access within a field installation, though, would have varied restrictions that would limit the scanning to less than 360°, and a prototype deployment system would be required to evaluate the techniques in a field inspection environment.

Evaluation tasks were structured as follows:

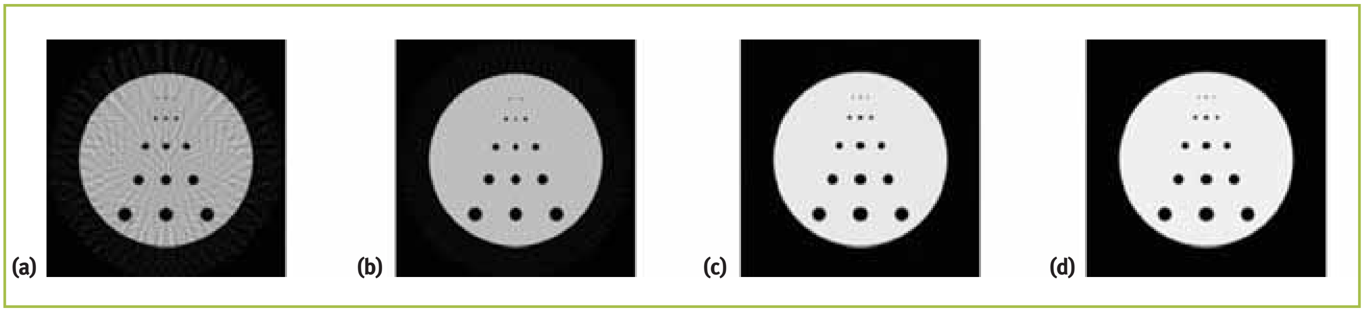

Figure 5. Variations in reconstruction quality based on the number of projections acquired: (a) 60 views; (b) 120 views; (c) 360 views; and (d) 720 views.

- Limited angle and region of interest computed tomography evaluation,
- Prototype deployment system,
- Acquisition of limited angle computed tomography data on a feeder cable,
- Reconstruction of computed tomography data and analysis.

During laboratory concept testing, computed tomography scanning was performed with half-scan or offset-scan techniques, enabling full coverage of the object but requiring 360° angular coverage of the object (Schneberk et al., 2015). Inspection of the selected in-the-field locations for scanning feeder cables showed 360° angular coverage was not achievable. While this was expected, it was discovered that a continuous 200° degree coverage was possible, making it feasible to utilize established 180° plus two-fan-angle techniques (Yang et al., 2004). As was the case in the lab, the projected pipe size was larger than the detector. Consequently, region of interest (ROI) techniques were adapted and used, scanning only the inside of the pipe and adjusting the reconstruction to account for the regions of the feeder cable outside the field of view (Martz et al., 2016).

Since access in the field is limited to much less than 360° of coverage and the number of rotational views is limited, the reconstruction achieved will include more artifacts compared to lab results. Figure 5 is a simulation of the impact of the limited angle technique on the results using a comparison between fewer and more projections acquired through 360°. The prototype deployment system was designed to be operated in a typical field location, as shown in Figure 6.

The field testing objectives can be summarized as follows:

- Perform limited angle computed tomography of a feeder joint sample in a laboratory environment.
- Develop and optimize imaging configuration based on physical space constraints within the underground feeder joint location.
- Determine limited angle computed tomography

Figure 6. Photograph of underground high-pressure, fluid-filled feeder cable joints.

Figure 7. Prototype deployed in lab.

imaging parameters including orientations, positions, and manipulation.
- Investigate and optimize limited angle computed tomography algorithms for best detectability level.
- Determine detectability of failure indications from the results (Martz et al., 2016; Schneberk et al., 2015).

Figure 7 shows the prototype system deployed on the sample feeder cable in the test laboratory, and Figure 8 shows the prototype system deployed in situ on the feeder cable prior to data acquisition.

Field Data Analysis

One specific area of interest for field inspection was at the feeder cable's joint interface. Figure 9 shows the 2D digital radiographic images of the conductors, insulation, and ground ropes on a field feeder joint interface showing gaps between the conductors at the joints (1) and distortions on the ground ropes (2).

For this field ROI scan, nearly 80 2D digital radiographic images were made over a span of 206° around the circumference of the high-pressure, fluid-filled pipe to produce these limited angle reconstruction results. Figure 10 shows all three conductors,

Figure 8. Prototype deployed at site installation.

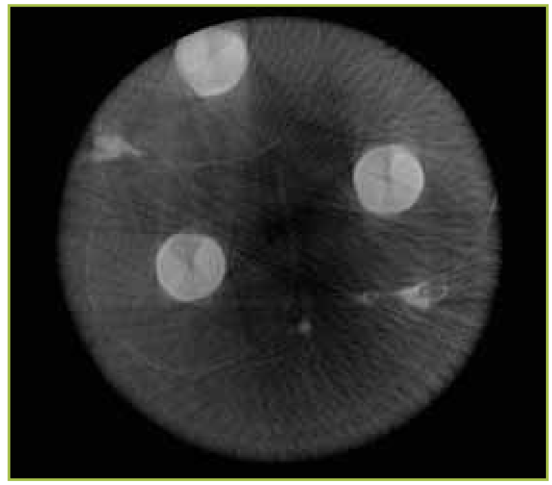

Figure 10. Cross-sectional slice in the reconstructed volume showing the conductors, insulation, ground ropes, and oil within the pipe.

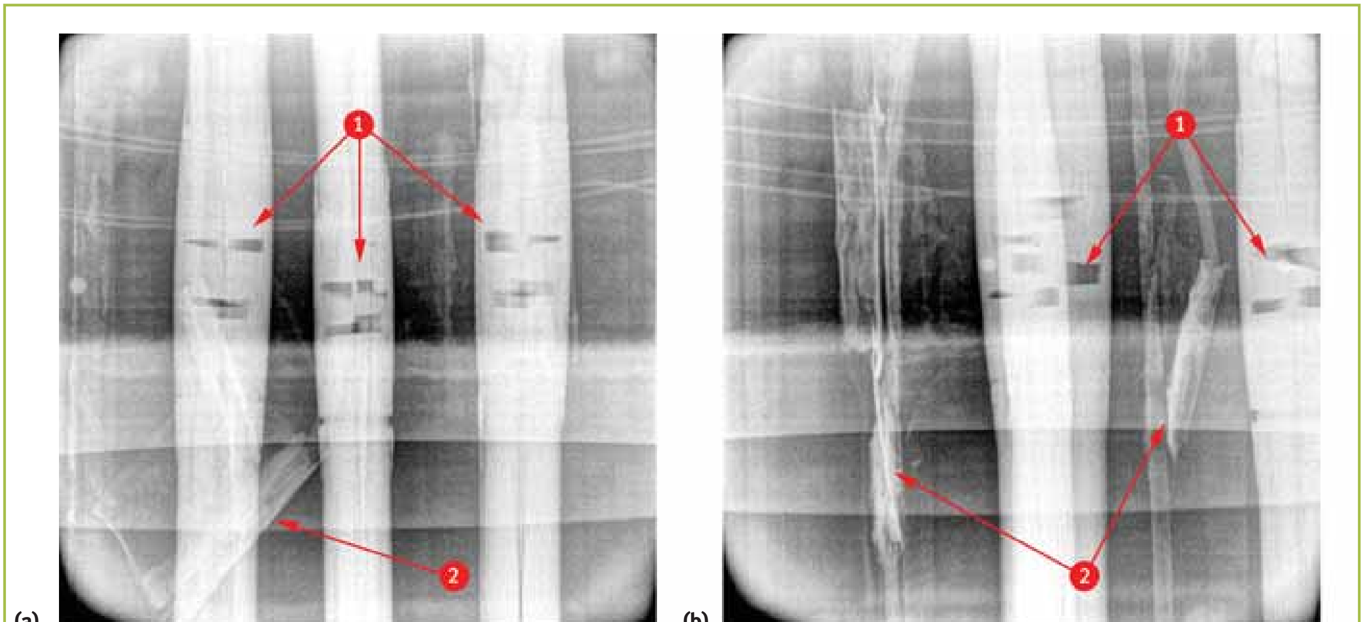

Figure 9. Digital radiographic field images showing (1) gaps between the conductors and (2) distortion in the ground ropes: (a) 0° view showing three conductors; and (b) 90° view showing two overlapping conductors and a third partially clipped from view.

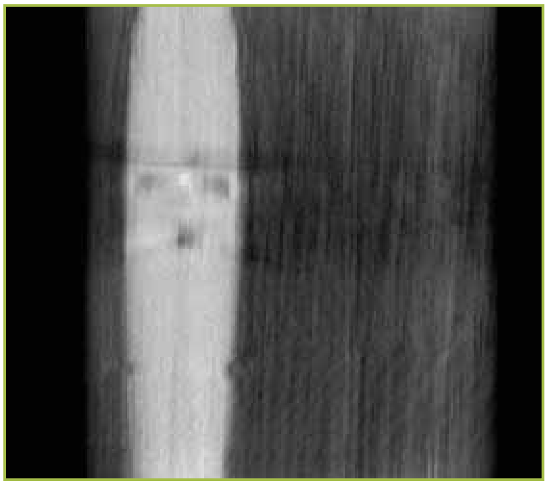

Figure 11. Longitudinal slice through a conductor at the joint showing a gap in the conductor.

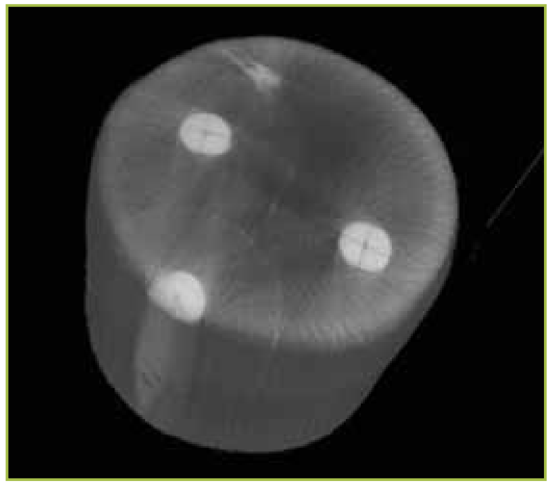

Figure 12. Three-dimensional reconstructed volume rendering representing the internal contents in space within the region of interest of the high-pressure, fluid-filled pipe scanned in the field.

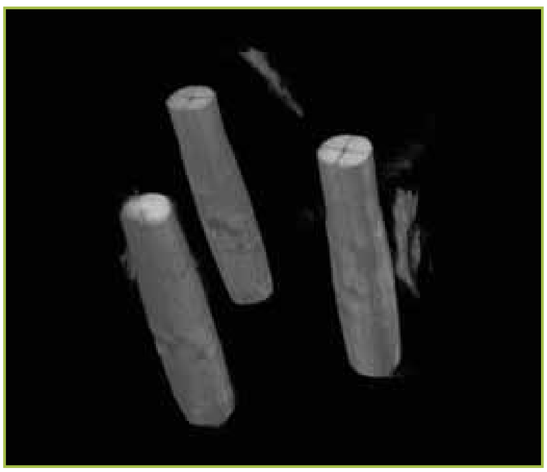

Figure 13. The oil and insulation have been subtracted from the virtual volume display to isolate and highlight the conductors.

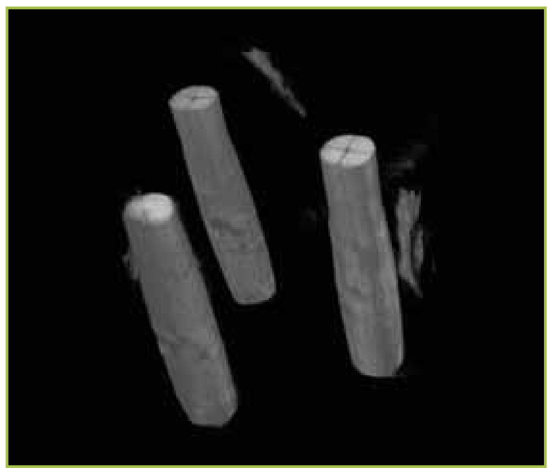

Figure 14. Slice planes applied to the virtual volume display reveal internal features of components such as the gaps in the joints of the conductors.

insulation, and ground ropes as well as the oil in the pipe.

The ability to "slice" through the volume helps to isolate specific areas of interest for analysis. Figure 11 illustrates a slice in the reconstructed volume that highlights the gap in one single conductor at the joint. The 3D rendering of the reconstructed volume shows the high-pressure, fluid-filled pipe scanned in the field (see Figure 12). The virtual volume display can be manipulated by moving it in different orientations or rotating it for a different view. The intensity profile of the image also can be adjusted to highlight certain features (see Figure 13). Slice planes can also be applied to the virtual volume display to reveal internal features of components such as the gaps in the conductors' joints shown in Figure 14.

The Future

The success of this and similar programs bring significant management improvements safeguarding the utility sector's assets. This advanced inspection technology, performed while allowing continued full operation, also is likely to provide major benefits in other industries, including the petrochemical sector (pumps and valves), where future financial success also is underpinned by enhanced management and continuous operation of high value assets.

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