Weld Inspection Process Improvement

by

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B.S. Mechanical Engineering, Hope College, 2008

Submitted to the MIT Sloan School of Management and the Department of Mechanical
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ABSTRACT

This project addressed challenges within the weld inspection process in one factory at Caterpillar through the implementation of phased array ultrasonic testing. The chosen factory fabricates and machines large weldments for track-type tractors. The industry trend towards lighter weight, lower cost, higher performance structures requires greater confidence in weld quality than can currently be ensured with existing inspection methods in use at Caterpillar. Previous attempts to implement phased array technology in production factories at Caterpillar were unsuccessful due to the perceived costs of the technology, a lack of training, a lack of internal standards, and a lack of a change agent.

The first step in the project began with understanding the current state of weld inspections. This was accomplished through factory visits, as well as interviews with vendors and Caterpillar's non-destructive evaluation community. Statistical analysis of quality data was conducted to understand current welding and inspection performance. This revealed several problems with the process that led to inaccurate inspection results and unnecessary factory rework.

Next, the project identified a pilot case to introduce the phased array technology. After acquiring the necessary phased array equipment, a robust, repeatable, cost effective process was developed where data is stored, and can be recalled and used to improve quality and future designs. Necessary fixtures were prototyped and tested to demonstrate the value of implementation. The implementation phase focused on training the operators to use the new equipment and procedures while still ensuring that the quality of parts released downstream was not compromised. The final phase of the implementation validated the quality of the inspection data and focused on improving the speed and safety of the phased array ultrasonic inspections.

This project integrated phased array ultrasonic testing into a factory and provided a framework for Caterpillar to continue to develop and deploy this technology across the enterprise. By identifying and solving gaps in the technology rollout process in collaboration with Caterpillar's non-destructive evaluation community, this project created positive change in the culture and execution of how improvements are made to weld inspection processes.

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1. INTRODUCTION

In an ideal world, quality inspectors would use the best and most accurate measurement technology available, allowing them to identify defective parts in production and address the root cause of a problem as soon as possible. In order to facilitate the introduction of a new technology in a manufacturing environment, structured processes like technology readiness levels (TRL) are used to carefully plan the implementation of technology to help management in making decisions concerning the development and transitioning of technology. However, the relevance of the product's operating environment and organizational barriers can limit the usefulness of some TRL processes in practice. In cases where the TRL process falls short, quality inspectors must be enabled and incentivized to adopt new technology on their own, and successfully manage changes during implementation. The research described in this thesis describes how the processes of new technology implementation can be improved so that quality inspectors at Caterpillar can more successfully integrate and spread the use of more accurate measurement technology in their daily work.

1.1 COMPANY BACKGROUND

Caterpillar Incorporated is a multinational company with over 90 years of history in producing a wide range of products including construction equipment, earthmoving equipment, mining equipment, engines, locomotives, and power systems. Caterpillar operates through three product segments: Resource Industries, Construction Industries, and Energy & Transportation. Caterpillar posted revenues of over $47 billion for the fiscal year ending in 2015. These results represent a net income of approximately $2.1 billion, a decrease of more than 40% from 2014.

(Caterpillar, 2016). Caterpillar is headquartered in Peoria, Illinois, and has several facilities dedicated to building track type tractors in the greater Peoria area.

1.2 PROJECT MOTIVATION

In recent years, several impactful, large warranty claims on large structures related to weld quality and inadequate inspection technology has driven Caterpillar to find a better way to ensure higher quality parts. In the early life of one particular series of products, a series of failures led to significant structural frame damage, causing extensive machine downtime and substantial repair costs. Though not a major safety concern to machine operators, the failures showed a pattern of originating from the same welds in the frame structure, and resulted in large fatigue crack propagation throughout the joined structure. One typical example is shown in Figure 1.

FIGURE 1: VIEW OF CRACK ORIGINATING FROM LARGE GROOVE WELD DEFECT

A cross-functional team was assembled to find a better way inspect weld joints that are difficult or impossible to inspect with the tools and methods that were previously in use at Caterpillar. Through extensive research and laboratory testing, a technology called phased array ultrasonic testing was proven to be the best fit for Caterpillar's weld inspection standards.

Although phased array ultrasonic technology has been used for decades in other industrial sectors like aerospace and oil and gas, previous attempts to implement phased array technology in production factories at Caterpillar were unsuccessful due to the perceived costs of the technology, a lack of training, a lack of internal standards, and a lack of a change agent. As Caterpillar's large structures are made leaner and customers continue to demand higher performance and lower costs, greater confidence is needed in the weld quality of fabrications coming out of the factory. Implementing a robust, repeatable, and cost-effective phased array ultrasonic inspection process represented a significant opportunity for Caterpillar to inspect weld joints with greater accuracy. Additionally, many phased array ultrasonic testing solutions offer the ability to save raw inspection data, which could be stored, recalled, and used to improve quality in future designs.

1.3 PROBLEM STATEMENT AND HYPOTHESIS

Accuracy of weld inspections is not good enough. Previous attempts to improve the accuracy of weld inspections led to the development of new processes and sensitivity criteria with only marginally better inspection accuracy. This project hypothesizes that by addressing the organizational challenges of new technology implementation, in addition to the technical challenges, weld inspection accuracy and reporting can be significantly improved.

1.4 THESIS OVERVIEW

The thesis is organized into 4 chapters. The first chapter introduces the project and provides an approach for how to solve the challenges. The second chapter provides a background on quality management systems and technology implementation success factors and barriers, as well as an introduction to weld inspection technology, notably conventional ultrasonic testing and phased array ultrasonic testing. The third chapter explores the implementation of phased array ultrasonic testing at Caterpillar through a case study at one facility in East Peoria, Illinois. It analyzes the organizational and technical challenges to implementing new technology in a large organization. The process solution that was implemented is detailed and the immediate improvements in production quality data are highlighted. In the fourth chapter, the work is summarized and recommendations are provided that show how the work implementing phased array ultrasonic testing can be leveraged for future improvements elsewhere at Caterpillar. Finally, future projects related to phased array ultrasonic testing at Caterpillar are suggested.

2. LITERATURE REVIEW

In this chapter, literature relevant to the project is reviewed and presented. First, quality management systems, technology readiness frameworks, and change management process are explained. Then, methods for weld inspection are discussed. Finally, standard operating procedures for ultrasonic weld inspections are reviewed.

2.1 QUALITY MANAGEMENT SYSTEMS

The modern quality management system was born out of the rise and spread of manufacturing, and the recognition of random variation in processes. Major milestones included Shewhart inventing the statistical process control chart in 1924, and management systems for quality designed by Duran and Deming in the second half of the 20th century (Bisgaard, 2006). Quality management functions comprise of quality planning, quality control, and quality improvement (Ebrahimi, 2014). Quality improvements have short term costs, and in order to remain competitive, long term benefits must outweigh the short term costs.

Quality control (QC)) and quality assurance (QA) provide structures for categorizing activities related to quality. Quality control often includes inspection, product testing, and work done to eliminate causes of defects. Quality assurance focuses on preventing defects from occurring in the first place by guaranteeing that every part of the production process is controlled (Heath, 2016).

It is helpful to quantify the cost of quality when considering quality improvement projects. Joseph Juran developed an "Economic Conformance Model" to understand the relationship between appraisal and prevention costs, and failure costs. Juran noted that at a low quality level, small increases in prevention costs yield large increases in product quality. However, once quality is sufficiently high and failures are low, increasing investments in prevention actually increase the total overall cost of quality (Juran, 1974). Quality improvements must be carefully monitored in order to maximize quality without investing beyond any realizable benefits.

2.2 TECHNOLOGY READINESS FRAMEWORKS

Firms have limited resources when it comes to new technology development and implementation. As such, it is important to have an actual process to determine which projects will be worked on, and how to allocate resources. NASA's Technology Readiness Level (TRL) scale provides a well-documented and widely used scale for measuring the degree of maturity in a given component. Table 1 summarizes the different levels of the NASA TRL scale.

Table 1: SUMMARY OF TECHNOLOGY READINESS LEVELS (NASA Office of the Chief Engineer, 2013)

TRL	DEFINITION
9	Actual system "flight proven" through successful mission operations
8	Actual system completed and "flight qualified" through test and demonstration (ground or flight)
7	System prototype demonstration in a target/space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

Originally meant to assess the technology readiness of components in a spacecraft design, the TRL scale helps management make decisions related to the development and transitioning of technology. Through the process of design, testing, and integration, managers are able to use

TRLs as checkpoints to reduce the likelihood that a component will originate an engineering change. Some key advantages of the TRLs are: risk management, providing a common understanding of technology status in an organization, and it can be used to make decisions regarding funding or transition of technology. However, the utility of TRLs can be limited because the readiness does not necessarily fit with the appropriateness or technology maturity, a mature technology may not adequately fit in a system with a lower maturity, and the product's operational environment and any potential product-system architectural mismatches (Dawson, 2007). While TRLs are primarily evaluated on a component level, interfaces between components and systems need to be taken into account to properly evaluate the technology readiness.

Since its introduction in the 1970s, variations on the TRL methodology have spread to other complex engineering industries such as automotive, oil and gas, semiconductor, healthcare, and software. Sauser et al. (2010) introduced Integration Readiness Levels (IRLs) to include the explicit assessment of the integration readiness of components in the decision making process. However, the assessment can be costly and overly complex. To simplify the IRL, Jimenez and Mavris (2014) proposed an approach where integration readiness is just considered as a sub-attribute of technology readiness. This method preserves the common language for communicating technology readiness while simplifying the cost to analyze the integration readiness.

While TRLs and its variants are usually used in new product development cycles relating to new technologies, they can also be used to drive implementation of new technology internally at a firm in a top-down approach. The highly structured nature of TRLs offer important risk mitigation checkpoints, but may not be the most appropriate technique for technologies that are proven and mature elsewhere in industry and only new to the processes and people at the firm implementing the technology. An organization with strict funding cycles can especially challenge the implementation of small introductions of new technology solutions. With limited funding sources, but countless projects to work on, each department or manager has an incentive to only focus on its own area of responsibility. This pushes management to focus on short term results, and new technologies that are not a primary strategic focus of the business can be forgotten, even if they offer significant long term value (Repenning and Sterman, 2001). To break out out of fixed cycle loop, a continuous review and iterative process is needed.

2.3 CHANGE MANAGEMENT PROCESSES

At its most basic, change management is a process to guide individuals and organization from the current state to some desired future state. There are several prominent change management processes, like Dr. John Kotter's "8-Step Process for Leading Change" or the "Plan-Do-Check-Act" cycle pioneered by Edward Deming, but the actions in most change management processes are very similar, despite having different numbers of steps. Beyond the basic steps of understanding and defining the problem, developing and planning a vision, engaging and implementing the change, and embedding and sustaining the change, change management processes are iterative, and must be regularly updated to adapt to the individual or organization.

First, it is crucial to understand the change and have a clear sense of purpose, scope, outcomes, and implications of the change. This will elucidate the change and help bring up expected barriers to adoption for consideration. The person in charge of the change should define the problem as early as possible, and communicate the design of the initiative early in the process. By studying the organization structure and stakeholders in the initiative, change leaders can better articulate a complete and compelling case for change and start planning a strategic and tactical plan for implementation (Ancona et al. 1999).

The work done to achieve the commitment of people is the foundation for the change initiative. A detailed vision statement for various audiences and collective ownership of the problem will generate a clear future state to everyone in the organization to build alignment. Ownership can be created by understanding various needs in the organization and involved people whose perspectives are critical to identify issues and create solutions. The ownership should be reinforced with indicators and incentives throughout the change process. The change leader can plan a work breakdown structure to clearly define roles in the change process for all parties involved.

Implementing the change is the most critical part of the process, and managers are required to play an active role in embracing new behaviors, advocating other employees do so as well, and engaging in the transformation. Implementation relies heavily on the bottom of the organization, and so it is crucial that ownership must be cascaded down from management to ensure a successful implementation. The employees at the foundation of the change must receive necessary training, skills, and behaviors to accommodate the change. Providing resources early or late in the process can have a significant impact on the transformation. Figure 2 shows the importance of making resources available on time, and what happens when resources to process capabilities when resources are constrained (Morrison, 2003).

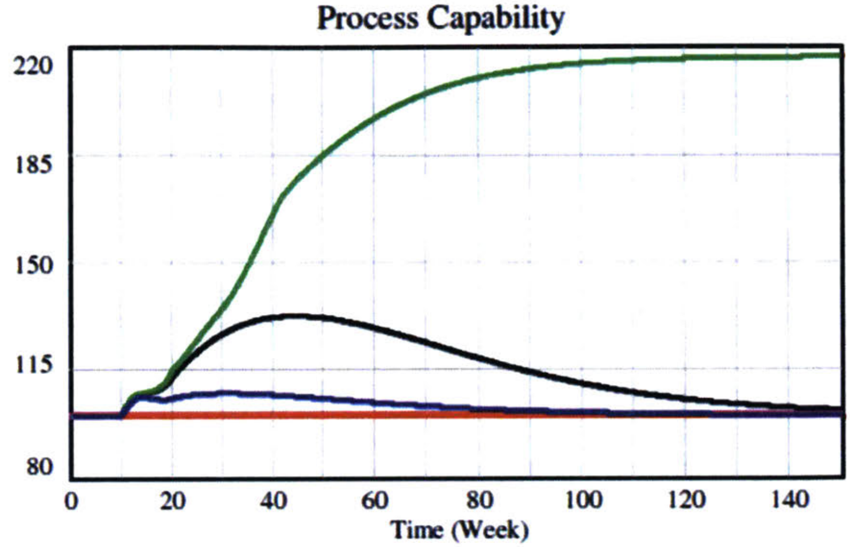

FIGURE 2: PROCESS CAPABILITY RESPONSE TO NEW IDEAS WITH RESOURCES AVAILABILITY

(Morrison, 2003)

Using system dynamics modeling, Morrison shows how the blue and black lines exhibit the organization returning to original process capabilities as support degrades over time and employee experience stabilizes. The green line shows sustained improvement value because managers collaborate with workers' ideas for improvements on a high proportion of tasks. The same amount of resources are required for each color line; the only difference is the timing of when supporting resources were introduced. Therefore, the critical factor in a successful process change is the timing and availability of support and resources. Once a change has been initiated, it is not enough to let the change continue on its own – it is imperative to embed the change in the organizational structure, business processes, and people's mindsets to make the change initiative sustainable and achieve continuous improvement. Management must provide the support early on, while also actively adjusting and improving the incentives for employees at the ground level to preserve the change.

Embedding the change in the organization by aligning incentives and consistency among objectives ensures that the transformation will be sustainable. The organization's metrics, systems, and processes must drive and support the change. Worker training and development programs are key enablers for embedding the change in the organization. In this way, change management processes can better address the integration of new technologies in an organization. Where TRLs primarily focus on assessing technology maturity to manage risks, change management process incorporate human and social behaviors to enable positive results. Usually, unsuccessful change transformations point to people's initial hesitance towards a change as the main cause for failure, when in reality, people will implement a change if they believe that doing so will benefit them.

2.4 METHODS FOR CRITICAL WELD INSPECTION

Many different types of defects and discontinuities can occur in the welding process. Methods to nondestructively detect and measure defects in welds include: visual testing (VT), penetrant testing (PT), magnetic particle testing (MT), radiographic testing (RT), conventional ultrasonic testing (CUT), and phased array ultrasonic testing (PAUT). Based on the capabilities and need of the inspection, different methods may be more appropriate for different applications. Table 2 summarizes the advantages and disadvantages of several weld inspection technologies (Buelsing, 2016).

TABLE 2: CAPABILITIES OF NONDESTRUCTIVE TECHNOLOGIES FOR WELD INSPECTION

NDT Technology	**Applicable Materials**	**Detection Capability**	**Depth Information**	**Sizing Information**	**Safety Concerns**
Visual	All	Surface	No	Yes	No
Liquid penetrant	All	Surface	No	Yes	No
Magnetic particle	Ferromagnetic	Surface	No	Yes	No
Radiography	All	Internal	No	Yes	Yes
Conventional UT	All	Internal	Yes	Yes	No
Phased array UT	All	Internal	Yes	Yes	No
Magnetic flux leakage	Ferromagnetic	Surface	No	Yes	No
Eddy current	Electrically conductive	Near surface	No	Yes	No
Thermography	All	Surface	No	Yes	No
Electromagnetic acoustics	Ferromagnetic	Internal	Limited	Limited	No

Visual testing is most commonly used because it is cheap and easy to do in a production environment. Gauges are often used to visually measure fillet weld sizes and concavity. Visual testing includes checking for surface defects like weld overlap, underfill, undercut, slag inclusions, or porosity. In addition to surface defects, Figure 3 illustrates additional sub-surface weld defects like lack of fusion, cracks, or incomplete penetration that can not be seen with visual inspection.

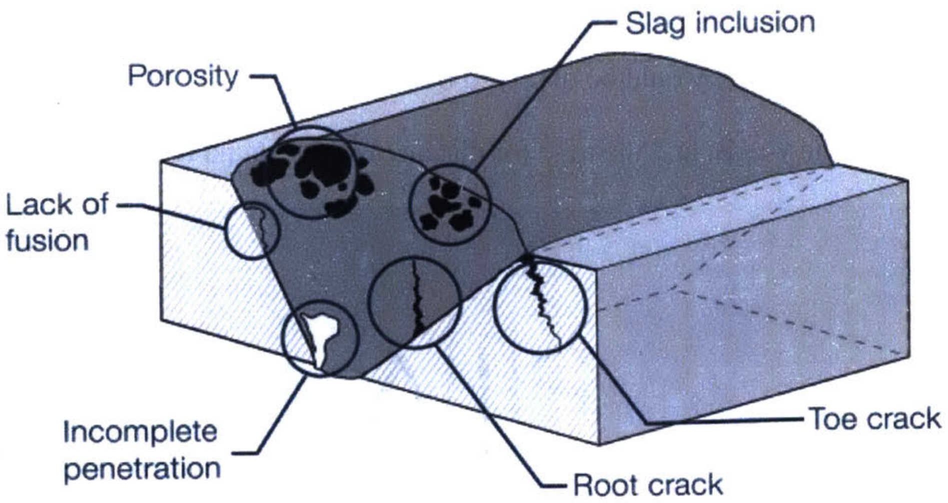

FIGURE 3: SUB-SURFACE WELD DEFECTS (OLYMPUS IMD, N.D.)

Conventional ultrasonic testing and phased array ultrasonic testing are often the next most commonly used methods because they can detect internal defects in welds and are safe to use. At Caterpillar, visual testing and conventional ultrasonic testing were used most often. On limited critical welds, magnetic particle testing was introduced to detect surface cracks in addition to conventional ultrasonic testing.

CONVENTIONAL ULTRASONIC TESTING

Since the 1940s, ultrasonic inspections have used the properties of high frequency sounds waves as they propagate through solid materials to detect internal discontinuities in metals, composites, plastics, and ceramics. High frequency sound waves reflect from flaws in predictable ways. Conventional ultrasonic testing uses a single piezoelectric element in a transducer to send high frequency sound waves and listen for any sound energy reflections. The transducer translates the sound reflections into a waveform that can be displayed by microprocessor-based instruments, which is then interpreted by a trained operator to locate and categorize flaws. Figure 4 shows the path of sound waves from a transducer to known flaws in a steel block and the corresponding Amplitude-Scan (A-scan) that would be observed by the instrument. The instrument plots the signal amplitude on the y-axis, and the time (or distance) of the sound reflection on the x-axis.

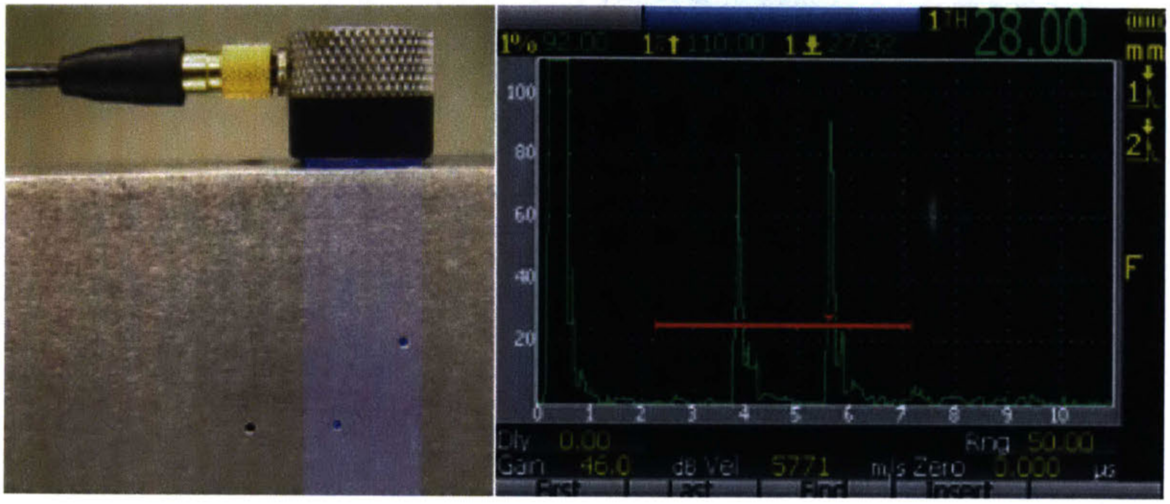

FIGURE 4: ULTRASONIC STRAIGHT BEAM INSPECTION AND A-SCAN (OLYMPUS IMS, N.D.)

Ultrasonic flaw detection is a comparative technique that relies on using an appropriate reference standard and its known echo pattern to determine the condition of the part being inspected. Discrepancies can arise when the orientation of a discontinuity is varied, resulting in different acoustic reflectivity amplitudes. For example, a planar defect that is perpendicular to the sound path will have a much larger reflection than the same size planar defect that is parallel to the sound path.

Another source of uncertainty can come from weld joints that allow for inherent discontinuities by design. The partial-penetration flare-bevel weld joint studied by Buelsing shows how the corner reflection from the unfused material in the designed joint is indistinguishable from the corner reflection from a grossly defective joint. The images in Figure 5 show destructively sampled cross sections of the joint with full weld penetration, partial weld penetration, and gross lack of fusion, along with the corresponding A-scans that make any comparative inspection impossible to accurately categorize.

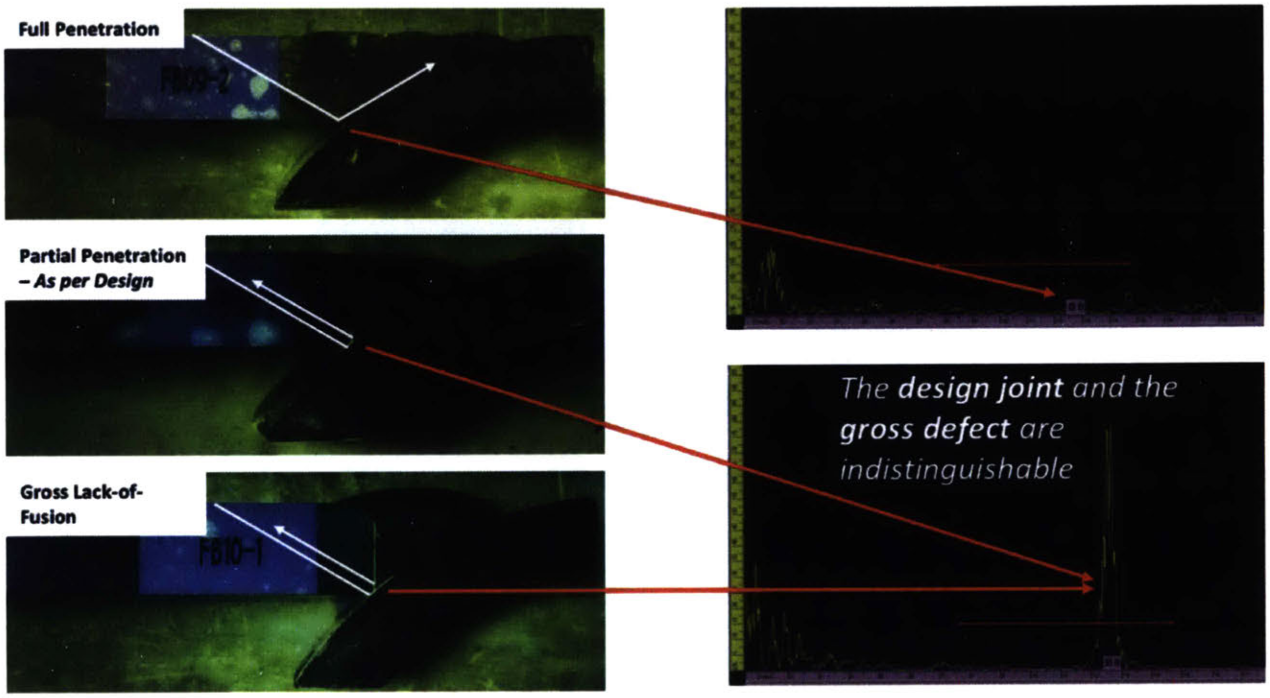

FIGURE 5: CONVENTIONAL UT LIMITATIONS REGARDING PARTIAL-PENETRATION JOINTS (BUELSING, 2016)

PHASED ARRAY ULTRASONIC TESTING

In contrast to the single piezoelectric element found in conventional ultrasonic testing transducers, Phased Array Ultrasonic Testing (PAUT) transducers typically consist of an assembly of 16 to 256 small individual elements that can each be pulsed separately. By varying the timing of the sound pulses from each element, the sound energy can be swept through a range of refracted angles, or focused at a certain depth, greatly increasing the flexibility of phased array systems. Sound waves that combine in phase will reinforce (constructive interference) each other, while waves out-of-phase will cancel each other out (destructive interference). Figure 6 shows an example of how constructive interference and delays in sound waves from different elements can form an angled beam from a flat transducer.

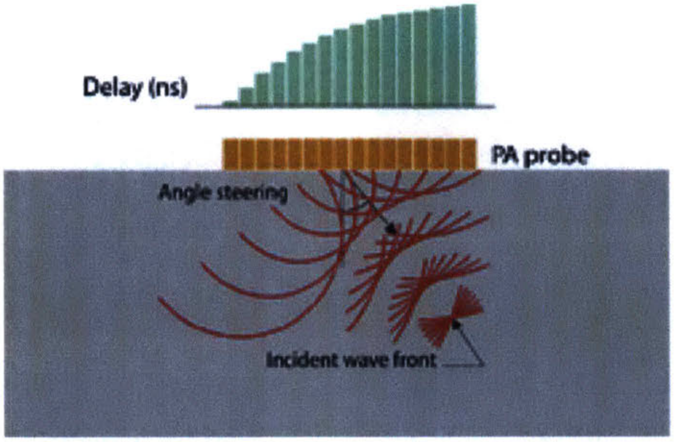

FIGURE 6: ANGLED BEAM GENERATION BY VARIABLE DELAY (OLYMPUS IMS, N.D.)

Phased array transducers were first developed in the 1970's for use in medical diagnostics. Using steered beams and aided by the fact that the human body had a predictable composition and structure, cross-sectional images of the human body could be created with relatively straightforward instrument designs. The technology was next pushed heavily in the nuclear market, which required more critical assessment and an improved probability of detection of defects. The first portable phased array instruments for industrial use did not appear until the 1990's, enabled by the transition from the analog to the digital world and the development of inexpensive embedded microprocessors.

With the ability to use multiple elements to steer, focus, and scan beams with a single transducer, the potential advantages of phased array technology over conventional UT include an increased probability of detection of defects, improved sizing of defects in volumetric inspections, simplified inspections of complex geometries, and easier signal interpretation by inspectors.

Figure 7 shows an example of a PAUT inspection and a resulting 2-dimensional Sectorial-Scan (S-scan). The image on the left shows a phased array transducer, a steel block with several side-drilled holes, and a white line representing one angle in the range of the inspection. The PAUT instrument collects an A-scan for every angle in the range, converts the amplitude of the A-scan to a color scale, and then plots each A-scan side-by-side into a composite 2-dimensional S-scan. The image on the right shows a single A-scan at the same angle as the white line in the left image, as well as the composite S-scan of the entire volume. In this way, the S-scan can convey more meaningful information about the discontinuities in the volume, and allow a UT inspector to more easily scan and analyze the nature of the discontinuities within the whole part.

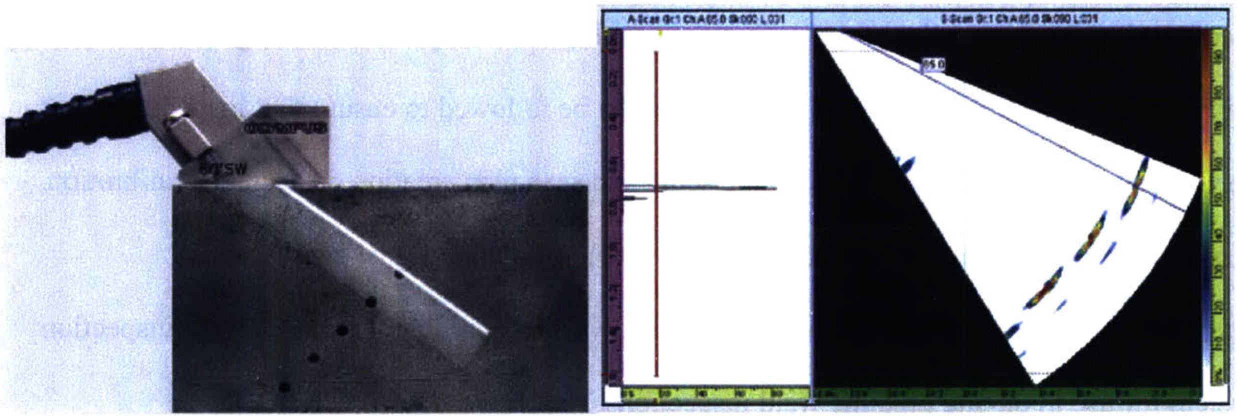

FIGURE 7: PHASED ARRAY INPSECTION AND SECTORIAL SCAN (OLYMPUS IMS, N.D.)

In the same way that A-scans can be combined into a composite S-scan showing a sectional view of a volume, when a phased array probe is moved across the test piece surface, the instrument can also create a composite B-scan to plot the depth of reflections with respect to their linear position, or a composite C-scan that gives a 2-dimensional presentation of data displayed as a top view of a test piece.

The potential disadvantages of phased array systems are an increase in operator training and higher equipment costs, but these costs are frequently offset by the greater flexibility and time saved in any given inspection.

2.5 STANDARD OPERATION PROCEDURES FOR ADVANCED ULTRASONIC WELD INSPECTION

For many industries and manufacturers, inspections are codified and mandated by regulatory agencies like the Federal Aviation Administration (FAA) and Department of Defense (DOD). Non-destructive ultrasonic weld inspections are especially useful for the oil and gas industry as a means to inspect the quality of welds in pipelines. Pipelines may be welded together in the field for hundreds of miles, so standard procedures must be followed to ensure that inspections are performed properly. This includes offline setup and scan plan creation, instrument calibration, inspection by a certified non-destructive test (NDT) technician, signal analysis and interpretation, and report generation. Figure 8 shows the operation of an automated inspection system for use in on-site pipeline weld inspections.

FIGURE 8: AUTOMATED ULTRASONIC PHASED ARRAY SYSTEM FOR PIPELINE GIRTH WELD INSPECTION (OLYMPUS IMS, N.D)

SCAN SETUP AND PLANNING

In order to properly conduct repeatable weld inspections with minimal variation, it is important to plan out each scan to ensure that the weld joint is properly scanned and machine setup is performed correctly. Software tools like "BeamTool" by Eclipse Scientific or "NDT SetupBuilder" by Olympus IMS allow inspectors to import weld joint geometry and select suitable transducers, wedges, and sectorial scans to allow for full scan coverage of the weld. With these scan plan outputs, inspection coordinators can create setup files on the phased array machines to specify further parameters like transducer aperture and beam focal depth. Once setup files are loaded onto phased array machines, inspectors only need to load the correct file for the particular weld joint they are going to inspect, and then proceed to calibration.

CALIBRATION

Calibration blocks, like the one shown in Figure 9, are used to confirm that the ultrasonic machine and parts will produce an accurate output. The material in the calibration block should be the same material being inspected, and the artificial flaw in the block should resemble the actual flaw being tested for (ASTM E2491-13).

FIGURE 9: CALIBRATION BLOCK USED FOR ULTRASONIC TESTING (SONATEST, N.D)

Before performing an inspection, the following settings must be calibrated:

- Transducer element operability – this verification determines the performance and cable conductivity of each transmitter/receiver module to ensure that the phased array probe is working properly.
- Wedge delay – the machine is calibrated for the specific sound path distance for the wedge that is attached to the transducer.
- Sensitivity – the signal amplitude of a flaw with a known size is calibrated to allow for proper flaw sizing during inspection.

- Time-of-flight Corrected Gain (TCG) – the TCG adjusts signal amplitudes at various distances in the calibration block to account for how the signal weakens at further distances.
- Encoder – the distance reading, the direction of positive movement, and the start/end scan distances must be verified for the encoder.

INSPECTION AND SIGNAL ANALYSIS

The British Standard BS7910:2005 "Guide to methods for assessing the acceptability of flaws in metallic structures" provides a recommended sequence of operations to assess a known flaw:

1. Identify the flaw type, i.e. planar, non-planar or shape.
2. Establish the essential data, relevant to the particular structure.
3. Determine the size of the flaw.
4. Assess possible material damage mechanisms and damage rates
5. Determine the limiting size for the final modes of failure.
6. Assess whether the flaw would grow to this final size within the remaining life of the structure.
7. Assess the consequences of failure.
8. Carry out sensitivity analysis, including appropriate safety factors (BS7910, 2005).

The inspection process specifies controls on inspection parameters like scan rate, scan path, and dwell time. Following the inspection plan for the specific weld joint, the inspector will evaluate whether the amplitude of the signal exceeds a reference calibration signal for the known flaw size to be detected. If any discontinuities are detected within a specified length, the discontinuity is recorded as a defect and marked for repair.

Some common methods for quantifying inspection performance is to evaluate the Probability of Detection (POD) or the sizing accuracy (a *vs.* $\hat{a}$). Using experimental data, sizing accuracy implies that for every flaw of a certain size a (the actual crack height), a response value $\hat{a}$ (the conditional crack height) was measured. With a known sizing accuracy for a given phased array inspection setup, one can use the POD curve to study the reliability of equipment and procedures (Department of Defense Handbook, 2009). Knowing the probability of detecting a flaw of a particular size is especially helpful when developing new testing techniques and quality defect criteria for new products.

In many situations, the human inspector is the most significant variable in the process. Human inspector performance has been shown to diminish over the first 20-30 minutes of a vigilant task, and continue to decline towards a lower bound. The effect is especially prominent for difficult tasks that offer no feedback on performance, involve rare events, and are completed in social isolation (Drury, 2000). In automated systems used in applications like pipeline weld inspections, the on-site inspector will not do any signal evaluation. The signal will either be captured and analyzed by a more highly trained technician off-site, or in some instances, can be automatically analyzed with software to generate defect reports without any further human input (Department of Defense Handbook, 2009).

3. RESEARCH ANALYSIS

3.1 CASE STUDY: WELD INSPECTIONS IN EAST PEORIA

At one factory in East Peoria, large structural weldments for D11 track type tractors are fabricated and machined. A typical configuration of the D11 is shown in Figure 10.

FIGURE 10: D11T DOZER

The factory in East Peoria is the only location in the world where the D11 is fabricated. Some of the most critical welds produced on the D11 are large "K-shaped" butt welds that connect a pair of castings to side rails of the frame. There are eight of these welds in total, four to connect the front casting (weld joints A, B, C, D) and four to connect the rear case casting (weld joints E, F, G, H as detailed in Figure 11).

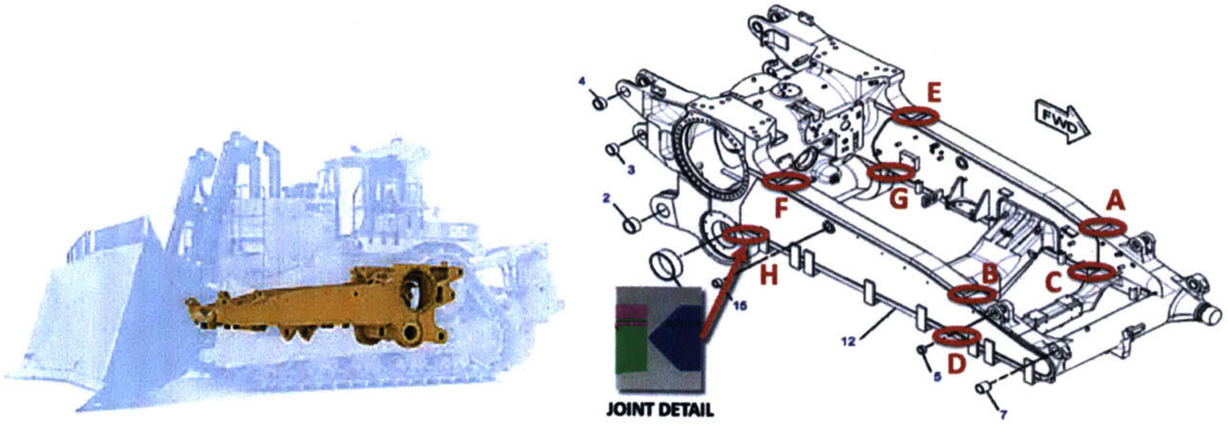

FIGURE 11: D11 CASE TO FRAME WELDMENT AND MODEL WITH BUTT WELD DETAIL

These welds were being inspected with conventional ultrasonic testing using three different angled wedges. Each time a wedge is changed, the instrument should be re-calibrated, but this was rarely done. Instead, the instrument was usually only calibrated at the beginning of the shift, and therefore the true time cost of an accurate inspection with multiple wedge changes was not always realized. When the field issues with D11 case to frame butt welds were first known, a review of the inspection procedures was conducted that found blind spots in the way inspections were being conducted. The inspection procedures were improved to include new magnetic particle inspections as well as an additional conventional ultrasonic inspection using a pitch-catch fixture to mitigate these blind spots. Using a pitch-catch fixture with two conventional ultrasonic probes enables the detection of off-angle discontinuities at the center of a thick weld. One probe acts as a transmitter, and one probe acts as a receiver. The left half of Figure 11 shows how the sound path from one UT probe can reflect off of a discontinuity and be detected by a second UT probe. Before the pitch-catch procedure was included in the inspection process, a single probe could miss defects at the center of the weld because the sound path would never be reflected to the transmitting probe to be detected anywhere along the raster scan path. Due to the geometry and welding procedures of the case to frame weld joint, the center of the weld was more likely to have defects than other areas of the weld joint, and so it was critical to eliminate the blind spots inherent to the single probe conventional UT procedure. The right half of Figure 12 shows a typical phased array probe with an array of sound paths that can detect the same discontinuity without the need for a second probe.

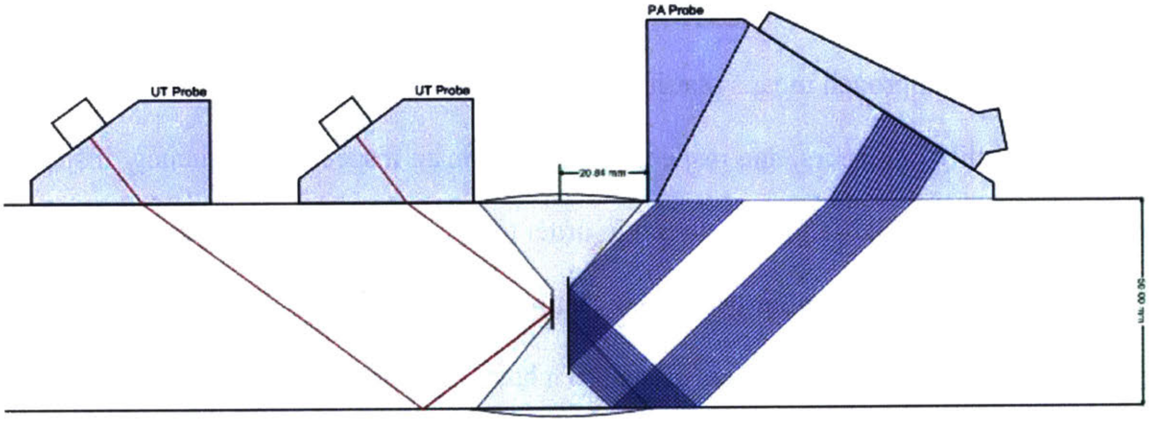

FIGURE 12: PITCH-CATCH (LEFT) AND PHASED ARRAY (RIGHT) SETUP AND SOUND PATHS TO DETECT VERTICAL WELD DISCONTINUITY (NDT.net, n.d.)

These butt welds were selected to be the first to be changed to an inspection standard using PAUT because of their critical nature, the facility in East Peoria was the only facility to produce these parts, added conventional inspection procedures still did not resolve all of the blind spots, and the welds failed inspections at a much higher rate than any other welds in the facility. There was a strong desire to know more data about what was really occurring inside these welds to cause so much rework in the factory and still have so many field failures at these joints. This chapter details the work done to understand the weld inspection processes that already existed, the current quality of parts being measured with the existing weld inspections, an organizational analysis to better understand how to implement PAUT, and the technical and process solutions that were ultimately implemented at the facility in East Peoria.

3.1.1 CURRENT STATE OF WELD INSPECTIONS AT CATERPILLAR

Weld inspections are used in order to prevent defective parts from being released downstream and ultimately getting shipped to customers. Although many inspections in other industries are mandated by code requirements, Caterpillar is subjected to little outside regulation regarding weld inspections. Caterpillar has developed their own internal set of weld inspection standards and procedures. This approach means that it is the responsibility of design engineers, manufacturing quality engineers, and inspectors to agree on an inspection frequency, inspection method, and sensitivity criteria for each weld in order to optimize the manufacturing costs and failure costs. In practice, Caterpillar uses a few distinct classifications to simplify weld inspections. Welds in critical high-stress areas often have a unique set of inspection standards that are more stringent than most welds.

Across all global facilities at Caterpillar, weld inspection procedures are developed locally that adhere to Caterpillar's manufacturing standard. This means that even though multiple facilities around the world may produce the same product, there is no formal way to ensure that inspections are carried out the same way at different facilities. In the researcher's survey of several different facilities, weld inspection technology in use varied with the skill and availability of local inspectors. Some facilities only conducted visual weld inspection because they did not have the resources to train or hire someone skilled in ultrasonic inspection. In effect, advanced inspections were seen as non-essential by facility managers in these locations, and not worth fighting for the money to develop them. Although not all welds are structurally critical and need to be inspected beyond a visual inspection, the limited amount of NDT resources and support available to smaller facilities in Caterpillar's footprint precluded them from making the same quality gains that were possible at larger facilities. Most facilities relied on conventional ultrasonic inspection for the majority of their required weld inspections. At a select few facilities, phased array ultrasonic equipment is used, but to varying degrees of sophistication. Caterpillar lacked manufacturing standards for phased array ultrasonic inspections, which meant that any facility that wanted to use PAUT had to develop their own procedures and standards. This raised the barrier to adoption for many facilities because they could not afford the resources to develop the necessary standards, and because they did not experiment with unknown equipment that could jeopardize the existing quality checks if any errors were made.

Improving the manufacturing standards and processes to incorporate PAUT was key to increasing support and adoption of PAUT inspections. PAUT offers many benefits over conventional UT, including but not limited to:

- The ability to inspect weld joint geometries that are impossible to inspect with conventional UT.
- The PAUT inspection can be encoded along the length of the weld and the raw data can be permanently stored.
- The PAUT scan data can be more easily interpreted by welders and welding engineers to identify defects and investigate root causes.
- A PAUT transducer collects information at a number of different angles, improving the speed of inspection and removing the need to switch between angled wedges on a conventional UT setup.
- A PAUT inspection can more easily be automated because the transducer only needs to move in one dimension, and the data can potentially be automatically interpreted.

- Scan data can be stored and recalled at any time in the future, and be used to improve future weld joint designs.

3.1.2 ANALYSIS OF WELD QUALITY DATA IN THE FACTORY

Recording and reporting the weld quality is a manual task that focuses mainly on tracking and reducing the length of defective millimeters of welds produced. After completing an inspection, an inspector enters weld inspection results in a database at their desk near the center of the factory. Inspectors are able to record who welded the joint, the depth of any defect found, what angle wedge was used to find that defect, how long the defect was, and any comments they feel would be helpful to troubleshoot a problem. A team manager uses the database to create charts and spreadsheets that are used for quality reviews and to identify key quality trends or issues.

Every time that a defective weld is entered into the database, and email alert is automatically sent to weld quality engineering managers so that they can take immediate action, if necessary. At the end of every month, the inspection manager compiles a summary report that lists the total length of welds checked and the length of defective welds found for each product group. Once a year, a more in depth meeting is held with weld quality engineering, design engineers, weld inspectors, and manufacturing engineers to review the past twelve monthly reports and discuss any overall trends found or changes that may be necessary to the inspection frequency moving forward.

With the data that had historically been collected, there were rarely significant actionable insights that could be used to materially improve either the quality of the welds, or the accuracy of the weld inspections. Figure 13 shows the percentage of millimeters of defective weld that were inspected on one particular part over nine months. The length of defective welds found was the main metric that inspectors reported and welding engineers tried to improve on.

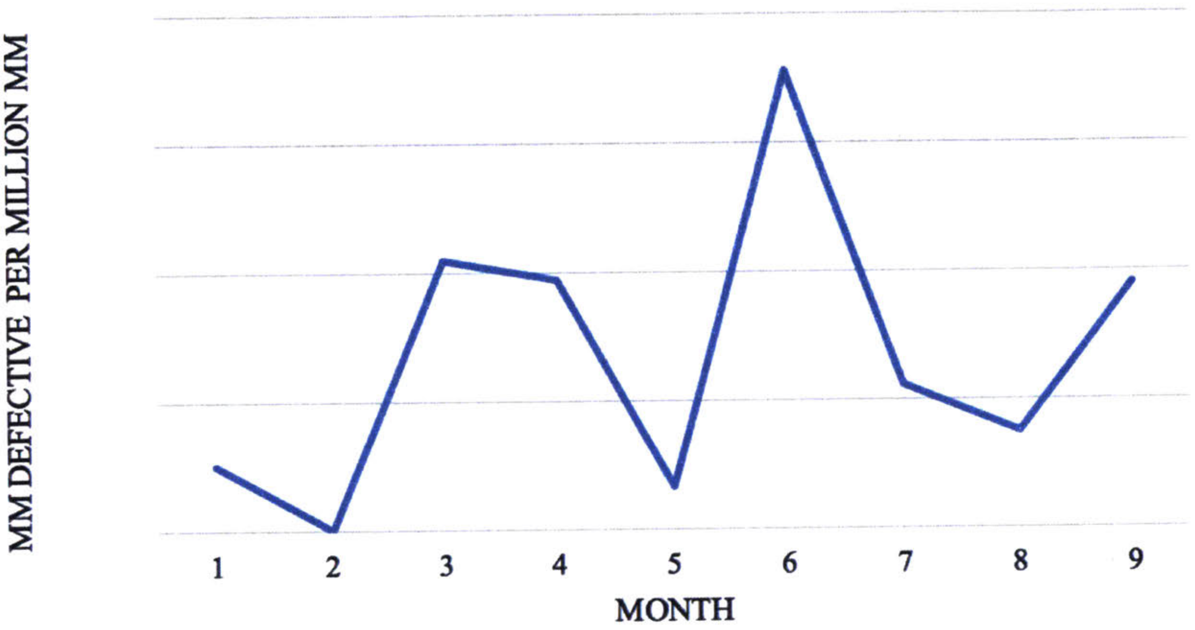

FIGURE 13: DEFECTIVE WELD RATE FOR TWO PARTS FOR FIRST NINE MONTHS OF 2016

While the total length of defective welds could be useful to quickly check the overall percentage of bad welds, it offers no information that could help improve the quality of welds or the cost to fabricate the parts. Any time a defective weld is found, it must be repaired, but this rework was not tracked. A part could be held up by rework for the same amount of time whether 30mm or 300mm of the weld were defective. Additionally, the data recorded provided no insight into what type of defect occurred. It was up to the welding engineering managers to hope that individual comments left on database entries might offer a clue as to whether the defect was porosity, lack of fusion, a crack, or something else. Because of the lack of detailed data, welding engineers were sometimes skeptical of the inspection results. It was thought that some inspectors were more meticulous than others, and welders would sometimes hold on to parts until the end of their shift so that less thorough inspectors on the next shift would inspect their parts. Because of the inherent distrust that welders had of the inspection results, efforts to improve the welding process itself were difficult to enforce. During the researcher's time in East Peoria, one weld quality engineer made great efforts to measure, analyze, and improve the setup and manual welding of D11 case to frame butt welds. Over several months, he was able to significantly reduce the variation in part fit-up prior to welding, and after introducing a new back-gouging procedure in the welding process, significantly reduced the amount of defects found (through conventional ultrasonic testing) at the root of the butt weld joint. However, shortly after getting the process in control, the quality engineer had to focus more time on other issues in the facility, and welder adherence to the new procedure dropped. By the end of the researcher's time at the facility, the quality engineer had moved on to another job completely, and without anyone to cover his work, welders knew they were no longer being forced to use the back-gouging procedure and conformance to the procedure was thought to be very low.

Inspectors were never audited, but the quality data showed that there was a significant difference in defects found between inspectors. Even after controlling for outside variables that might have affected a robotic welding operation, Figure 14 shows one example weldment where the inspector on third shift found defects at a much higher rate than the inspectors on other shifts.

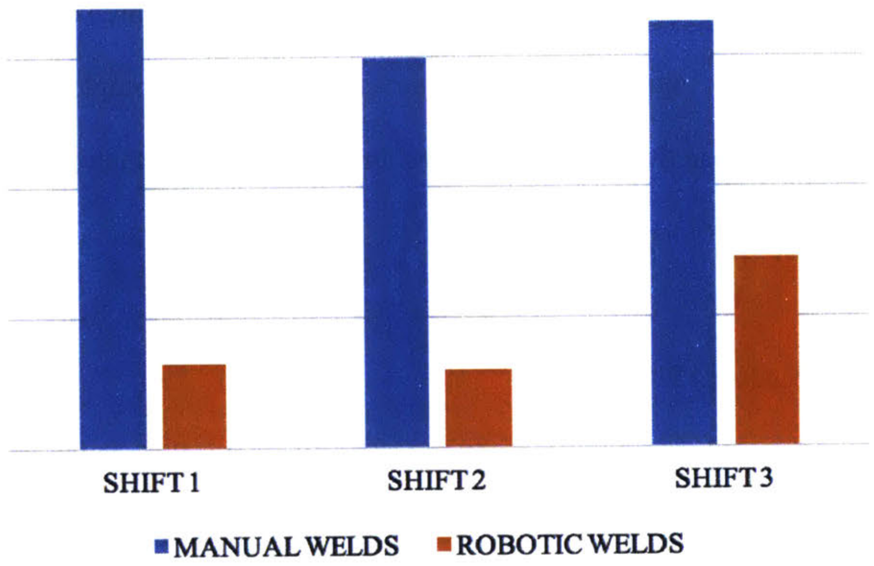

FIGURE 14: CHART OF THE PERCENTAGE OF D11 FRAMES WITH AT LEAST ONE DEFECTIVE WELD RECORDED BY SHIFT

With the limited amount of data that was currently captured by the inspections, it was difficult to know how to improve the weld quality, and whether or not any process changes actually had a significant impact on the output weld quality. Phased array UT offers the ability to view and save much more data. In particular, a record of the raw scan data could remove much of the subjectivity from individual inspectors and provide information about the specific location and type of defects found.

3.1.3 MATRIX ORGANIZATION ANALYSIS

An organizational design lens is a tool that is used to drive towards a deeper understanding of an organizational problem. By understanding the organization better, more inclusive and effective changes can be planned to more successfully address complex issues. The three organizational design lenses are strategic, cultural, and political. Each lens provides a different framework for analyzing an organization. Using the three lenses provides an examination of organizational issues from several perspectives. Investigating an organization from three different perspectives may lead to contradictory suggestions, but it is nevertheless a more complete and detailed analysis of the organization that can lead to better organizational and tactical recommendations (Ancona, 1999).

STRATEGIC LENS ANALYSIS

There are three main work organizations within Caterpillar that influence the implementation of weld inspections in East Peoria: Large Track Type Tractor (LTTT) product managers, research and development, and facility quality inspectors. Caterpillar is a highly matrixed organization in the sense that for each particular product, there is one manager and a range of specialized workers on one team. Each manager controls the development and maintenance of their product, but that control does not extend into production. As a result, product managers are closely linked with the research and development organization, but loosely connected to the factory managers responsible for making the product.

Product managers are interested in improving the quality of the products and avoiding field failures that cost money and hurt their end customers. Initially, engineers at Caterpillar thought that the cause of the D11 case to frame weldment field failures was design related because they believed the inspection process was accurately preventing defects from leaving the factory. However, after seeing warranty claims rise and re-examining the root causes of defects found in field failures, they discovered that the inspection process was not as robust as previously believed. The project managers originally spurred the need for better inspections, and teamed up with the research and development group to find a way to improve Caterpillar's current inspection capabilities. Previous work had been done with the research and development group to prove the effectiveness of phased array ultrasonic testing on weld joints like those found on the D11.

Caterpillar has recently had a poor track record of effectively implementing new ideas from research and development into their factories. Several years ago, there was an entire group dedicated to serving as an implementation engine and acting as a bridge between research and development and production, but it was dissolved around 2012, and there has been no formal connection since then. Additionally, although many current technology rollouts follow a structured Technology Readiness Level (TRL) process at Caterpillar, phased array ultrasonic testing had never been included in any formal project in the TRL process. As a result, resources to implement the technology in production had never fully been committed, and phased array ultrasonic testing was only being used in several small laboratory settings at Caterpillar.

Facility quality inspectors in the East Peoria factory report to the plant manager. Their incentives are focused strongly on production output according to current weld inspection standards and are not aligned with product managers' incentives to continuously improve the products. There was little formal coordination between facility inspectors and either product managers or research and development workers.

CULTURAL LENS ANALYSIS

Caterpillar has a long history built on developing the highest quality and most dependable products in the industry. Track type tractors have been built in East Peoria since the company was founded, and people who work on track type tractors are very proud of the work they do. Because of the history and size of operations in East Peoria, the culture within the factory is very risk-averse. High quality machines seem to be built on a norm of containment rather than on the elimination of defects. This makes changing quality metrics and implementing any new technology difficult. Continuous improvement becomes difficult because most of the less difficult quality issues have already been resolved, and the remaining quality issues are hard to resolve without a massive change.

Recently, there have been large budget cuts and layoffs across the company. Every dime that is spent is now closely monitored. "Who's going to pay for that?" is a common excuse in weekly team meetings to not progress further. Additionally, one entire research and development organization was folded and merged with another research group in mid-2016, which introduced many short-term stoppages. Many people are still fearful of losing their job, as additional layoffs and consolidations are possible.

POLITICAL LENS ANALYSIS

Product managers are hoping to take phased array ultrasonic testing and replicate it in other factories beyond East Peoria, so they are cheering from the sidelines for a successful implementation. Because of this desire, other managers donated money from their budgets to pay for some phased array ultrasonic equipment and a training class for inspectors. Meanwhile, inspectors were unwilling to add an extra project to their current workload. With the ability to effectively stop any technology implementation that was deemed unnecessary or too time consuming, the inspection group could use their power to halt any changes to their work that did not come from a more powerful group.

The key stakeholders and their support levels for the program near the beginning of the project are shown in Figure 15 below. Stakeholders are listed with a plus, minus, or question mark to indicate their interest in the success of the project, as well as their willingness to commit time and resources to the implementation. Lines indicate the most prevalent communication pathways between people and groups.

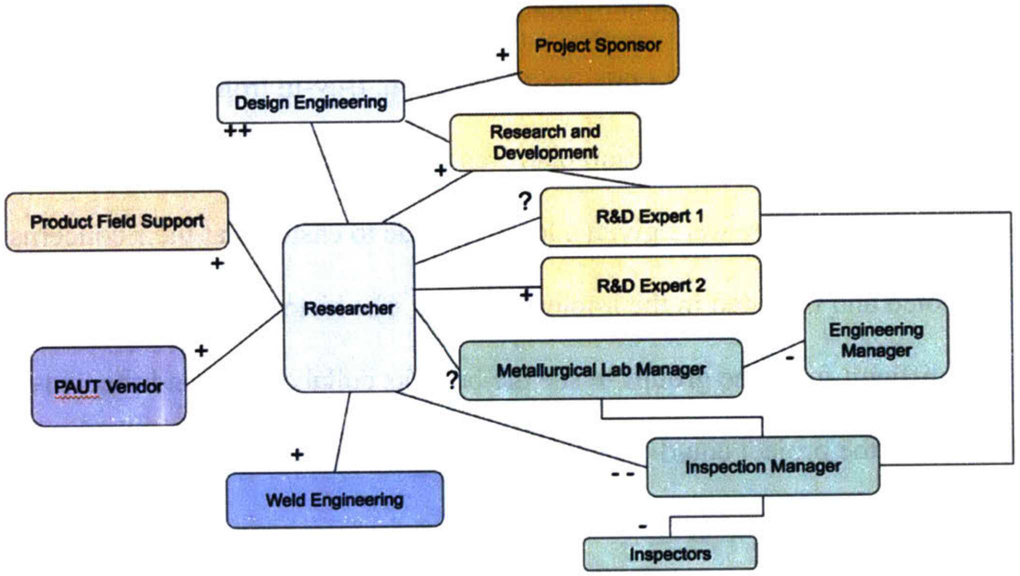

FIGURE 15: KEY POLITICAL STAKEHOLDERS

The facility inspectors in the selected factory were initially extremely reluctant to try using phased array ultrasonic technology in production. Their incentives are to inspect X parts in Y hours, deliver a report, and go home. Any new process or solution was seen as a roadblock, and immediately discounted. They expected any new process to be perfect without flaws or kinks, and were unwilling to experiment in order to drive continuous improvements. They had a difficult time seeing the overall benefit to the corporation that enhanced quality screening would bring.

ORGANIZATIONAL CONCLUSIONS

Implementing a new technology is heavily dependent on effective change management, so each group of stakeholders needs to feels understood and involved. In particular, the facility inspectors have the least direct incentive to change their daily work, but need to see the larger benefit that phased array ultrasonic testing will bring to the corporate bottom line. Inspectors also remembered the history of a failed implementation of phased array UT almost ten years ago, which made them strongly resistant to this implementation. Buy-in from the inspectors is essential, and therefore the implementation plan was developed in small steps that allowed feedback and adjustment. They were given a lot of latitude to ensure that their concerns and interests were noted and included in the implementation. The history of interactions between parties made it difficult for some groups to see the benefits collaboration and the win-win implementation that the project could bring to the entire company.

3.1.4 CHALLENGES

Careful attention to the three lenses illustrates the strengths and weaknesses of the current organization structure when it comes to implementing new inspection technology in the facility. The strategic lens shows the silo nature of the distinct research and development and production inspection groups. Although formal communication channels like the Technology Readiness Level system provide some links between the groups, projects that are more informal in nature suffer from a lack of communication on the road towards implementation.

The cultural lens displays a proud tradition of quality, but recent company performance has forced groups to split a much smaller quantity of resources to accomplish work. Competition for limited resources also makes some groups reluctant to try new ideas and programs if the financial payoff is not easily defined or if the payoff timeline is too long.

The political lens shows the split of power throughout the organization. Key players resisted any changes in resource distribution, whether it was project funds or employee-hours worked, and wielded their power to ensure that they did not lose control of their work processes to outside groups. Navigating the organizational structure requires a thoughtful change agent who can leverage the strengths of the organization to drive change and improve inspection quality (Delisle, 2001). By analyzing and utilizing the assets in place throughout the organization, the researcher was able to facilitate the implementation of phased array UT in the factory and close the quality gap in weld inspections.

3.2 TECHNOLOGICAL AND PROCESS SOLUTIONS

In order to address the weld inspection and quality problems described in the current state of weld inspections, technological and process solutions were developed. Having identified phased array UT as the best technological solution to improve weld inspections, the implementation proceeded in multiple steps. First, key inspectors were trained in general phased array ultrasonic knowledge, then they were trained and practiced using an Olympus Omniscan MX machine. Following this, calibration procedures were developed and inspectors were further trained in signal interpretation. The process solutions started with raster scanning procedures to more closely resemble the conventional ultrasonic procedures that inspectors were familiar with, and then transitioned to encoded scanning procedures. Throughout the process, key stakeholders in the inspections process, weld engineering, and product managers were involved.

3.2.1 PHASED ARRAY INSPECTION PROCESS

The next challenge was to develop a robust process for facility inspectors to follow. With phased array ultrasonic technology, new procedures were needed for machine setup, machine calibration, and inspection instructions specific to each weld joint. New machine setup procedures included instructions for proper time-of-flight-corrected gain (TCG) curves, element operability, wedge delay, and encoder calibration. While developing new calibration procedures, a larger and entirely new calibration block with side drilled holes was produced to validate second and third leg signal reflections. After machine setup and calibration procedures were developed and refined, quality inspection instructions (QII) and specific weld joint inspection instructions were established and tested. Creating a new QII was especially important because it was critical that by moving to phased array ultrasonic testing, there would be no loss in the sensitivity of decision criteria to rate acceptable and rejectable discontinuities in welds.

In order to fully complete the inspection of a weld, the phased array equipment was calibrated weekly, with daily checks in the morning to ensure the equipment was still within calibration targets. The weekly calibrations were a new step from the conventional ultrasonic procedure, which, in order to save time, had erroneously ignored updating the Distance Amplitude Correction (DAC) curves in the instruments and instead relied on DAC curve programs saved on the instruments that had been created years ago. While the saved programs were likely close to accurate, no one had invested time to quantify how accurate the DAC curves in the saved programs actually were. They were a major source of inspection error that otherwise relied on detecting very small defects. By eliminating the reliance on tribal knowledge passed down throughout the years and incorporating robust calibration procedures, the overall inspection accuracy was improved.

Using ultrasonic couplant gel, the inspector would perform a raster scan with the transducer and wedge to inspect the full volume of the weld. The inspector would watch the phased array screen output for any signals that appeared close to or above the threshold level set during calibration. While the conventional ultrasonic inspection process required four different set of angled transducers to completely inspect the weld volume, the phased array inspection covered the entire section of angles necessary to see the entire weld, significantly reducing the amount of time necessary to properly inspect a weld. For the eight butt welds on a D11 case to frame weldment, inspectors averaged over 60 minutes total to inspect all welds using the conventional process. By eliminating the need to switch transducers and recalibrate each one before using it, the phased array inspection process reasonably saved an average of 40 minutes per weldment. The inspector's job becomes less menial and they have more time to inspect other parts in the factory or investigate defects in more detail.

3.2.2 PHASED ARRAY SCAN PLANNING

In order to develop a highly repeatable phased array scan procedure, several steps were taken to enable raw scan data to be stored while limiting the chance of operator error. First, a scan plan was developed to ensure that wedge locations were standardized and offered coverage of the entire weld joint. BeamTool software offers the ability to define an effective approach to any inspection. Figure 16 shows an example of one of the scan plans that was trialed during development of the final scan plan for the D11 butt welds. The scan plan includes important information about the type of transducer used, the wedge used, the angle coverage of the sectorial scan, the groups of elements in the transducer to use, and the distance that each scan should be recorded from a known point.

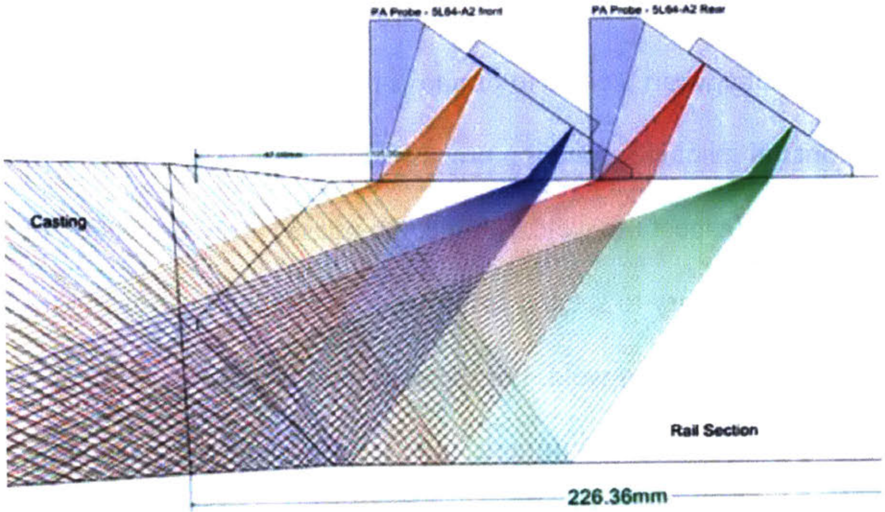

FIGURE 16: SAMPLE BEAMTOOL SCAN PLAN INSPECTION LAYOUT FOR D11 BUTT WELD

After developing a scan plan for the D11 butt weld joints that worked best for the equipment Caterpillar already owned, the next step was to prototype a fixture that allowed for easy and consistent encoded scanning. A fixture was fabricated and refined that attached to the D11 rail section with magnets. The fixture allowed for easy attachment to a string encoder as well as a straight edge to necessitate the consistent one-dimensional movement of the phased array transducer and wedge. Distance locations markings were made prior to welding the joint that allowed for proper location of the fixture upon inspection. Figure 17 shows the first functional prototype of the fixture, encoder, transducer, and Omniscan MX used that could accurately record weld inspection data on the D11 butt welds.

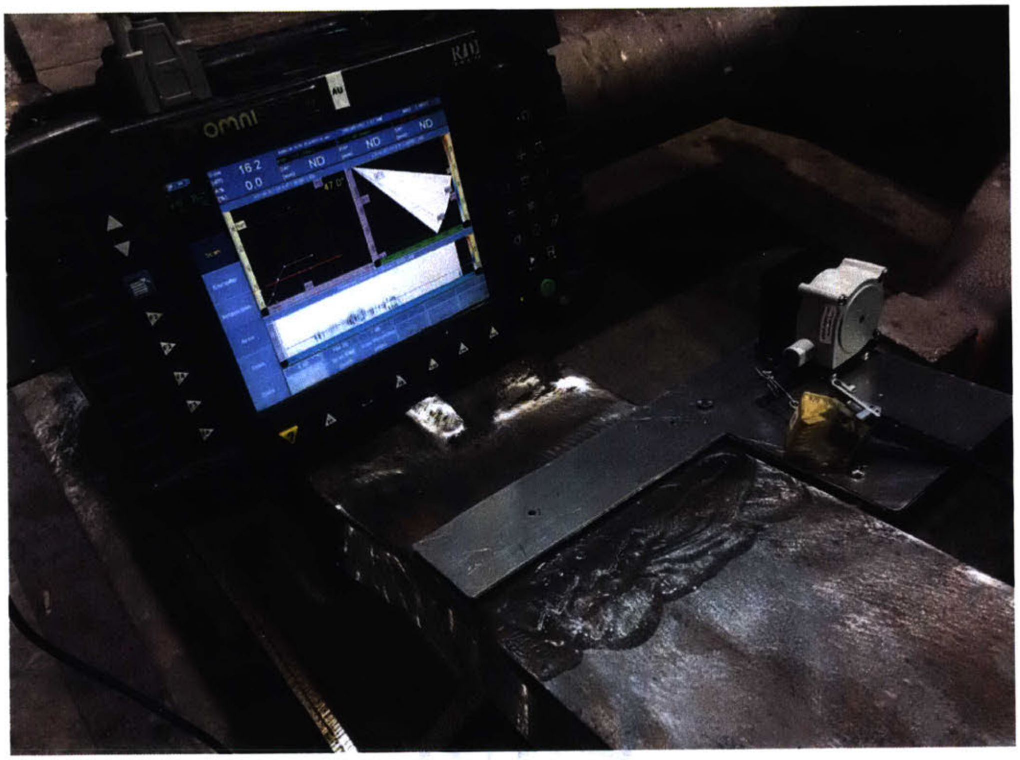

FIGURE 17: OMNISCAN MX WITH PROBE, ENCODER, AND FIXTURE TO INSPECT A D11 BUTT WELD

3.2.3 SCAN DATA DIGITIZATION AND STORAGE

Given the problems surrounding the limited granularity of inspection data and inspector performance, a scan data digitization solution was proposed. Using procedures developed alongside the phased array inspection process, encoded scan data can be digitally saved with each inspection and stored on a network drive. The weld quality inspection results will still be recorded manually by the inspectors in order to maintain production flow in the factory, but the scan data can more easily and quickly be shared on any computer with free software like TomoVIEWER by Olympus IMS. Subsequently, facility weld engineers, ultrasonic inspectors at other Caterpillar facilities, and quality managers gained access to a previously unavailable large data set about weld quality which enables further data analytics and statistical process control. The scan data can show volumetric data at every point in the weld. A screenshot from one scan on a D11 butt weld is shown in Figure 18 with the A-scan, S-scan, and C-scan focused at one minor discontinuity. This particular weld passed inspection, but the scan data allows for accurate sizing and classification of all discontinuities in the weld volume, even if they are smaller than Caterpillar's rejectable criteria.

Compared to the conventional ultrasonic inspection data in use before the implementation of phased array, the new raw scan data provides several orders of magnitude more information about weld quality. Additionally, the results of the inspections are much easier to interpret and understand for individuals who are not trained as ultrasonic inspectors.

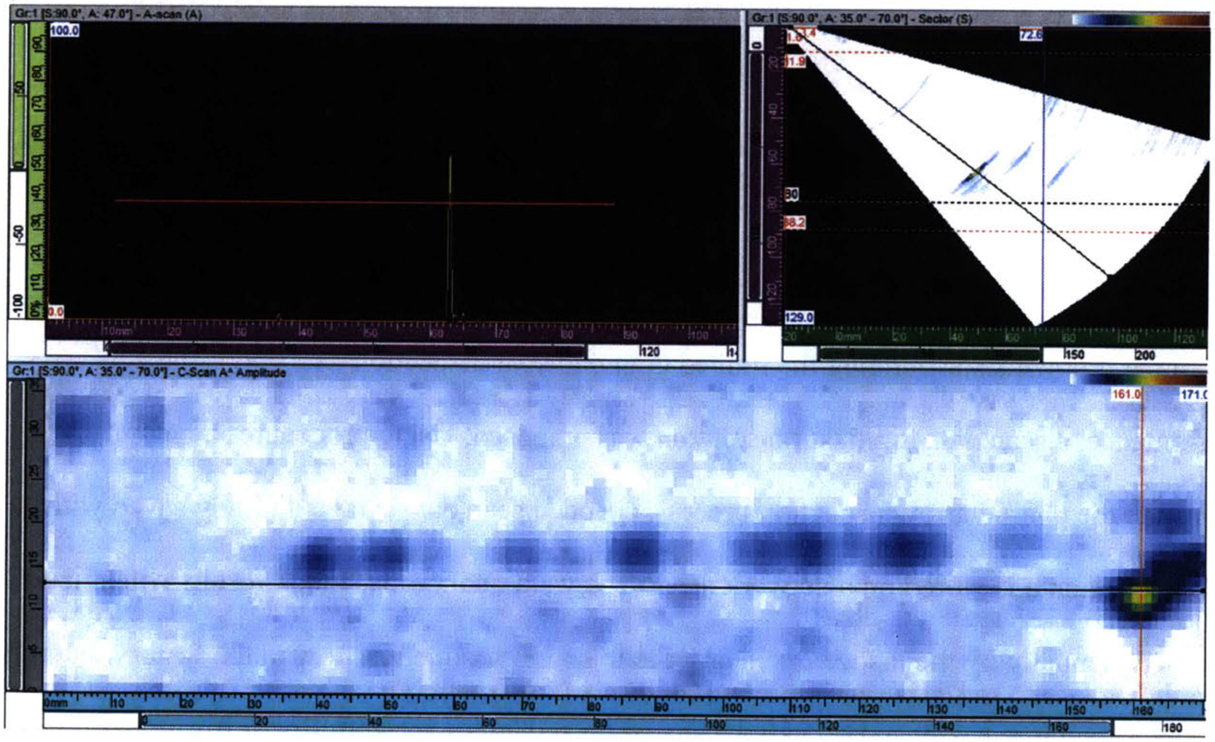

FIGURE 18: SAVED PHASED ARRAY SCAN DATA FROM D11 BUTT WELD

3.2.4 NEW QUALITY METRICS

Engineering and inspection managers currently have little visibility into the quality of weld inspections. As a result, it is difficult to tell which welders perform well, which inspectors have low error rates, and which process changes made in the factory actually improve quality. High level summary statistics are available, but they don't offer the granularity needed to fully understand defects or make lasting quality improvements. For example, defect rates are viewed as monthly averages, and those monthly averages are only formally reviewed with a larger management team on an annual basis. Therefore, quality trends are more frequently heard about from anecdotal evidence from the inspectors or welders. In more severe cases where critical defects are missed by inspectors, the quality problems are reported by customers, which can lag the actual production of the product by several years.

As Caterpillar begins to save more scan data, this will give better insight into welder and inspector performance. With this information, inspection managers can perform audits on inspectors to see if they are making the correct quality decisions. In the future, the identification of defects from scan data can be run through a computer program which would reveal which inspectors have unusual inspection behavior around defect limits. Even if only a small sample of scans were manually checked by a manager or third-party, this allows for a much better measure of inspector performance than the current state, where no tests or checks are conducted. While not available in real time, this analysis would give managers better data for annual performance evaluations.

Welding engineers can also use feedback from the scan data to communicate performance issues with welders or to test the effectiveness of process improvement changes. For instance, before the phased array inspection process was introduced, welding engineers noticed a trend of weld defects occurring near the root of butt welds on the D11 case to frame weldment. They introduced an additional step in the welding process to back-gouge and clean the far side of the weld before continuing to weld the second side of the weld joint. This resulted in a small improvement in the aggregate number of welds that passed inspection, but it was difficult to study how much of an improvement was made in the weld root conditions over time. Going forward with the phased array inspection process, the welding engineers can examine scan data from before and after the process change was made to quantify the improvement in weld quality and test their hypothesis that back-gouging the weld root significantly reduced the number of defects.

These metrics and visualizations cost additional time and resources before they are implemented as part of a standard process, but they offer extra tools and capabilities to study and improve quality information. Before the implementation of phased array ultrasonic testing, these capabilities were impossible to realize and become useful to managers at Caterpillar.

4. CONCLUSIONS AND RECOMMENDATIONS

This project focused on implementing phased array ultrasonic testing at Caterpillar to improve the weld inspection process in one factory. However, this solution is only a portion of the improvements in inspection quality possible at Caterpillar. This chapter provides a summary of the project and further recommendations based on the researcher's experience working at Caterpillar.

4.1 CONCLUSIONS FOR THE WELD INSPECTIONS AT CATERPILLAR

This project began with the known state that the current weld inspections at Caterpillar were not good enough. A trend of lower-hour fatigue failures in customer machines highlighted the costs of poor quality to Caterpillar and motivated the desire to improve inspections. Failures occurred at about one-third of the expected life of the machines, which meant that issues would usually only be discovered 2-3 years after manufacture. By analyzing the organizational structure and aligning key stakeholder interests, phased array ultrasonic technology was implemented in a factory in East Peoria.

Overall, the project demonstrated the value of following an organized technology development process when implementing technological changes in an operational environment. The solutions proposed and developed were to increase inspection accuracy, increase inspector efficiency, reduce costs, and improve quality. Caterpillar should continue to investigate further improvements in phased array procedures and facilities to expand the usage of phased array technology as it offers the prospect for considerable payoffs.

4.2 RECOMMENDATIONS FOR FUTURE INITIATIVES

While this project was specifically focused on the implementation of PAUT on one set of weld joints at one factory, to further capture the value of PAUT, it is recommended that Caterpillar take four actions: 1) Establish PAUT inspection procedures for additional weld joints that are not able to be inspected with conventional UT; 2) Develop internal software to easily parse encoded scan data and automatically identify and report defects; 3) Proceed with upgrading all of the production welding facilities with PAUT equipment and training; 4) Align incentives for inspectors to encourage continuous improvement of weld inspections.

ESTABLISH PAUT INSPECTION PROCEDURES FOR ADDITIONAL WELD JOINTS

With the work done to create standard work procedures for phased array UT setup and calibration that fit within Caterpillar's existing weld quality standards, there is opportunity to more quickly develop procedures for additional weld joints. In particular, there are a number of welds that are only visually inspected because the limitations inherent to conventional UT do not allow sub-surface inspection. Several cases were examined and development was started in parallel with procedures for welds in East Peoria.

The complicated joint geometry on a main frame rail weld on the 793F off-highway truck produced in Decatur, Illinois (as shown in Figure 19) prevented conventional UT inspections from occurring. A preliminary procedure was developed to scan and record the weld using phased array UT. The procedure utilized more advanced features of the phased array equipment to allow encoded scan data to be completed in one pass. One inspector was sent to a field site to examine the welds on a customers' machines. Figure 20 shows one of the scans performed in the field by the inspector. Establishing the ability to scan new weld joints not only improves product quality management, but also necessitates phased array training for inspectors that can then be leveraged to improve inspections efficiency on other weld joints.

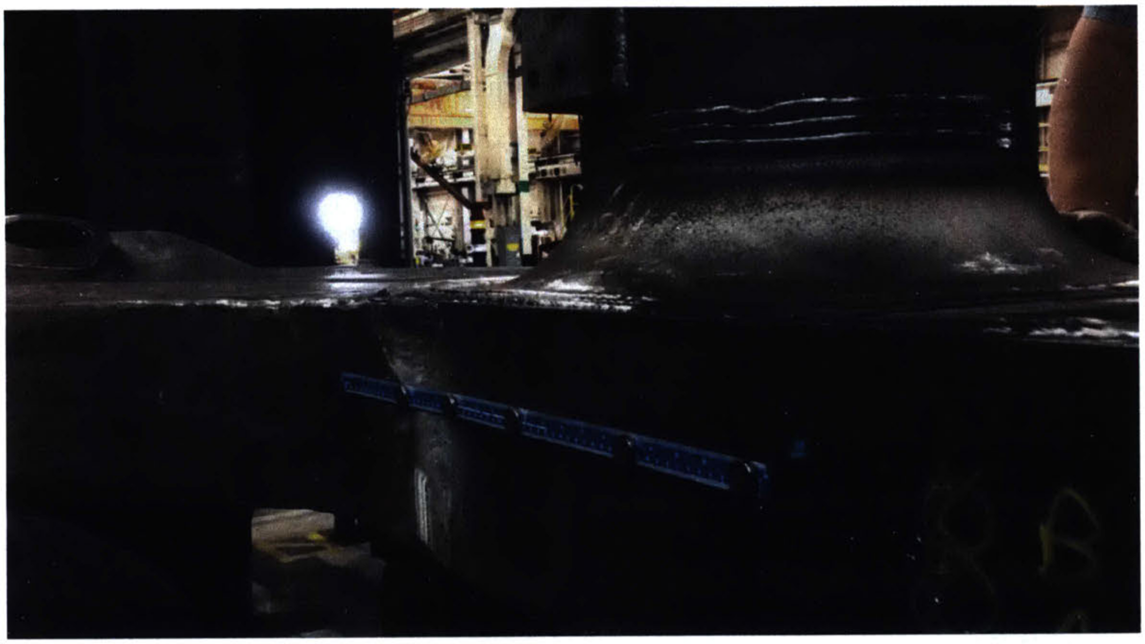

FIGURE 19: PHASED ARRAY WELD INSPECTION SET UP FOR 793F FRAME

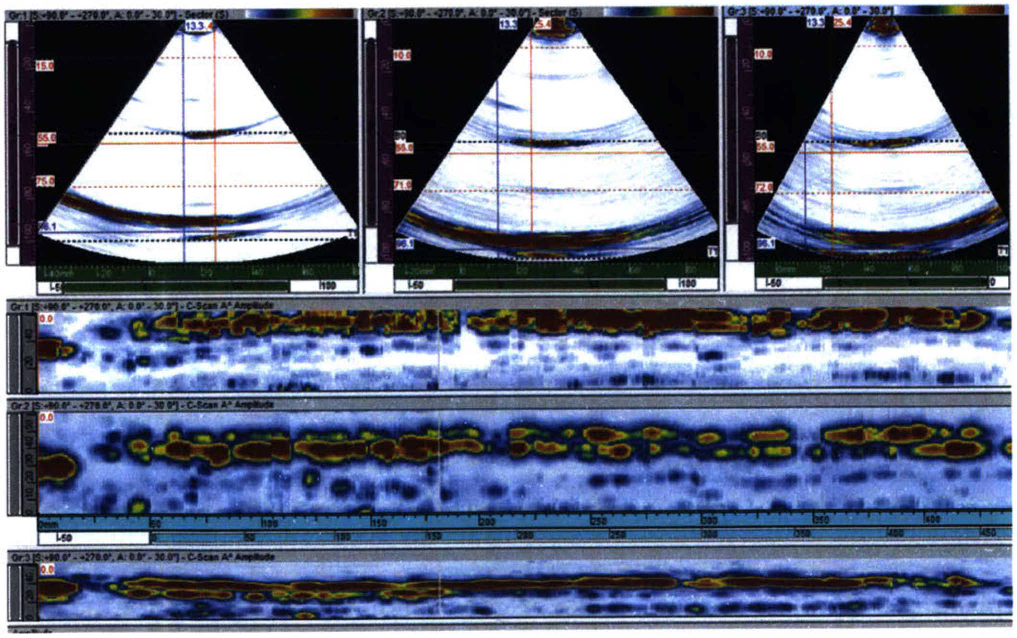

FIGURE 20: 793F FRAME PHASED ARRAY SCAN DATA COLLECTED IN THE FIELD

At another facility in China where excavator booms and sticks are fabricated, certain fillet welds were unable to be inspected with conventional UT. Training and procedures for phased array UT were shared and piloted in conjunction with the work done by the researcher in East Peoria. Figure 21 shows an image from one of the training documents that was used to teach inspectors about how to correctly use the phased array UT procedure on an excavator boom fillet weld. This work should be continued and fully implemented to realize the potential significant improvements in inspection and product quality.

FIGURE 21: PHASED ARRAY SCAN SETUP FOR EXCAVATOR BOOM IN CHINA

During the implementation of phased array UT in East Peoria, the researcher found that telling realistic stories about the future state of inspections to key stakeholders was critical to getting buy-in and pushing the project forward. A list of good candidate weld joints for the next implementation of phased array UT was created with help from the Caterpillar inspection community. As more phased array UT success cases are proven within Caterpillar, these stories can spread to other managers and facilities and further sell the value of phased array UT to skeptical stakeholders.

DEVELOP SOFTWARE TO READ AND IDENTIFY DEFECTS IN ENCODED SCAN DATA

The current weld inspection process is entirely subjective, and steps should be taken to develop and prove more reliable, objective systems. An initiative to improve data analytics is prioritized across the company, but the current focus of much of the internal data analytics is on using customer facing data to provide services. With an internal software development team dedicated to creating a program to automate defect detection in Caterpillar specific phased array UT encoded scans, there is significant opportunity to reduce the subjectivity of inspections. The researcher feels that this deserves further study.

UPGRADE ALL PRODUCTION FACILITIES WITH PAUT EQUIPMENT AND TRAINING

The researcher observed that access to the proper equipment and training was one of the largest barriers in the way to successfully implement phased array UT. With standard procedures in place, specific models and accessories can be chosen to simplify the introduction to the technology for other facilities. Internal training led by one of Caterpillar's own experts in phased array UT can help overcome the knowledge gap for inspectors. Although the cost of new phased array UT equipment is not trivial, it was shown that the benefits of higher weld and inspection quality greatly outweigh the costs of equipment and training for Caterpillar as a whole.

PRIORITIZE AND INCENTIVIZE CONTINUOUS IMPROVEMENT PROJECTS

The current organizational structure that includes inspectors and factory managers prioritizes maximizing defect containment and not negatively affecting production throughput. Most managers are not willing to commit resources to new inspection improvements because they do not understand the potential value. The adverse financial costs of warranty failures related to inadequate inspections are often delayed by years from the manufacture date, and do not have a formal feedback path to factory managers and weld inspectors. As a result, managers do not see why they should invest tens of thousands of dollars from their own budgets in better equipment, even though warranty costs from one recent quality problem alone exceeded a million dollars. Clear priorities for managers that incentivize proactive – instead of reactive – implementation of continuous improvement ideas from across the Caterpillar NDE community will greatly improve process quality and efficiency.

Inspectors on the factory floor will always have the most expertise about the current processes, and need to be incentivized to generate ideas for continuous improvement. Additionally, they need to be offered the time and support to develop the ideas into realized improvements. At the facility in Decatur, the inspection manager coaches and trains the inspectors on new inspection technology during normal working hours. This allows the inspectors to learn new skills, stay engaged with best practices, and offer new ideas for how to make their job better. Managers in other facilities need to have the same level of support from their own supervisors that allows them to use normal working hours to improve their own skills, the skills of their employees, and the inspection processes used in their facility. Managers will better understand quality issues, the potential cost savings to Caterpillar, and be able to better communicate them upstream.

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